AN ABSTRACT OF THE THESIS OF

Kylie M. Pace for the degree of Master of Science in Water Resources Science presented on September 17, 2015.

Title: Sediment Pulse Behavior in Gravel-bedded Rivers

Abstract approved:

Desirée D. Tullos Stephen T. Lancaster

As dams approach the end of their useful life, there is need to predict where and how accumulated sediment will move following their removal to estimate impacts on aquatic habitat and infrastructure. Flume studies suggest that sediment pulses disperse in place for most dams, but it is hypothesized that a low Froude number and relatively fine pulse grain size may characterize pulses that translate downstream. However, quantitative analyses of sediment pulse behavior have not been widely conducted in field settings. This research seeks to evaluate flume-derived hypotheses in field settings by 1) investigating whether dispersion or translation dominates pulse behavior observed in the field across a range of dam removal physiographies; and 2) evaluating whether Froude number, pulse material grain size, pulse size, and discharge can explain pulse behavior.

Based on results from flume experiments, translation is hypothesized to dominate pulse behavior in cases of low Froude number, fine pulse material, small pulse size, and large peak discharge. We evaluate the ability to explain pulse behavior by Froude number, grain size, pulse size, and discharge by comparing quantified predictors to visual and quantitative measurements of sediment movement at four field sites. Changes in pulse volume are calculated from bathymetry data and provide evidence of translational movement at all four sites. The results observe that dispersion dominates pulse behavior except when the site is characterized by a Froude number less than or equal to 0.4, and document a connection between translational behavior and wet water years.

Sediment Pulse Behavior in Gravel-bedded Rivers

by

Kylie M. Pace

A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Presented September 17, 2015

Commencement June 2016

Master of Science thesis of Kylie M. Pace presented on September 17, 2015.

APPROVED:

Co-Major Professor, representing Water Resources Science

Co-Major Professor, representing Water Resources Science

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of the Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Kylie M. Pace, Author

ACKNOWLEDGEMENTS

Thanks first goes to Dr. Desirée Tullos for providing the inspiration, guidance, infrastructure, and supporting brainpower from the beginning to the end. Thank you for taking me on! The lab groups of both my advisors patiently thought about the most tedious details of this work and coached me in everything from GIS to differential equations. Thanks are especially due to Cara Walter, who not only assisted in the collection and preparation of data, but also answered many a late-night question and should be recognized as an unofficial member of my committee. On that note, my entire committee was dedicated to helping me raise the quality of my work and tutoring me in their respective fields as I made the transition from policy to science. My place in the water science program would not be possible without the support of Dr. Mary Santelmann, who not only did not bat an eye when I changed programs, but also worked to keep me funded. Not only was I funded, the CEOAS staff and especially Lori, Robert, Stacey, and Melinda went above and beyond in supporting me as a teaching assistant. Jon Viducich, Caroline Nash, and Laura Hempel also graciously reviewed my much rougher early drafts.

On a more personal note, I want to thank my friends at OSU. I underestimated how graduate school would affect my stress level, but I even more so underestimated the bond that forms among each cohort. Lauren Smitherman, thank you for being my partner in the three-legged race that was our graduate school experience. Jacqueline Brenner, J$, thank you for reminding me what perspective looks like. Andrew, thank you for locating your office in Bombs and thank you for providing a dose of the social sciences. Laurel and Leah, I still can't quite believe that I actually know people as simultaneously talented and generous as you both are. Thanks to all the Hydrophiles and fellow TAs for further encouraging my life outside of classes, and my officemates Brett, Mike, Malia, Haley, Ingrid, and Dakotah for brightening my life on campus. Finally, it's no surprise that I am grateful to my partner, but I am extra lucky that he is a thoughtful and patient environmental engineer who is good at editing thesis manuscripts. Thank you!

CONTRIBUTION OF AUTHORS

The lab group of Dr. Desirée Tullos, including Cara Walter and Jack Zunka, collected the field data used in this research. Cara Walter prepared the DEMs for Savage Rapids, Brownsville, and Oak Creek, and regressed hydrologic data in order to estimate daily discharge at Brownsville.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX FIGURES

1 INTRODUCTION

As more dams reach the end of their useful lifespans (Graf 1999, Hart et al. 2002, O'Connor et al. 2015) and the decommissioning of dams gains popularity as a river restoration strategy (Grant 2001, Pizzuto 2002), it is increasingly important to understand how a site will respond to removal of dams and weirs. While the response of rivers to dam removal has been studied from the perspective of geomorphological processes and sediment transport (Pizzuto 2002, Kibler et al. 2011, Wang et al. 2014, Grant and Lewis 2015), questions remain regarding the fate of sediment released from the reservoir. Understanding the distance and rate at which stored reservoir sediments may move following barrier removal will improve predictions for critical management concerns, including aquatic species habitat (Greig et al. 2005), channel stability (Doyle et al. 2003), flood risk and infrastructure (Born et al. 1998), and water quality (Riggsbee et al. 2007, Tuckerman and Zawiski 2007).

Researchers commonly analyze the sediment released with dam removal as a wave or pulse (*sensu* Lisle 2008) of sediment, which facilitates describing the timing and location of transported sediment in terms of translational and dispersive behavior. The pulse is delineated by the apex and the upstream and downstream edges. The apex and both edges of a purely translational pulse migrate downstream at uniform rates, while a dispersive pulse is characterized by diminishment of the longitudinally-stationary apex and lengthening of the distance between edges (Lisle *et al.* 2001, Kasai *et al.* 2004). In both cases, the amplitude of the apex diminishes (Cui, Parker, Lisle, *et al.* 2003). The impacts of dispersive pulse evolution will be concentrated in one area, while those of a translational pulse will propagate farther downstream (Pizzuto 2002, Cui, Parker, Lisle, *et al.* 2003). Flume studies indicate that dispersion generally characterizes pulses in gravel-bedded streams, but some degree of translation may also occur (Lisle *et al.* 1997, Cui, Parker, Lisle, *et al.* 2003, Lisle 2008). For the purposes of this study, dispersive behavior is said to dominate pulse behavior when the measurements of dispersive movement exceed those of translational movement.

Past work has considered how site conditions affect pulse behavior. Translational behavior has been observed in flume experiments when the Froude number is low (Lisle *et al.* 1997, 2001), when the pulse material is finer than the ambient bed material (Cui and Parker 1997, Cui, Parker, Lisle, *et al.* 2003, Sklar *et al.* 2009), when the pulse size is small relative to the channel (Lisle *et al.* 2001, Sklar *et al.* 2009), and when peak discharge reaches at least three times the entrainment threshold discharge (Humphries *et al.* 2012). Numerical models also support an inverse relationship between Froude number and translational behavior (Lisle *et al.* 2001, Cao and Carling 2003, Cui, Parker, Lisle, *et al.* 2003, Cui *et al.* 2005, 2008).

Froude number, sediment grain size, pulse volume and discharge values relate to pulse behavior as descriptors of the stream's ability to transport sediment. The Froude number compares the velocity and geometry that influence a site's sediment transport rate. A low Froude number characterizes conditions of low velocity relative to depth (Williams 1970), and a trend has emerged from flume and field experiments that translation is only observed at Froude numbers of 0.4 or lower (Meade 1985, Lisle *et al.* 2001b, Sutherland *et al.* 2002, Cui, Parker, Pizzuto, *et al.* 2003), suggesting that a threshold may exist. The pulse sediment grain size affects the mobility of the pulse material. When the pulse material is finer than ambient sediment, the pulse sediment is more mobile and therefore it is relatively easier for trailing limb to be transported downstream (Lisle *et al.* 2001). A large pulse may obstruct flow, reducing sediment transport capacity upstream (Lisle *et al.* 2001, Cui *et al.* 2003) and encouraging deposition on the upstream edge of the pulse (Sklar *et al.* 2009) that prevents the pulse from moving downstream. It is not known at what volume, relative to channel geometry, the pulse may be expected to translate. Large peak discharges likely promote translation, as the sediment transport rate increases with discharge (Wilcock and Crowe 2003) and the greater flow depth increases the bed load transport zone (Humphries *et al.* 2012). The effect is that more pulse material may be transported downstream, adding to the measured translational movement. In flume studies, translation was observed for a peaked hydrograph with a peak discharge over three times the entrainment threshold discharge (Humphries *et al.* 2012).

It is not yet clear how closely relationships observed in flume experiments and derived numerically match responses in the field setting. Natural channels are subject to substantial complexity not present in physical models, including variability in channel geometry, planform, and flow resistance from vegetation and large wood (Madej 2001, Hart *et al.* 2002, Cui *et al.* 2008). Meanwhile, previous field studies have not quantitatively measured pulse movement, relying instead on patterns of erosion and deposition or changes in sediment transport rates to infer pulse behavior (Wohl and Cenderelli 2000, Kasai *et al.* 2004, Miyazaki *et al.* 2006, Cheng and Granata 2007, Humphries *et al.* 2012, East *et al.* 2015).

This research seeks to bridge the gap between flume and field methodology by quantifying field-observed behavior of sediment pulses following barrier removal at four gravel-bedded rivers. The broad objectives are to 1) investigate whether dispersion or translation dominates pulse behavior observed in the field across a range of dam removal physiographies; and 2) evaluate whether Froude number, pulse material grain size, pulse size, and discharge can explain pulse behavior. We evaluate the hypothesis, derived from flume studies, that dispersion dominates pulse behavior except in conditions of Froude number less than 0.4 and pulse material finer than surrounding bed material. In addition, we expect that large pulse volume is likely to move by dispersion, whereas high discharge is likely associated with translation. Finally, the assumptions and limitations of each technique to characterize pulse behavior are compared.

2 SITE BACKGROUND

Analysis is undertaken on four barriers located on three rivers in Oregon (Figure 1, Table 1). Two sites are former dams on the Rogue River in Southern Oregon. In the Willamette Valley, one site is a former dam on the Calapooia River and the fourth site is a creek crossing in the town of Corvallis.

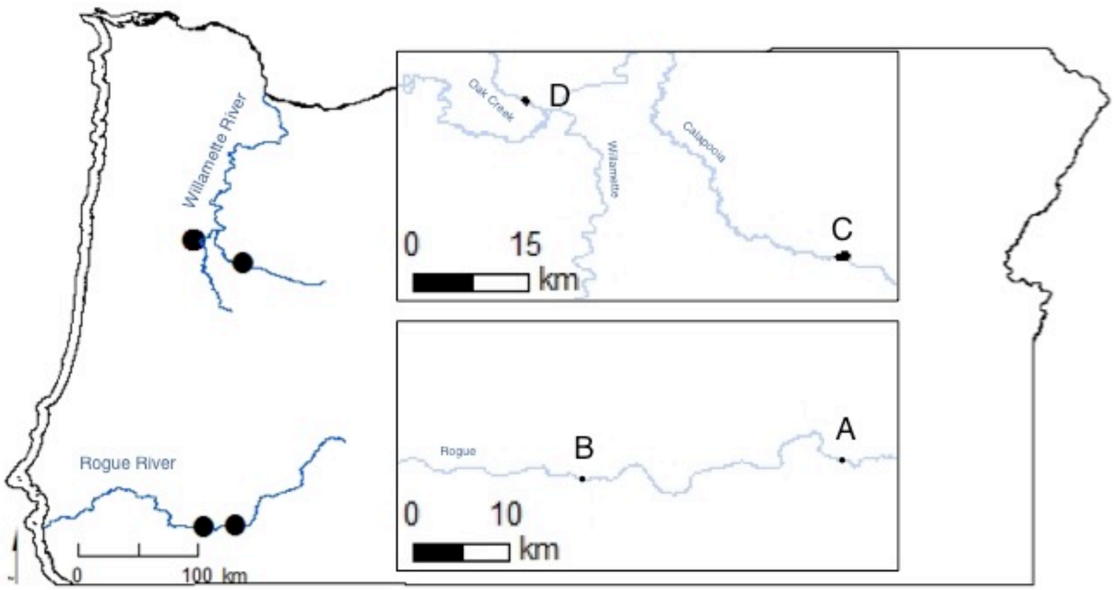


Figure 1. Locations of Gold Ray Dam (A), Savage Rapids Dam (B), Brownsville Dam (C), and Oak Creek Culvert (D)

Table 1. Barrier and site characteristics.

	Gold Ray	Savage Rapids	Brownsville	Oak Creek
Dam height (m)	12	12.5	1.8	n/a
Dam width (m)	110	142	33.5	n/a
Removal year	2010	2009	2007	2007
Stream Name	Rogue River	Rogue River	Calapooia River	Oak Creek
Channel Gradient (%)	0.21	0.27	0.23	0.65
Mean Annual Precipitation (cm)	103	100	173	150
Mean Discharge (m^3s^{-1})	83	98	12	0.17
Drainage Area (km^2)	5309	6294	394	31
Average Channel Width (m)	60	90	35	12
Initial Apex Height (m)	9.7	3.9	1.8	2.0
Initial Pulse Volume (m^3)	526,000	153,000	17,100	444
1.2 Return Interval Discharge (m^3s^{-1})	348	456	100	-

2.1 Gold Ray Dam

The Rogue River begins in the Cascade mountain range, flowing 346 km to the Pacific Ocean. Over half of the 13,390km^2 watershed is forested, and the underlying geology includes mudstone, black chert, limestone, andesite, and basalt (Pessagno and Blome 1990). The mountainous headwaters are also fed by snowmelt, contributing to long-duration peak discharge in the winter season November through May. The mean annual precipitation for the Gold Ray Dam watershed, calculated from USGS data, is greater than the mean annual precipitation for the larger Savage Rapids Dam watershed (Table 1).

Gold Ray Dam was a concrete dam on river kilometer (RK) 202 of the Rogue River, measured from the river's outlet at the Pacific Ocean. A crib dam was built in 1904 for hydroelectricity and was upgraded in 1941 to a concrete 12-meter tall dam. Power generation ceased in 1971, shortly before Jackson County began managing the site. By August 2010, when the concrete dam was removed, it was a liability risk to the County and an obstacle to fish migration. The reservoir stored a mixture of gravel (75%), sand (15%), and finer sediment (10%) (Elliott and Dittmer 2009). The post-removal gradient is measured from water surface elevations measured at the dam site to a riffle 2 km upstream (Elliott and Dittmer 2009). Two areas of stagnant backwater extended half a kilometer upstream of the dam and had drained by the third year following dam removal. The annual sediment transport rate is unknown. Historic hydrologic data were recorded at the USGS gage at Gold Ray Dam (#14359000).

2.2 Savage Rapids Dam

Savage Rapids Dam was a combination gravity and multiple-arch diversion dam located on RK 172 of the Rogue River, 31 RK downstream of Gold Ray Dam. Built in 1921 for irrigation to the Grants Pass Irrigation District, the dam was removed in 2009 to facilitate migration of steelhead, chinook salmon, and other anadromous fish. A pumping station now provides head for irrigation withdrawals. The channel bed along the survey area includes exposed bedrock and coarse gravel. The sediment in the reservoir comprised sand (71%), gravel (27%), and finer sediment (2%) (Reclamation 2001). The gradient is calculated from post-removal water surface elevations measured at the dam and a riffle 2 km upstream of the dam and is steeper than at Gold Ray Dam (Elliott and Dittmer 2009). The initial pulse volume is estimated by the Department of the Interior to represent 2 years of sediment load passing Grants Pass (Reclamation 2001). Historic hydrologic data were recorded from 1940 to 2009 at the USGS gage at Grants Pass (#14361500), 9 km downstream of Savage Rapids Dam and representing 101% of the Savage Rapids Dam watershed.

2.3 Brownsville Dam

The Calapooia River begins in the Western Cascades and flows through the Willamette Valley before joining the Willamette River near Albany (Runyon *et al.* 2004). The geology of the 947 km^2 watershed is formed by highly dissected basalt and andesite, but some bedrock is exposed at the dam site (Sherrod and Smith 2000). Precipitation is characterized by long-duration, low-intensity events from November to May (Weyerhaeuser 1998). The mean annual precipitation for the Brownsville watershed, calculated from USGS data, is the greatest of all four watersheds.

Brownsville Dam was a run-of-river, hollow, concrete dam located at RK 62 of the Calapooia River near the town of Brownsville. The dam's height increased to 4 meters from May to October. Built in the 1960s to replace a canal diversion, the dam obstructed fish passage and was a structural hazard (Runyon *et al.* 2004). It was removed in 2007, leaving a previously buried, one-meter-tall log-crib dam that dates to the late 1800s. The site consists of exposed partially-lithified Missoula flood deposits and clay hardpan from the dam to 400 meters downstream, where the gradient jumps to 33% (Kibler *et al.* 2011). The bed material covering the rest of the surveyed channel is an undocumented mix of silt and gravel, but the reservoir stored coarse gravel. The gradient was calculated in 2004 from water surface elevations measured at the dam to RK 69 (Runyon *et al.* 2004). The initial pulse volume represents less than one year of the sediment load measured 38 km upstream of the Brownsville dam (Runyon *et al.* 2004). Historic hydrologic data were recorded from 1935 to 1990 at the USGS gage at Holley (#14172000), 18 km upstream of Brownsville Dam and representing 66% of the Brownsville Dam watershed.

2.4 Oak Creek Culvert

Oak Creek originates in the Oregon Coast Range, near the town of Corvallis. The underlying geology of the 34 km^2 watershed is volcanic basalt (Klingeman 1979). Rain-fed discharge is highest from October to April (Meadows 2009). Mean annual precipitation for the Oak Creek watershed is similar to the mean annual precipitation at Brownsville.

Less than 2 km from Oak Creek's entry to the Marys River, a bike path crosses the stream and necessitates a culvert. The original crossing hindered flow, resulting in an accumulation of sediment. A new culvert was installed in 2007. The site's geology consists of quaternary terrace deposits. Bed material is dominated by gravel (Jones and Dillinger 2004). The gradient of the stream is calculated from the post-removal longitudinal profile at the culvert to 180m upstream and is the steepest of all sites' gradients (Table 1). Discharge data covering the survey period were regressed from the nearest USGS gages, located on the Marys River (#14171000) and Luckiamute River (#14190500) (Toman 2004).

3 METHODS

3.1 Field Data Collection

Topographic surveys before and after dam removal employed a Nikon DTM-352 Total Station at Brownsville and Oak Creek, and RTK-GPS at all sites. Elevation was referenced to the Oregon Department of Transportation datum. Measurements were taken within the reservoirs, longitudinally along the main channels and the thalweg, and at bar surfaces. A Teledyne RD Instruments Workhorse Rio Grande Acoustic Doppler Current Profiler (ADCP) attached to a cataraft was used to measure the bathymetry in non-wadable areas of the Rogue in combination with an RTK-GPS (Kibler *et al.* 2011, Tullos *et al.* 2014). Particle counts (Wolman 1954) were conducted at accessible bars at all sites. The nearest USGS gage or, where absent, a regression based on gages in nearby streams, yielded a discharge time series for each site, as described in further detail for each site below.

3.1.1 Gold Ray

Topography was surveyed annually from 8.5km upstream to 37.8km downstream of Gold Ray Dam, although gaps exist within this range where rapids prevented survey access. The analyzed survey area began 3300 meters upstream of the dam and continued to 5460 meters downstream of the dam. Surveying consisted of three to five longitudinal ADCP surveys spread across the width of the main channel and ground surveys on bars and along the sloughs. Data were collected prior to removal and each summer after removal in 2011, 2012, and 2013. The sloughs were not included in the 2013 survey, as they had by then ceased to be part of the active channel. Prior to dam removal, pebble counts were taken on four bars and two riffles. Subsequent pebble counts were taken from ten bars in 2011 and 2012 and from thirty-one bars in 2013. Discharge measurements from 1906 to 2014 were taken by a USGS gage at Raygold (#14359000).

