MARMOT DAM REMOVAL GEOMORPHIC MONITORING & MODELING PROJECT

ANNUAL REPORT
June 2008 – May 2009

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June 2010

ACKNOWLEDGEMENTS

We would like to sincerely thank all who assisted with the Marmot Dam Removal Geomorphic Monitoring & Modeling Project:

Oregon Watershed Enhancement Board – funding

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EXECUTIVE SUMMARY

This report describes the data collection and presents the results from an Oregon Watershed Enhancement Board (OWEB)-funded project, conducted by Johns Hopkins University, the National Center for Earth-surface Dynamics, and Graham Matthews and Associates in cooperation with the Sandy River Basin Watershed Council, to monitor the geomorphic changes in the Sandy River, Oregon following the removal of the Marmot Dam.

The 80 kilometer-long (50 mi) Sandy River drains 1,300 km^2 (500 mi^2) of the western Cascade Range and had been dammed by the Marmot Dam 48 km (30 mi) upstream from the Columbia River since 1913. As part of the decommissioning of the Bull Run Hydroelectric Project, Portland General Electric opted to remove the 15 meter-tall (50 ft) concrete capped dam. Its 2007 removal and subsequent exposure of 750,000 m^3 (980,000 yd^3) of impounded sand and gravel to fluvial erosion provided an excellent opportunity to measure the response of an energetic gravel-bed river to a temporary increase in sediment available for transport.

We partnered with several federal agencies (US Geological Survey, US Forest Service, and the Bureau of Reclamation) and other universities (Portland State University, Oregon State University) to establish a comprehensive multi-year sediment and geomorphic monitoring program on the Sandy River. The program collected morphologic data (long profile surveys, high density local topographic and bathymetric surveys, and LiDAR acquisition), grain size data (surface pebble counts and subsurface bulk samples), photographic (time lapse photography at as fine as 15 minute intervals, annual repeat panoramic photographs, and aerial photography), water discharge, and sediment transport measurements (suspended load and bedload). Measurements were taken throughout a 42 kilometer (26 mile) reach from well above the dam site downstream nearly to the Columbia.

Our contribution to the group effort primarily focused on measuring ‘sediment at rest’ during the summer by surveying two downstream reaches and characterizing the grain size distribution of three downstream reaches. Additionally, during the winter high flows we measured ‘sediment in motion’ at a station upstream of the reservoir to measure the sediment input into the system. By combining our measures of change from 2007 to 2008 with other contributors data we were able to describe the change in the river bed as a result of the dam removal.

In reaches 13 km (8 mi) and 20 km (12 mi) downstream of the dam we found no significant overall change in the river bed elevation. We measured a progressive downstream decrease in grain size which was unaffected by the dam removal, and a progressing downstream increase in sand present on the surface – which increased 10% after the dam removal. Upstream of the dam we computed an annual sediment load (in a slightly drier than normal year) equivalent to approximately one tenth of the volume of the impounded sediment. We were able to show that the timing and gross patterns of erosion and deposition were well predicted by pre-removal numerical models.

Our data collected through the first and second year after the Marmot Dam removal allows us to confidently describe the morphologic response of the Sandy River to the Marmot Dam sediment. We have used the knowledge gained in the first year to modify the follow-on year’s monitoring plan and have shared the data gathered thus far in local, regional, and national forums.

1. INTRODUCTION

This report describes the data collection and presents the results from an Oregon Watershed Enhancement Board (OWEB)-funded project to monitor the geomorphic changes in the Sandy River, Oregon following the removal of the Marmot Dam. This project, conducted by Johns Hopkins University (JHU), the National Center for Earth-surface Dynamics (NCED), and Graham Matthews & Associates (GMA) in cooperation with the Sandy River Basin Watershed Council (SRBWC), is one component of a multi-year research project involving several other universities and multiple federal agencies.

1.1. BACKGROUND

1.1.1. Project Setting & History

The Sandy River drains 1,300 km^2 (500 mi^2) of the western Cascade Range (Figure 1). It flows nearly 80 km (50 mi) from the western flanks of Mt. Hood to the confluence with the Columbia River immediately upstream of Portland, Oregon. Most of the basin's precipitation comes in the late fall through early spring as a mix of rain and snow (depending on elevation). A typical hydrograph of the Sandy River has peaks occurring during winter storms, a modest snowmelt runoff in the late spring, followed by a gradual decrease throughout the summer, with the lowest flows occurring in the late summer and early fall (Stillwater Sciences, 2000a).

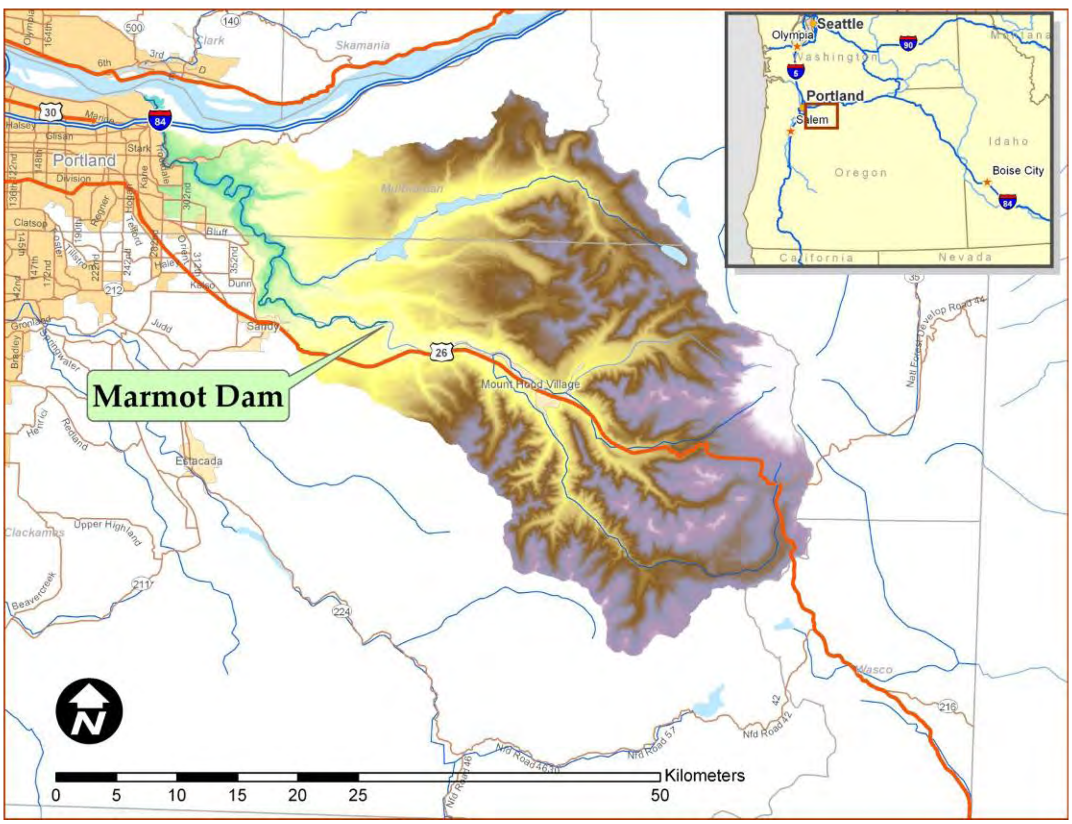

Figure 1 - Overview of the Sandy River Basin

In 1906 the Mt. Hood Railway and Power Company began construction of the Bull Run Hydroelectric Project (Taylor, 1998). The project involved diverting water from the Sandy River, transporting it through canals, flumes, and tunnels into the Little Sandy River, via the Little Sandy Dam, through a flume, into Roslyn Lake, through the Bull Run Powerhouse, and into the Bull Run River (a tributary to the Sandy River) (Figure 2). The Bull Run Hydroelectric Project provided its current owner, Portland General Electric, with 22 MW of generating capacity (Esler, 2009).

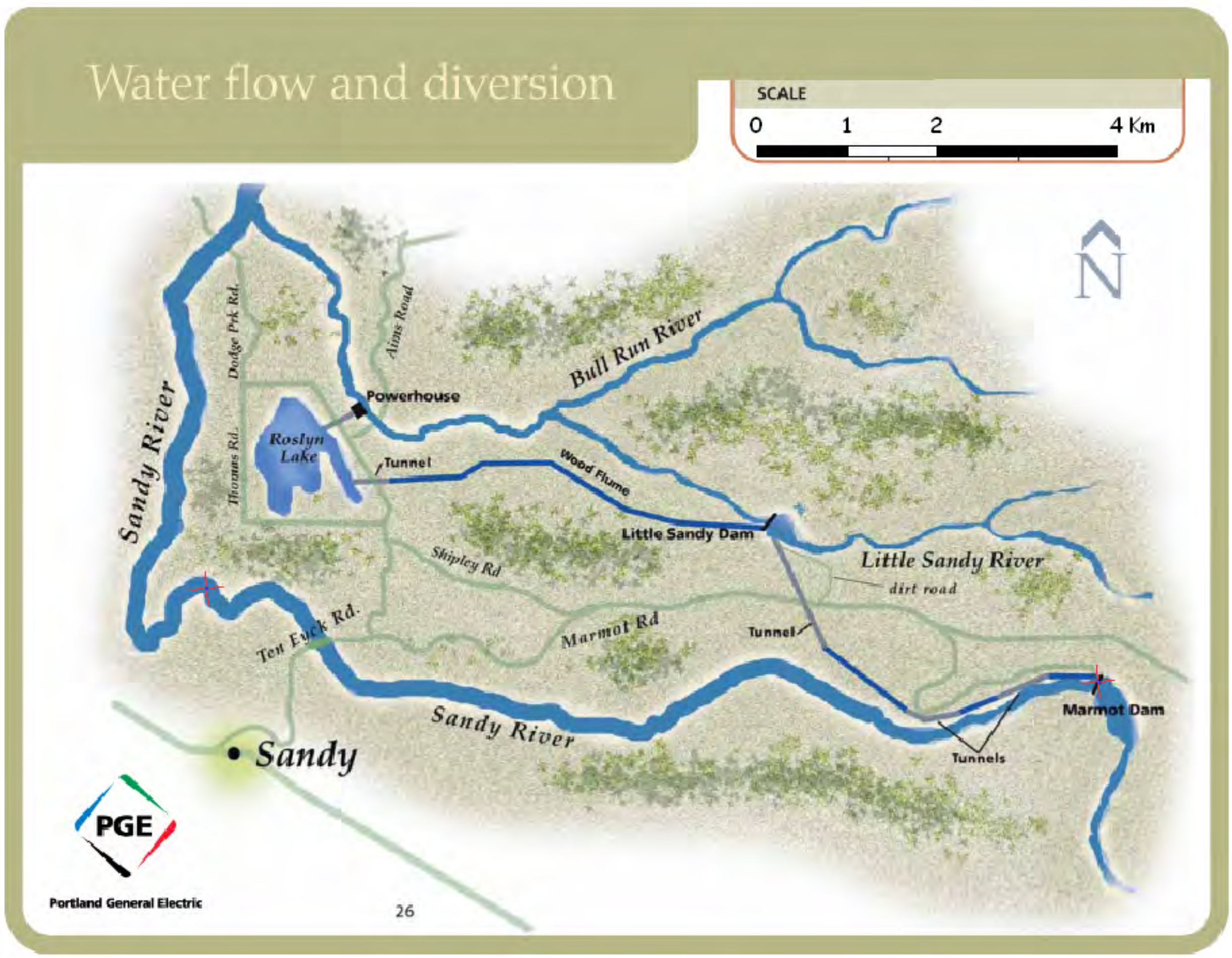

Figure 2 - Overview of the Bull Run Hydroelectric Project. (courtesy of PGE)

The diversion of Sandy River water into the Bull Run Project was accomplished by constructing the Marmot Dam 48 km (30 mi) upstream from the Columbia River in 1913. The dam site was located approximately halfway down the Sandy River and diverted water from the upper 680 km^2 (260 mi^2) of the watershed. Originally it was a timber crib dam, which was replaced in 1989 by a concrete dam (Esler, 2009). The concrete dam (Figure 3) was 15 m (50 ft) tall and 59 m (194 ft) wide, and was essentially a run-of-the-river dam which had nearly completely filled with sediment delivered from upstream, leaving no room for water storage. Typical summer flows at the dam site are between 15 and 45 cms (500 and 1,500 cfs) (USGS gauge #14137000) (Figure 4) with a 1.5 year recurrence interval discharge of 310 cms (11,000 cfs) (http://waterdata.usgs.gov). Between 0 and 17 cms (600 cfs) of water was diverted, subject to seasonally adjusting minimum instream-flow requirements below Marmot Dam, and a 23 cms (800 cfs) combined limit between the Sandy and the Little Sandy (PGE, 2002).

Figure 3 - Marmot Dam Sitein July 2007 (left) and January 2008 (right). Construction of the cofferdam is visible in the 2007 photograph.

In 1998 PGE began the process of renewing the Federal Energy Regulatory Commission (FERC) operating license, which was due to expire in 2004 (Esler, 2009). Weighing the likely cost of complying with the new licensing requirements against the economic benefit, PGE elected to decommission the Bull Run Hydroelectric Project and in October 2002, it reached a settlement agreement to decommission the project and surrender its license (PGE, 2002). A critical element of the decommissioning was the 2007 removal of Marmot Dam. Over the lifespan of the dam, it had trapped nearly 750,000 m^3 (980,000 yd^3) of sediment. The fate of this sediment was one of the important factors in the decision-making process. The reintroduction of such a large amount of sediment back into the river had the potential to significantly alter the form of the river bed and impact anadromous salmonid habitat. Potential effects were: 1) increases in turbidity, 2) adverse changes to fish spawning, rearing, or holding habitat due to scour or deposition, 3) negative effects on food supply due to burial or scour, and/or 4) the creation of passage barriers (Stillwater Sciences, 2000a).

Following an analysis of several removal options, a 'blow and go' option was selected – removing a minimal amount of sediment, demolishing the dam and allowing the river to mobilize and redistribute the remaining sediment (PGE, 2002). A small earthen cofferdam was constructed in the reservoir 70 m (230 ft) upstream of the concrete dam (Figure 3). By drilling wells and installing pumps, PGE dewatered the sediment below the cofferdam. The concrete dam and a portion of the impounded sediment below the concrete dam and cofferdam were removed during the summer and early fall of 2007. The cofferdam was designed to withstand a flow of 71 cms, (2,500 cfs). When a storm of sufficient magnitude approached in the fall rainy season the cofferdam would be breached and fail. A storm with enough rainfall to cause the river to rise to the desired discharge occurred on October 19, 2007 (Figure 4). The pumps were turned off, removed, and a small notch was carved in the top of the cofferdam. The rising river subsequently broke through the cofferdam, began to incise into the reservoir sediment, and transport it downstream.