3.1.2 Savage Rapids

Using similar methods as at the Gold Ray site, topography of the main channel and bars was surveyed from 5.7 km upstream to 8.7 km downstream of Savage Rapids Dam. Although the U.S. Bureau of Reclamation collected pre-removal bathymetry in 1999 and 2002, the extent of available pre-removal data is limited. An ADCP was used in 2010 and 2011 following dam removal. ADCP surveying of the Gold Ray site also reached the Savage Rapids site in 2012 and 2013. Pebble counts were collected in 2008, 2009, 2010, and 2011 at the margins and tails of up to 16 bars. Discharge data from 1940 to 2014 were collected from the USGS gage at Grants Pass (#14361500).

3.1.3 Brownsville

Topography was surveyed from 0.4km upstream to 1.4km downstream of Brownsville Dam. Data were collected at cross-sections, along the thalweg, and on bars in 2007, before removal, and in the summers of 2008 and 2009, after removal. The channel was divided according to pre-removal morphology (e.g. riffles, pools, glides) and four equally spaced cross-sections were placed within each unit (Walter and Tullos 2010, Zunka *et al.* 2015). Particle counts as well as both surface and subsurface bulk sediment samples were collected from at least 6 bars and at least 4 riffles within the survey extent. A pressure transducer was installed on the Calapooia River 3km downstream of the study site in order to record water height data starting in September 2007. A rating curve was developed using discrete flow measurements (Kibler *et al.* 2011). Discharge data from 1935 to 1990 collected at the former USGS gage at Holley (#14172000) were regressed with nearby USGS gages on Wiley Creek (#14187000), the South Santiam (#14185000), and Mohawk River (#14165000) to estimate average daily discharge at Holley over the survey period (Walter and Tullos 2010). At 18 km upstream of the Brownsville dam, the gage at Holley is closest to the dam site.

3.1.4 Oak Creek

Topography of the main channel was surveyed annually from 160m upstream to 164m downstream of the culvert site, and pebble counts were collected at transects across the entire channel every 5 meters. Data were collected in 2007, prior to the culvert replacement, and again in 2008 and 2009. Historical discharge data were not available for this site.

3.2 Processing of Field Observations

Changes in bed elevation and sediment volumes are used to evaluate pulse movement. Annual bathymetry data are first imported to ESRI ArcMap and used to build triangular irregular networks (TINs) over the wetted channel. The TIN to Raster tool is then applied to convert the TINs to digital elevation models (DEMs). The natural neighbors interpolation method is used, with the sampling distance of 1 meter (Wheaton 2008).

The Geomorphic Change Detection (GCD) tool creates Digital Elevation Models of Difference (DoD) between pre-removal and post-removal DEM surfaces (Wheaton *et al.* 2009). Changes in topography and point density contribute to the estimation of uncertainty in the DoD through the application of a Fuzzy Inference System (Wheaton *et al.* 2009). The probability uncertainties of the DoDs range from 2% to 86% and are highest at Brownsville and Oak Creek.

Pulse volumes are calculated from DoDs masked by the survey area. The survey area contains the survey points from both compared years and is divided into equally-spaced polygons. The longitudinal length of each polygon equals the average channel width for each reference site (Table 1). The net volume is calculated for every equally-spaced polygon by multiplying the mean change in elevation by the polygon area. The gross volume of each polygon is found by adding the net volume to the pre-removal gross volume.

The pre-removal gross volume is assumed to be zero downstream of the dam and is calculated as the volume between a valley surface and the pre-removal DEM. The valley surface is constructed at Gold Ray Dam and Oak Creek by linearly interpolating between two cross-sections. The cross-sections are located at riffles upstream and downstream of the immediate vicinity of the dam and reservoir where sediment deposition is less expected and valley slope points therefore likely represent the historical elevations of the channel (White *et al.* 2010). The lack of pre-removal surveys at Savage Rapids means that the pre-removal gross volume is unknown at Savage Rapids. The Brownsville surface is based upon the results of a seismic refraction survey conducted in 2006 (Northwest Geophysical Associates 2006). This method of calculating pre-removal gross volume considers all deposition downstream of the flow barrier to be part of the pulse.

3.3 Methods of Predicting Pulse Behavior

3.3.1 Froude Number

The Froude number is a dimensionless measurement of inertial to gravitational forces. In the field, the Froude number is calculated from stream velocity v and hydraulic radius R;

$$Fr = \frac{v}{\sqrt{gR}}, \qquad (1)$$

where hydraulic radius R is the cross-sectional area divided by the wetted perimeter. We calculate the Froude number over the initial pulse area by using the geometric mean of bankfull channel dimensions measured at reservoir cross-sections. The effective discharge Q calculated in section 3.3.4 and the geometric mean of cross-sectional areas A determine stream velocity. We evaluate the hypothesis that translational movement will exceed dispersive movement only for sites characterized by a Froude number less than or equal to 0.4.

$$v = \frac{Q}{A} \qquad (2)$$

3.3.2 D_{50} Grain Size

The relative pulse grain size is measured by analyzing the mean D_{50} grain size of pre-removal particle counts collected from accumulated pulse material and from bed material. The surface material in the impoundment is assumed to be the pulse material. The surface material downstream of the barrier is assumed to be non-pulse, ambient bed material. The mean D_{50} grain size in the impoundment is divided by the mean D_{50} grain size downstream of the dam. A resulting ratio less than 1 indicates that the pulse material is finer than the bed material and predicts that the greater mobility of pulse sediment will result in translation. A ratio greater than 1 indicates that the pulse material is coarser than the bed material and predicts that the trailing edge of the pulse will remain in place.

3.3.3 Relative Pulse Size

The size of the pulse relative to channel geometry is calculated as a ratio of the initial pulse apex height to active channel width. The apex height is the maximum change in elevation measured between the valley and pre-removal DEM surfaces. Because no limit has yet been established as the maximum pulse size for translation, we include the comparison of pulse size in order to inform further development of pulse behavior predictors.

3.3.4 Volume Ratio

The volume ratio compares a site's flow volume to the initial pulse volume. The 1.2 return interval (RI) is applied as a proxy for the channel's effective discharge (Biedenharn *et al.* 2000). The 1.2 RI is calculated from annual daily maximum flows. Because historical discharge data at Oak Creek were not available, return intervals are not calculated at Oak Creek. The flow volume is the volume of water that passes a cross-section in the first two water years following barrier removal. The flow volume is calculated by identifying all flow rates greater than the 1.2 RI, multiplying each identified flow rate by its duration, and summing the results. Flow rates are measured in 15-minute intervals. The DoD analysis comparing the pre-removal and valley surfaces measures the initial pulse volume, except at Savage Rapids where previous work by Elliott and Dittmer (2009) estimated the initial pulse volume. We include the comparison of volume ratio in order to inform further development of pulse behavior predictors.

3.3.5 Peak Discharge

Finally, we compare peak discharges for each year following removal to investigate how conditions following barrier removal may affect pulse behavior. We hypothesize that evidence of translation will exist in relatively wet water years, when discharge exceeds the 1.2 RI. The water years are numbered from the first full water year (October 1 to September 30) following barrier removal. For example, if a dam is removed on September 1st, the water year matching the first year of barrier removal begins one month later. Water years are evaluated by comparing the duration and magnitude of discharges greater than the 1.2 RI discharge. We calculate the duration of high flow by the percent of the minutes in a year when discharge exceeds the 1.2 RI. The magnitude of the peak flow is presented as a multiple of the 1.2 RI.

3.4 Indicators of Pulse Behavior

The methods for characterizing observed pulse behavior in flume experiments (Sklar *et al.* 2009) are applied to the gross volumes for each field site. For the purposes of this study, dispersive behavior is defined to dominate pulse behavior when dispersive movement exceeds translational movement. Dispersive and translational movement is evaluated by: 1) visual observation of apex movement; or changes in 2) Péclet number, 3) the middle 50% of volume, 4) mean and variance, and 5) cumulative volume.

3.4.1 Visual Observation

Pulse behavior is first evaluated visually from DoD results. Translation is distinguished by the shift of the pulse apex downstream over time, where the apex is identified as the location of maximum change in elevation. Dispersion is interpreted from the lengthening of areas of accumulated pulse sediment. Observed changes in total pulse volume are quantified by gross volume results.

3.4.2 Péclet Number

The Péclet number is a dimensionless ratio commonly used to model convective heat transfer, applied herein such that the advective and diffusive movements described by the Péclet number are analogous to translation and dispersion, respectively (Sklar *et al.* 2009).

Péclet numbers greater than 1 indicate the dominance of advective and therefore translational movement, whereas Péclet numbers less than 1 are evidence of the dominance of dispersion. Negative Péclet numbers calculated from decreasing variance are inconclusive.

$$Pe = \frac{A_{eff}}{D_{eff}} \quad (3)$$

$$A_{eff} = \frac{(\mu_{t+1} - \mu_t)^2}{L*t} \quad (4)$$

$$m = \frac{\sigma^2}{L} - \left(\frac{\mu}{L}\right)^2 \quad (5)$$

$$D_{eff} = \frac{1}{2}\frac{dm}{dt} \quad (6)$$

The numerator A_{eff}, representing advection, is calculated from the mean locations of pulse volume at consecutive survey years, μ_t and μ_{t+1}, the total pulse length L, and the time t between surveys (Equation 4). The denominator of the Péclet number is an effective dispersion coefficient that is calculated from the change in spatial moments over time (Aris 1956, Roberts and Goltz 1987). The first and second spatial moments are the mean location μ and variance σ^2, respectively, described in section 3.4.4. Both the mean location and variance are normalized by the total length L of the pulse (Equation 5).

3.4.3 Middle 50%

The middle 50% method is similar to the Péclet number method in that it calculates a ratio comparing translational movement to dispersive movement. Downstream movement of the median location measures translation, while the spreading of the length of the middle 50% of volume measures dispersion (Sklar et al. 2009). Cutting off the outer 50% of volume removes the noisy, small accumulations on the upstream and downstream survey extents. The length of the middle 50% of the pulse is found by dividing the cumulative gross volume into quarters and measuring the longitudinal distance covered by the middle two quarters (Figure 2A). The pulse center is represented by the median location at which half of the total gross volume exists (Figure 2A). The spacing of polygons (described in section 3.2) determines the resolution of the gross volume values. When median locations do not fall on a polygon boundary, they are linearly interpolated from equally spaced polygon locations. A ratio of the change in median location to the change in pulse length, visualized as the slope of the line in Figure 2B, compares translational to dispersive movement.

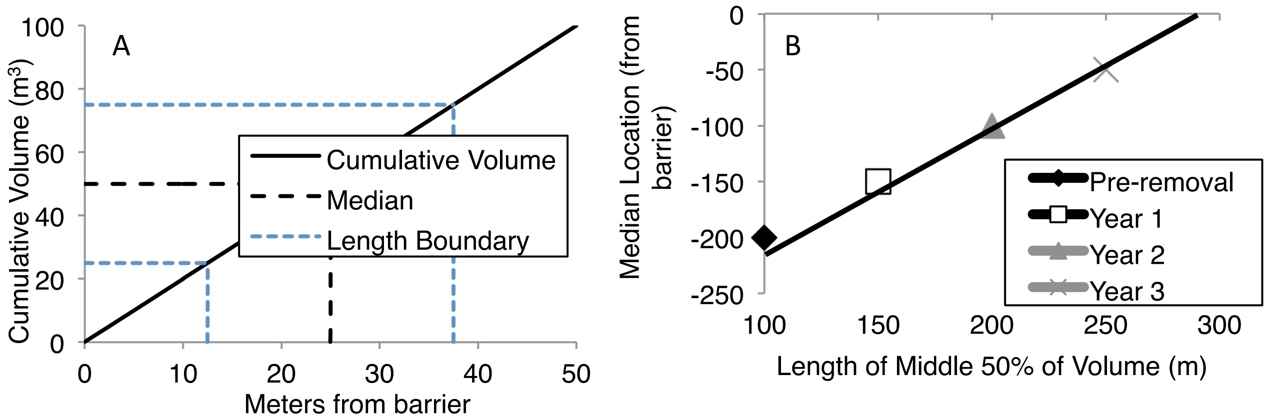


Figure 2. Conceptual graphs of (A) identifying the length of the middle 50% of volume based on the cumulative volume, and (B) comparing the movement of median location, indicating translation, to increasing length of middle 50% of pulse volume, indicating dispersion

3.4.4 Mean and Standard Deviation

Changes in the mean and standard deviation of gross volume location also describe pulse behavior. The downstream movement of the mean location measures translational movement, while increasing standard deviation measures dispersive movement. Volume values are represented by the gross pulse volume measured within each equally-spaced polygon (section 3.2). The location of each polygon is measured as the number of meters between the polygon's downstream boundary and the most upstream survey location. The mean location of volume μ is calculated by summing the products of volume and location and then dividing by the total cumulative volume as if the spatial distribution were a probability distribution with distance from the barrier on the x-axis and the fraction of total volume on the y-axis.

$$\mu = \frac{\sum(distance * volume)}{total\ volume} \tag{7}$$

The standard deviation σ is calculated by summing the products of volume and squared location and then dividing by the total cumulative volume.

$$\sigma = \sqrt{\frac{\sum(distance^2 * volume)}{total\ volume}} \tag{8}$$

The ratio of translational to dispersive movement is calculated by dividing the change in mean location by the change in standard deviation.

3.4.5 Cumulative Volume

Changes in the spatial distributions of annual cumulative gross volumes measure changing pulse shape and therefore indicate pulse behavior (Sklar *et al.* 2009). The cumulative volume distribution represents the integral of the volume density function. As the apex of a dispersive pulse diminishes in volume over time, the curve of a dispersive cumulative volume will flatten (Figure 4). Cumulative volume curves that do not flatten between years indicate that the pulse shape does not change, as characterizes translation. The flattening of the cumulative distribution is measured by linear trendlines fit to each cumulative distribution. Linear trendlines are used in order to quantifiably measure change in the cumulative distributions. The strength of dispersion is noted by the magnitude of the percent of change in the trendline slope from one year to the next.

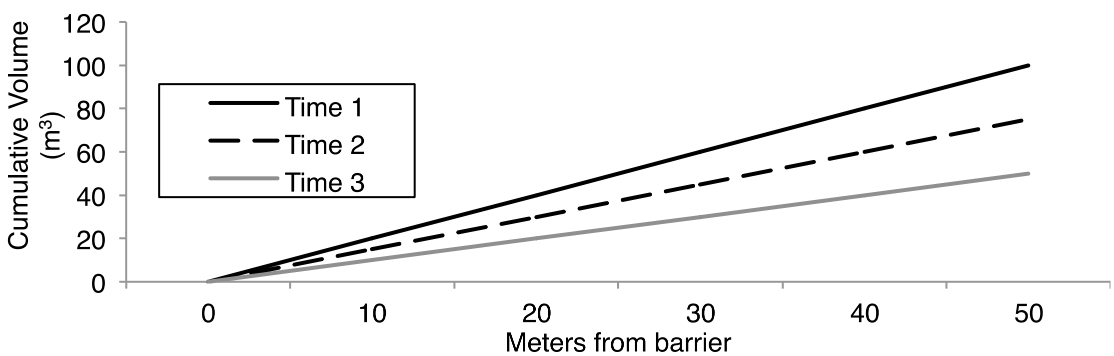


Figure 3. Conceptual graph of the flattening cumulative volume indicative of a dispersive pulse

4 RESULTS

4.1 Predicted Pulse Behavior

If Froude number less than 0.4, grain size ratio less than 1.0, small pulse size ratio, and large volume ratio might predict translational pulse behavior, then the results indicate that the most evidence of translation is predicted at Savage Rapids. Savage Rapids and Brownsville are the only sites where the Froude numbers are less than or equal to 0.4, and Savage Rapids also has the smallest pulse size ratio and the largest volume ratio (Table 2). Although the Froude number at Brownsville is low, the grain size ratio is greater than 1.0 and the pulse size ratio is the largest (Table 2), both suggestive of dispersive pulse behavior. The Oak Creek site is noticeable for its large Froude number and small grain size ratio (Table 2), predicting both dispersive and translational behavior, respectively.

Table 2. Results of methods to predict pulse behavior at each site. Shaded boxes indicate a prediction that translational movement will exceed dispersive movement.

	Gold Ray	Savage Rapids	Brownsville	Oak Creek
Froude number	0.82	0.23	0.40	0.93
Grain size ratio	0.40	0.38	1.3	0.23
Pulse size ratio	0.16	0.04	0.19	0.17
Volume ratio	205	318	81	-

Analysis of daily mean discharge values indicates that Gold Ray, Savage Rapids, and Brownsville all experience at least one wet water year when peak discharge exceeds the 1.2 RI (Table 3). The duration of peak discharge is largest in the second year following barrier removal at Brownsville, lasting for 0.8% of the water year (Table 3). The magnitude of peak discharge relative to the 1.2 RI is largest in the third year at Gold Ray (Table 3).

Table 3. Percent of water year with flows exceeding the 1.2 RI and peak flow as a multiple of the 1.2 RI (in parenthesis). Water years that exceed the 1.2 RI discharge are shaded.

	Gold Ray	Savage Rapids	Brownsville
Year 1	0.4% (1.5)	0 (0.6)	0 (0.8)
Year 2	0.4% (1.6)	0.2% (1.2)	0.8% (1.2)
Year 3	0.7% (3.1)	0.1% (1.2)	-
Year 4	-	0.4% (2.4)	-

4.2 Geomorphic Change

Based upon visual inspection of net erosion and deposition (Figures 4-7), dispersion appears to dominate at all sites except Savage Rapids (Figure 5), as illustrated by the stationary apexes.. At Savage Rapids, the peak elevation of deposition downstream, relative to the first year following removal, is greatest in the third year following barrier removal and appears to shift upstream by 50 meters in the fourth year, indicating neither translation nor dispersion (Figure 5).

Visual inspection of gross volumes (Figure 8) indicates a mix of translation and dispersion at all sites but Brownsville (Figure 8C). The apex of the gross volume diminishes in volume and moves downstream at Gold Ray, Savage Rapids, and Oak Creek, while the apex at Brownsville diminishes in volume but does not move downstream, indicating dispersion (Figure 8). For all sites but Gold Ray, the total area under the curve diminishes (Figure 8). More sediment is eroded from the upstream survey area than is deposited in the downstream survey area, indicating a total net loss of recorded pulse sediment (Figure 9).