By the afternoon of October 19, 2007, for the first time in 94 years, the Sandy River flowed freely from its Mt. Hood headwaters 80 km to the Columbia, and onward, undammed, to the Pacific Ocean.

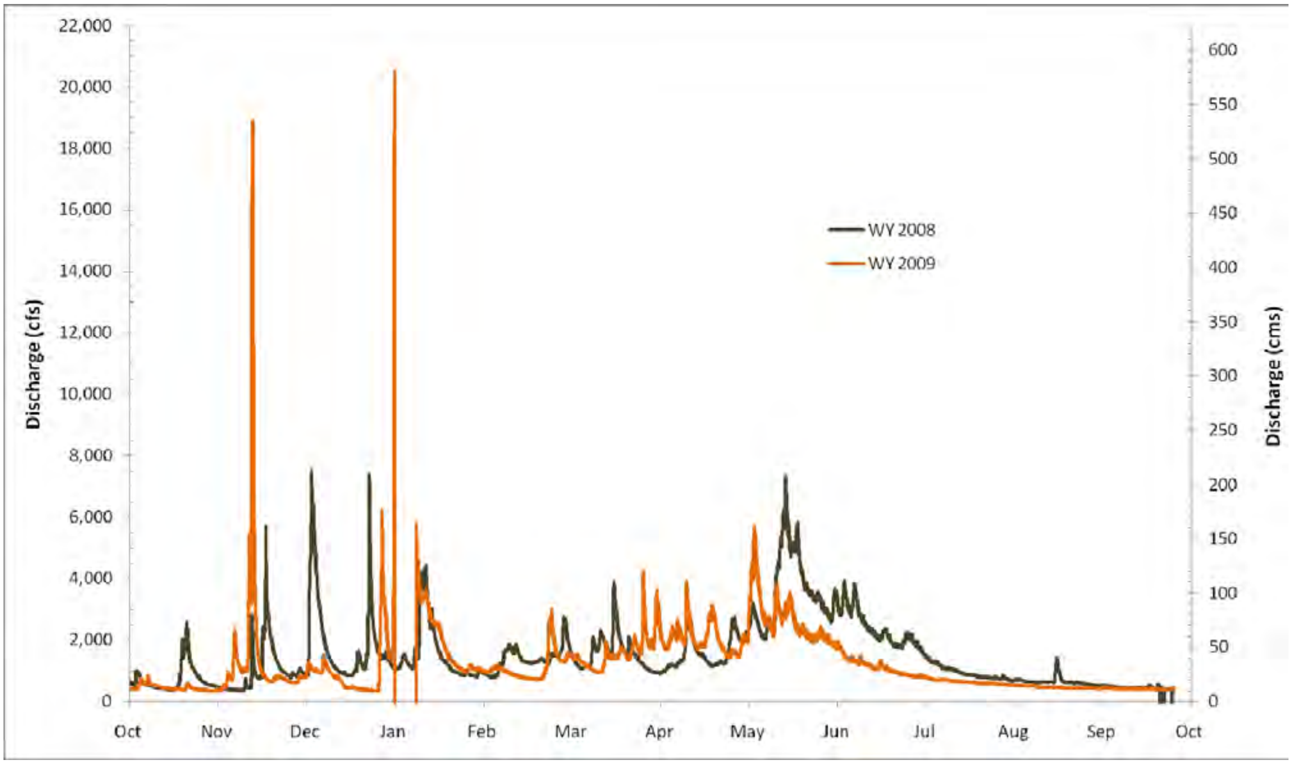

Figure 4 - Hydrograph for Water Years 2008 & 2009at Sandy River below Salmon River, nr Brightwood, OR (gauge number 14136500)(downloaded from the USGS)

1.1.2. Previous Work

Prior to the decommissioning there were several studies on the Sandy River and the potential effects of the Marmot Dam removal. During the early phases of the relicensing process, Taylor (1998) produced a report on the historical perspective of the salmon and steelhead runs in the Sandy River basin. She describes chinook, coho, and steelhead populations in decline since the late 19^{th} century in both the Sandy River basin and the Columbia River Basin as a whole. The report explains how land use and water resource development in the Sandy River basin changed over the past 200 years, and what impacts those changes might have had on the salmonid populations. The long list of factors influencing salmon and steelhead production in the Sandy River basin includes overharvest by commercial and sport fisheries, habitat degradation from land use and municipal water supply development, hatchery fish introduction, and flow and passage restrictions from the Bull Run Hydroelectric Project (Taylor, 1998). On the final factor, Taylor lists the numerous fish passage accommodations that have been made since the original construction of the Marmot Dam. While the Taylor report is not specifically focused on the dam removal decision and its potential consequences, the point is sufficiently well made that since there are many factors accounting for the decline of Sandy River salmonid populations, the removal of the dam should not be seen as a 'magic bullet' which would restore populations to early 19^{th} century levels.

Two reports which focus specifically on evaluating the effects of the dam removal were prepared by Stillwater Sciences for PGE in 2000 (Stillwater Sciences, 2000a & b). Fundamental to the Stillwater Sciences analysis was a numerical model of river bed evolution, (Stillwater Sciences, 2000b; Cui & Wilcox, 2008 describe the same model). The model used measures of the river elevation and width taken from aerial photography, measurements of the bed grain size, and the historical record of discharge as inputs. The calculations treat the river in a single dimension – the river is seen as a series of cross-sectional averaged values. With the ability to simulate the dam removal, erosion of the reservoir sediment, downstream transport, and deposition, multiple scenarios could be analyzed. Four removal alternatives were tested:

1. removal of all sediment up to 1,700 m (1.1 mi) above the dam,
2. a single season removal with only minimal sediment excavation,
3. a 2-year staged removal with partial sediment excavation, and
4. a single year removal with partial sediment excavation.

To deal with uncertainty in precipitation-runoff patterns, each of the scenarios was tested with streamflows that represented normal, wet, and dry years. The result of the modeling was a one-dimensional depiction of the bed elevation over time (Figure 5). The modeled results were not intended as an exact prediction of the state of the river, but rather a suggestion of the general locations and magnitudes of erosion and deposition, and the timescales associated with predicted changes. Using the results of the model (the predicted changes in river morphology), the likelihoods of the adverse outcomes were assessed for the proposed removal scenarios (Stillwater Sciences, 2000a), and ultimately incorporated into the Environmental Impact Statement for the project (FERC, 2003). For the alternative which was ultimately chosen, the model results predicted a large amount of deposition (up to 4 m [13 ft]) in the reach within the first 2.4 km (1.5 mi) of the dam during the first year (Stillwater Sciences, 2000b). Within the first 10 years there would be measurable deposition (1.5 – 2 m [5-7 ft]) in the area just above Revenue Bridge, although the deposition rates would be less than 0.5 m (1.6 ft) per year. Roughly half of the reservoir sediment was predicted to erode during the first year. Most of the sand eroded was expected to move through the system and deposit in the lower 3 km (1.9 mi) of the river (near the Columbia confluence). The differences in results for wetter-than-normal or drier-than-normal years were primarily to change the timing of the deposition, not the magnitude. In the dry scenario, it could take up to five years to 'catch up' to the bed condition of the normal years. The Stillwater Sciences study became the basis for predicting the likely river bed configuration following dam removal, and the potential impacts to anadromous salmonid habitat.

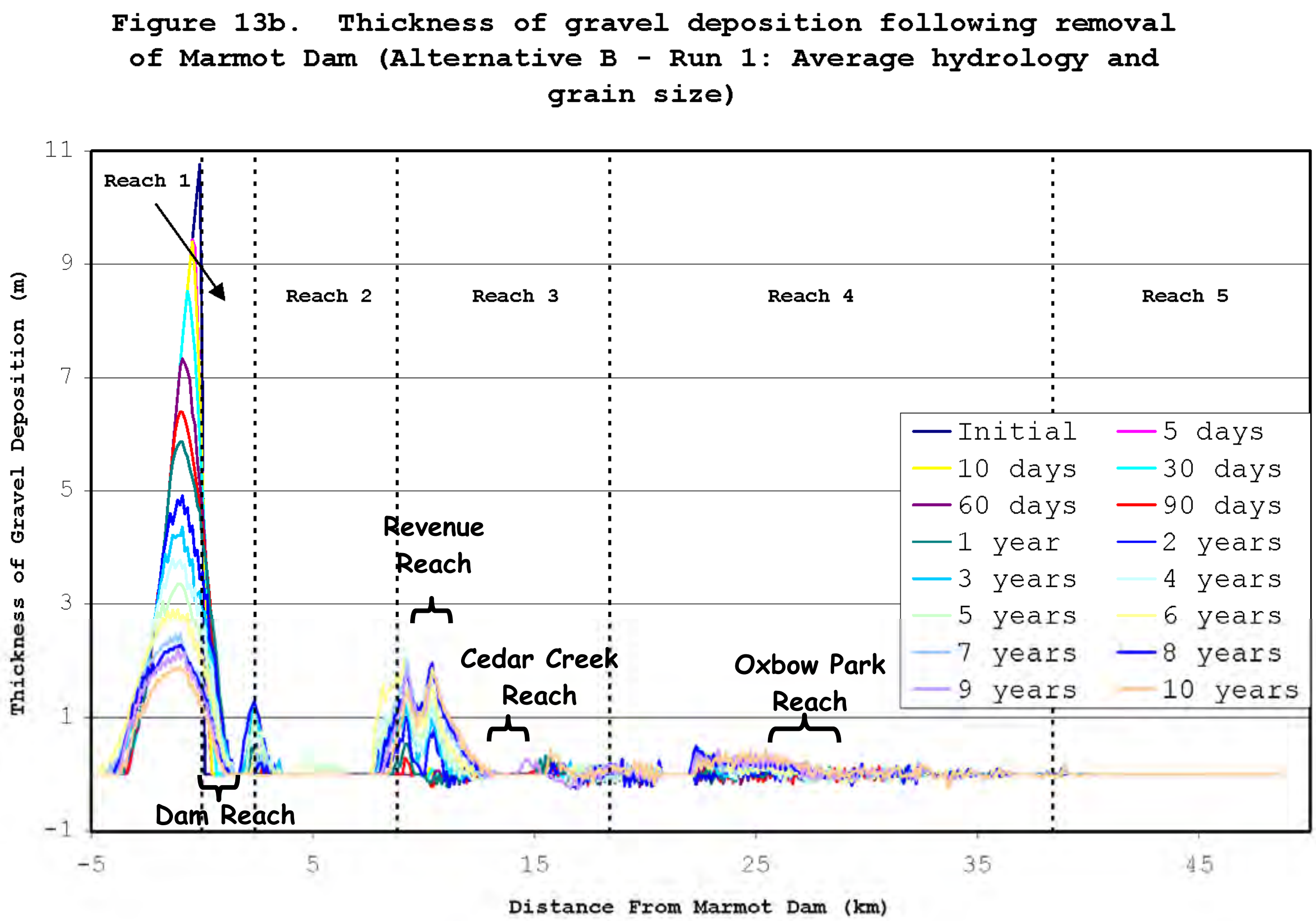

Figure 5 - Predicted deposition from Stillwater Sciences (2000b) showing study reaches

A follow-on study to the Stillwater Sciences work was commissioned by PGE (Stewart & Grant, 2005). It built upon the findings and modeling of Stillwater Sciences, but investigated several processes which were not explicitly addressed in the previous studies. A one-dimensional model makes calculations at points along a river in the streamwise direction. Each of these points (or nodes) is meant to represent the entire width, depth, and length of the river between the nodes upstream and downstream of it. This method reduces the complexity of the model and the data collection required to support it, however it cannot explicitly deal with certain processes and cannot describe the topography within the averaged area. The Stewart & Grant study looks at two such processes – knickpoint migration, and pool filling. They used several other dam removals as analogues and argued that the reservoir erosion would occur by a stepped knickpoint migration [a persistent steep drop in the river bed which migrates upstream], rather than by a rotating mechanism [where the steep slope created by the dam removal gradually decreases in slope without moving upstream] as used in the Stillwater model. The implications of differing erosion mechanisms affect the rate of erosion of fine sediment. Stewart & Grant argued that a stepped knickpoint migration erosion mechanism could produce significantly higher amounts of suspended sediment, but for a shorter duration. They also used measurements of velocity, depth, and grain size to evaluate the storage potential of pools for fine sediment. They concluded that there should be limited accommodation space for fine sediment and shared the Stillwater Sciences conclusion that most of the fine sediment evacuated from the reservoir would not deposit above the lower few kilometers of the river. Finally, using other dam removals and the existing Sandy River topography, they predicted the form of the predicted deposition in the near-dam area. They predicted a relatively uniform deposition in the 0.8 km (0.5 mi) below the dam, and a transition from pool-riffle morphology to a step-pool morphology below that. Finally, they predicted the deposition in the reach above Revenue Rapid will be moderated by the rapid immediately downstream. Generally, Stewart & Grant agreed with the Stillwater Sciences predictions, they disagreed on the reservoir erosion mechanism, and they speculated on the form of the deposition that Stillwater Sciences predicted.

1.1.3. Why Sediment?

Monitoring of the Marmot Dam removal focused on the river morphology and the movement of sediment. Many possible effects of the dam removal were identified and analyzed in the Environmental Impact Statement (EIS) – from geological and water resources, to fisheries, recreation, and land use, as well as cultural and socioeconomic impacts (FERC, 2003). The EIS concluded that "in the long term, removal of Marmot dam is anticipated to substantially benefit salmonid populations in the basin," (FERC, 2003, p. 142). However, many of the potential adverse impacts of the dam removal were related to the sediment stored behind the dam – increases in the suspended sediment concentration, fish passage impairment, habitat degradation, and channel instability. The alternative decommissioning plans which called for a more complete removal of the reservoir sediment were significantly more expensive ($10-12 million) than the alternative with minimal sediment excavation ($3 million) (FERC, 2003). The question arose: is it possible to remove the dam and deal with the sediment in a cost effective manner? The answer provided by the geomorphic analysis (Stillwater Sciences, 2000a & b; Stewart & Grant, 2005) was “yes,” and the decision was made to remove the dam and let the river redistribute the sediment.

Since geomorphic predictions weighed so heavily in the decision making process, the comparison of predicted to actual outcomes was critical to improving future geomorphic predictions. Monitoring instream changes and sediment movement on the Sandy River allowed researchers to critically assess geomorphic predictions, and refine predictive capability for future dam removal assessments.