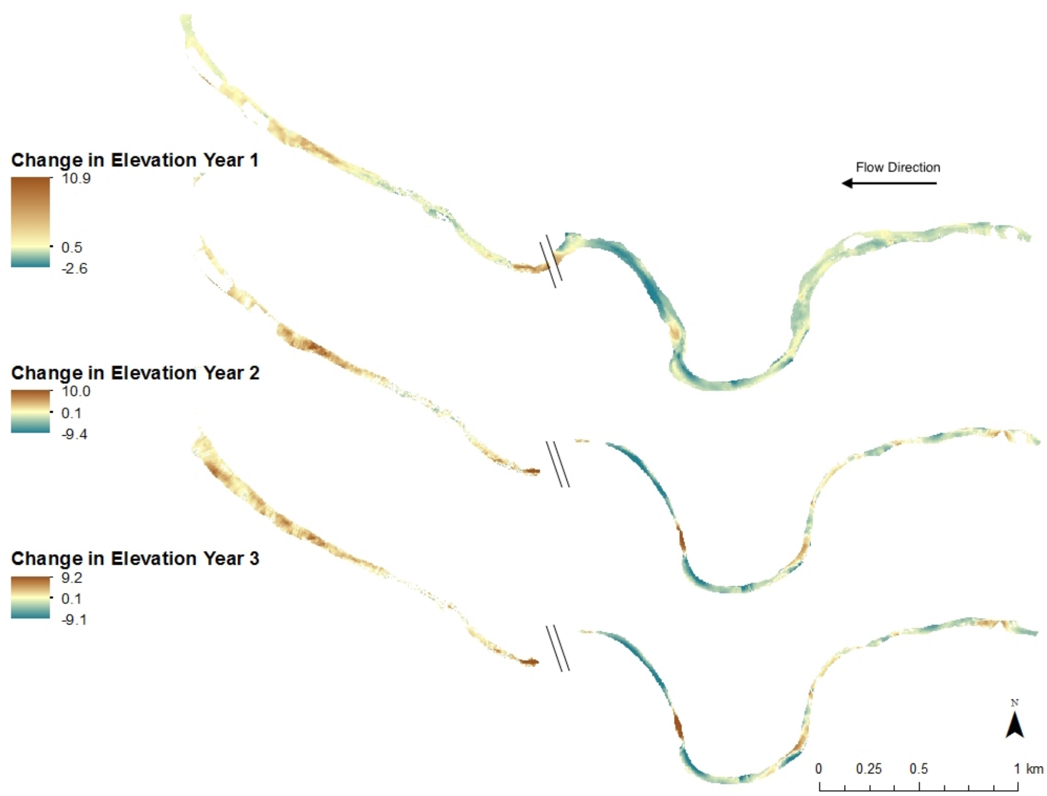


Figure 4. DoDs relative to pre-removal DEM at Gold Ray Dam on the Rogue River. The uncertainty probability ranges from 2% to 48%.

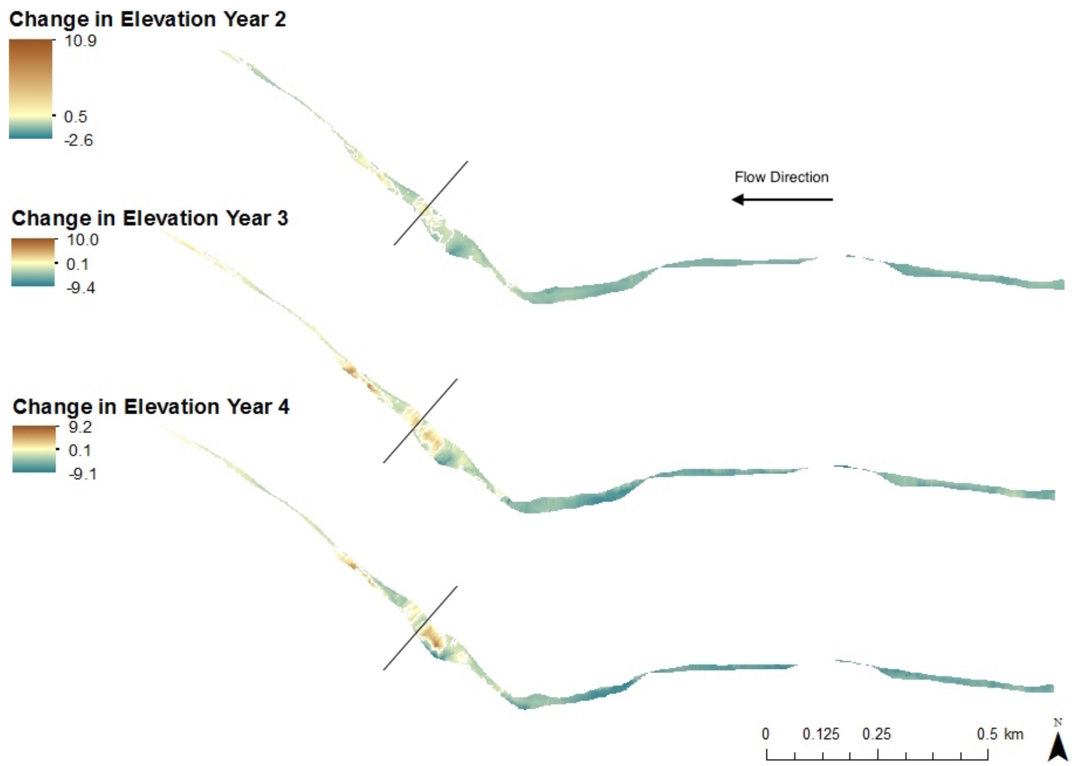


Figure 5. DoDs relative to Year 1 DEM at Savage Rapids Dam on the Rogue River. The uncertainty probability ranges from 2% to 48%.

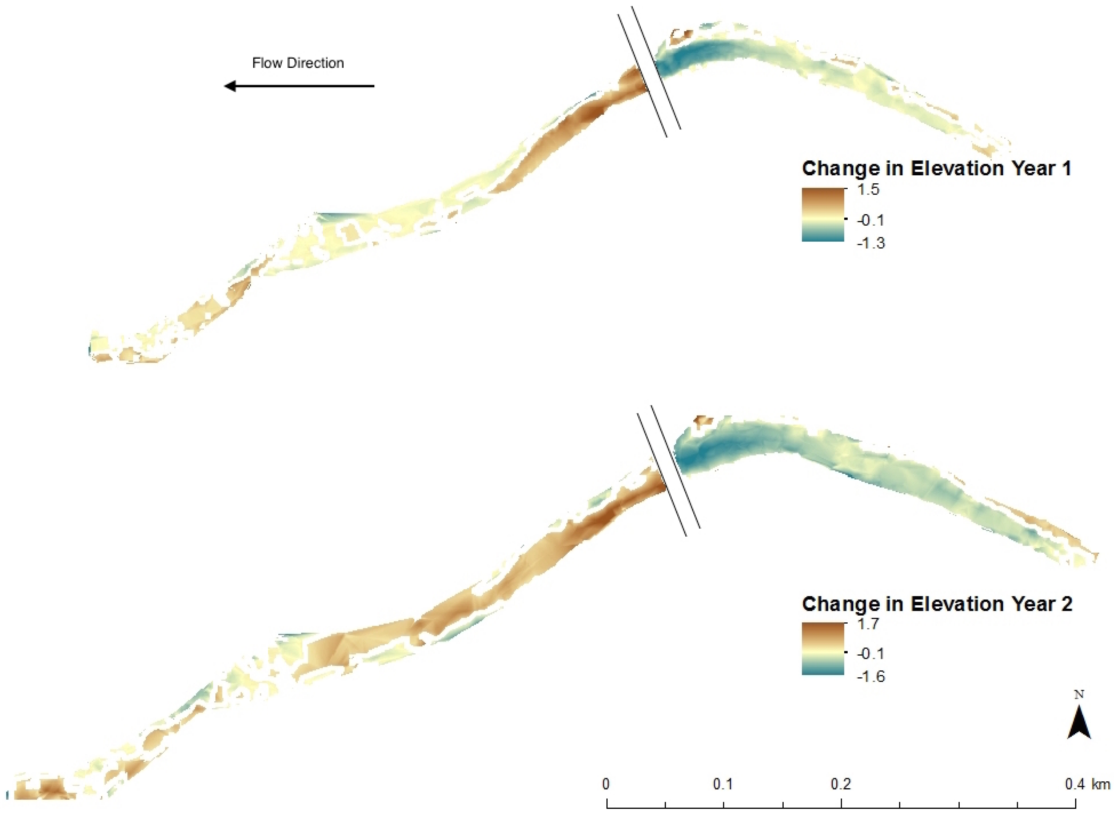


Figure 6. DoDs relative to pre-removal DEM at Brownsville Dam on the Calapooia River. The uncertainty probability ranges from 5% to 86%.

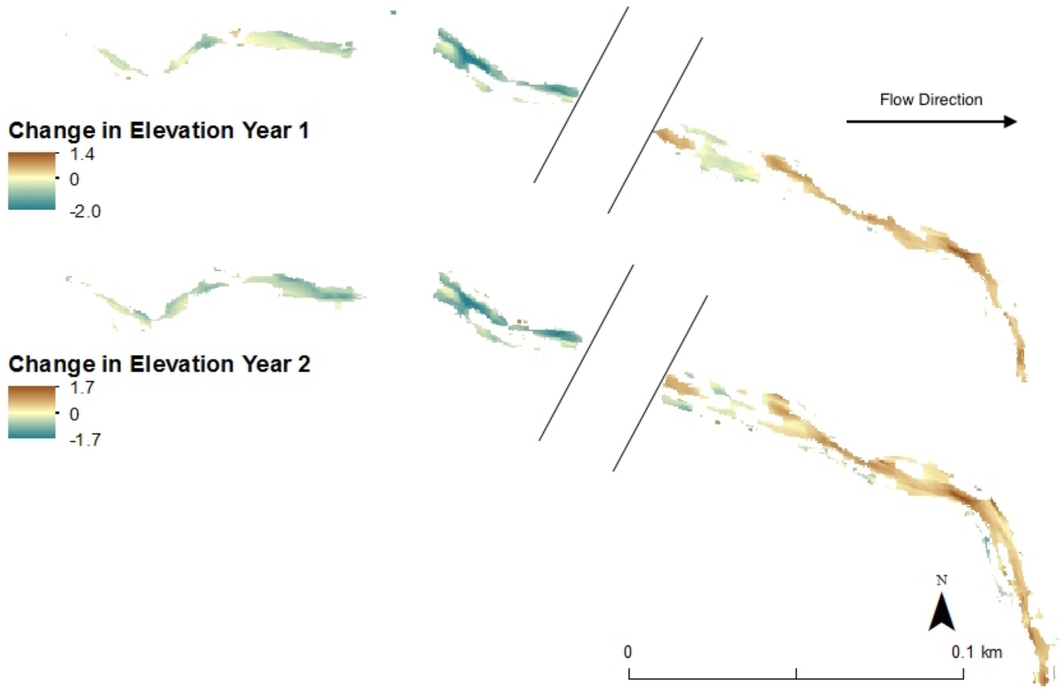


Figure 7. DoDs relative to pre-removal DEM at Oak Creek culvert on Oak Creek. The uncertainty probability ranges from 2% to 86%.

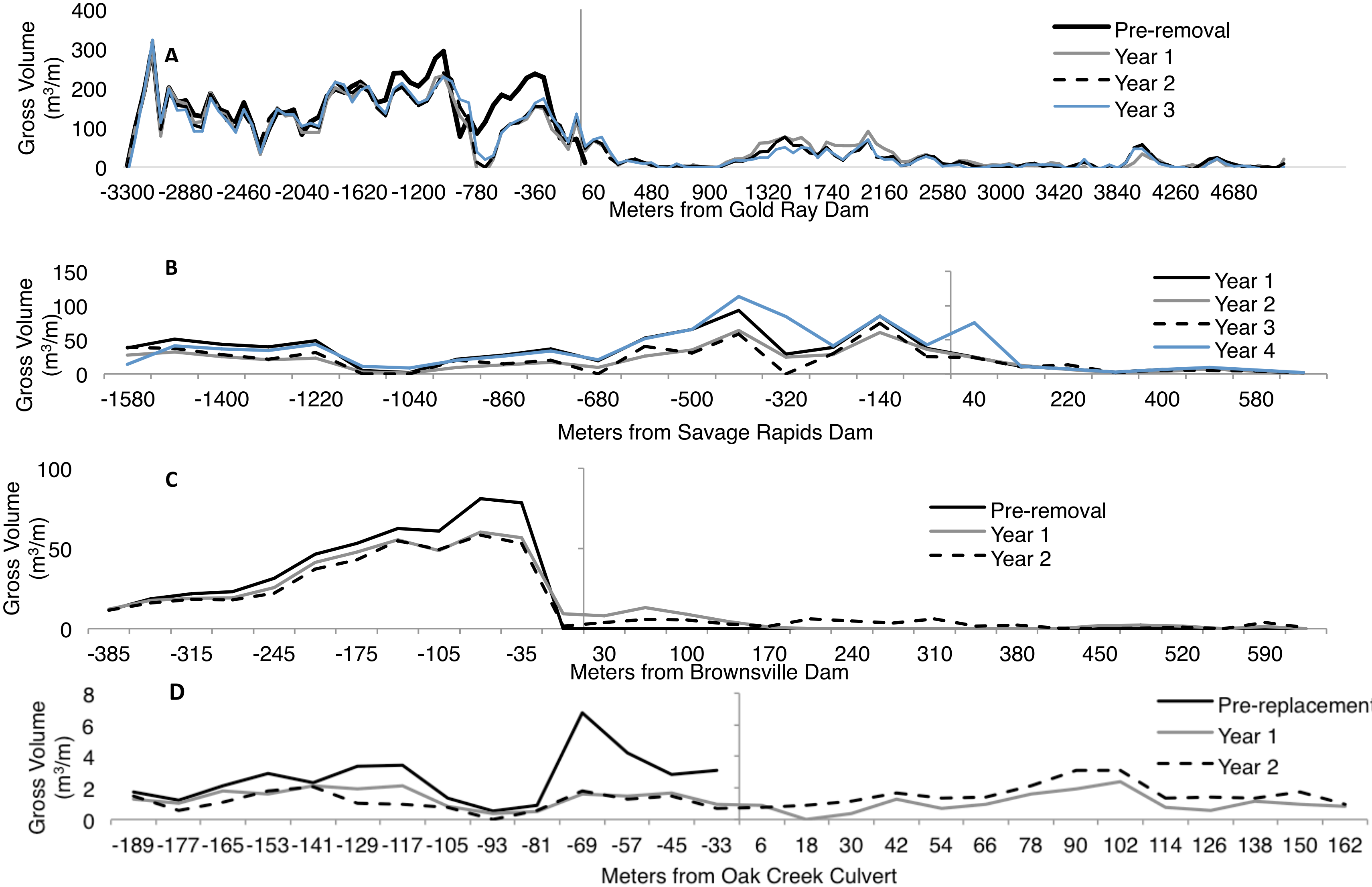


Figure 8. Gross volumes at (A) Gold Ray, (B) Savage Rapids, (C) Brownsville, and (D) Oak Creek

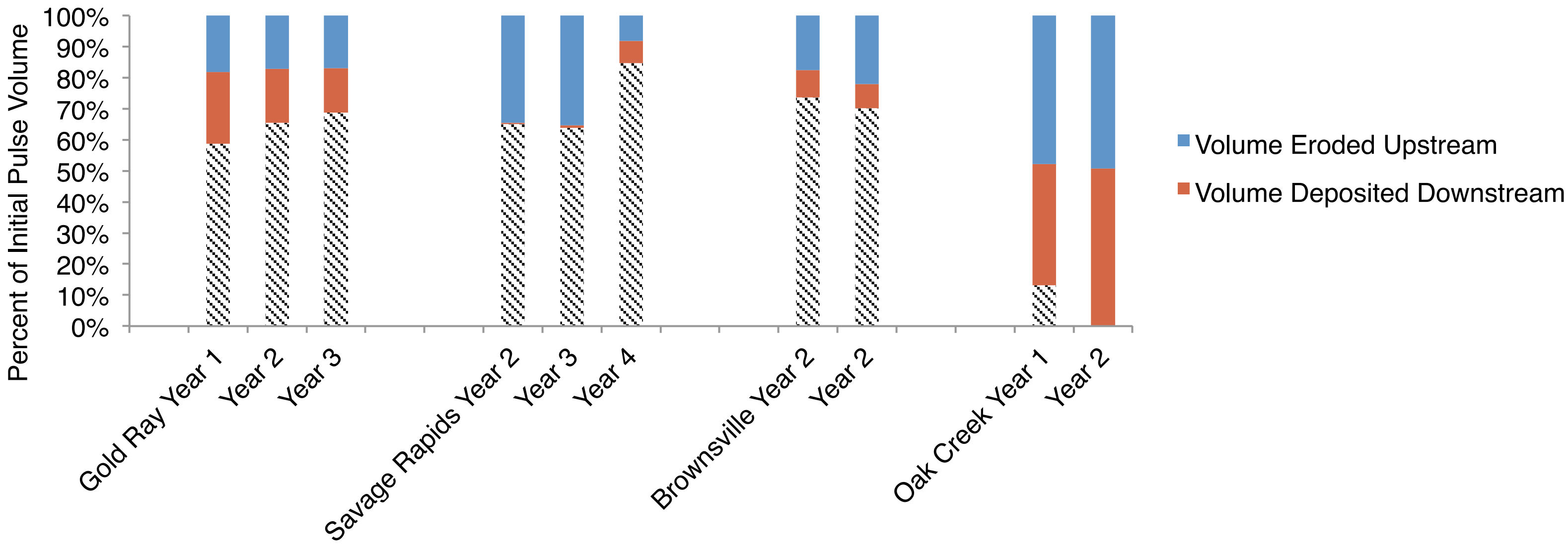


Figure 9. Eroded and deposited volumes as percentage of initial pulse volume. Remaining post-removal pulse volume upstream of the barrier is not represented. The grey hatched area represents the remaining percent of the initial pulse volume that either remains upstream, erodes downstream, or is lost to the downstream barrier.

4.3 Evaluated Pulse Behavior

The results of the quantitative methods to evaluate pulse behavior provide evidence of translation at all sites, but also suggest that dispersive movement exceeds translational movement for all but one pulse. Changes in the median and mean locations indicate translational behavior occurred at all sites, but the ratio comparing changing median location to pulse length is greater than 1, and therefore indicates the dominance of translation, only for the second year at Savage Rapids (Table 4). The ratio of changing mean location to standard deviation is greater than 1, indicating the dominance of translation, in the fourth year at Savage Rapids and the second year at Brownsville (Table 4). The Péclet number is less than 1 for all survey years, suggesting dispersive pulse behavior dominates translational behavior.

Table 3. Quantitative indicators to evaluate pulse behavior. Evidence of translation is marked (T), dispersion is marked (D), and inconclusive results are marked (-). Evidence of translation exceeding dispersion is shaded. Ratios are in boxed rows.

Site name	Gold Ray				Savage Rapids				Brownsville			Oak Creek		
Year	Pre	1	2	3	1	2	3	4	Pre	1	2	Pre	1	2
Percent change in cumulative volume linear coefficient		-67 (D)	-1.6 (D)	2.8 (-)		-34 (D)	-1.3 (D)	87 (-)		-68 (D)	-5 (D)		-65 (D)	18 (-)
Median location (meters from upstream survey boundary)	1734	1895 (T)	1800 (-)	1821 (T)	734	795 (T)	752 (-)	801 (T)	232	238 (T)	242 (T)	83	127 (T)	224 (T)
Length of middle 50% of cumulative volume (m)	1505	1970 (D)	1704 (-)	1636 (-)	667	675 (D)	729 (D)	464 (-)	144	155 (D)	152 (-)	81	221 (D)	200 (-)
Ratio of changing median and length		0.3 (D)	0.4 (D)	(-)		7.6 (T)	(-)	(-)		0.6 (D)	(-)		0.3 (D)	(-)
Mean location (meters from upstream survey boundary)	1675	2458 (T)	2139 (-)	2210 (T)	678	732 (T)	695 (-)	757 (T)	232	257 (T)	274 (T)	88	162 (T)	194 (T)
Standard deviation (m)	2000	2830 (D)	2650 (-)	2830 (D)	770	820 (D)	800 (-)	829 (D)	250	240 (-)	250 (D)	100	200 (D)	500 (D)
Ratio of changing mean to s.d.		0.95 (D)	(-)	0.39 (D)		0.99 (D)	(-)	2.1 (T)		(-)	10 (T)		0.38 (D)	0.19 (D)
Péclet number		0.2 (D)	(-)	(-)		0.07 (D)	(-)	0.2 (D)		(-)	0.7 (D)		0.4 (D)	0.2 (D)

Indicators provide inconclusive evidence regarding the dominance of translation or dispersion at each site. The middle 50% method measures decreasing pulse length at all sites, resulting in an inconclusive ratio (Table 4). Decreasing pulse length causes standard deviation to decrease over time, leading to inconclusive Péclet numbers at Gold Ray, Savage Rapids, and Brownsville (Table 4). Measurement of upstream movement of the pulse median and mean locations during year 2 at Gold Ray and year 3 at Savage Rapids suggests sediment accumulation upstream of the sediment pulse, confounding evaluation of dispersion and translation. These cases of upstream movement of pulse median are accompanied by the shortening of pulse length. .

4.3.1 Gold Ray Dam

Quantitative methods to evaluate pulse behavior indicate that dispersive behavior exceeds translational behavior at Gold Ray Dam (Table 4). For the cumulative volume method, we find that the linear trendline flattens in the first and second years following dam removal, providing evidence of dispersion. The additional rotation in the second year is 2% of the rotation that occurs in the first year, indicating that the degree of dispersive movement diminishes over time. The downstream movement of the median and mean locations provides quantitative evidence of translation in the first and third years following dam removal. The changes in median and mean locations do not exceed the lengthening of the pulse. The Péclet numbers are less than 1 for all years, indicating the dominance of dispersion.

4.3.2 Savage Rapids Dam

Evidence of translation relative to the year 1 channel is found in the second and fourth years following dam removal. The cumulative volume method measures diminishing dispersive movement in the second and third years. The ratio of changing median location to pulse length is greater than 1 in the second year, indicating that translational movement exceeds dispersive movement (Table 4). The ratio of changing mean location to standard deviation is greater than 1 and indicative of greater translational movement in the fourth year. However, the Péclet number is always less than 1, indicating the dominance of dispersion.

4.3.3 Brownsville Dam

Quantitative methods to evaluate pulse behavior indicate that dispersion dominates behavior at Brownsville. The trendline fit to the cumulative volume flattens in both years, indicating dispersion. The ratio of changing mean location to standard deviation is greater than 1 in the second year, indicating that translational movement exceeds dispersive movement, but both the ratio of changing median location to pulse length and Péclet number are less than 1, indicating that dispersion exceeds translation (Table 4).

4.3.4 Oak Creek culvert

Quantitative methods to evaluate pulse behavior indicate the dominance of dispersion in the first and second years following culvert replacement (Table 4). The trendline fit to the cumulative volume distribution rotates downward in the first year, indicating dispersion, but is inconclusive in the second. The median and mean locations move downstream in both years, indicating translation, but the middle 50% ratio concludes that dispersive movement exceeds translational movement (Table 4). The Péclet number is less than 1 in both years following culvert installation, indicating the dominance of-dispersion.

5 DISCUSSION

The ultimate intent of our study is to improve the ability to predict pulse behavior at dam removal sites. Anticipating how pulse sediment will move following dam removal is important in supporting the ability of managers and planners to anticipate designs needs for sediment management, stabilization, and/or excavation necessary to protect downstream infrastructure or habitat. Predicting pulse behavior according to variables that are measurable in the field prior to dam removal would enable future dam removals to confidently plan for the effects of either translational or dispersive pulse behavior.

5.1 Hypothesized and Observed Pulse Behavior

The results agree with past work that dispersion dominates pulse behavior (Cui *et al.* 2003, Lisle 2008) and find no evidence of translational movement exceeding dispersive movement in the first year following barrier removal. Following the first year post-removal, two of the three ratios of translational to dispersive movement indicate that translation characterizes the sediment pulse at Savage Rapids (Table 4). One ratio indicates that translational behavior occurred at Brownsville in the second year following barrier removal (Table 4).

The results support the application of Froude number as a predictor of pulse behavior. The two sites with evidence of translation exceeding dispersion are characterized by Froude numbers less than or equal to the 0.4 threshold observed in flume studies (Lisle *et al.* 2001, Cui, Parker, Lisle, *et al.* 2003). The two sites characterized by Froude numbers greater than 0.4 (Table 2) have no evidence of translational movement exceeding dispersive movement (Table 4).

The results do not support the application of grain size, pulse size, or volume ratio as predictors of pulse behavior. If the increased mobility of finer pulse grain size increases the translational behavior of the pulse (Lisle *et al.* 2001), then we would expect the Brownsville pulse, with a grain size ratio greater than 1, to move with less evidence of translation than the other pulses with grain size ratios less than 1. However, the ratios of translational to dispersive movement do not provide evidence that the Brownsville pulse is the most dispersive of all the observed pulses (Table 4). Instead, indicators suggest that dispersive pulse behavior is most dominant at the Gold Ray Dam removal. Savage Rapids has the smallest pulse size ratio and largest volume ratio, but the quantitative results to evaluate pulse behavior resemble those from Brownsville (Table 4), which has the largest pulse size ratio and the smallest volume ratio (Table 2). These conflicting results suggest that the indicators of grain size, pulse size, and volume ratio may not be reliable in predicting the dominance of dispersive or translative pulse behavior.

Although the post-removal hydrograph cannot be applied as a predictor of pulse behavior, a comparison of observed behavior to hydrologic year indicates a connection between evidence of translation and wet water years (Table 3). Evidence of translation is found only in water years when discharge exceeds the 1.2 RI at least once. The observed degree of translational behavior increases with the duration and magnitude peak discharge at Savage Rapids and Brownsville (Table 3), in keeping with the flume observation large discharge encourages translation (Humphries *et al.* 2012). However, as indicated by the third year at Gold Ray (Table 3), large peak discharge alone does not result in translational movement exceeding dispersive movement (Table 4).

5.2 Limitations of Methods to Explain Pulse Behavior

The methods to predict pulse behavior are constrained by the framework of translation and dispersion used to interpret sediment movement, and assumptions made in calculations of Froude number, grain ratio, and pulse size. Every result considered in this study assumes that the pulse moves according to the models of translation and dispersion. However, the downstream accumulations visible for every post-removal DoD (Figures 4-7) call into question the translation/dispersive framework due to the influence of local variability in channel and valley geometry on pulse behavior. However, the separate downstream accumulations represent little of the main pulse volume (Figure 8). These results suggest that models of translation and dispersion are useful in predicting reach-scale patterns.

Our observations of pulse behavior are limited by the length of time separating surveys. More frequent surveys would provide greater insight into the timing of pulse movement. Consistent with other studies (e.g. Tullos and Wang 2014, East *et al*. 2015) quantitative and visual observations of pulse movement indicate that the largest rate of erosion from the initial pulse occurs in the first year following barrier removal. It would be useful to understand the sub-annual timescales over which translation is expected to dominate, and to consider how pulse behavior changes throughout the hydrologic year, in order to better link generalized sediment pulse behavior to sediment mobilization and transport processes.

5.3 Limits of Quantitative Methods to Evaluate Pulse Behavior

The methods to characterize pulse behavior offer quantitative approaches to evaluating sediment pulse behavior, but the results highlight limitations in accurately measuring initial volume and assessing translation in field settings. The limitations also inform further development of quantitative methods to evaluate pulse behavior.

The method of measuring initial pulse volume in the field is limited by two assumptions. The method assumes that all sediment between a linear valley slope and the pre-removal surface is pulse material. If some of the initial volume were to include the channel bed, the initial volume would be overestimated. The volume of sediment deposited downstream following dam removal would appear to be a smaller percent of the initial volume, causing an underestimation of translational movement. Secondly, the initial gross volume value is assumed to be zero downstream of the barrier, despite the fact that all the barriers in this study were known to pass sediment prior to removal. If some of the pulse material were measured as pre-removal bed material downstream of the barrier, the gross volume of downstream deposits of pulse material would be underestimated. The potential error introduced by the second assumption has less effect on our conclusions because we are interested in patterns of pulse movement relative to a pre-removal surface. The error introduced by the first assumption is likely to vary between sites with degree of variability in the historical longitudinal profile.

The middle 50% results observed at each site exemplify one of the challenges in measuring pulse movement in the field. The decrease in pulse length that causes an inconclusive measurement of dispersion in five survey years (Table 4) may be explained by the loss of pulse material from the downstream edge of the pulse, as documented at Savage Rapids, Brownsville, and Oak Creek (Figure 9). This transport of pulse material out of the study reach can result in underestimating the pulse length. A loss of pulse material to the downstream boundary may also explain the inconclusive Péclet numbers at Gold Ray, Savage Rapids and Brownsville (Table 4), which are the result of decreasing variance in the spatial distributions of gross volume. In future studies, field surveys may include a broader extent to more completely capture pulse behavior.

6 CONCLUSION

Flume experiments suggest that sediment pulses disperse in place for most dams, but it is hypothesized that a Froude number less than 0.4, fine pulse grain size, small pulse size, and large discharge can be used to identify locations where pulses behavior may be dominated by translation. Flume experiments lack realism of in situ variability in geometry and roughness, whereas field studies of pulse behavior lack application of quantitative methods to the prediction and evaluation of pulse movement, even though the ability to predict pulse behavior may improve the management of dam removals. We thus evaluate both the evidence for dispersion and translation at four case studies, and the ability to explain pulse behavior by Froude number, grain size, pulse size, and discharge. Changes in pulse volume are calculated from bathymetry data and grain size data.

While results provide some evidence of translational movement at all four sites, we conclude that that dispersion generally dominates pulse behavior, and document a connection between translational behavior and wet water years. The results indicate that the 0.4 threshold in Froude number may help discriminate between dispersive and translational pulse behaviors, but do not support the application of grain size, pulse size, or volume ratio as reliable predictors of pulse behavior. Further research should investigate the physical processes underlying the Froude number threshold and study pulse behavior at sub-annual timescales, where translational behavior may be more evident.

BIBLIOGRAPHY

Aris, R., 1956. On the Dispersion of a Solute in a Fluid Flowing through a Tube On the dispersion of a solute in a fluid flowing through a tube. *In*: *Proceedings of the Royal Society of London*. The Royal Society, 67–77.

Biedenharn, D.S., Copeland, R.R., Thorne, C.R., Soar, P.J., and Hey, R.D., 2000. *Effective Discharge Calculation : A Practical Guide*.

Born, S.M., Genskow, K.D., Filbert, T.L., Hernandez-Mora, N., Keeper, M.L., and White, K. a., 1998. Socioeconomic and institutional dimensions of dam removals: The Wisconsin experience. *Environmental Management*, 22 (3), 359–370.

Cao, Z. and Carling, P. a., 2003. On evolution of bed material waves in alluvial rivers. *Earth Surface Processes and Landforms*, 28 (4), 437–441.

Cheng, F. and Granata, T., 2007. Sediment transport and channel adjustments associated with dam removal: Field observations. *Water Resources Research*, 43 (3).

Cui, Y. and Parker, G., 1997. A quasi-normal simulation of aggradation and downstream fining with shock fitting. *International Journal of Sediment Research*, 12 (2), 68–82.

Cui, Y., Parker, G., Lisle, T.E., Gott, J., Hansler-Ball, M.E., Pizzuto, J.E., Allmendinger, N.E., and Reed, J.M., 2003. Sediment pulses in mountain rivers: 1. Experiments. *Water Resources Research*, 39 (9).

Cui, Y., Parker, G., Lisle, T.E., Pizzuto, J.E., and Dodd, A.M., 2005. More on the evolution of bed material waves in alluvial rivers. *Earth Surface Processes and Landforms*, 30 (1), 107–114.

Cui, Y., Parker, G., Pizzuto, J., and Lisle, T.E., 2003. Sediment pulses in mountain rivers: 2. Comparison between experiments and numerical predictions. *Water Resources Research*, 39 (9).

Cui, Y., Wooster, J.K., Venditti, J.G., Dusterhoff, S.R., Dietrich, W.E., and Sklar, L.S., 2008. Simulating sediment transport in a flume with forced pool-riffle morphology : Examinations of two one-dimensional numerical models. *Journal of Hydraulic Engineering*, 134 (7), 892–904.

Downs, P.W., Cui, Y., Wooster, J.K., Dusterhoff, S.R., Booth, D.B., Dietrich, W.E., and Sklar, L.S., 2009. Managing reservoir sediment release in dam removal projects: An approach informed by physical and numerical modelling of non-cohesive sediment. *International Journal of River Basin Management*, 7 (4), 433–452.

Doyle, M.W., Stanley, E.H., and Harbor, J.M., 2003. Geomorphic analogies for assessing probable channel response to dam removal. *Journal of the American Water Resources Association*, 38 (6), 1567–1579.

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*, 228, 765–786.

Elliott, B. and Dittmer, E., 2009. *Preliminary Report of the Sediment Study Conducted at Gold Ray Reservoir, Jackson County, Oregon Completed for HDR Engineering, Inc.*

Graf, W.L., 1999. Dam nation: A geographic census of american dams and their large-scale hydrologic impacts. *Water Resources Research*, 35 (4), 1305–1311.

Grant, G., 2001. Dam removal: Panacea or Pandora for rivers? *Hydrological Processes*, 15 (8), 1531–1532.

Grant, G.E. and Lewis, S.L., 2015. The remains of the dam: What have we learned from 15 Years of US dam removals? *In*: G. et al Lollino, ed. *Engineering Geology for Society and Territory - Volume 3*. Spring, 31–35.

Greig, S.M., Sear, D. a, and Carling, P. a, 2005. The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. *The Science of the total environment*, 344 (1-3), 241–58.

Greimann, B., Randle, T., and Huang, J., 2006. Movement of Finite Amplitude Sediment Accumulations. *Journal of Hydraulic Engineering*, (July), 731–736.

Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, a T., Charles, D.F., Kreeger, D. a, and Velinsky, D.J., 2002. Dam removal: Challenges and opportunities for ecological research and river restoration. *Bioscience*, 52 (8), 669–681.

Humphries, R., Venditti, J.G., Sklar, L.S., and Wooster, J.K., 2012. Experimental evidence for the effect of hydrographs on sediment pulse dynamics in gravel-bedded rivers. *Water Resources Research*, 48 (1), W01533.

Jones, B. and Dillinger, R., 2004. *City of Corvallis Salmon Response Plan Chapter 5 . Baseline Conditions*.

Kasai, M., Marutani, T., and Brierley, G.J., 2004. Patterns of sediment slug translation and dispersion following typhoon-induced disturbance, Oyabu Creek, Kyushu, Japan. *Earth Surface Processes and Landforms*, 29 (1), 59–76.

Kibler, K., Tullos, D., and Kondolf, M., 2011. Evolving expectations of dam removal outcomes: Downstream geomorphic effects following removal of a small, gravel-filled dam. *JAWRA Journal of the American Water Resources Association*, 47 (2), 408–423.

Klingeman, P., 1979. *Oak Creek Sediment Transport Report*.

Lisle, T.E., 2008. The evolution of sediment waves influenced by varying transport capacity in heterogeneous rivers. *In*: H. Habersack, H. Piegay, and M. Rinaldi, eds. *Gravel-Bed Rivers VI: From Process Understanding to River Restoration*. Elsevier B.V., 443–472.

Lisle, T.E., Cui, Y., Parker, G., Pizzuto, J.E., and Dodd, A.M., 2001. The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. *Earth Surface Processes and Landforms*, 26 (13), 1409–1420.

Lisle, T.E., Pizzuto, J.E., Ikeda, H., and Iseya, F., 1997. Evolution of a sediment wave in an experimental channel. *Water Resources Research*, 33 (8), 1971–1981.

Madej, M.A., 2001. Development of channel organization and roughness following sediment pulses in single-thread , gravel bed rivers, 37 (8), 2259–2272.

Meade, R.H., 1985. Wavelike movement of bedload sediment, East Fork River, Wyoming. *Environmental Geology*, 7 (4), 215–225.

Miyazaki, T., Kurebayasi, M., Yamada, T., and Marutani, T., 2006. Translation and Dispersion of Sediment Pulses Induced by an Extreme Rainfall in. *In*: *Disaster Mitigation of Debris Flows, Slope Failures and Landslides*. 331–341.

Northwest Geophysical Associates, I., 2006. *Seismic Refraction Study Brownsville Dam*. Corvallis, OR.

O'Connor, J.E., Duda, J.J., and Grant, G.E., 2015. 1000 dams down and counting. *Science*, 348 (6234), 496–498.

Pessagno, E. a. and Blome, C.D., 1990. Implications of new Jurassic stratigraphic, geochronometric, and paleolatitudinal data from the western Klamath terrane (Smith River and Rogue Valley subterranes). *Geology*, 18 (7), 665–668.

Pizzuto, J., 2002. Effects of Dam Removal on River Form and Process. *BioScience*, 52 (8), 683–691.

Reclamation, B. of, 2001. *Savage Rapids Dam Sediment Evaluation Study*.

Riggsbee, J.A., Julian, J.P., Doyle, M.W., and Wetzel, R.G., 2007. Suspended sediment, dissolved organic carbon, and dissolved nitrogen export during the dam removal process. *Water Resources Research*, 43 (9), 1–16.

Roberts, P. V and Goltz, M.N., 1987. Using the Method of Moments to Analyze Three-Dimensional Diffusion-Limited Solute Transport from Temporal and Spatial Perspectives. *Water Resources Research*, 23 (8), 1575–1585.

Runyon, J., Andrus, C., and Schwindt, R., 2004. *Calapooia River Watershed Assessment*.

Sherrod, D.R. and Smith, J.G., 2000. *Geologic map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon: U.S. Geological Survey Geologic Investigations Series Map I-2569*.

Sklar, L.S., Fadde, J., Venditti, J.G., Nelson, P., Wydzga, M.A., Cui, Y., and Dietrich, W.E., 2009. Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams. *Water Resources Research*, 45 (8), n/a–n/a.

Sutherland, D.G., Ball, M.H., Hilton, S.J., and Lisle, T.E., 2002. Evolution of a landslide-induced sediment wave in the Navarro River , California Evolution of a landslide-induced sediment wave in the Navarro River , California. *GSA Bulletin*, 114 (8), 1036–1048.

Toman, E., 2004. Forest Road Hydrology : The Influence of Forest Roads on Stream Flow at Stream Crossings. Oregon State University.

Tuckerman, S. and Zawiski, B., 2007. Case Studies of Dam Removal and TMDLs: Process and Results. *Journal of Great Lakes Research*, 33, 103–116.

Tullos, D. and Wang, H.-W., 2014. Morphological responses and sediment processes following a typhoon-induced dam failure, Dahan River, Taiwan. *Earth Surface Processes and Landforms*, 39 (2), 245–258.

Tullos, D.D., Finn, D.S., and Walter, C., 2014. Geomorphic and Ecological Disturbance and Recovery from Two Small Dams and Their Removal. *PLoS ONE*, 9 (9), e108091.

Walter, C. and Tullos, D.D., 2010. Downstream Channel Changes After A Small Dam Removal: Using Aerial Photos and Measurement Error for Context; Calapooia River, Oregon. *River Research and Applications*, 1245 (November 2009), 1220–1245.

Wang, H.-W., Cheng, Y.-C., and Lin, C.-Y., 2014. Experiments on channel evolution due to dam removal in Taiwan. *Journal of Mountain Science*, 11 (6), 1396–1405.

Weyerhaeuser, 1998. Calapooia River Watershed Assessment, (August).

Wheaton, J.M., 2008. Uncertainty in Morphological Sediment Budgeting of Rivers. Unpublished PhD Thesis, University of Southampton.

Wheaton, J.M., Brasington, J., Darby, S.E., and Sear, D. a., 2009. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms*, (35), 136–156.