1.2. Overall Decommissioning Monitoring

At the time it was removed the Marmot Dam was one of the largest dams to be removed in the previous 40 years (Major et al, 2008). The dam's size, the volume of sediment to be released, the ecological ramifications and the existence of detailed pre-removal studies (baseline data) made the Marmot Dam removal an ideal candidate for an extensive monitoring project. Many of the previously studied dam removals have been in the eastern and mid-western United States – especially Pennsylvania, Tennessee, Ohio, and Wisconsin (American Rivers, 1999; Doyle et al, 2003a; Cheng & Granata, 2007). Monitoring the Marmot Dam removal would provide the opportunity to add a steep, gravel-bed, western Cascade Mountain river to this growing body of knowledge (Pizzuto, 2002; Doyle et al, 2003b; O’Connor et al, 2008). To that end, a group of geomorphologists convened in the spring of 2007 with the goal of conducting a multi-year monitoring effort documenting geomorphic changes in the Sandy River following the Marmot Dam removal.

1.2.1. Collection Goals

The monitoring effort required data collection at a spatial and temporal resolution sufficient to document and analyze changes in the river. The Stillwater Sciences reports and the Stewart & Grant report predicted changes in the bed of the river from several kilometers upstream of the dam to several kilometers below with isolated effects all the way down to the mouth, and estimate that these changes could be expected to take place over hours and days initially but could persist as long as 10 years or more. The monitoring group had to decide what types of data to collect, where to collect it, how often to collect it, and for how long to collect it.

1.2.1.1. Data Types

Aerial Photography – In several hours at a moderate cost, the 50 km (31 mi) of river can be photographed from an airplane. When the photographs are orthorectified they can be overlain with other photographs or maps in order to make comparisons over time. Photography is primarily a 2-dimensional data type – it can only describe the planform but not the depth of the river, although some progress has been made on other Oregon rivers extracting river bathymetry from aerial photography (Walther et al, 2009). Repeat photography of the river from October 2006, Fall 2007, and October 2008 was used to identify channel change during these periods.

LiDAR – Light Detection And Ranging (LiDAR) is another airborne remote sensing tool which has been used on the Sandy River, though at a greater time and monetary cost than aerial photography. LiDAR uses an aircraft-mounted laser to generate measures of the ground surface elevation. There are variants of airborne LiDAR which can penetrate the water surface; however the LiDAR systems used on the Sandy River do not possess this ability (Watershed Sciences, 2006, 2008, & 2009). The LiDAR data can be processed into a digital elevation model (DEM) of all the land above the water surface from several kilometers upstream of the dam down to the confluence with the Columbia. Comparing the LiDAR maps from one year to another yields a measure of the annual change in surface elevation.

Longitudinal Profile Surveys – Without water-penetrating LiDAR, assessments of below-water bed elevations require direct measurement in the field. Conducting a complete bed survey over the entire 50 km of the river is time and cost prohibitive, but several longitudinal profile surveys have been conducted (Stewart, 2003; Bauer & Bountry, 2007). These surveys measure the water surface elevation and depth of the water using a survey-grade real time kinematic (RTK) GPS system coupled with a depth-sounder or acoustic Doppler current profiler (ADCP). The boat-based surveys can also be supplemented with conventional survey methods (e.g. total station) in wadeable sections of the river. The result of a longitudinal profile survey is a 1-dimensional representation of the water surface elevation (WSEL) or bed elevation plotted against downstream distance (Figure 6).

Topographic Surveys – At several places on the river, topographic surveys provide a detailed spatial representation of the ground elevation. The surveys have all been conducted with either total stations or RTK GPS. Topographic surveys map and define features of geomorphic significance such as the tops of banks, the channel thalweg, and the water's edge. Furthermore, monumented cross section surveys which are repeated each year provide detailed monitoring of channel change at the exact same section.

Both types of surveys are combined to produce a three dimensional, geo-referenced representation of the topography above and below the water.

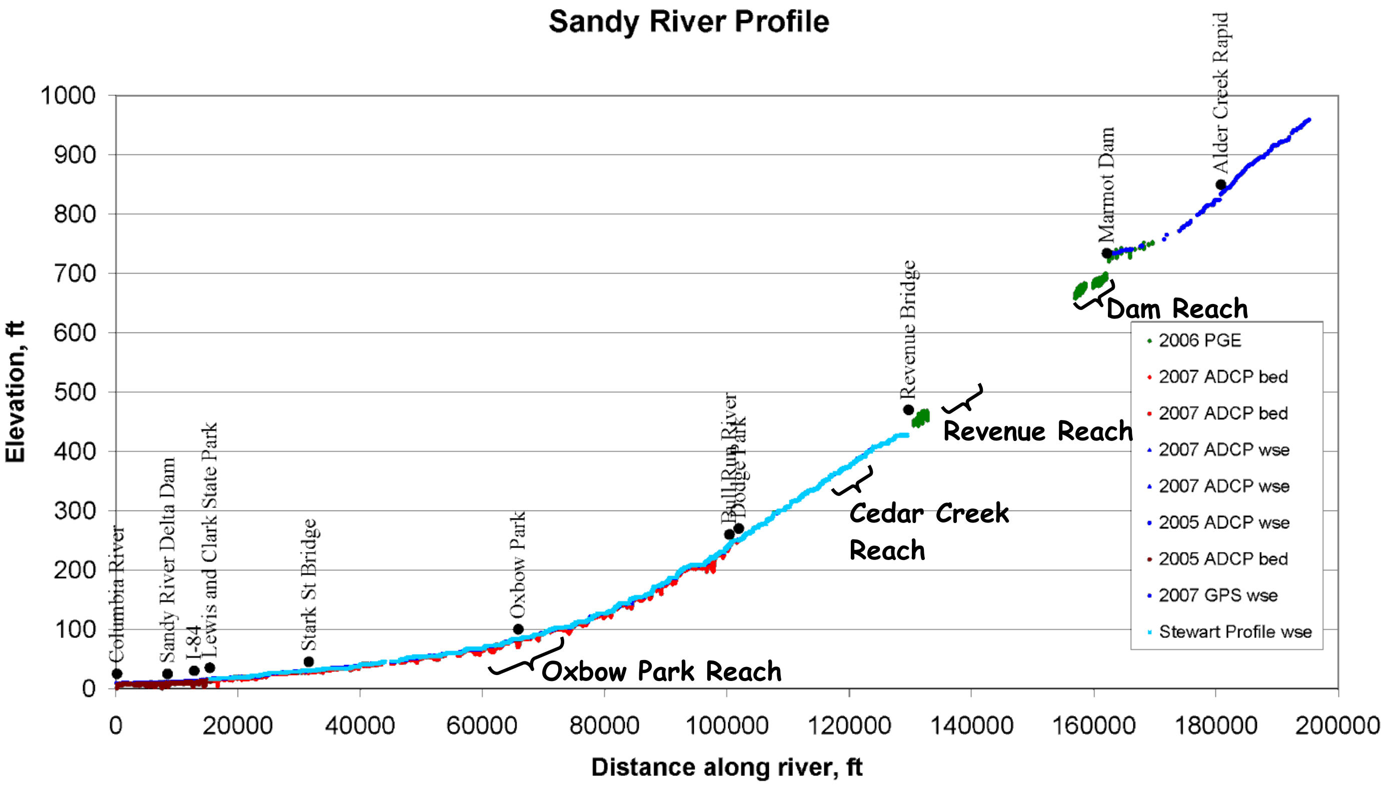

Figure 6 - Long Profile of the Sandy River (taken from Bauer & Bountry, 2007 [Figure 5]) showing study reaches

Grain Size Measurements – LiDAR and ground-based surveys measure the shape of the river bed, however the texture (or the distribution of grain sizes of the sediment particles making up the bed, banks, and bars) of the river bed is also of interest. In order to measure the texture two methods were used. To measure the surface grain size distribution (GSD) surface pebble counts were make. The pebble count involves measuring the size of several hundred (100-300) grains from the surface material (Wolman, 1954). To measure the GSD below the surface, bulk samples were taken. The bulk sample is conducted by excavating a volume of material, sieving it, and weighing the sieved portions by size-class.

Ground-based Photography – The annual aerial photography, was supplemented by ground-based photography. During the first year following the dam removal five digital cameras on timers recorded the failing of the cofferdam and much of the reservoir erosion. At 32 locations on the river (concentrated in the upper 28 km [17 mi]), repeated panoramic photographs have been taken from surveyed photo-points. Additionally, there are a plethora of photographs taken since July 2007 at many points along the river, often coincident with large storm events.

Sediment Transport Measurements – The changes in bed configuration are a result of sediment being eroded and deposited throughout the river. To make sense of the changes and to test predictions, actual measurements of sediment transport were required. At various locations samples of both suspended sediment and bedload were taken during high-flow events. These samples, when correlated with streamflow, provide equations from which sediment loads can be computed.

Water Discharge – It is impossible to evaluate sediment transport in the river without understanding the hydrology. There are three USGS gauges (14136500, 14137000, and 14142500) on the Sandy River which provide a continuous record of water discharge. At two of the sediment sampling locations temporary gauges were installed to provide an additional measure of water discharge.

1.2.1.2. Spatial Extent (Figure 7)

The effects of the Marmot Dam removal were expected to manifest themselves for several kilometers upstream of the dam. The surveys, LiDAR, and aerial photography extended upstream at least 3 km (1.8 mi), to the end of the reservoir-influenced reach. Water discharge and sediment transport measurements were made at the first bridge, 11 km (6.8), upstream of the dam, however the 8 km (5 mi) between the bridge and the upper reach of the reservoir was not considered to be part of the study reach.

The 2.5 km (1.6 mi) downstream of the dam was expected to exhibit the greatest deposition, and was thus heavily documented with photographs and surveys. Sediment sampling was also conducted in this reach, immediately below the dam. A short reach 9 km (5.6) below the dam was predicted to be the lowest reach that would show any significant gravel accumulation (Stillwater Sciences, 2000a). This reach was also thoroughly surveyed and photographed and a sediment sampling site was located in this reach.

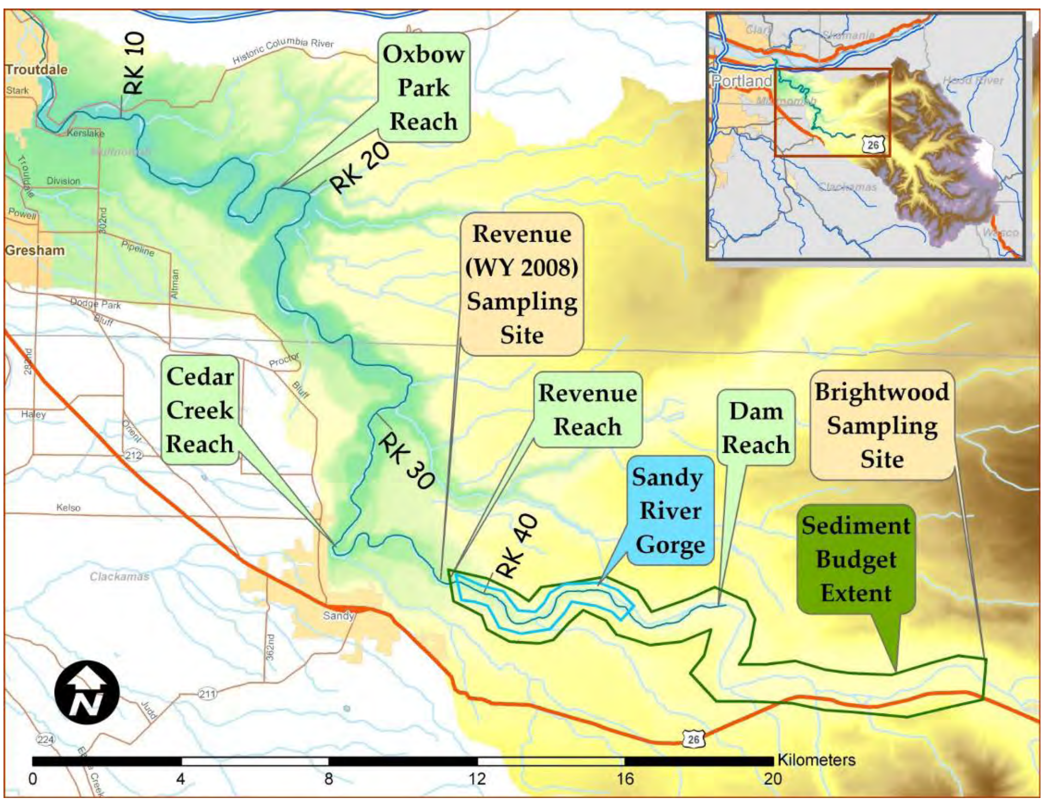

Figure 7 - Overview of Sandy River Study Reaches

In the reach 10 to 31 km (6-19 mi) below the dam (River Kilometer [RK] 38 to 17, as measured upstream from the Columbia or RM 23.6 - 10.6) two reaches originally assessed as possible depositional reaches were selected for detailed topographic surveys and GSD characterization. Within this reach, several sediment transport samples were taken during high flows. Finally, in the lower 17 km (10.6 mi) of the river, there were a few sediment transport samples taken but no detailed surveys were made.

Through LiDAR, aerial photography, and the long profile, some measures of river form are available above the waterline, and very limited data exist for the wetted portion (bathymetry) of the river below the dam. The 5 km (3 mi) reach including the dam site is well described by detailed topography and bathymetry, in addition to sediment transport measurements above and below this reach. Finally, at several downstream locations where deposition might be expected, there is more detailed data. The spatial extent of data collection and the resolution of that data correspond to areas of expected change in the river bed.

1.2.1.3. Temporal Extent

Data were collected (or analyzed) at a variety of timescales, ranging from minutes to decades. For most of the data collected during the study, there exists a baseline measure from the year preceding dam removal. The finest temporal resolution was for the photographic documentation of the reservoir erosion and for the water discharge measurements during the coffer dam failure – both were made several times per hour. During the first winter following removal, sediment transport was measured during nearly every significant high-flow event, and surveys in the near-dam area were conducted almost as frequently. Much of the data is collected on an annual basis (surveys, LiDAR, aerial photography), and will continue to be collected through the summer of 2010 (nearly 3 years post-removal). Although changes were predicted to persist for up to 10 years, the timescale of the current project is unlikely to extend beyond the 3-year point.

1.2.2. Partners

The monitoring effort was too large an undertaking (in terms of money and resources) to be taken on by any single entity. Many of the interested parties were able to bring some (but not all) of the required resources to the table, so a coordinated effort was required. There is no formal organization or leadership of this group of researchers. The data collected is freely shared between the partners and the publications / presentations arising out of the effort have been joint efforts.

1.2.2.1. JHU / NCED / GMA / SRBWC / OWEB

One group of partners is a team from Johns Hopkins University (graduate student Chuck Podolak and advisor Dr. Peter Wilcock) and the National Center for Earth-surface Dynamics (NCED). This group is responsible for much of the surveying in the lower reaches, the grain-size characterization, photography, and sediment transport measurements. Much of the fieldwork and analysis has been handled by the consultants Graham Matthews & Associates (project manager Smokey Pittman). NCED has contributed a National Science Foundation-funded team of undergraduates to help conduct summer fieldwork for three years. The team has partnered with the Sandy River Basin Watershed council and has been well-supported through several grants by OWEB.

1.2.2.2. USGS (with Oregon State University & Portland State University)

A second group of partners comes from the USGS (Drs. Jim O'Connor and Jon Major, graduate students Rose Wallick – OSU, and Mackenzie Keith – PSU). This group has contributed much of the work upstream of the damsite, the storm-by-storm surveys, sediment transport measurements, and the photography of the reservoir erosion.

1.2.2.3. Oregon State University / USFS

Dr. Gordon Grant (Oregon State University and USFS) contributes the benefit of a long involvement with the project -- much longer than the 2007 beginning of the current monitoring project.

1.2.2.4. Portland General Electric

PGE has been a partner in the monitoring effort providing access and logistical support as well as funding several data collection efforts (surveys, LiDAR, and aerial photography). This data was collected by the consultants Watershed Sciences (LiDAR and aerial photography) and Dave Evans & Associates (surveys), and analyzed by Stillwater Sciences.

1.2.2.5. Bureau of Reclamation (BOR)

The BOR (Travis Bauer & Jennifer Bountry) surveyed a long profile of the river prior to the dam removal to serve as a baseline.

1.2.2.6. USFS

In 2007 the USFS contracted a study to document, through repeat photography, changes in the channel and riparian areas between June 2007 and September 2008 (Bruce McCammon Photography, 2009).

1.3. JHU / NCED / GMA PREVIOUS WORK

1.3.1. Summer 2007

In July 2007 the JHU team along with 5 NCED interns and a crew from GMA began to collect the baseline data for the downstream monitoring. They selected the four downstream study reaches, photographed them, surveyed them, and collected GSD information (the techniques and site selection criteria are described in detail in Section 2). These efforts established the 'before' conditions against which all the post-removal measurements would be compared.

1.3.2. Winter 2007-2008

Between October 2007 and May 2008, a team lead by GMA collected sediment samples at a site 9 km (5.6 mi) downstream from the dam. This effort was integrated into the USGS plan to collect sediment samples at 4 other locations on the river. The winter 2007-2008 work was funded by an out-of-cycle OWEB grant (Application # 204-932) and the results are described in detail in the report to the Sandy River Basin Watershed Council (GMA, 2008).

2. METHODS

The purpose of this section is to present the methods used for data collection and analysis. All field notes are maintained in notebooks and duplicate copies (photocopies or electronic scans) exist for all field notes. Digital data is backed up and stored off-site.

2.1. Overall goal

The goal of the 2008-2009 OWEB-funded research was to describe the changes in morphology of the Sandy River between 2007 and 2008 and to collect sediment transport measurements which would help explain the changes. The locations and data collected were chosen to fit into the larger effort described in section 1.2 above

2.2. Site Selection

Several sites on the river were chosen at which to measure changes in the bed. These sites were measured in the summer while the river discharge was low. Minimal sediment transport was occurring and much of the river was accessible. These summer-time measurements were of the 'sediment at rest', and comparisons of the same measures from year to year provided the annual changes. To explain how the changes occurred, measures were also needed of the 'sediment in motion'. These measurements of bedload and suspended load transport were made during the winter high-flow season at locations above and below the 'sediment at rest' reaches.

2.2.1. 'At Rest' Reaches

In the spring of 2007 four reaches of interest were designated by the JHU/NCED team (section 1.3.1 above) (Figure 7). Several factors played a role in the site selection including: 1) predicted deposition by Stillwater Sciences (2000b) (Figure 5), 2) evidence of past deposition – bars & islands, 3) accessibility – either public lands or cooperative landowners, and 4) geomorphic heterogeneity. Since one goal of this research was to observe how different bedforms (pools, lateral bars, medial bars, point bars, etc…) respond to increases in sediment supply, reaches were favored that showed a variety of bedforms.

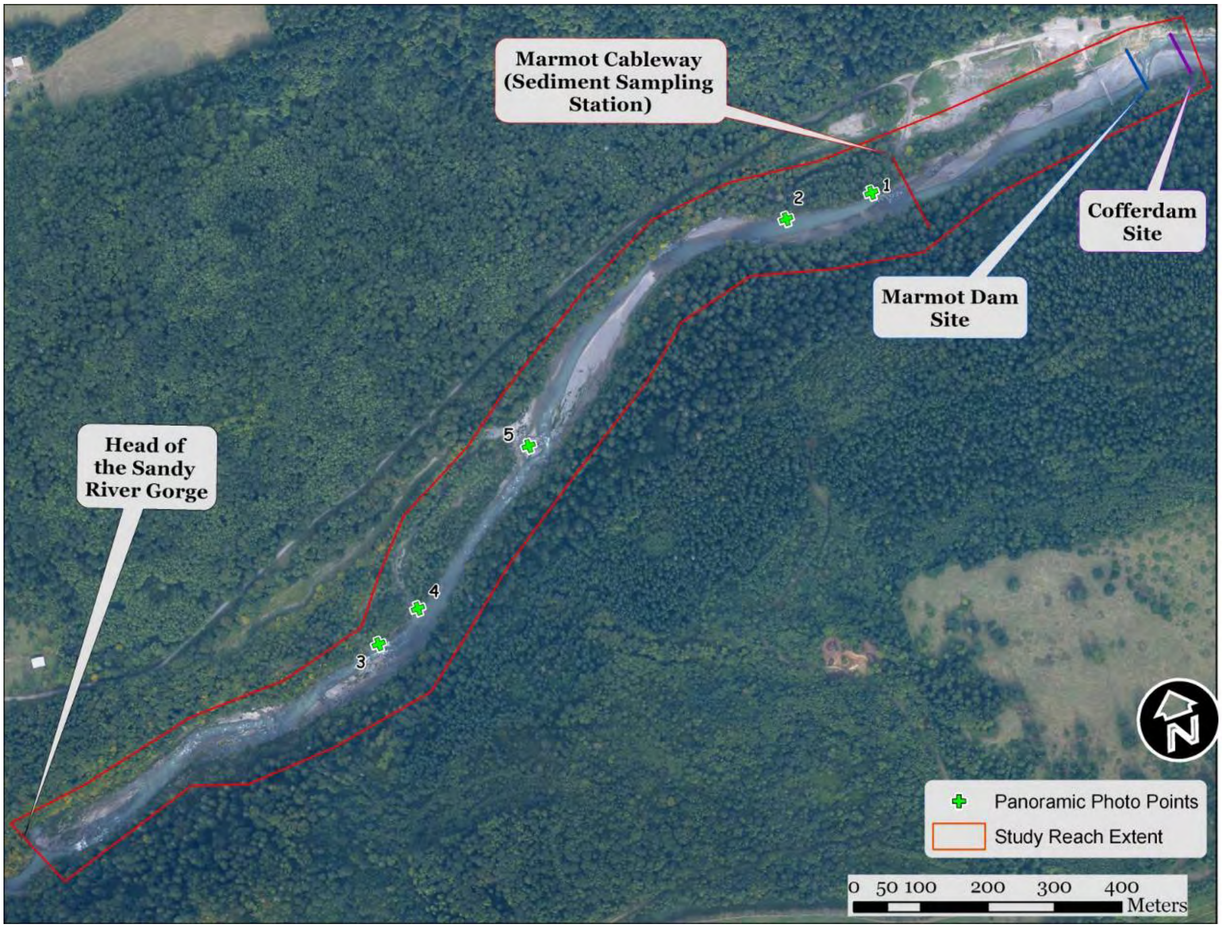

Figure 8 - Overview of Dam Reach (panoramic photo points shown in green; locations of dam and cofferdam noted)

2.2.1.1. Dam area

Our upstream-most monitoring reach was located in the immediate vicinity of the dam site (RK 49.2 – 46.0 [RM 30.6 – 28.6]) (Figure 8). Since this portion of the monitoring effort was concerned with deposition, the upstream limit of this reach was the location of the cofferdam. For 2.2 km (1.4 mi) below the dam, the river flows through an alluvial reach. At the end of the alluvial reach is the head of a 6.9 km-long (4.3 mi) bedrock gorge. The wetted width in the alluvial reach at low flows is ≈16-40 m (50-140 ft). The floodplains, islands, and bars occupy the rest of the valley bottom width of ≈120-140 m (400-460 ft). This reach was predicted to receive the bulk of the sediment deposition, receiving between 1 and 4 m (3.2 – 13 ft) of average deposition (Downs et al, 2009).

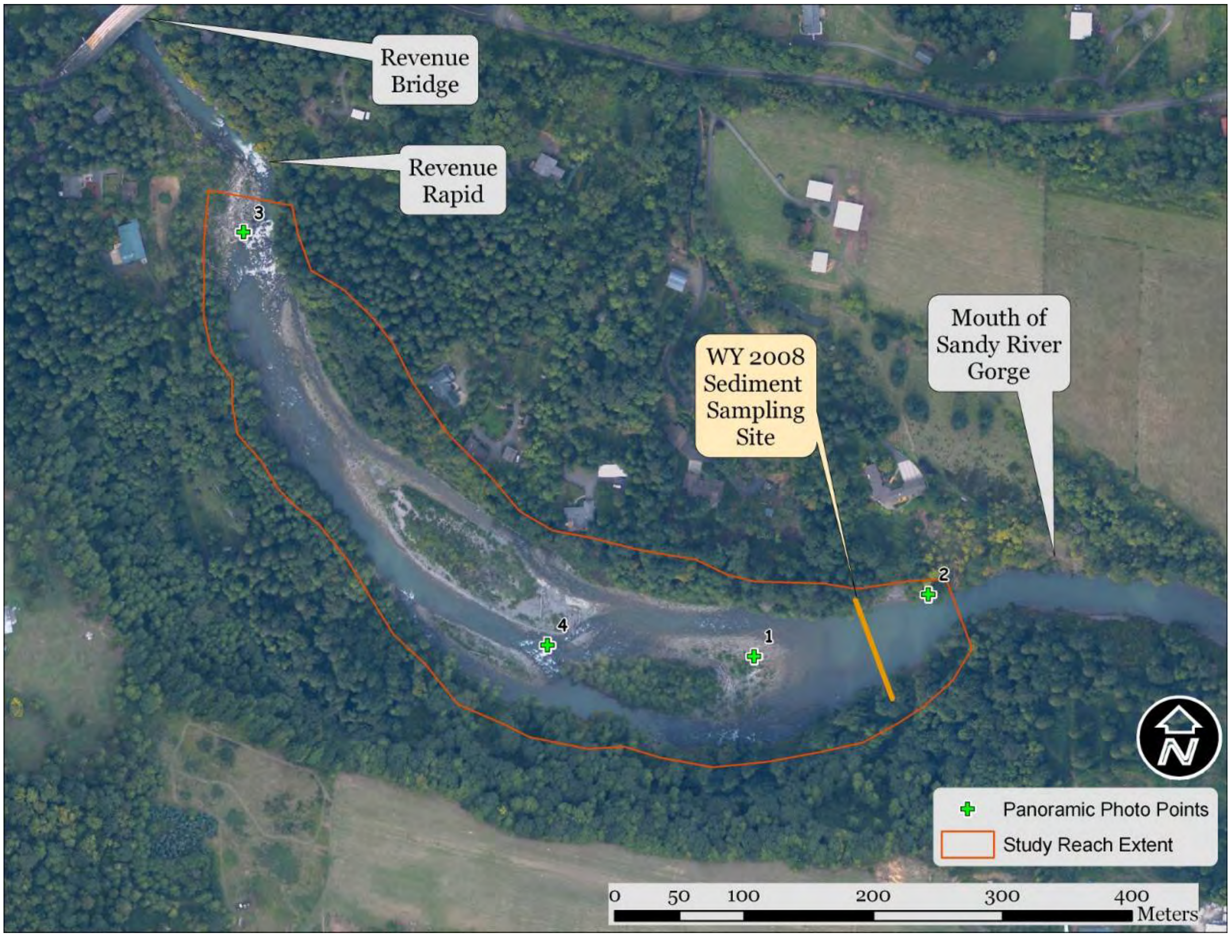

Figure 9 - Overview of Revenue Reach (panoramic photo points shown in green)

2.2.1.2. Revenue Bridge Area

The second study reach (RK 39.1 – 38.4 [RM 24.3 – 23.9]) lies immediately below the 6.9 km-long (4.3 mi) bedrock gorge, in which the river and valley are confined to 30-40 m (100-130 ft) wide. In the Revenue Bridge study reach, the river expands to as much as 70 m (230 ft) as the valley expands to nearly 300 m (980 ft) (Figure 9). Both the existence of bedforms such as mid-channel bars / islands and the Stillwater Sciences report suggest that this reach would receive deposition. The Revenue Bridge reach is short, bounded at the top by the gorge and at the lower end by Revenue Rapid.

Figure 10 - Overview of Cedar Creek Reach (panoramic photo points shown in green)

2.2.1.3. Cedar Creek Area

The third reach is located approximately three kilometers below the Revenue Bridge / Revenue Rapid area. The river between the Cedar Creek reach and the Revenue Bridge reach consists of an alluvial channel with occasional bedrock outcrops. The study reach contains the confluence of Cedar Creek and the Sandy River at RK 35.6 – 34.3 (RM 22.1-21.3) and included a unique 180 degree bend in the river (Figure 10). The reach average values of deposition from the Stillwater Sciences predictions were minimal; however there was evidence of historic deposition in the form of point bars, mid-channel islands, and lateral bars. The reach is popular with fishermen and they reported channel change (pool filling) associated with a large storm in November 2006, indicating the reach may exhibit channel change following sediment introductions.

Figure 11 - Overview of Oxbow Reach (panoramic photo points shown in green)

2.2.1.4. Oxbow Park Area

The final downstream reach is contained within Oxbow Park (RK 20.1 – 16.8 [RM 12.5 – 10.4]) (Figure 11). The park area is lower gradient (Figure 6) and the deposits are sandier, providing a different geomorphic setting than the steeper, coarser Cedar Creek Area. The upstream limit of this reach is the confluence of Gordon Creek. Following the storm in November 2006, there were significant changes to the morphology of the river at the Gordon Creek confluence. The Oxbow Park area was included to examine differences in depositional patterns in a dynamic and lower gradient reach.