White, J.Q., Pasternack, G.B., and Moir, H.J., 2010. Valley width variation influences riffle-pool location and persistence on a rapidly incising gravel-bed river. *Geomorphology*, 121 (3-4), 206–221.

Wilcock, P.R. and Crowe, J.C., 2003. Surface-based Transport Model for Mixed-Size Sediment. *Journal of Hydraulic Engineering*, 129 (February), 120–128.

Williams, G.P., 1970. *Flume Width and Water Depth Effects in Experiments Flume Width and Water Depth Effects in Sediment-Transport Experiments*.

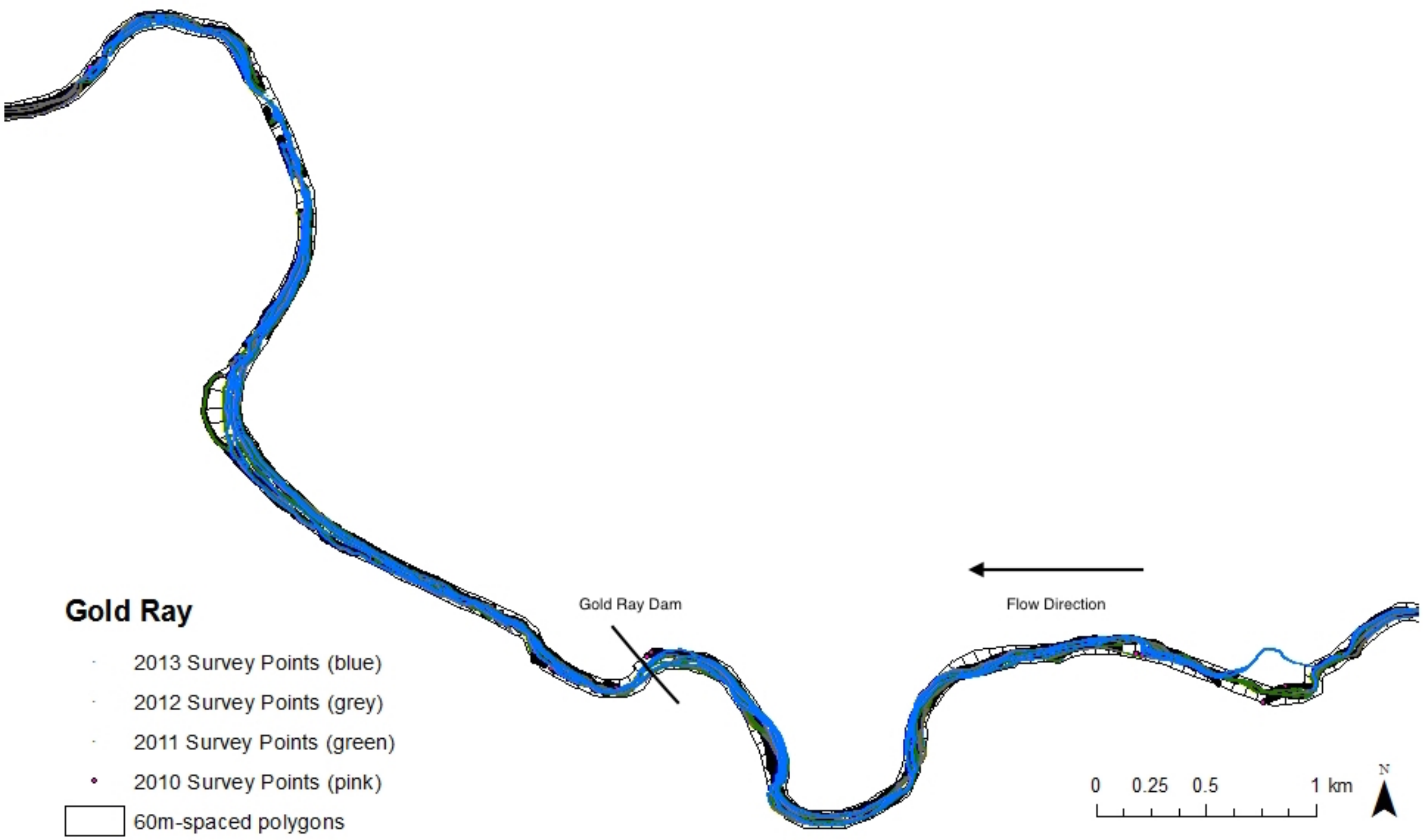
Wohl, E. and Cenderelli, D., 2000. Sediment deposition and transport patterns following a reservoir sediment release. *Water Resources Research*, 36 (1), 319–333.

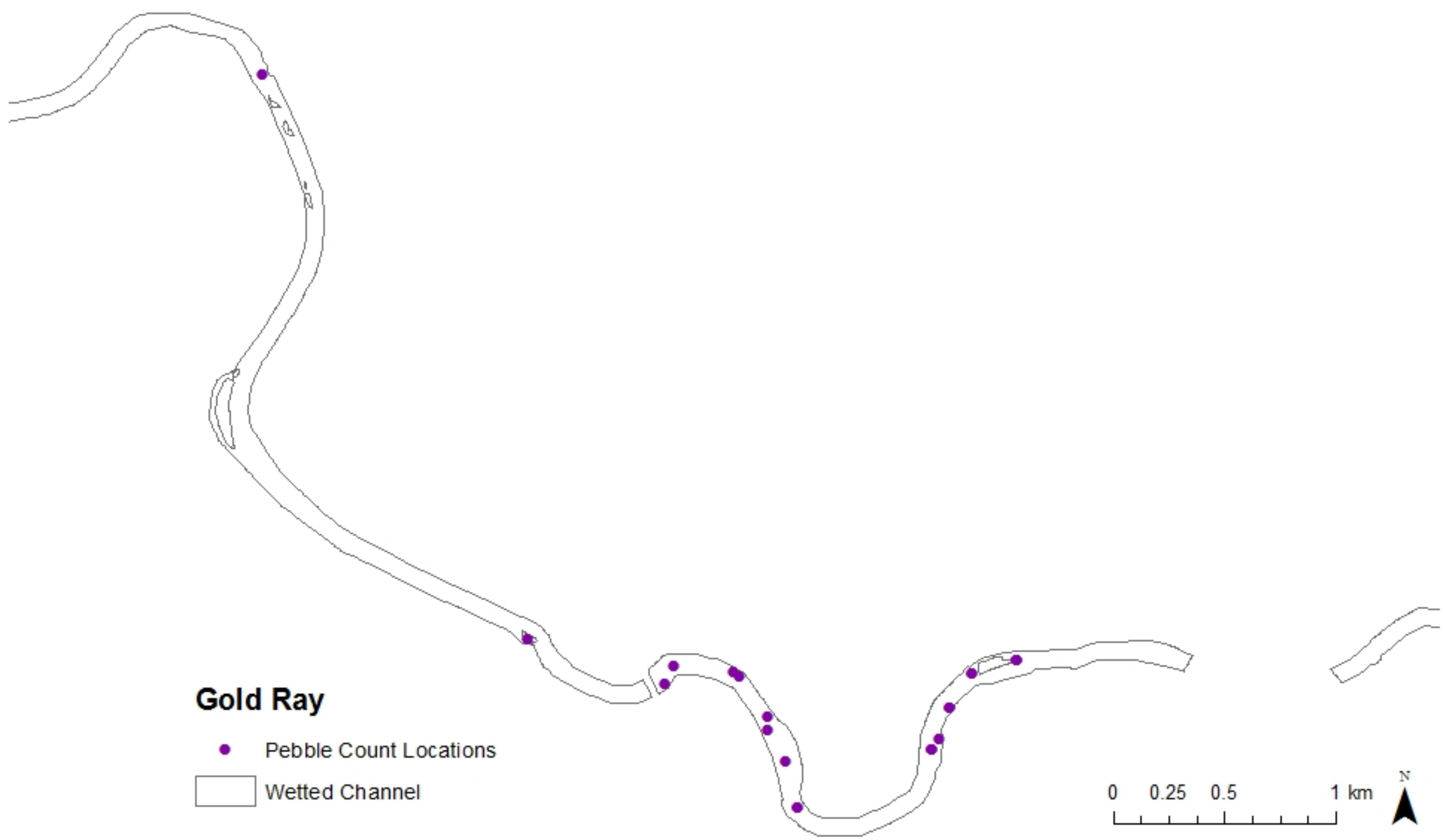
Wolman, M.G., 1954. A Method of Sampling Coarse River-Bed Material. *Transactions, American Geophysical Union*, 35 (6), 951–956.

Zunka, J.P.P., Tullos, D.D., and Lancaster, S.T., 2015. Effects of sediment pulses on bed relief in bar-pool channels. *Earth Surface Processes and Landforms*.

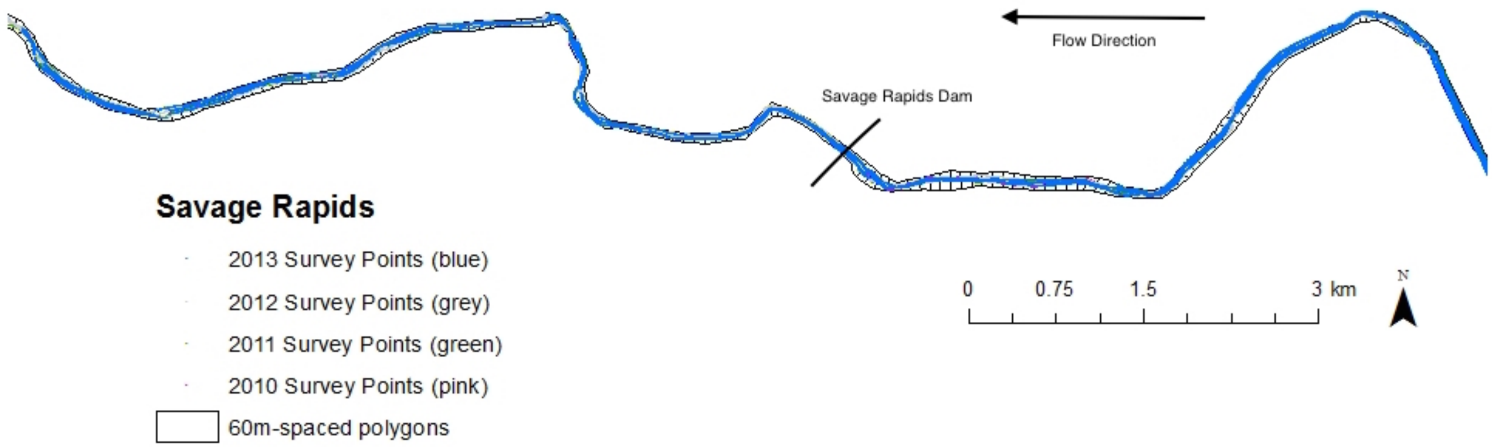
APPENDICES

Appendix 1: Examples of Geomorphic Change Detection Inputs and Method

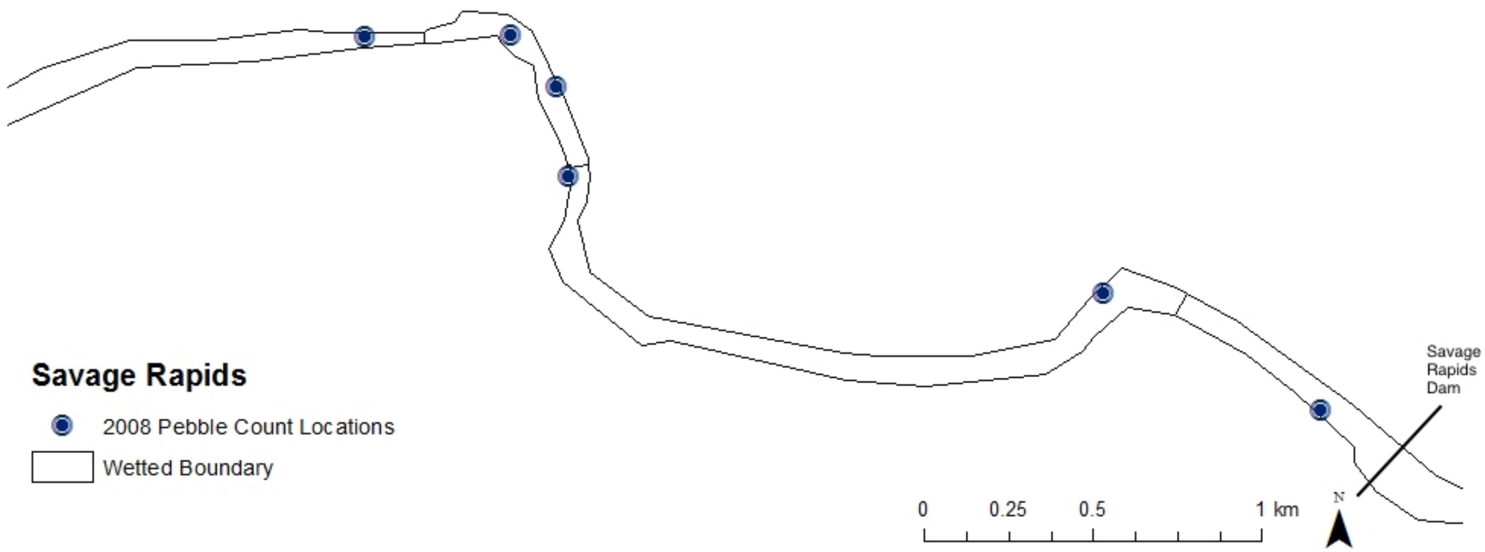




Appendix 1.2 Gold Ray pre-removal particle count locations

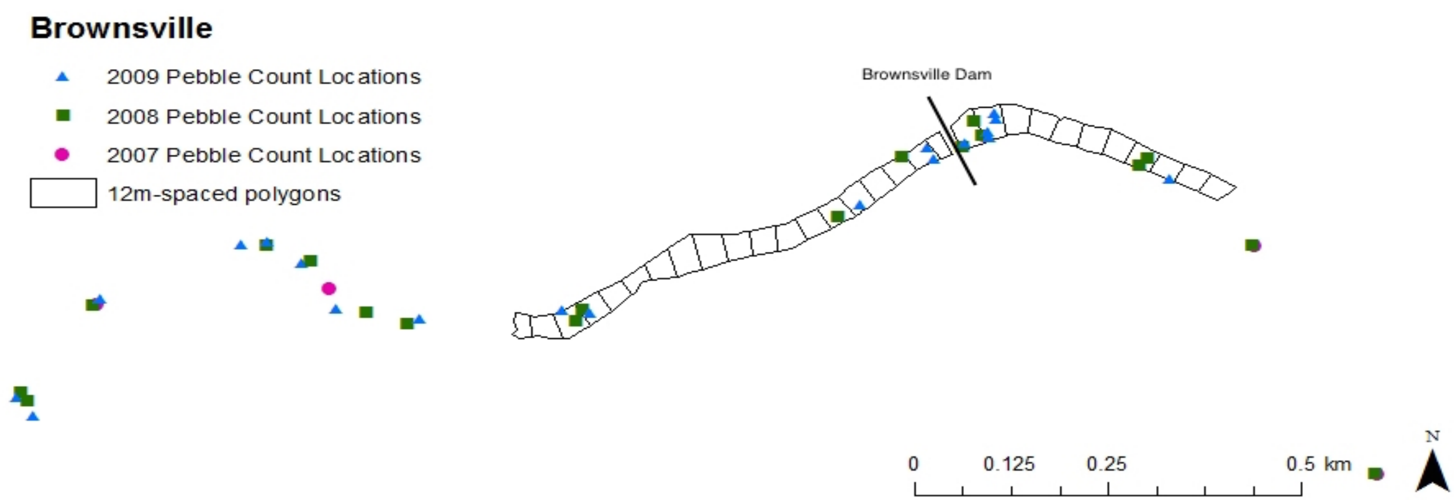


Appendix 1.3 Savage Rapids survey points

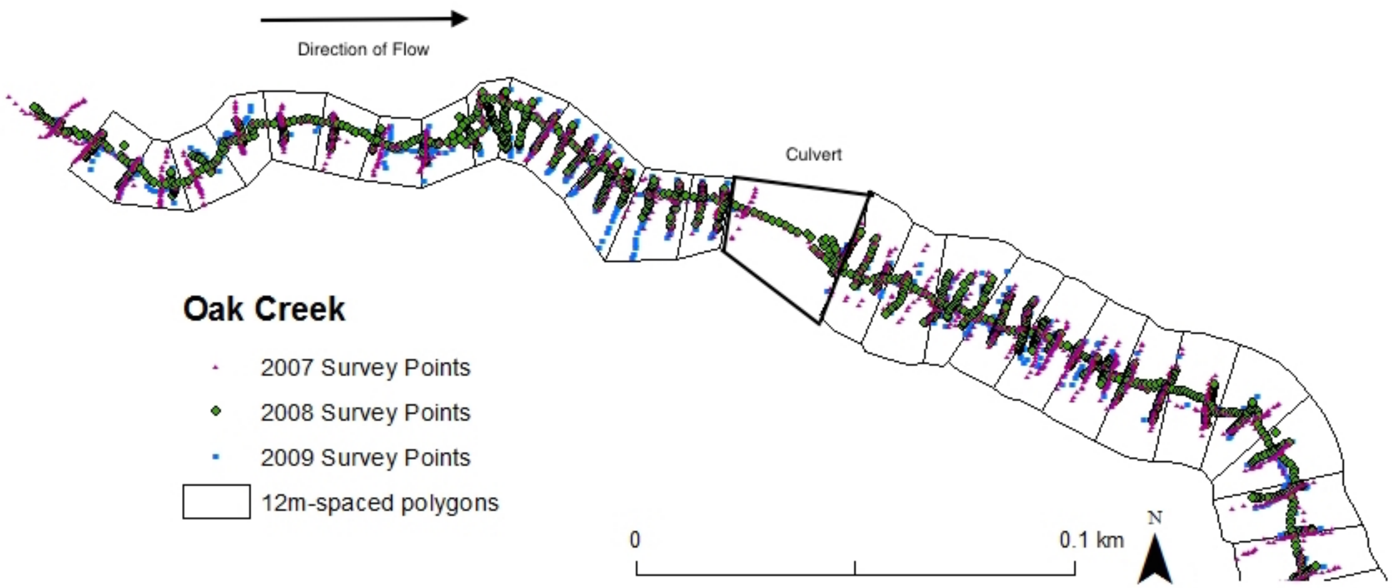


Appendix 1.4 Savage Rapids pre-removal particle count locations

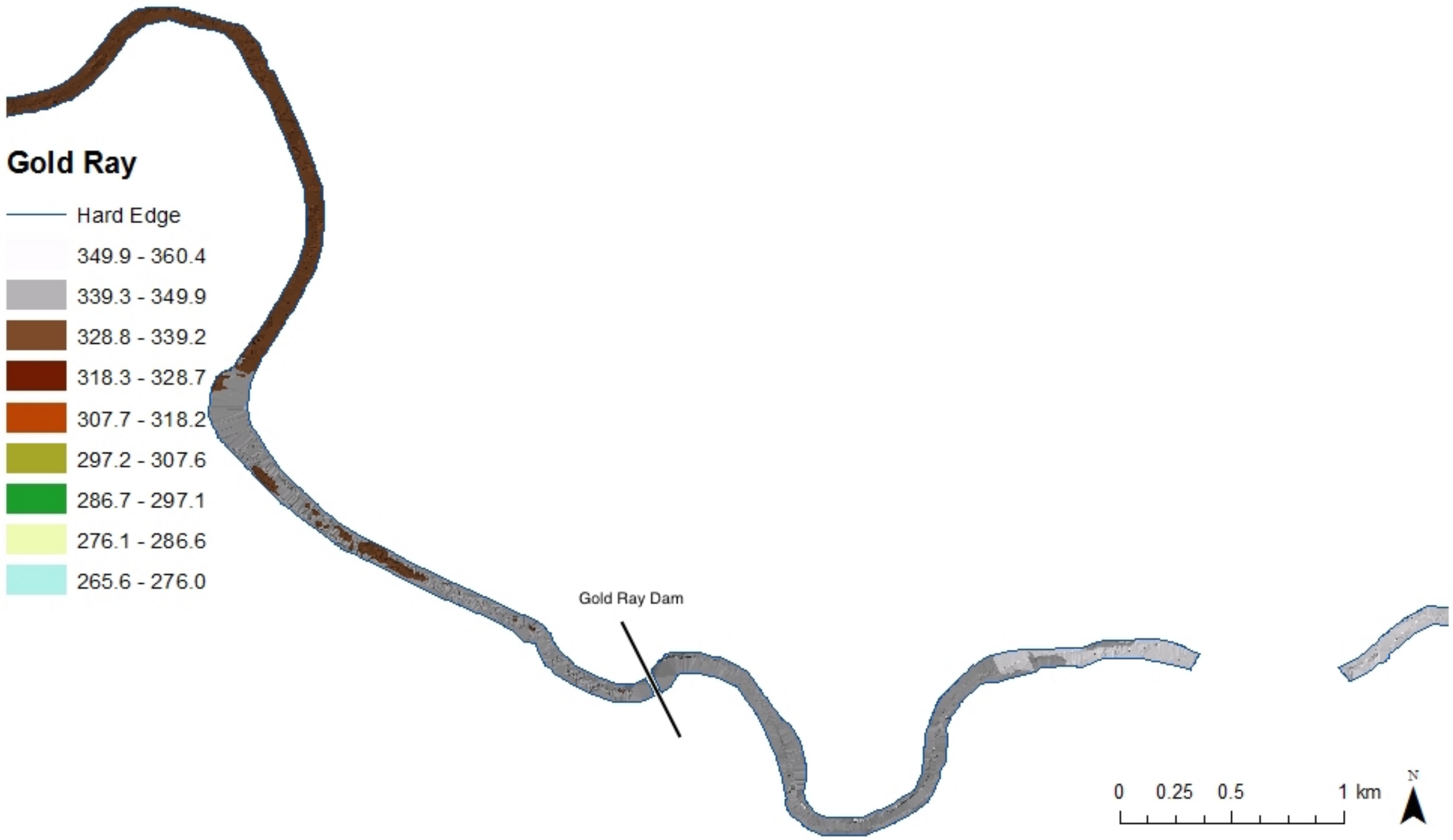
Appendix 1.5 Brownsville survey points



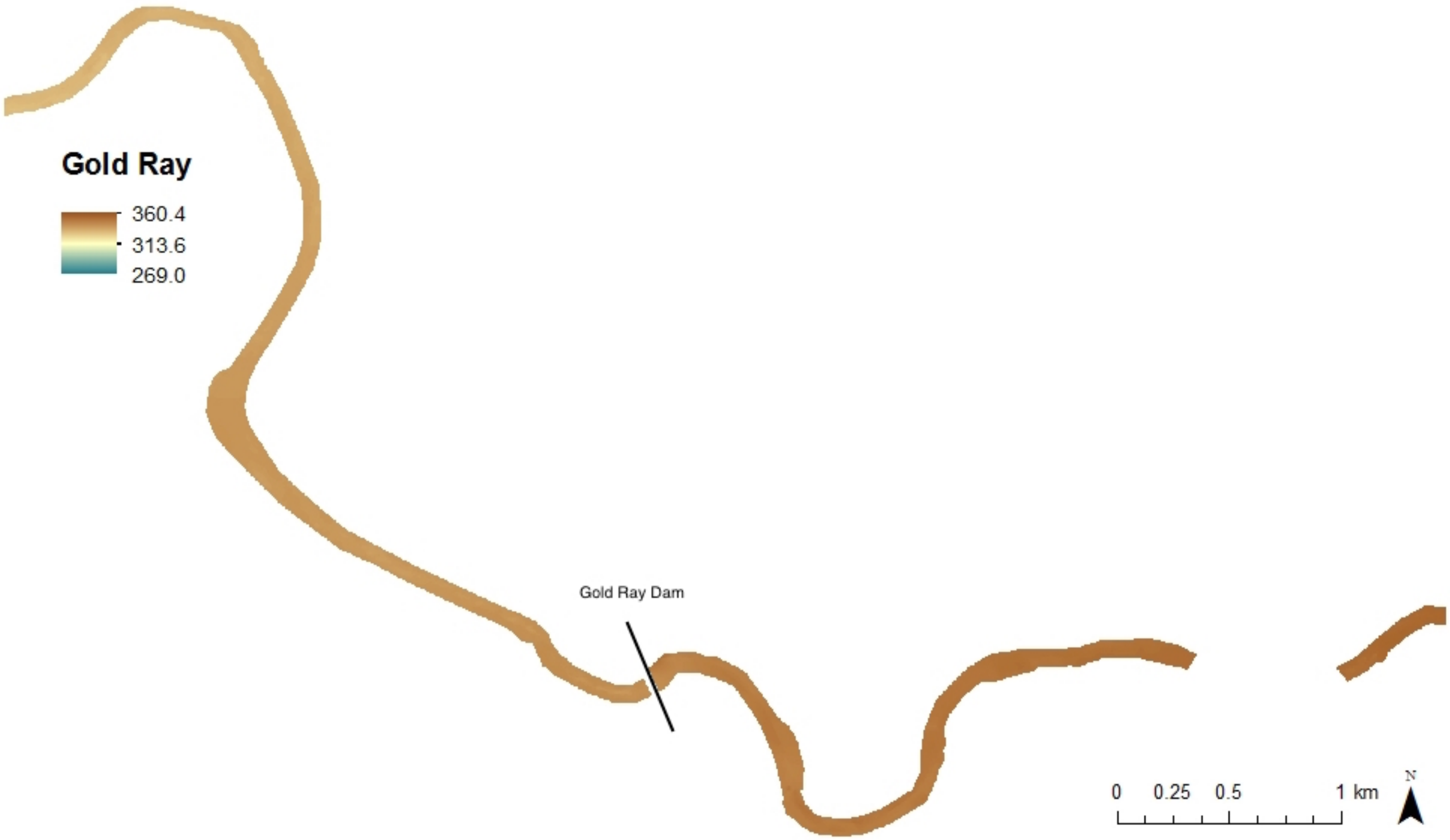
Appendix 1.6 Brownsville particle count locations



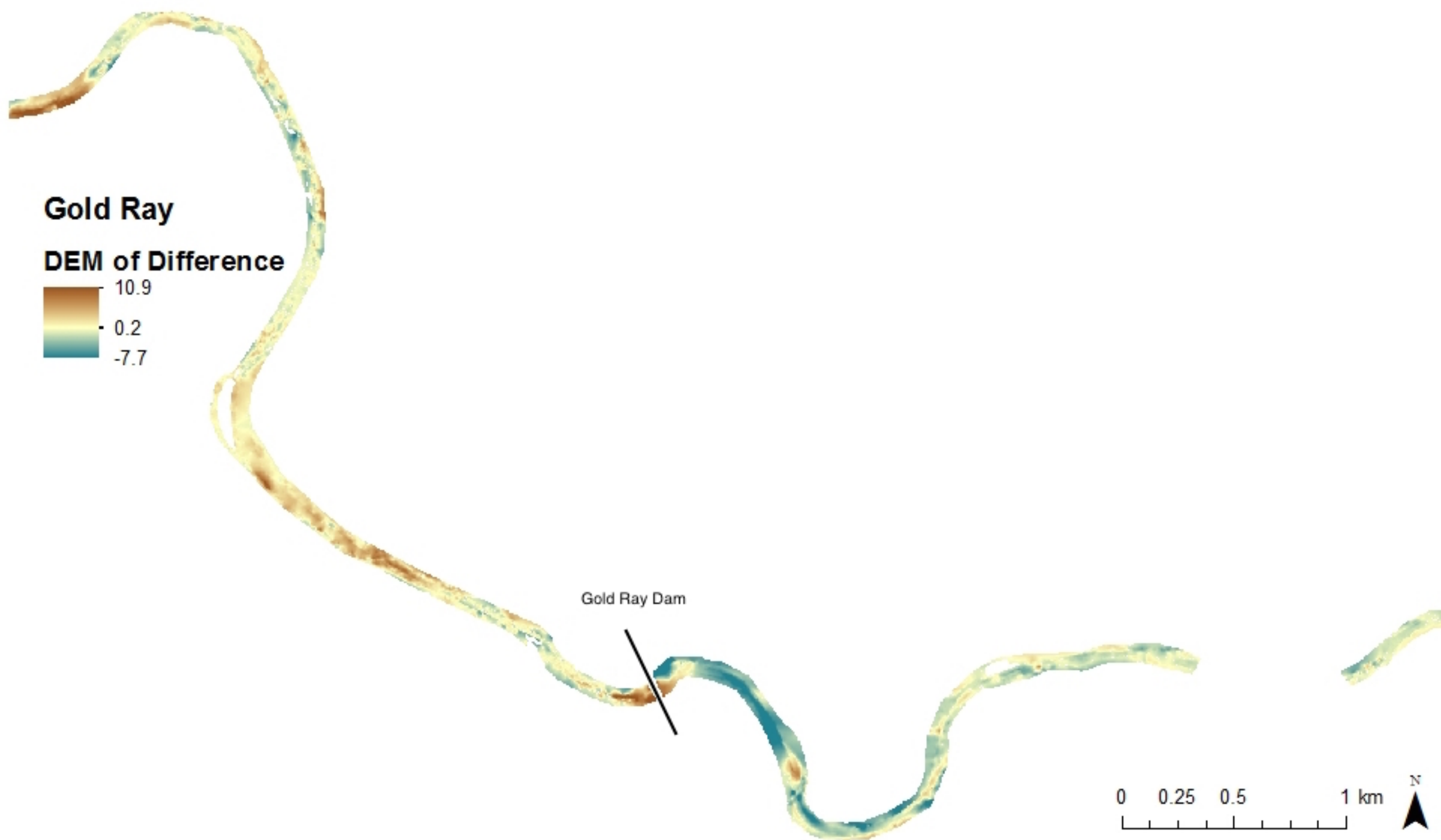
Appendix 1.7 Oak Creek survey points



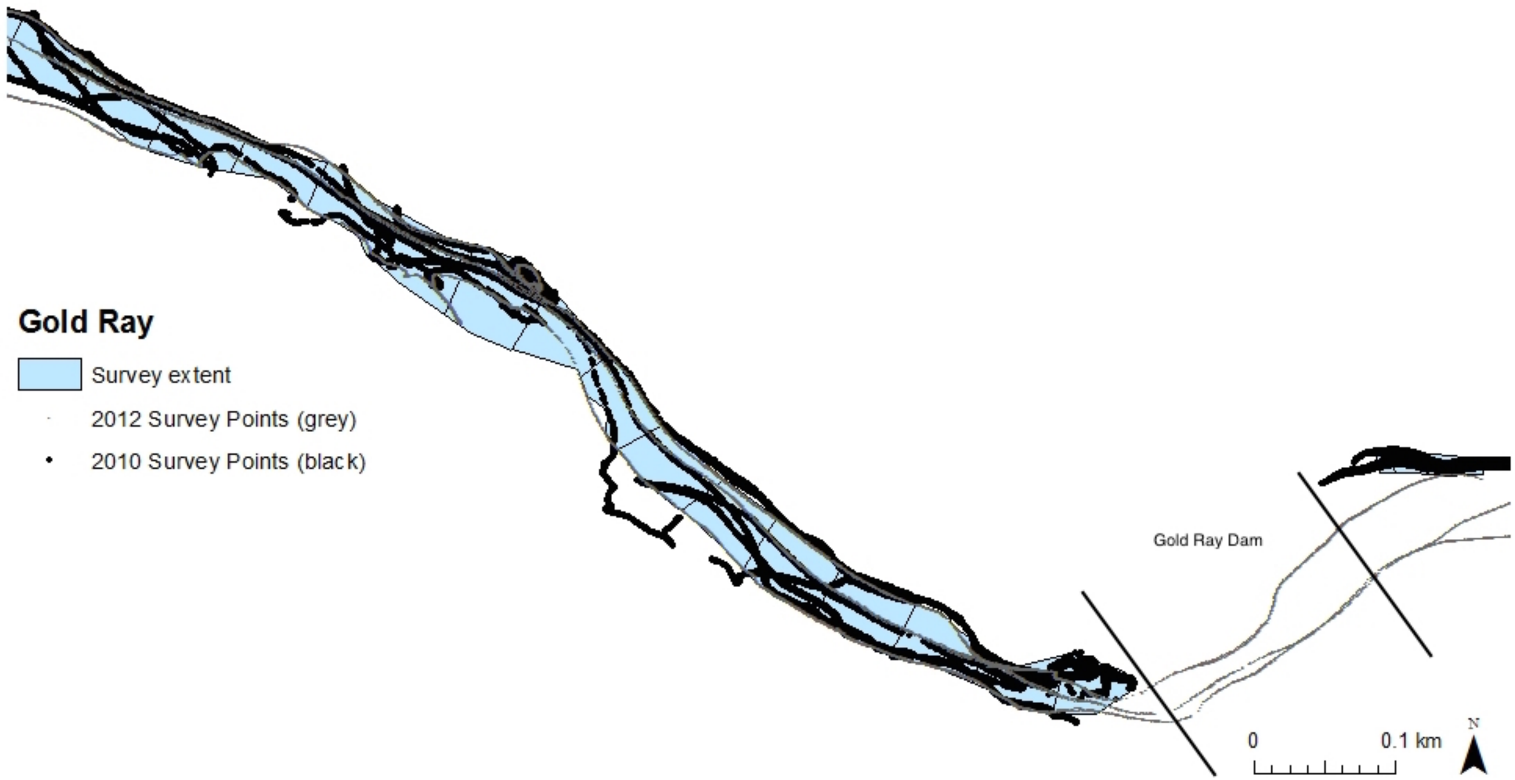
Appendix 1.8 Example of TIN at 2010 Gold Ray site showing elevation in meters



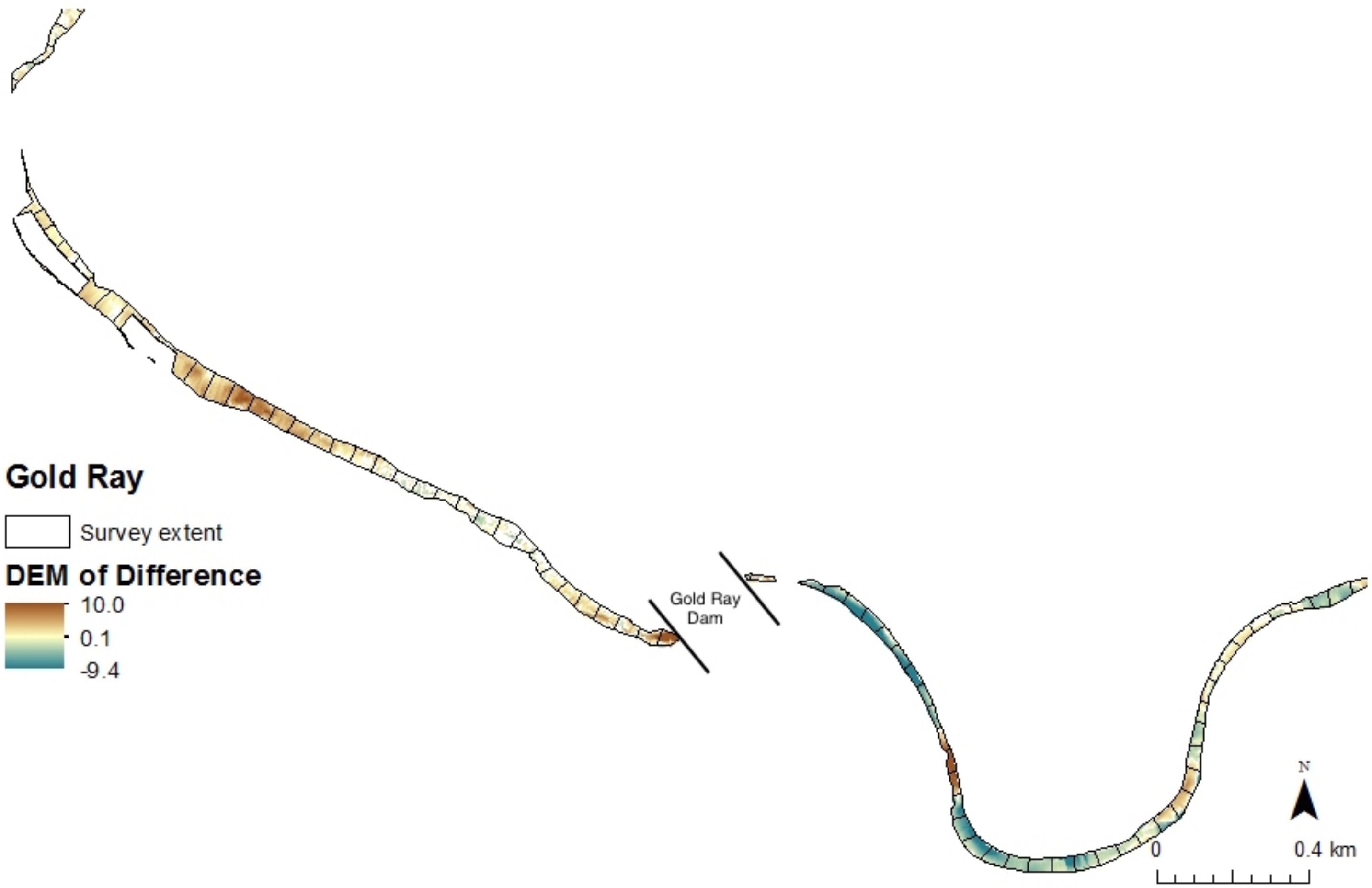
Appendix 1.9 Example of Digital Elevation Model (DEM) at 2010 Gold Ray site showing elevation in meters