2.2.2. 'In Motion' Sites

The sediment responsible for geomorphic change was transported by the river, primarily during isolated high-flow events during the late fall, winter, and spring. By measuring the transport above and below the 'at rest' reaches, the changes in those reaches can be reconciled with the transport into and out of them. During Water Year 2008, the USGS and GMA occupied several sampling sites along the river (Major et al, 2008; GMA, 2008). For the 2008-2009 winter (Water Year 2009) season, only the JHU/NCED/GMA sampling crew made sediment transport measurements. A combination of landowner access problems in the Revenue Bridge area, where the measurements were made the previous year, and the need for a more robust data collection effort in the vicinity of Sleepy Hollow (USGS gauge

14136500) led the team to concentrate the sampling effort for 2008-2009 at Sleepy Hollow. There had been very few good measurements of sediment transport into the reservoir / dam area and therefore describing the upstream flux of sediment into the system was considered a priority.

2.3. Sediment at Rest (Summer)

The data collection effort for the 'at rest' reaches took place during July 2008, by a crew of one graduate student, one student assistant, five undergraduate interns, and a crew from GMA. Documenting change required repeating the same measurements using the same protocols as the previous year.

2.3.1. Survey

Describing changes in the form of the river bed from one year to the next relied on detailed topographic surveys of the entire bed for each year. Non-bathymetric LiDAR was available for 2006, 2007, and 2008, and as a result the survey focused on collecting topographic data near and below the summertime waterline. LiDAR topography was used for the higher elevations.

2.3.1.1. Collection Methods

Topographic survey data were collected using a variety of methods (Figure 13 & Figure 14):

1. Dry bars, riffles and shallow pools were surveyed by hand using a total station (Topcon APL-1A or Sokkia SET2110) (Figure 12 [right) and conventional methods of mapping breaks in grade and significant features (water edge, bar top, etc…). In areas of uniform topography, a grid pattern (approximately 10m^2) was utilized. Detailed, monumented cross section surveys supplemented topographic surveys.
2. Deep pools and riffles in the Oxbow reach were surveyed using a depth sounder integrated with an RTK GPS (Figure 12 [left]). Equipment was mounted to a 4.8m (16 ft) cataraft which traversed the rivers, mapping features > 0.43m (1.4 ft) in depth.

Figure 12 - Surveying Setups. Cataraft (left) with GPS antenna mounted on the mast. Total station (right).

Many of the coarser riffles were punctuated by large numbers of extremely large particles (>1m). Such particles were not defined by the surveys and we assume that in coarse riffles our surveys will only detect change >0.5 m.

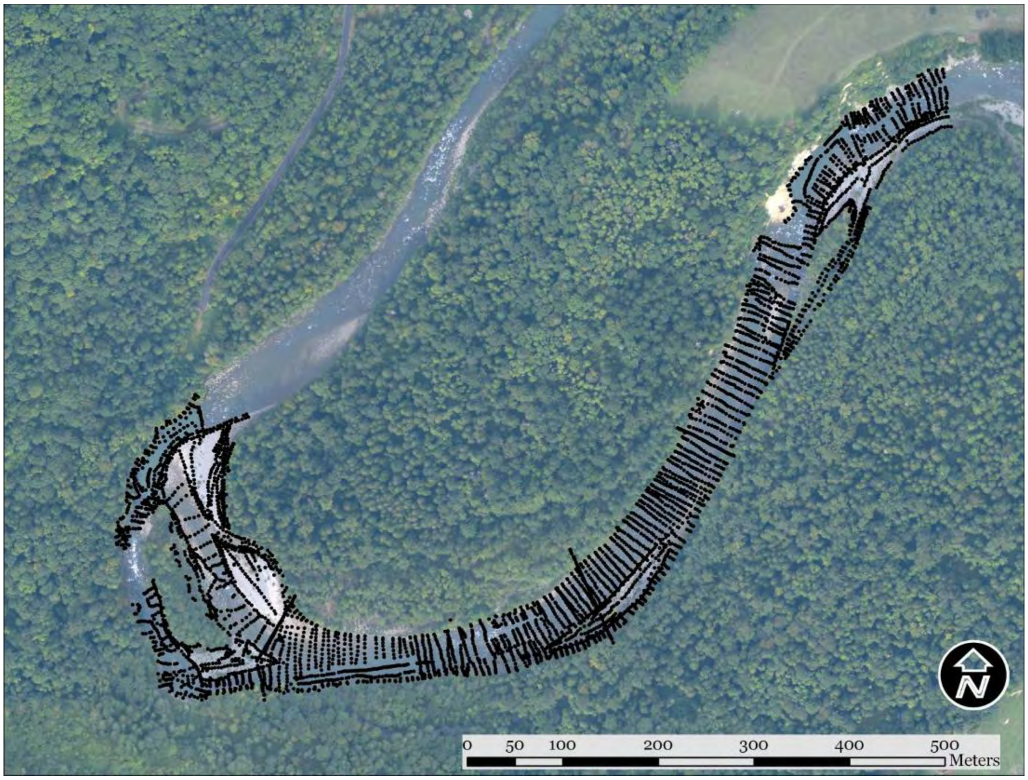

Figure 13 - July 2008 Survey Points for Cedar Creek Reach

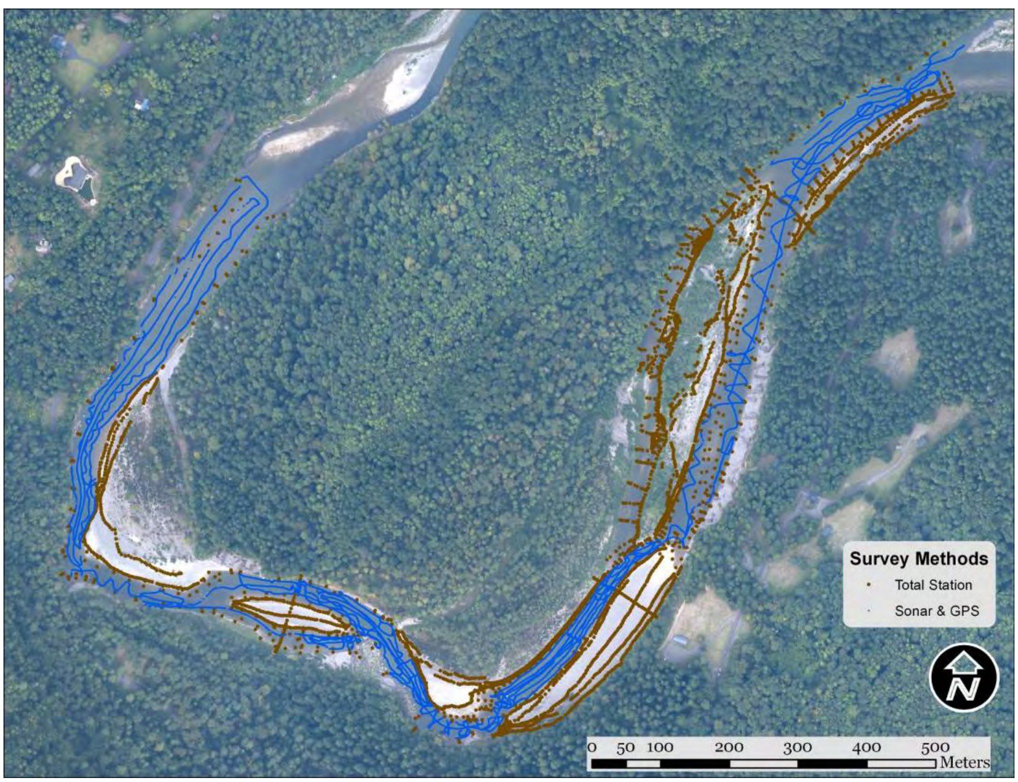

Figure 14 - July 2008 Survey Points for Oxbow Reach(brown points were taken with the total station, blue were taken with a GPS/depth sounder combination).

2.3.1.2. Processing Methods

The survey data (x,y,z coordinates) from the total station data collectors were downloaded daily from the survey instruments using Sokkia Prolink Version 1.15 and TDS Survey Link software. The raw coordinate and elevation data was then exported as a text file. The points from all the survey sources were post-processed together using ESRI's ArcGIS software. Breaklines were created using the survey points as vertices and the points were interpolated into a digital elevation model using the TIN (triangular irregular network) creation tool (Figure 15 & Figure 16). In order to compare changes from year to year, TINs were converted to ESRI Grids. All the Grid DEMs were projected into the NAD 1983 Oregon North State Plane (feet) coordinate system and resampled to ensure identical (1 m^2 [1.2 yd^2]) cell size and cell alignment. In the unsurveyed areas, the DEM was supplemented with a DEM developed by Watershed Sciences from the LiDAR data (Watershed Sciences 2006, 2008, 2009). A combined DEM was created for each study reach by merging (with the Mosaic tool in ArcGIS) the LiDAR DEM with the survey-derived DEM. Year-on-year differences were computed by subtracting the 2007 DEM from the 2008 DEM (Figure 23 [upper] & Figure 24 [upper]). Based on the large grain sizes, repeated annual surveys of unchanged areas, and repeated LiDAR measurements of unchanging areas, it was determined that there was a root-mean-squared [RMS] error of 0.33 m when calculating annual changes in elevation. The DEM differencing method captured changes in the surface elevation unrelated to fluvial erosion and deposition – for example landslides and bank failures. To exclude these changes in volume from the analysis, points which were greater than 2 meters above the 2007 water surface elevation were excluded from the analysis (Figure 23 [lower] & Figure 24 [lower]).
This report only discusses the analysis of the surveys collected under this project (Oxbow and Cedar Creek reaches). Similar analyses have been performed for the Revenue reach and the Dam reach, but are presented elsewhere (Podolak et al, 2008).

Figure 15 - DEM generated from survey & LiDAR for Cedar Creek Reach (2007 on top, 2008 on bottom)

Figure 16 - DEM generated from survey & LiDAR for Oxbow Reach (2007 on top, 2008 on bottom)

2.3.2. Grain Size

It was expected that not only would the river change the form of the river bed, but that the texture (grain size distribution) would also change. While the survey provided a measurement of the shape of the river bed, bars, and banks, a measurement of the grain size was made for all of the survey areas to assign a texture to the entire surveyed surface.

2.3.2.1. Collection Methods

Before measuring the grain size of the bed, the surface was mapped into distinct textural patches, or *facies* (Buffington and Montgomery, 1999). The facies were identified by the presence and relative abundance of grain size classes (sand, gravel, cobble, and boulder). The facies were mapped by hand in the field using 2007 aerial photography as a base map and a handheld GPS (Garmin Legend HCx) at assist with positioning (Figure 17 [upper], Figure 18, & Figure 19).

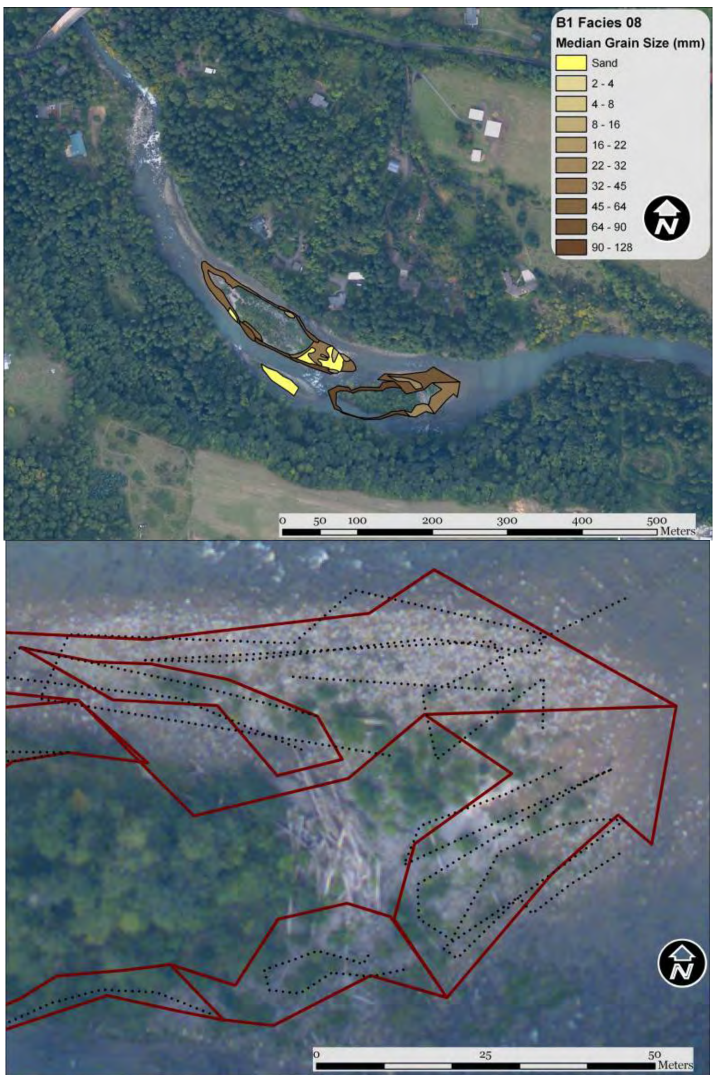

Figure 17 - Facies in Revenue Reach(colored by median grain size) [upper]. Record of pebble counts in Revenue Reach. Dots show 1m spacing along recorded locations of measuring tapes [lower]

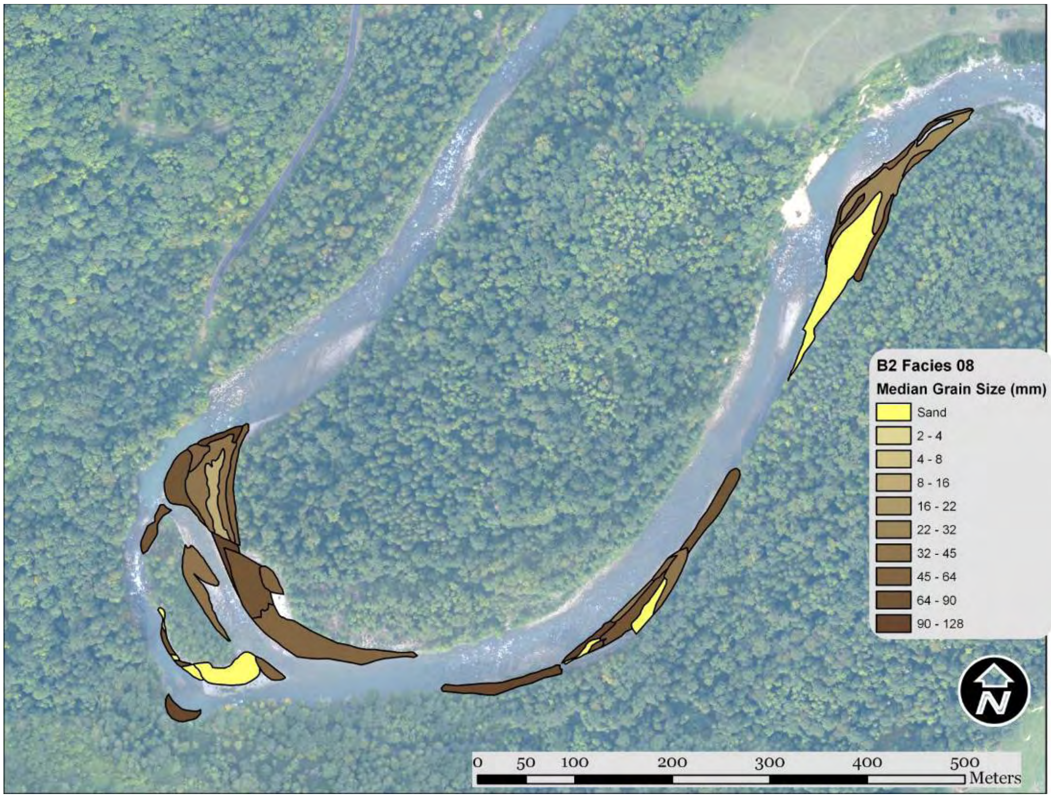

Figure 18 - Facies in Cedar Creek Reach (colored by median grain size)