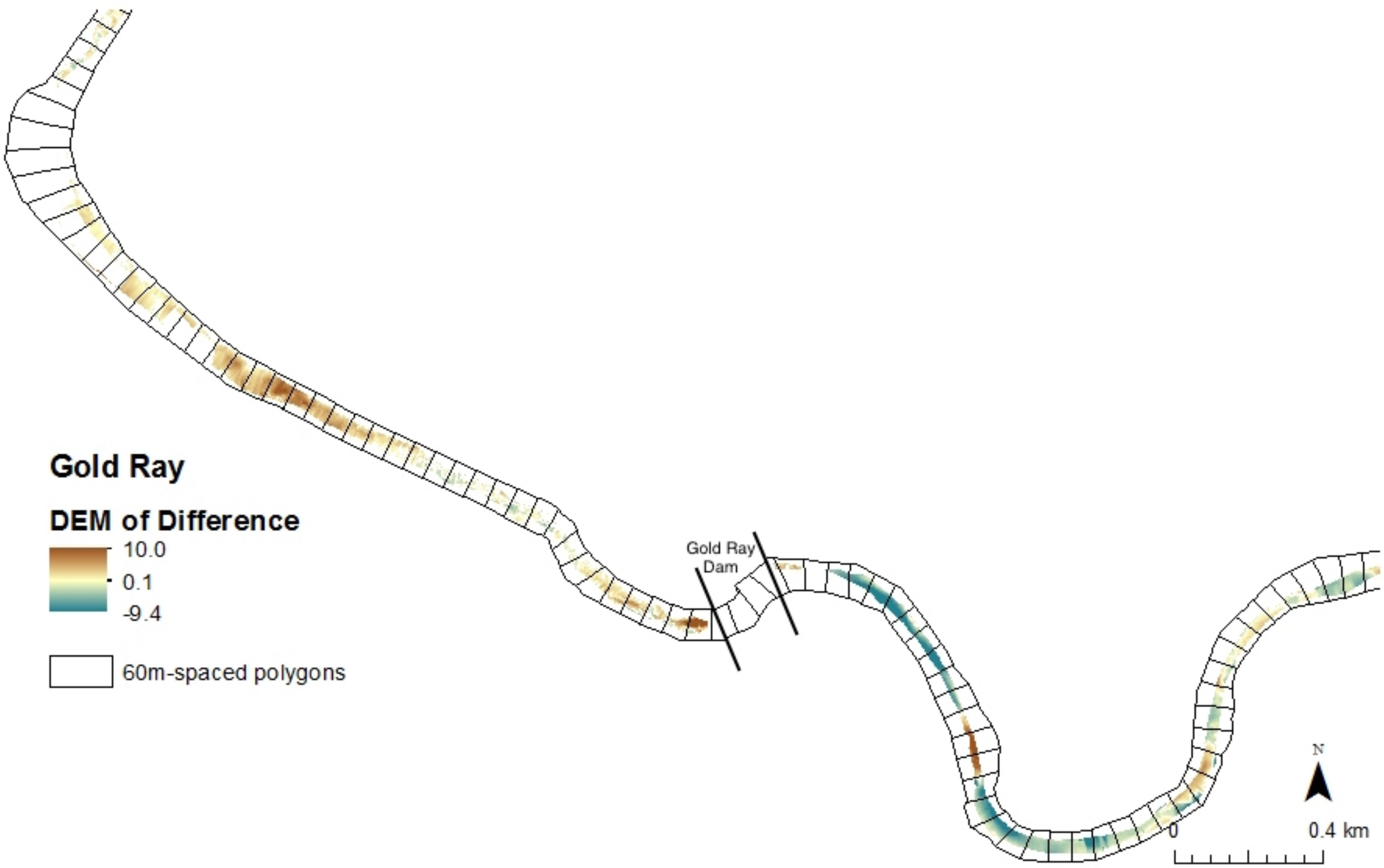
Appendix 1.10 Example of difference (in meters) between DEMs at Gold Ray site



Appendix 1.11 Example of survey extent between 2012 and 2010 survey points at Gold Ray site



Appendix 1.12 Example of extracted DoD at Gold Ray site showing difference in elevation (in meters) between 2012 and 2010 DEMs



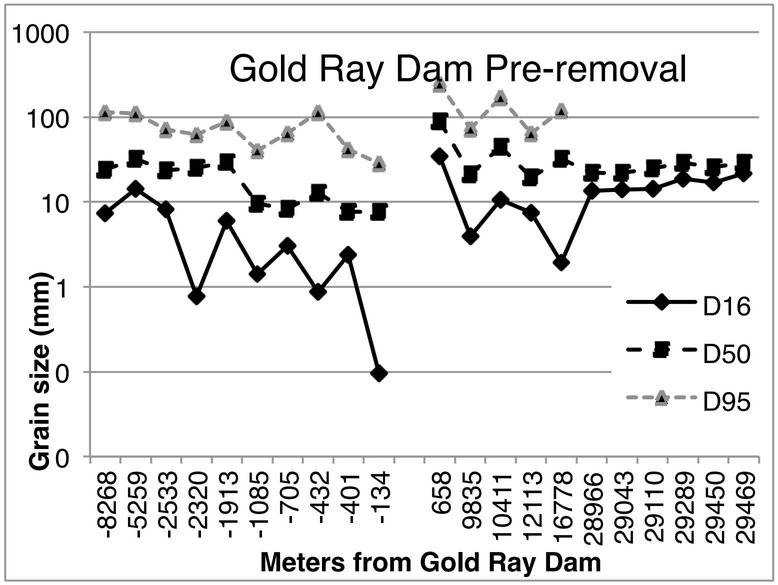
Appendix 1.13 Example of equally-spaced polygons at Gold Ray site

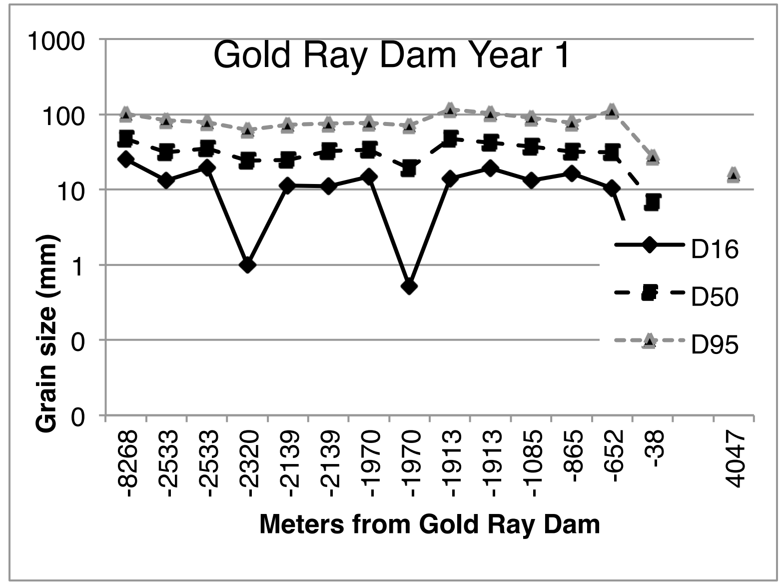
Appendix 2 Erosion and Deposition Total Volumes

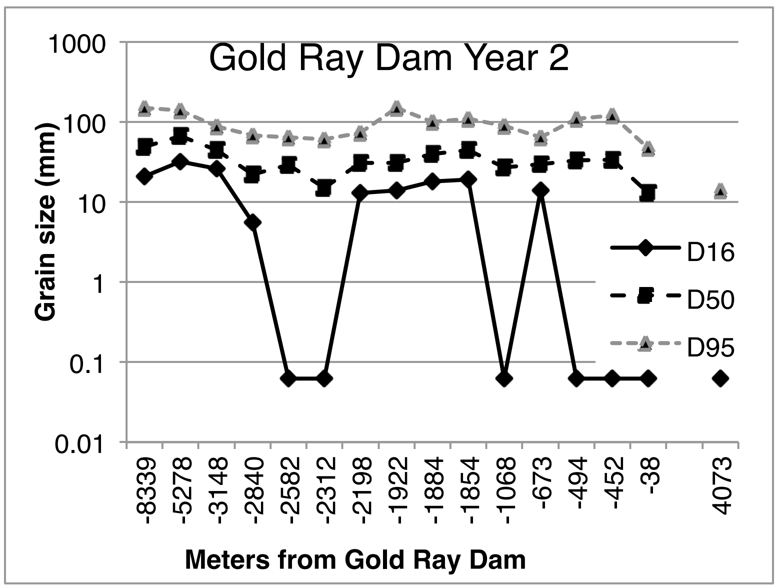
	Totals	Gold Ray	Savage Rapids	Brownsville	Oak Creek
Year 1	Erosion	-101,286	-	-3564	-230
	Deposition	132,879	-	1,828	173
Year 2	Erosion	-92,010	-25,173	-3,898	-258
	Deposition	116,041	236	1,349	259
Year 3	Erosion	-94,042	-25,700	-	-
	Deposition	104,433	730	-	-
Year 4	Erosion	-	-5,871	-	-
	Deposition	-	12,659	-	-

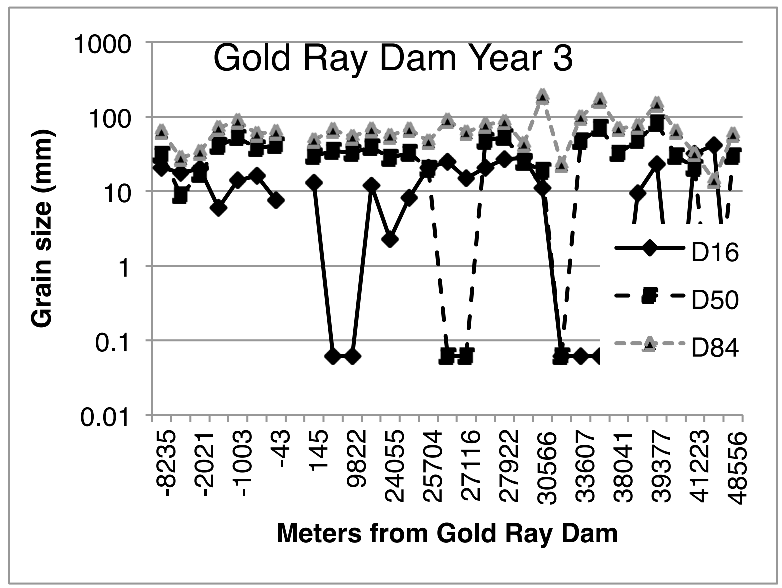
Appendix 2.1 Erosion and deposition total volume (m^3) across entire survey area. Water years with at least one daily mean discharge exceeding 1.2 RI discharge are shaded

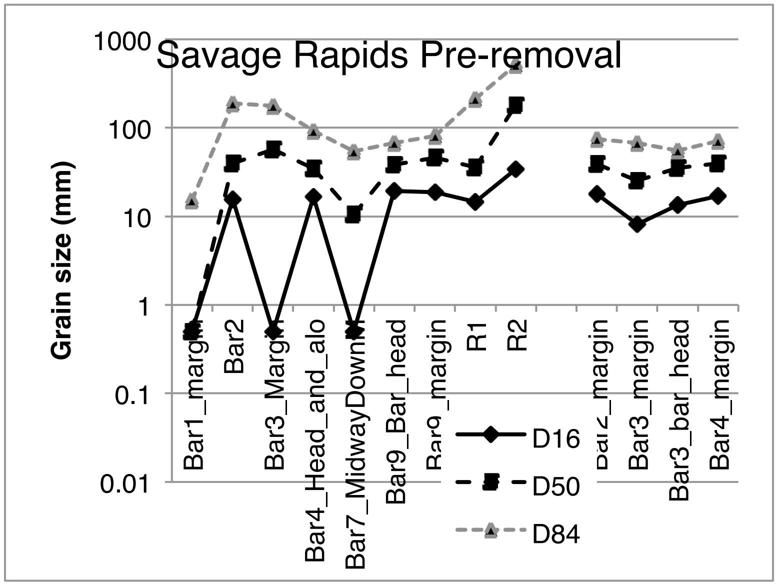
Appendix 3 Sediment Grain Size Distributions By Survey Year

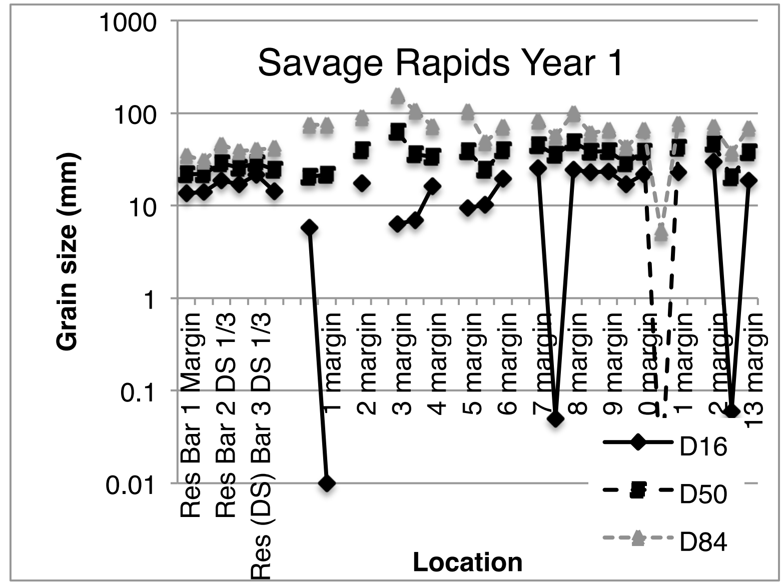


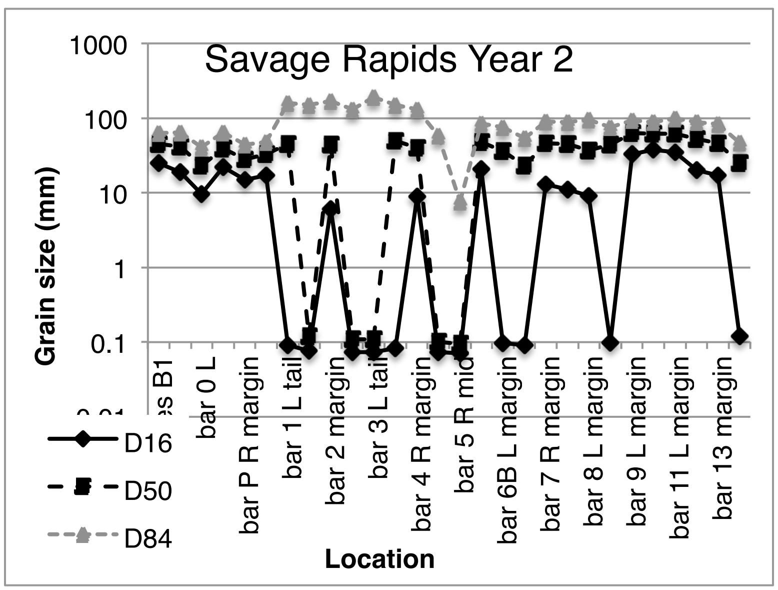


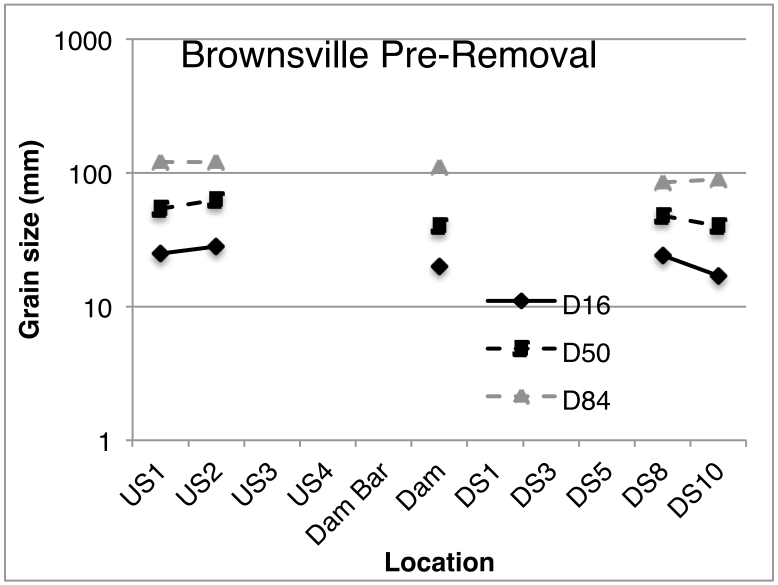


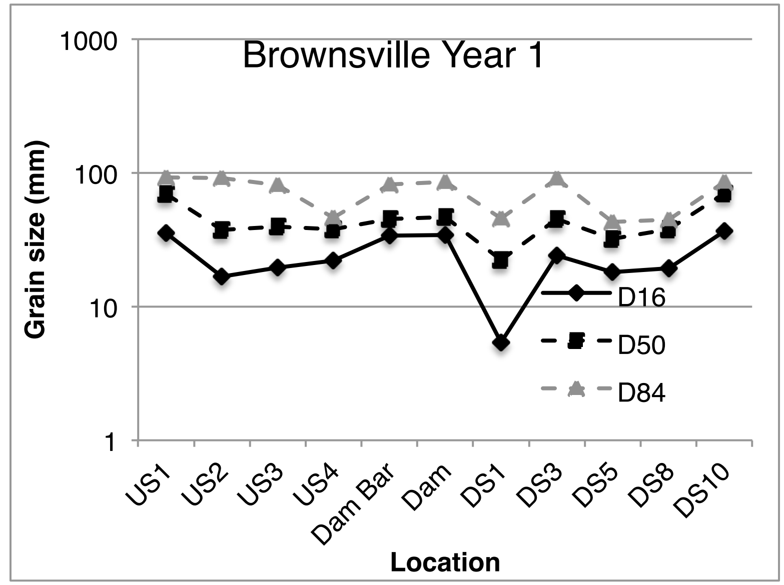


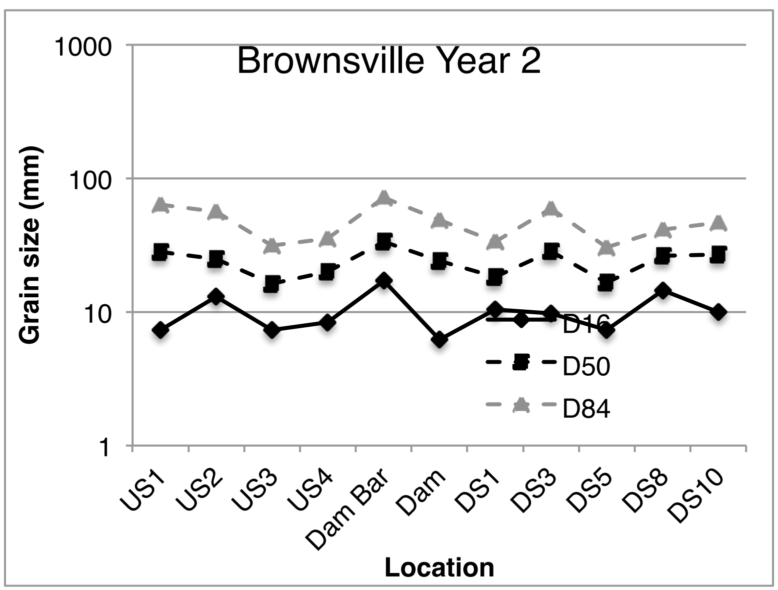

Savage Rapids Pre-removal
Grain size (mm)
1000
100
10
1
0.1
0.01
Bar1_margin
Bar2
Bar3_Margin
Bar4_Head_and_alo
Bar7_MidwayDown
Bar9_Bar_head
Bar9_margin
R1
R2
Bar2_margin
Bar3_margin
Bar3_bar_head
Bar4_margin
D16
D50
D84

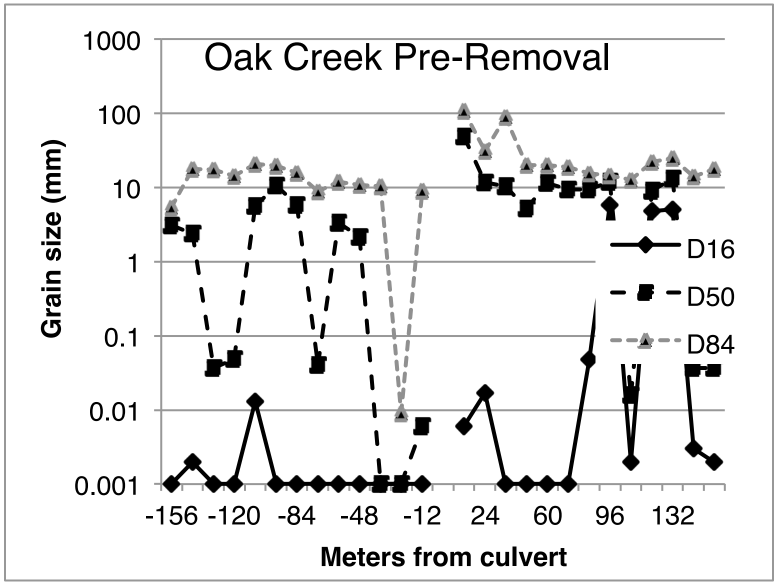

Savage Rapids Year 1
Grain size (mm)
1000
100
10
1
0.1
0.01
Res Bar 1 Margin
Res Bar 2 DS 1/3
Res (DS) Bar 3 DS 1/3
1 margin
2 margin
3 margin
4 margin
5 margin
6 margin
7 margin
8 margin
9 margin
0 margin
1 margin
2 margin
13 margin
Location
D16
D50
D84

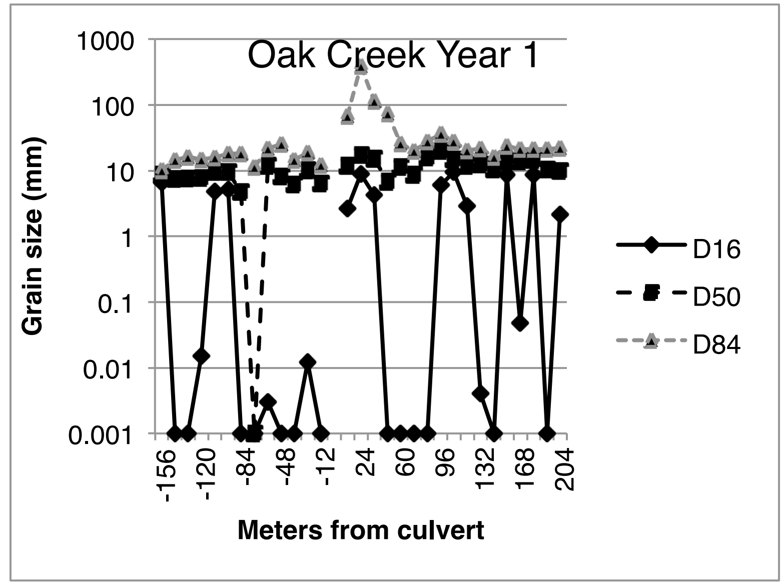

Savage Rapids Year 2
Grain size (mm)
1000
100
10
1
0.1
bar 0 L
bar P R margin
bar 1 L tail
bar 2 margin
bar 3 L tail
bar 4 R margin
bar 5 R mid
bar 6B L margin
bar 7 R margin
bar 8 L margin
bar 9 L margin
bar 11 L margin
bar 13 margin
Location
D16
D50
D84

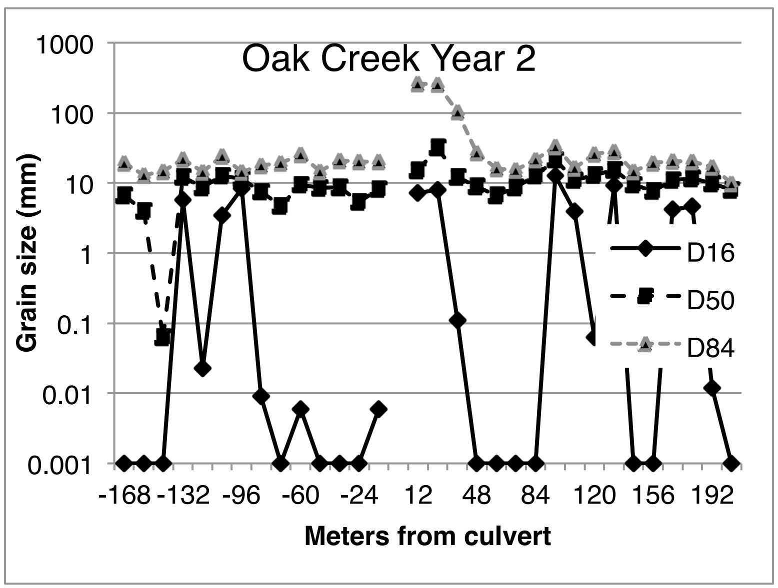

Brownsville Pre-Removal
1000
100
10
1
Grain size (mm)
US1
US2
US3
US4
Dam Bar
Dam
DS1
DS3
DS5
DS8
DS10
Location
D16
D50
D84


Brownsville Year 1
1000
100
10
1
Grain size (mm)
US1
US2
US3
US4
Dam Bar
Dam
DS1
DS3
DS5
DS8
DS10
Location
D16
D50
D84


Brownsville Year 2
1000
100
10
1
Grain size (mm)
US1
US2
US3
US4
Dam Bar
Dam
DS1
DS3
DS5
DS8
DS10
Location
D16
D50
D84


Oak Creek Pre-Removal
1000
100
10
1
0.1
0.01
0.001
Grain size (mm)
-156 -120 -84 -48 -12 24 60 96 132
Meters from culvert
D16
D50
D84


Oak Creek Year 1
1000
100
10
1
0.1
0.01
0.001
Grain size (mm)
-156 -120 -84 -48 -12 24 60 96 132 168 204
Meters from culvert
D16
D50
D84


Oak Creek Year 2
1000
100
10
1
0.1
0.01
0.001
Grain size (mm)
-168 -132 -96 -60 -24 12 48 84 120 156 192
Meters from culvert
D16
D50
D84

Appendix 4 Sensitivity of Greimann Péclet Number Calculation to Porosity and Sediment Transport Variables

The accuracy of the Péclet Number method is considered by comparing the result at Brownsville to an alternative method of calculating a Péclet number from the transport capacity rates of bed material and pulse material:

$$Pe = \frac{u_d h_d}{K_d} \quad (1)$$

$$u_d = \frac{G_d - G_0}{h_d(1-\lambda)} \quad (2)$$

$$K_d = \frac{(b_d G_d + b_0 G_d)}{6S_0(1-\lambda)}, \quad (3)$$

where G_0 is the bed material transport capacity rate, G_d is the pulse material transport capacity rate, h_d is the maximum pulse height, λ is sediment porosity, and *b* is a sediment transport coefficient expected to be between 4 and 6 (Greimann *et al.* 2006). Brownsville is selected as the comparison site because the DoDs capture the full extents of both the upstream and downstream edges of the pulse.

The geomorphic results at Brownsville are used to calculate an alternative Péclet number according to the method of Greimann et al. (2006). As measured by the GCD results, 3,464 m^3 of pulse sediment are eroded from the entire survey extent in the first year following dam removal. The transport capacity of the pulse material is 3.4E-09 m^2s^{-1}. The transport capacity of the bed material is calculated from the 25 m^3 of sediment that are deposited in the most upstream polygon in the first year following dam removal. The transport capacity of the bed material is 6.9E-10 m^2s^{-1}. The Greimann method result of 0.0008 is less than the measured Péclet numbers, but both results conclude that dispersion dominates pulse behavior.

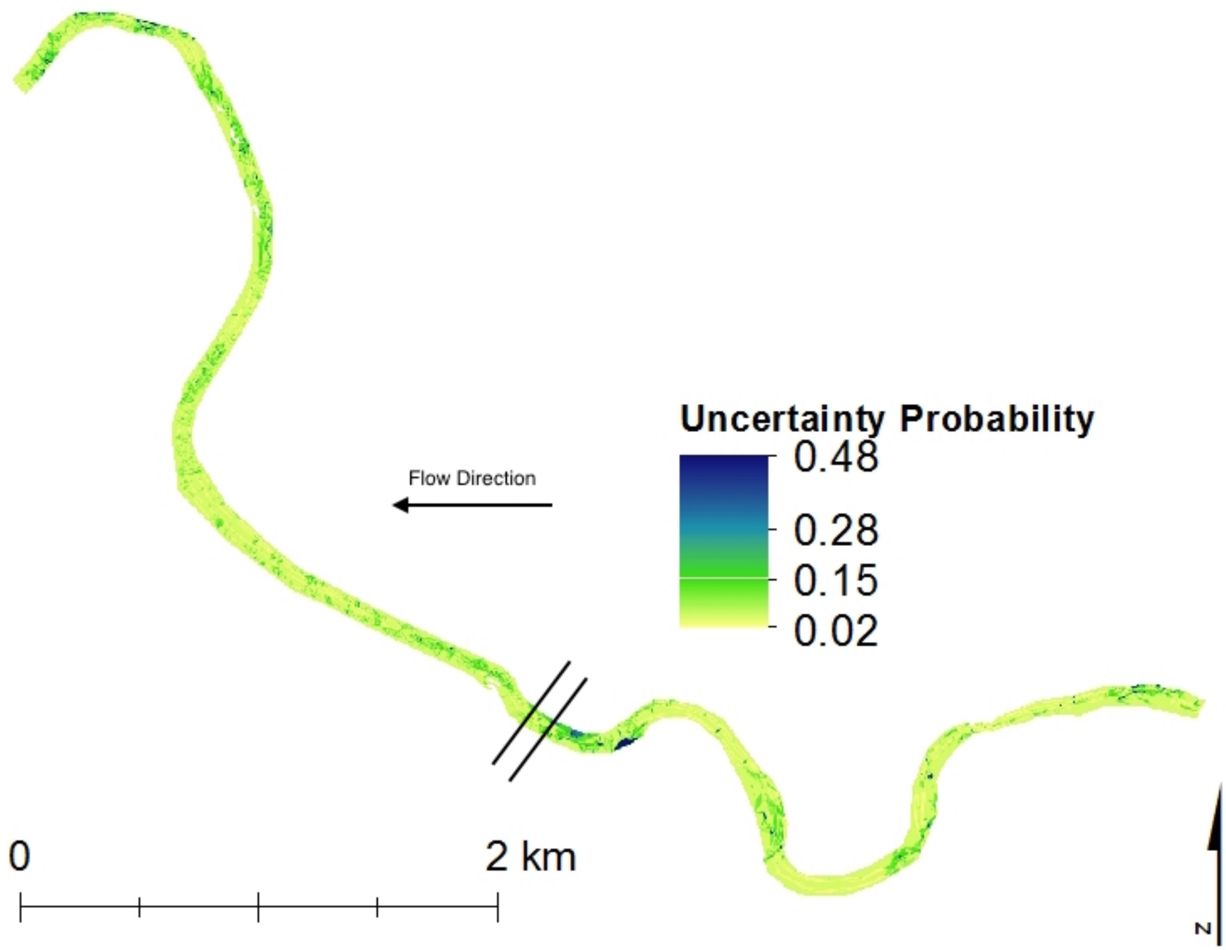
Appendix 4.1 Péclet numbers to one significant figure given sediment porosity $\boldsymbol{\lambda}$ between 0.3 to 0.5 and sediment transport coefficient *b* between 4 to 6

$\lambda = 0.3$	b	Pe
	4	0.002
	5	0.001
	6	0.0008
$\lambda = 0.4$		
	4	0.001
	5	0.0009
	6	0.0008
$\lambda = 0.5$		
	4	0.001
	5	0.0009
	6	0.0008

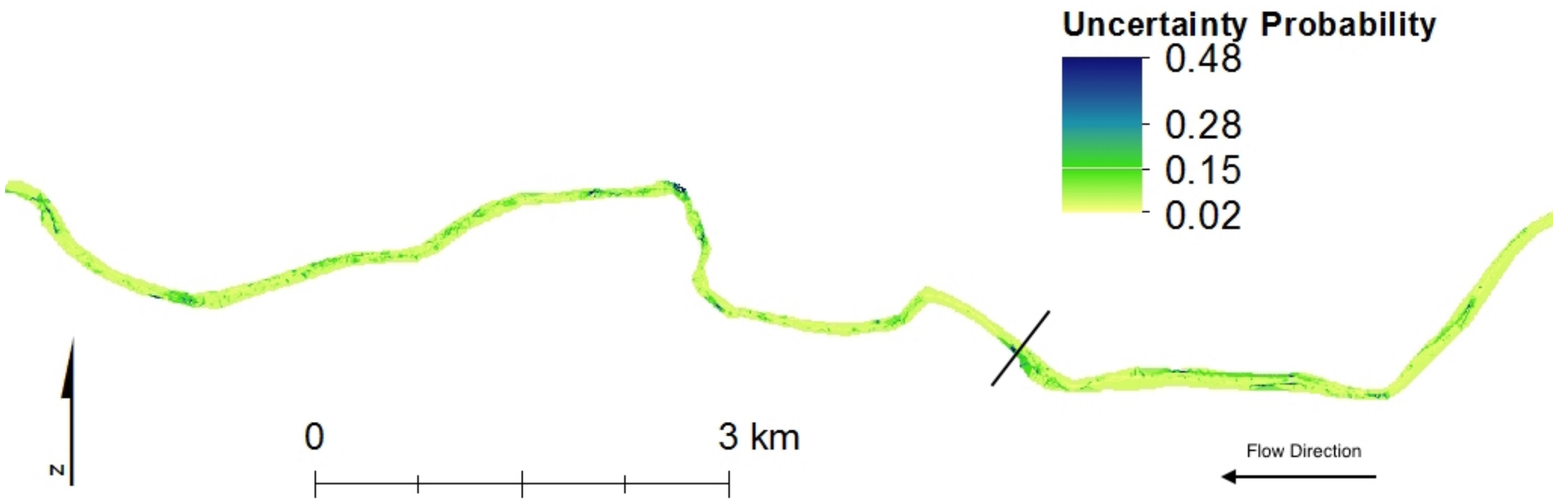
Appendix 4.2 Values of variables used in Greimann Péclet number calculation at Brownsville

Variable	Value
S	0.0008
λ	0.4
b	4
G_d ($m^2 s\text{-}^1$)	3.4E-09
G_o ($m^2 s^{-1}$)	6.9E-10

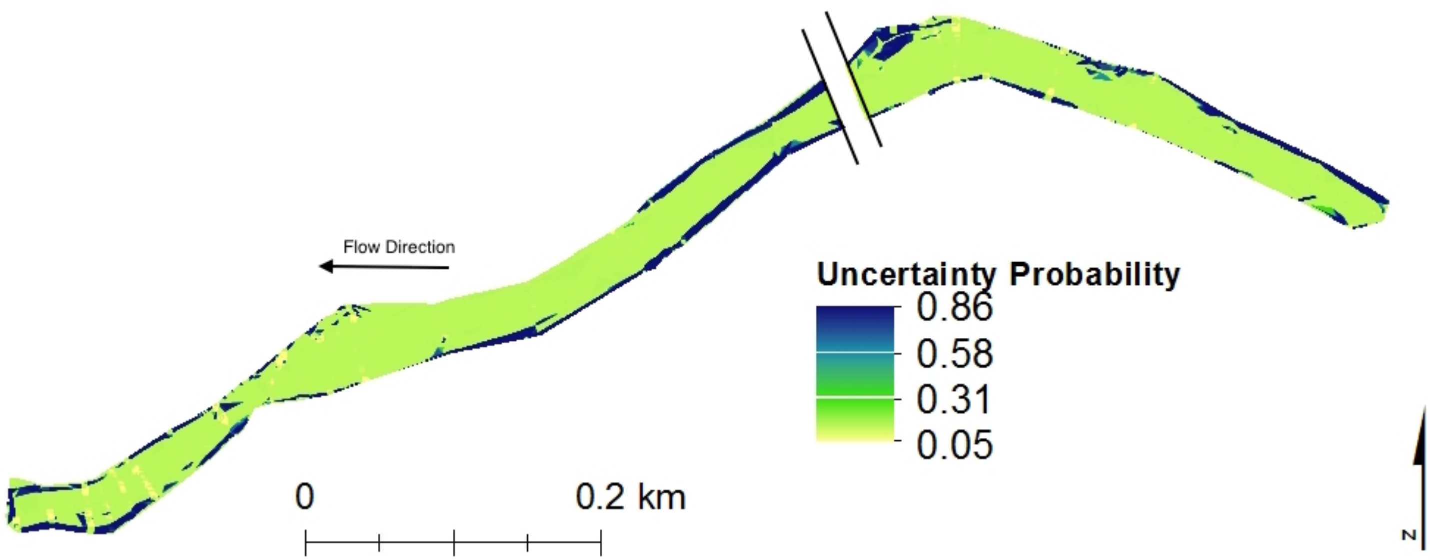
Appendix 5 Geomorphic Change Detection Uncertainty Probability



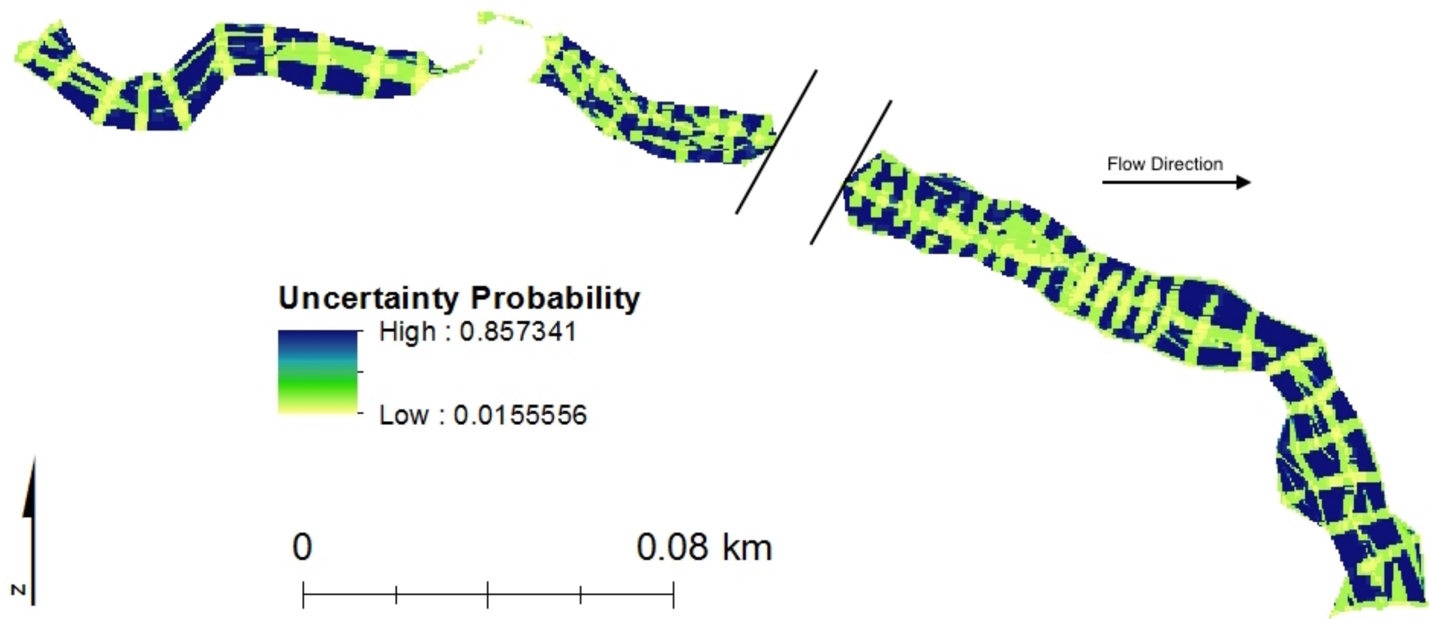
Appendix 5-1 Gold Ray GCD Uncertainty Probability



Appendix 5-2 Savage Rapids Uncertainty Probability



Appendix 5-3 Brownsville Uncertainty Probability



Appendix 5-4 Oak Creek Uncertainty Probability

Table 5-1 Range of Uncertainty Probability in DoDs at each site

	Gold Ray Dam	Savage Rapids	Brownsville	Oak Creek
FIS uncertainty probability	0.02-0.48	0.02-0.48	0.05-0.86	0.02-0.86