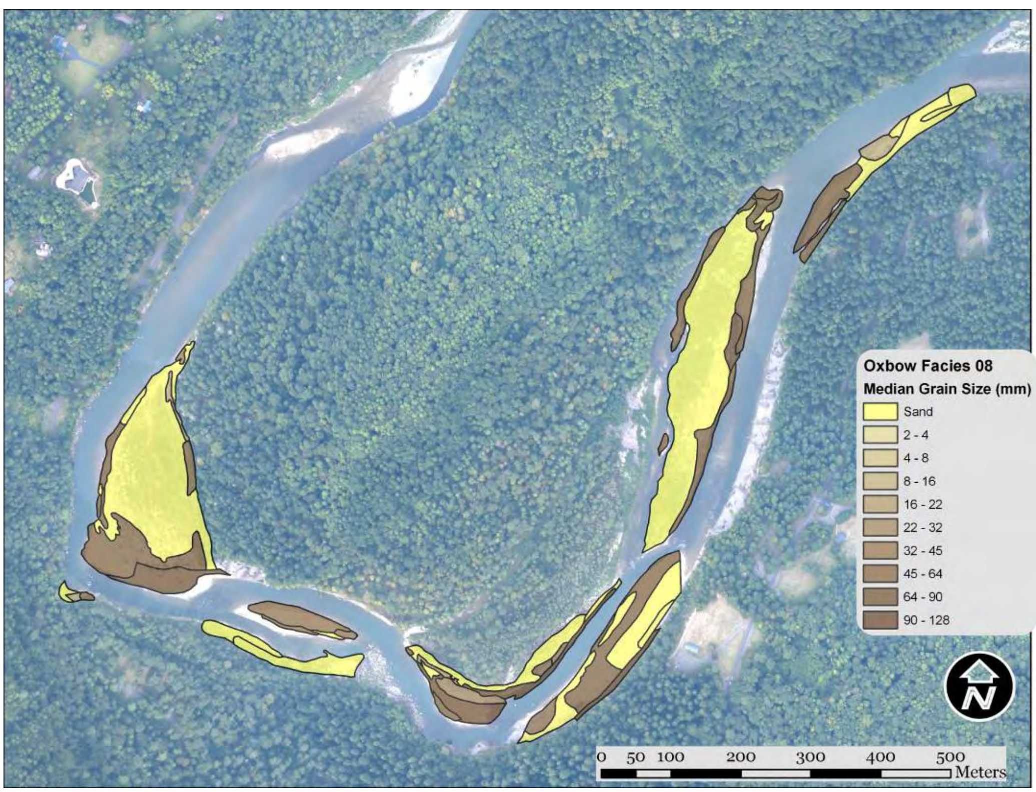

Figure 19 - Facies in Oxbow Reach (colored by median grain size)

After classifying all exposed bars, lightly vegetated islands, and shallow submerged areas of sediment into distinct facies, pebble counts were made of the each facies. Grains were selected for measurement by laying out several 100-meter fiberglass tapes in a manner that they were evenly distributed throughout the facies (Figure 17 [lower]). At fixed intervals on the tapes, the grains that were under a mark on the tape were picked up and measured using a gravelometer (a metal plate with square openings of 2, 4, 5.6, 8, 11.25, 16, 22.5, 32, 45, 64, 90, and 128 mm) (Figure 20). For grains larger than 128mm, the intermediate axis was measured. For nearly all the pebble counts three 100-meter tapes were used and grains were measured every meter. For few large facies more than three tapes were used, and similarly for several small or homogeneous facies either fewer than 3 tapes were used or the interval was decreased. In any case, the spacing of the tapes and measurement intervals were selected to avoid measuring the same grain twice.

Figure 20 - Gravelometer (demonstrated by Dr. Peter Wilcock, JHU)

2.3.2.2. Processing Methods

Each grain was classified into a size bin with the following breaks: 1m, 512mm, 256mm, 180mm, 128mm, 90mm, 64mm, 45mm, 32mm, 22.5mm, 16mm, 11.25mm, 8mm, and 2mm. A cumulative frequency distribution was computed for each facies, and from the distribution the fraction of sand [f_s] (grains less than 2 mm) as well as the median grain size of the gravel fraction [D_{50g}] (grains greater than or equal to 2 mm) were calculated.

Facies delineation is a subjective decision – looking at the same bar, reasonable people can disagree how many facies exist. Therefore, for year-on-year change, individual facies were not the unit of comparison, but rather bars as a whole served as the unit. Facies were digitized as polygons in ArcGIS and their area was calculated. Values of f_s and D_{50g} for each bar were computed as an areal weighted average using the f_s and D_{50g} for the constituent facies. Finally, since several bars had large higher-elevation surfaces which would not be inundated except for the very high and infrequent discharges, a further analysis was conducted. To avoid potentially subtle grain size changes on the portions of the bars which had been inundated from being overshadowed by the unchanging grain sizes in uninundated areas, portions of the facies were censored. Using the surfaces created with the surveys (section 2.3.1) and the LiDAR, water surfaces were created 1,2,3,4, and 5 feet higher than the water surface at the time of the LiDAR measurements. Year-on-year change of the f_s and D_{50g} for each bar was then evaluated using an areal weighted average, not of the total area for each facies, but instead using the area inundated at various stages.

2.3.3. Photos

In addition to the survey data capturing the shape of the surface each year and the grain size data characterizing the texture of the surface, repeated photographs were taken at monumented photopoints at least once per year. Nineteen locations were chosen throughout the four study reaches (Figure 8, Figure 9, Figure 10, & Figure 11). The locations were selected for their views of the reach, ability to be reoccupied for multiple years, and accessibility during times of high discharge. Where practical the locations were surveyed using a total station, and where this was infeasible, the photo points were located using a handheld GPS receiver (Garmin Legend HCx). Photographs were taken with a handheld digital camera (Cannon Powershot S200 Digital Elph with 2.0 megapixals) at a 1600 x 1200 resolution. To keep the panning motion level, the photographs were made from the top of a survey rod at a fixed height keeping the bubble level centered while panning the camera. Between 7 and 18 photographs were taken per panorama at each location. The photo points were reoccupied each summer (July 2007, and July 2008) and opportunistically throughout the winter. The photographs were stitched together (Figure 36, Figure 37, Figure 38, & Figure 39) into a single image using Cannon Utilities PhotoStitch (version 3.1.7.19).

2.4. Sediment in Motion (Winter)

WY2009 sediment sampling efforts focused on developing the dataset initiated by the USGS at the Brightwood (Sleepy Hollow) Bridge above the reservoir in WY2008. Data collected in WY2008 were inadequate to compute sediment loads into the reservoir reach. Under the assumption that sediment transport as a function of discharge would be similar in WY2009, the bedload and suspended load relationships were expanded and developed to compute sediment loads into the reservoir reach in WY2008. This computation (for the previous year), filled a critical gap in the sediment budget.

2.4.1. Streamflow

Streamflow data were collected at the Brightwood gage by the USGS continuously in WY2008 and part of WY2009 (USGS 14136500) [total length of the published record: 1 October 2007 – 12 September 2008]. The stage-discharge rating was verified and expanded by GMA during the January 2009 storms with two discharge measurements taken from the bridge. Discharge measurements followed standard USGS protocol and utilized a Price AA current meter, 100c sounding weight and a B-reel deployed from a trailer-mounted crane. During periods of rapidly changing river stage fewer verticals were used in order to improve the accuracy of the measurement. Measurements typically contained at least 20 verticals at 0.6 depth.

2.4.2. Suspended Sediment Sampling

Depth-integrated suspended sediment sampling was performed using a US D-74 Depth-Integrating Suspended Sediment Sampler (cable-deployed from a bridge using a trailer-mounted crane) (Figure 21). Standard methods, as developed by the USGS and described in Edwards and Glysson (1998), were generally used for sampling. For each sample, the location, time, stage, number of verticals, distance between verticals, bottle #, and whether a field replicate was taken, were recorded. Suspended sediment concentrations were measured in the GMA sediment lab in Weaverville, California following USGS and ASTM D-3977 protocols. Samples were analyzed for concentrations at greater and less than 0.063mm. All sample data are stored together in a project notebook.

Figure 21 - Bridge Crane Sampling Setup

2.4.3. Bedload Sampling

The sampling section was located on the downstream side of the Brightwood Bridge (E. Barlow Trail Road bridge over the Sandy River, near the intersection with E. Sleepy Hollow Dr). An initial point (I.P.) was initially established on the right bank and used to anchor the tape for all measurements. A 15.2 x 30.5cm TR-2 bedload sampler **(**Figure 22**)** was lowered from the same crane assembly described in the methods for discharge and suspended sediment measurements. A stay-line was utilized to prevent the sampler from being swept too far downstream. Standard methods, as developed by the USGS and described in Edwards and Glysson (1998), were used. Beginning and end stations, sample interval, sample duration, start time and end time, beginning and end gage height, and pass number were recorded. All bedload sample data are stored together in a project notebook. Bedload samples were processed at the GMA coarse sediment lab in Arcata, California. Processing involves sieving and computing the percent retained in each sieve class as determined by weight. These data are entered into Excel spreadsheets for subsequent conversion to the cumulative percentage finer (by weight) than the corresponding sieve size.

Figure 22 - TR2 Bedload sampler

2.4.4. Computations

2.4.4.1. Water Discharge

Streamflow computations for annual records were completed by the USGS for WY2008. Gage malfunction precluded the development of the entire WY2009 record.

2.4.4.2. Continuous Sediment Discharge

Utilizing the annual streamflow record developed from gauging station data and the sample data, partial annual loads were computed for suspended sediment and bedload. Suspended sediment loads were computed using continuous discharge (Q, cms or cfs) as an index of continuous suspended sediment concentration (SSC). Equations were developed utilizing discharge as the independent variable, and concentration (in two size classes: greater and less than 0.063 mm) as the dependent variable in the form $SSC = aQ^b$. Continuous SSC (mg/l) was computed using the gauging record (Q, cms or cfs) and the appropriate equation for each 15 minute period in the gauging record (the early period of the record, prior to 18 November 2007 has only 30-minute records). The corresponding discharge for each period was used to compute the continuous loads (SSC x Q (in cfs) x 0.0027, in tons/day) which were then summed for the entire period of record.

Bedload discharge was computed in similar fashion as was suspended sediment discharge. Loads were computed for the Sandy River corresponding to the following size classes: < 2mm, 2-8mm and > 8mm. Bedload transport is spatially and temporally much more variable than suspended sediment transport and at present discharge is the most practical surrogate available to estimate loads continuously. Bedload sampling is far more labor, equipment and time intensive than suspended sediment sampling, consequently bedload transport relationships are usually based on far fewer observations than are suspended sediment transport relationships. Therefore, since (1) fewer samples typically describe the bedload-discharge relationship, (2) bedload is computed using discharge as a surrogate, and (3) bedload transport is poorly described by discharge (due to the aforementioned temporal and spatial variability in bedload transport in both sampling and seasonal time-scales), bedload transport estimates have greater uncertainty associated than do suspended sediment load estimates.

2.5. Annual Sediment Budget

A sediment budget is a tool to compare sediment flux measurements with changes in topography. At its core a sediment budget expresses a conservation of mass for sediment. The basic concept is not unlike a bank account – a change in storage (account balance), must be reconciled with a difference between sediment flux in (deposits) and sediment flux out (withdrawals). Often in geomorphology a sediment budget approach is used to estimate one component when the others have been measured. In the case of the Marmot Dam removal monitoring, nearly all of the components of a sediment budget were measured, providing the opportunity to construct a well-constrained budget.

The goal of constructing a sediment budget for WY2008 is to describe the dam removal event in terms of the background sediment transport and to quantify where the eroded sediment ended up. It was hypothesized that the transport and deposition of the coarser sediment sizes (gravel and larger) would be substantially different from that of the finer (sand and smaller) grain sizes. Therefore, a two-fraction sediment budget is being constructed, treating the gravel and sand fractions separately.

2.5.1. Boundaries

A budget involves accounting for changes in sediment stored within a fixed area, as well as sediment fluxes across the boundaries of the same area. The choice of the boundaries is therefore important. The face of the dam was one natural boundary, allowing us to describe what passed from upstream of the dam to what passed downstream of the dam. The upstream boundary was selected as the Brightwood / Sleepy Hollow sampling site. Ideally, the upstream boundary would be very near the upper limit of the reservoir, however sampling logistics dictated the upstream measurement of sediment flux was at Brightwood Bridge. With the sediment sampling location fixed, the choice presented itself whether to use the upper end of the reservoir as the boundary and estimate the flux there using the Brightwood values, or to use Brightwood as the flux and estimate changes in storage along the 7.5 km (4.7 mi) between the bridge and the upper limit of the reservoir. Based on perceived storage opportunities and employing the assumption that the reach between the bridge and the reservoir was in equilibrium (deposits equal withdrawals), the latter option was picked and the Brightwood / Sleepy Hollow was selected as the upstream limit. Similarly, the lower limit was set as the site which had been selected for sediment sampling in the winter of 2007-2008 above Revenue Bridge (GMA, 2008). This was less-than optimal since it meant the Sandy River Gorge (for which we had no bathymetry data to measure sediment storage) would be included.

2.5.2. Storage Values

In order to determine annual changes in storage, comparisons can be made between surveys (Stillwater Sciences, 2008, 2009) and LiDAR (Watershed Sciences 2006, 2008, 2009) in one year and the same measurements in the next year. With an assumed bulk density, the volume change measurements can be converted to changes in mass of sediment stored. Finally, with measurements of the bulk grain-size distributions, it is possible to allocate changes in the bulk sediment mass into the sand and gravel size fractions. Between Brightwood Bridge and the reservoir, and within the Sandy River Gorge, there were no repeated topography or bathymetry measurements. Above the reservoir, the assumption was made that changes in storage were negligible. In contrast, the mass stored in the gorge was assumed to be non-trivial, and was calculated as a residual – the difference between the computed flux into the gorge and the measured flux and the mouth of the gorge.

2.5.3. Flux Measurements

The boundaries were picked to more-or-less coincide with the locations where sediment transport was actually measured. At the upper and lower boundaries, the sediment rating curves generated from suspended and bedload transport were applied to the annual hydrograph in order to generate an annual load. Sediment transport was measured not at the dam site, but at a cableway 400 meters (1/4 mile) downstream. The flux estimate for the middle boundary will be calculated as the flux past the cableway (calculated as described above) plus the change in storage in the area between the dam and the cableway. Annual flux measurements are being derived both from the bedload measurements described in this report, the previous year's report (GMA 2008), and data collected by our USGS partners.

3. RESULTS

3.1. SURVEY

The surveys collected in July 2007 and the LiDAR collected from September 29th to October 7th, 2007 (Watershed Sciences, 2008) provided the elevation measurements to create a pre-removal DEM (Figure 15 & Figure 16). The surveys of July and August 2008, along with the LiDAR collected September 29th to October 1st, 2008 (Watershed Sciences, 2009), provided the elevation measurements to create a post-removal DEM (Figure 15 & Figure 16). The DEM differencing analysis showed a net increase of 10,800 m^3 (14,100 yd^3) of sediment in 126,600 m^2 (151,000 yd^2) of the Cedar Creek reach (average elevation increase of 9 cm [3.5 in]). There was a net decrease of 34,800 m^3 (45,500 yd^3) of sediment in 334,400 m^2 (40,000 yd^2) of the Oxbow Park reach (average elevation decrease of 10 cm [4 in]). Many of the large values (>2 meters [6.5 ft]) of annual elevation change occurred near tall banks (Figure 23 [upper] & Figure 24 [upper]). In both the Cedar Creek reach and the Oxbow reach there were mass failures of tall (>5 meter-tall [15 ft]) banks which deposited sediment into the river. After excluding the elevation change associated with all points which were (in 2007 or 2008) greater than 2 meters (6.5 ft) above the 2007 (11-13.1 cms / 388-462 cfs) water surface elevation, the changes in volume dramatically decreased (Figure 23 [lower] & Figure 24 [lower]). In Cedar Creek, there was a net decrease in volume of 2,200 m^3 (14,100 yd^3) of sediment in 91,000 m^2 (109,000 yd^2) for an average elevation decrease of *2 cm (0.8 in)*. In Oxbow Park, there was a net decrease in volume of 16,000 m^3 (19,200 yd^3) of sediment in 208,000 m^2 (249,000 yd^2) for an average elevation decrease of *8 cm (3 in)*.

In Oxbow Park in additional to scattered bed elevation changes throughout the study reach, there were two systematic trends. First, at the upper and lower ends of the reach, there was pool scour. Second, in the middle portion of the reach, there was a leftward migration of the channel with left bank erosion nearly matched by right bank deposition. Oxbow Park is a dynamic reach which has shown planform changes due to large storms. It is likely that the observed changes in the bed elevation change in Oxbow Park are not attributable to the Marmot Dam removal. In the Cedar Creek reach, there was a small amount of bank erosion of the left bank in the middle of the reach. The head of the right channel around a mid-channel island filled in slightly, and the pool at its downstream end showed local scour and deposition. Overall, the bed elevation changes in the Cedar Creek were minimal and we feel are not attributable to the Marmot Dam removal.

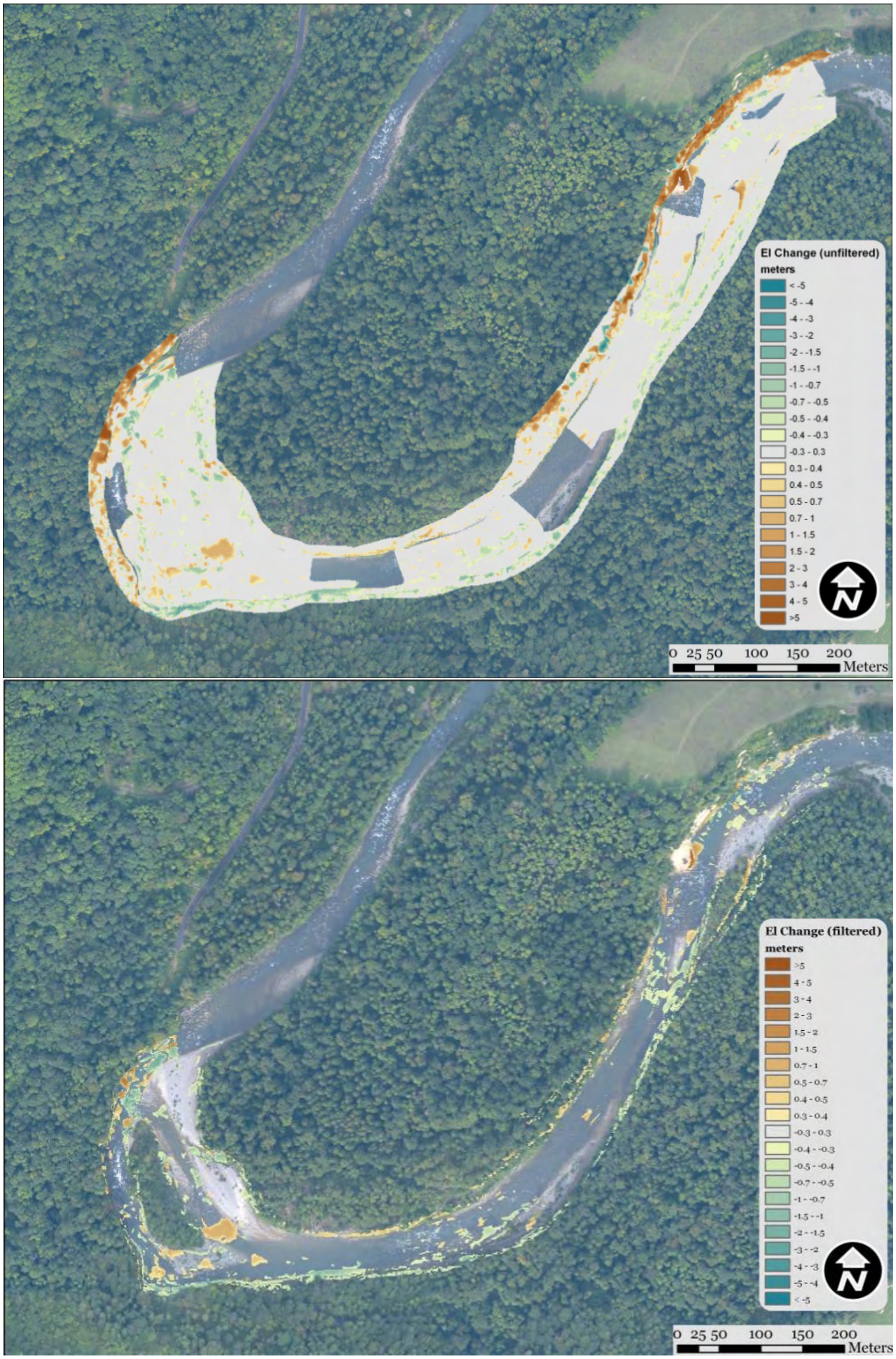

Figure 23 - Cedar Creek Elevation differences from 2007 to 2008(positive values show deposition) [lower figure has change values <0.3 m and points >2m above the WSEL filtered out]

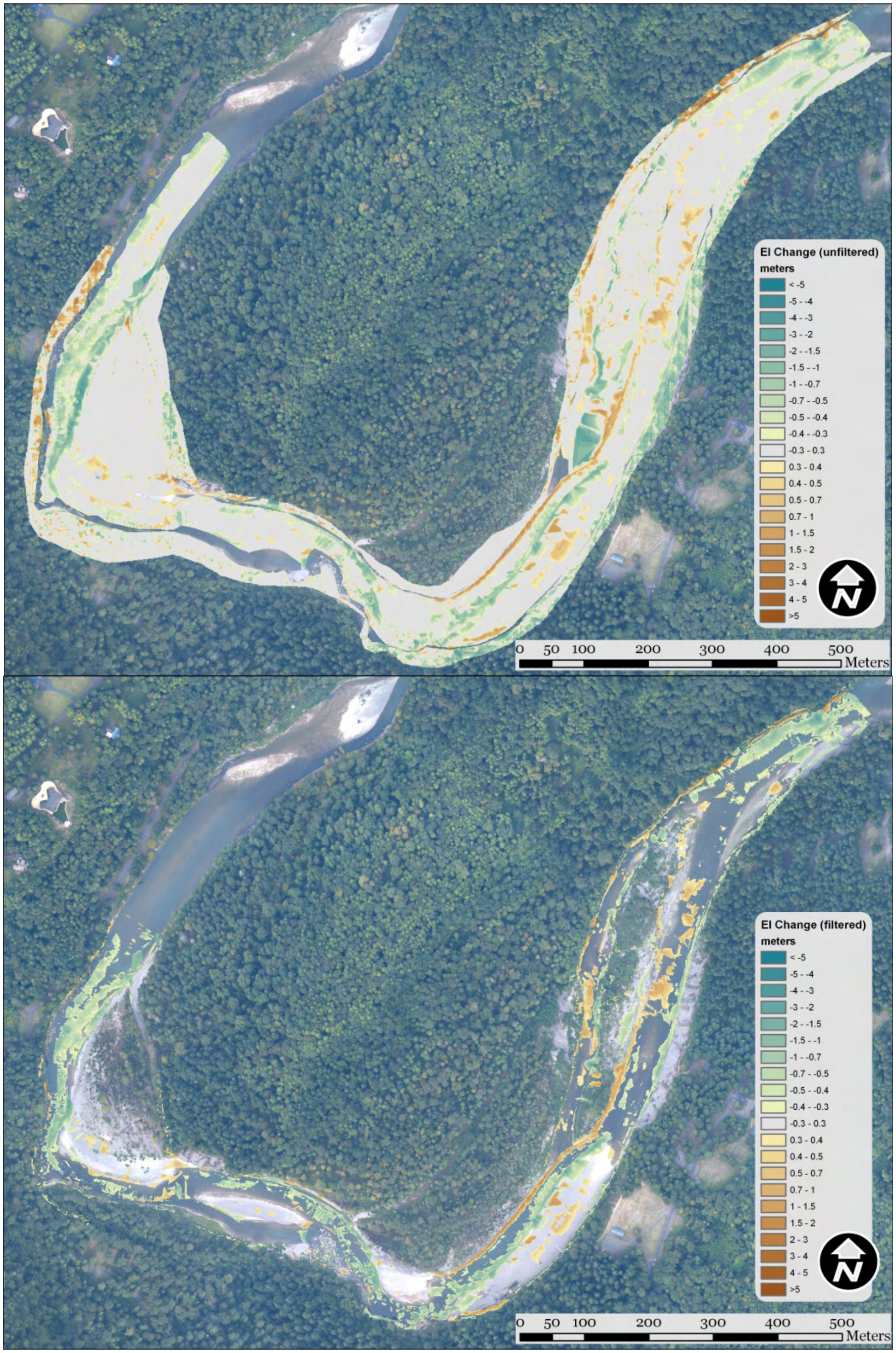

Figure 24 - Oxbow Park Elevation differences from 2007 to 2008(positive values show deposition) [lower figure has change values <0.3 m and points >2m above the WSEL filtered out]

3.2. Grain-Size Distribution

In the four reaches 126 facies were identified on 18 bars, and 25,776 pebbles were measured. From the grain-size distribution analysis, there was a pre-removal increasing downstream trend in the sand fraction, and a decreasing downstream trend in the median grain size of the gravel fraction (Figure 25). The downstream trend in gravel grain size was consistent with that found by Stillwater Sciences (2000b) and Stewart & Grant (2005). However, the downstream trend in the sand fraction was found by neither of the two previous studies. The gravel median grain size showed no difference between the two years. This lack of a change in the gravel fraction downstream of Revenue Bridge is consistent with the results found in sections 3.5 and 3.6 below. There was a consistent (roughly 10%) increase in the sand fraction in all three of the downstream sites, despite the minimal volume change at those same sites. The increase in sand without a significant change in volume is also consistent with sections 3.5 and 3.6 below.

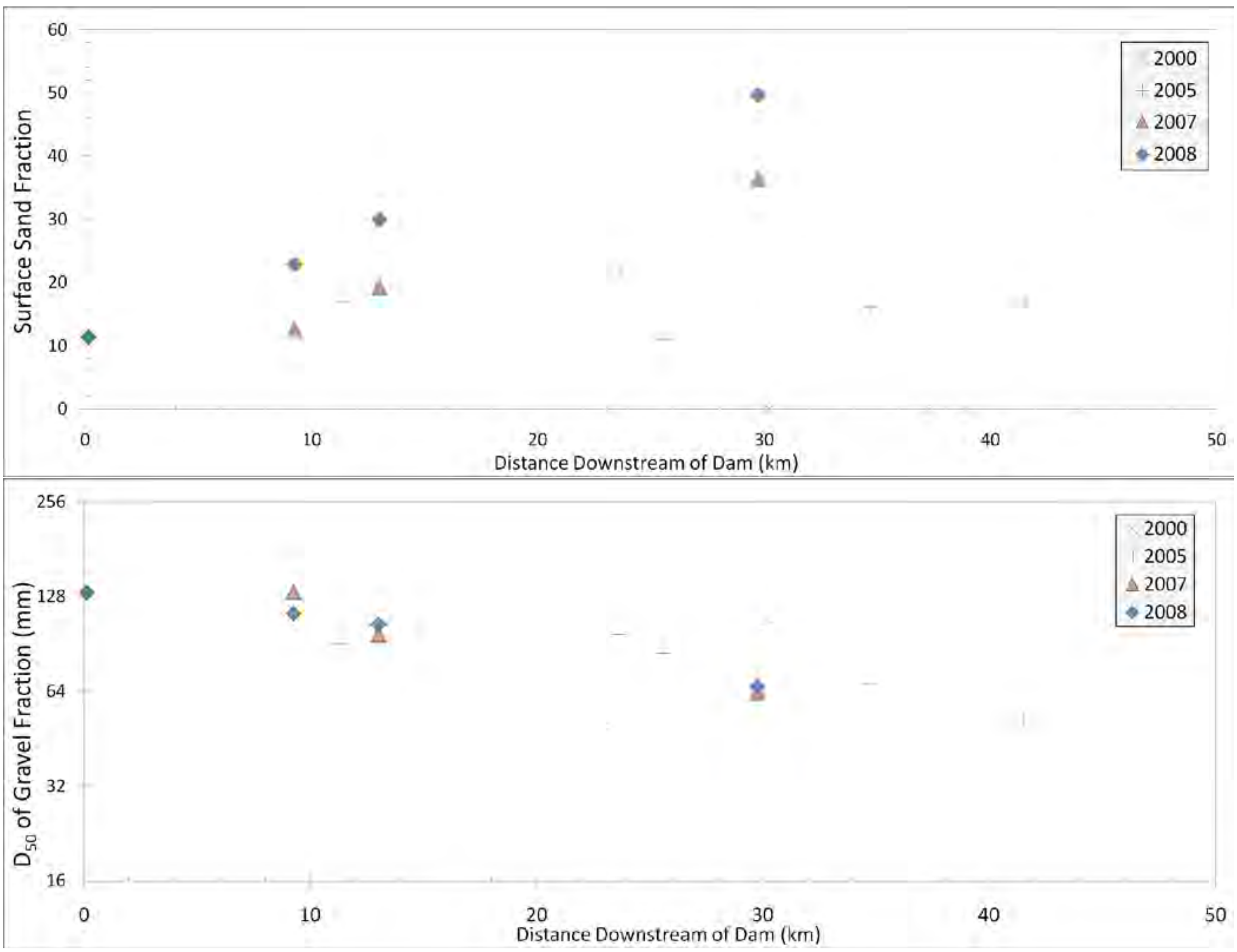

Figure 25 - Grain Size Distributions: Surface sand fraction and median surface grain size for gravel fraction (>2mm). 2000 values from Stillwater Sciences (2000a). 2005 Values from Stewart & Grant (2005).

3.3. Discharge

3.3.1. Water Year 2008

The October 19, 2007 storm peaked at 2,570 (73 cms) cfs on October 21 – this is the storm that triggered the cofferdam failure at Marmot (Figure 4). The balance of the hydrograph for WY2008 reveals a series of peaks from 4,400 to 7,500 cfs (125-212 cms) occurring from November to January. Following a period of much smaller peak flows was the prolonged snowmelt pulse in the latter half of May which peaked nearly as high as the winter storms at 7,300 cfs (207 cms).

3.3.2. Water Year 2009

The complete hydrograph for WY2009 is not available due to a malfunction in the USGS Brightwood gage. The peak flow for WY2009 was approximately 18,500 cfs on November 13, 2008 (USGS published data). The primary objective for collecting discharge measurements in WY2009 at the Sleepy Hollow (Brightwood site), was to expand the USGS discharge rating for the previous year. Streamflow data were collected at the Brightwood gage by the USGS continuously in WY2008 and partially in WY2009 (USGS 14136500). As of December 9, 2008, the USGS had collected 13 discharge measurements ranging from 8.5 to 169 cms (303 to 5,970 cfs). Ratings are commonly extrapolated to a maximum of two times the highest measured value, so the existing rating could conceivably predict up to 337 cms (11,900 cfs). As of January 2009, the Sandy had already peaked at much higher than 340 cms (12,000 cfs), though the gage had failed to record much of the December-January period.

The stage discharge rating was verified and expanded by GMA during the January 2009 storms with two discharge measurements taken from the bridge (Table 1).

1. January 6, 2009: gage height 11.39 ft, discharge 8,240 cfs (229 cms)
2. January 8, 2009; gage height 12.63 ft, discharge 11,600 cfs (320 cms)

These values were adjusted to provide the published values (8,070 and 11,300 cfs; 229 and 320 cms) following USGS bridge-angle corrections, thus allowing the rating to be extrapolated to 640 cms (22,600 cfs) should this become necessary. Sediment-discharge relationships were developed using the USGS rating curve extended with the adjusted GMA measurements.

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DISCHARGE SUMMARY SHEET

STATION: SANDY RIVER BELOW SALMON RIVER NEAR BRIGHTWOOD, OR **WATER YEAR:** 2009

STATION NUMBER: USGS 141365000

Measurement Number	WY Msmt #	Date	Made By	Width (feet)	Mean Depth (feet)	Area (ft2)	Mean Velocity (ft/sec)	Staff Height (feet)	Gage Height (feet)	Discharge (cfs)	Rating XX Comp. Shift (feet)	Rating XX Used Shift (feet)	Rating XX % Diff.	Method	Begin Time (hours)	End Time (hours)	Msmt Rating	GZF (feet)	Water Temp (F)	Comments
1	**2009-01**	01/06/09	S. Pittman	111	7.94	881	9.35	11.39		8,240					14:25	15:53	Poor			raw value -- adjusted for angle
2	**2009-02**	01/08/09	S. Pittman	112	9.04	1013	11.41	12.63		11,600					13:18	13:56	Poor			raw value -- adjusted for angle

Table 1 - Discharge Measurements

3.4. SUSPENDED LOAD

GMA collected five suspended sediment concentration (SSC) samples in January 2009 to complement the eight WY2008 USGS samples. The WY2009 objective was to further develop sediment-discharge relationships begun by the USGS in WY2008. The highest flow sampled was 11,580 cfs (328 cms) on January 8, 2009 with a corresponding concentration of 1,004 mg/l. Data collected in both water years are summarized in Table 2.

The computational objective was to estimate the suspended sediment load passing Brightwood in WY2008. Both >0.063 and <0.063mm fractions were computed in the English system of units and later converted to metric.

Relationships were developed from the data divided into two periods, similar to the procedure employed for the Revenue site in WY2008 (GMA 2008) (Figure 26, Figure 27, Figure 28). USGS May 2008 and GMA January 2009 sample data appear to describe the same Q-SSC relationship. The fall period, described by four USGS samples collected between September 13 and November 17, 2007, shows SSC and discharge to be poorly correlated. The same phenomenon was observed at Revenue, where the relationship improved dramatically beginning November 17, 2007 (GMA 2008). Much uncertainty surrounds this fall period, though the data suggest an important transport phenomenon occurred (higher rates). Loads were computed using a variety of methods to evaluate the effects of various assumptions regarding this fall period. The choice of which points to include in a regression and which periods within the hydrograph to which it is applied have great effects upon the magnitude of estimated loads. Preliminary load estimates (total suspended) ranged from 60,000 to 280,000 tons.

The data reveal numerous quandaries:

1. The fine fractions show anomalous transport thresholds (~2,200 vs ~1,800 cfs for <0.063 and >0.063mm respectively);
2. The September sample shows 75% <0.063mm while the rest of the samples show an average of 10%;
3. SSC is much higher in the fall and is poorly correlated with discharge;
4. No samples were collected between November 2007 and May 2008, making the determination of computational time periods less accurate.

Since the USGS May 2008 and GMA January 2009 samples appear to describe the "dominant" trend, the poorly correlated period of high transport was confined to the component of the hydrograph containing those samples (Oct 1 – Nov 28, 2007). The following set of assumptions was adopted for the computation:

1. For the fall (Oct-Nov 28) period, regressions were developed from the USGS sample data for Total SSC and >0.063mm SSC.
2. These regressions were applied to the hydrograph through the falling limb of the first major winter storm (November 28, 2007 13:00).
3. The <0.063mm component was poorly correlated with discharge and is the minor component of the load and it was computed as a residual.

4. Regressions were developed for the USGS-GMA samples collected after November 2007 and used to compute the remaining water year for Total and >.063mm SSC.
5. Passes were composited into single samples and all samples were included in the development of Total and >0.063mm regressions.
6. Equations by size class and period:
   a. >0.063mm (Fall): $SSC = 0.0059Q^{1.5101}$
   b. >0.063mm (Nov 28 – Sep 30): $SSC = 3E\text{-}08\ Q^{2.6072}$
   c. Total (Fall): $SSC = 0.5557\ Q^{0.9357}$
   d. Total (Nov 28 – Sep 30): $SSC = 8E\text{-}08\ Q^{2.5361}$
7. Continuous SSC was computed from the 15 minute USGS discharge data, then transformed to suspended sediment discharge using: SSC x Q x 0.0027, in tons/day, 15 minute suspended sediment discharge was then summed and divided by the discharge recording interval (96, for the number of 15 minute intervals in a day).
8. Results, (un-rounded) by size class:
   a. >0.063mm suspended load = 101,725 tons (92,283 Mg)
   b. <0.063mm suspended load = 34,317 tons (31,132 Mg)
   c. Total suspended load = 136,042 tons (123,415 Mg)

Sandy River near Brightwood -- WY2008-2009 Suspended Sediment Data
USGS and GMA

Sample	Pass	Date and Mean time	Discharge (cfs)	Discharge (cms)	Pass SSC (mg/l) <0.063mm	Pass SSC (mg/l) >0.063mm	Pass SSC (mg/l) TOTAL	Sample Mean SSC (mg/l) <0.063mm	Sample Mean SSC (mg/l) >0.063mm	Sample Mean SSC (mg/l) TOTAL
GMA-2009-01	1	01/06/2009 16:34	7,948	225	71.7	722	794	74.2	682	756
	2	01/06/2009 16:34			76.7	641	718			
GMA-2009-02	1	01/07/2009 10:07	7,707	218	51.4	492	543	51.3	574	625
	2	01/07/2009 10:07			51.1	656	707			
GMA-2009-03	1	01/08/2009 12:47	11,580	328	95.9	1042	1138	96.1	908	1004
	2	01/08/2009 12:47			96.3	773	869			
GMA-2009-04	1	01/09/2009 12:23	5,810	165	19.2	214	234	18.2	189	207
	2	01/09/2009 12:23			17.2	163	180			
GMA-2009-05	1	01/10/2009 13:26	3,556	100.7	6.8	59	65	5.8	52.4	58.2
	2	01/10/2009 13:26			4.8	46	51			
USGS-2008-01	1	09/13/2007 10:00	303	8.58	80.7	27	108	73.6	24.9	98.5
	2	09/13/2007 10:26			66.5	23	89			
USGS-2008-02	1	10/19/2007 15:35	1,678	47.5	84.8	547	632	79.7	858	938
	2	10/19/2007 16:13			74.6	1169	1244			
USGS-2008-03	1	10/20/2007 12:12	1,683	47.6	38.8	519	558	38.9	638	677
	2	10/20/2007 12:38			39.0	757	796			
USGS-2008-04	1	11/17/2007 11:08	3,110	88.1	143	568	712	133	511	645
	2	11/17/2007 11:34			124	454	578			
USGS-2008-05	1	05/15/2008 14:49	4,382	124	17.9	75.1	93.0	18.6	77.9	96.5
	2	05/15/2008 15:25			19.3	80.7	100			
USGS-2008-06	1	05/16/2008 16:03	5,225	148	33.9	217	251	29.6	189	219
	2	05/16/2008 16:04			25.2	162	187			
USGS-2008-07	1	05/17/2008 15:20	5,730	162	63.3	249	312	63.3	249	312
	2	05/17/2008 15:21			63.3	249	312			
USGS-2008-08	1	05/18/2008 14:11	5,410	153	86.2	304	390	82.8	292	375
	2	05/18/2008 14:12			79.3	280	359			

Table 2 - Suspended Sediment Measurements

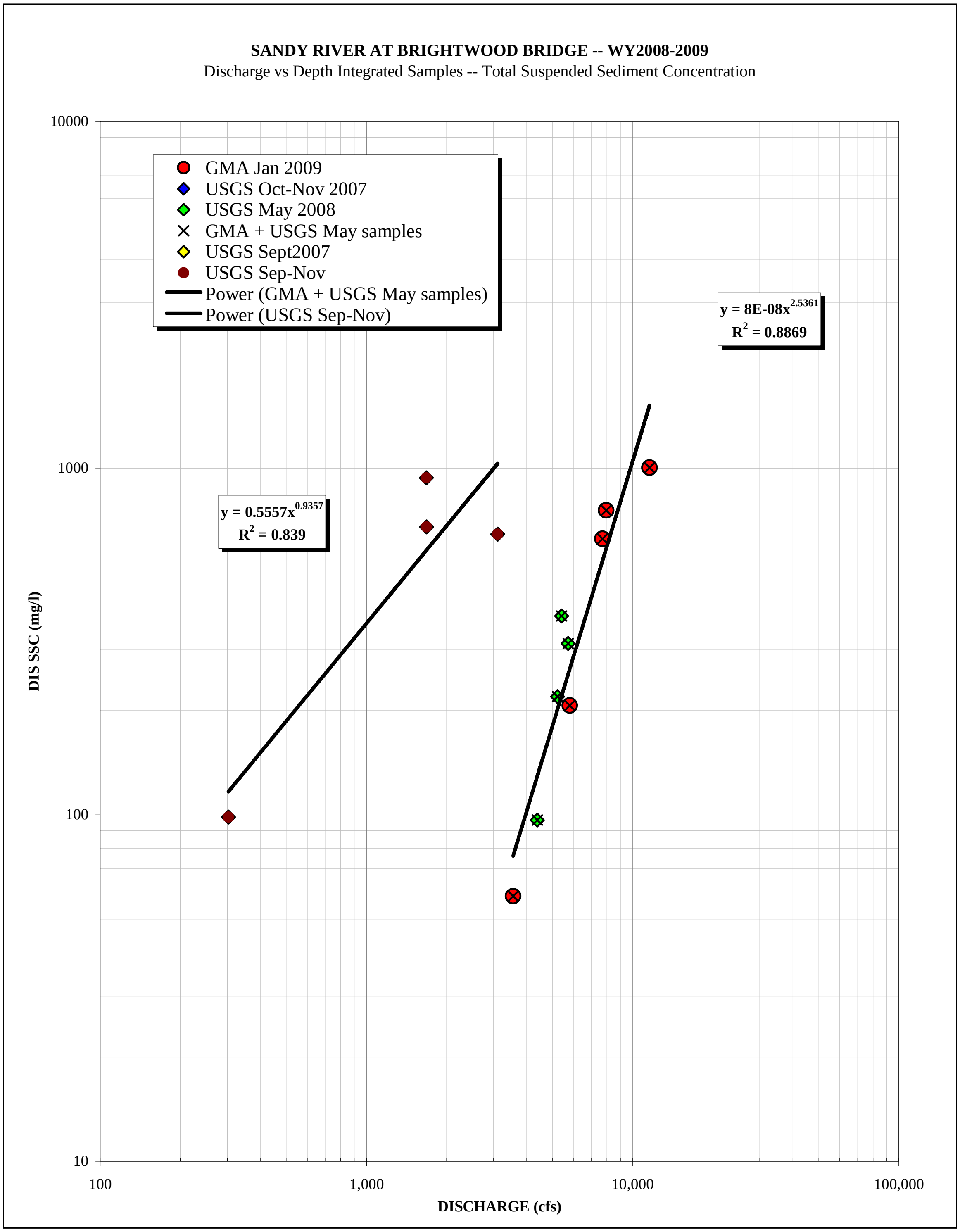

Figure 26 - Suspended Load Measurements - Total Load

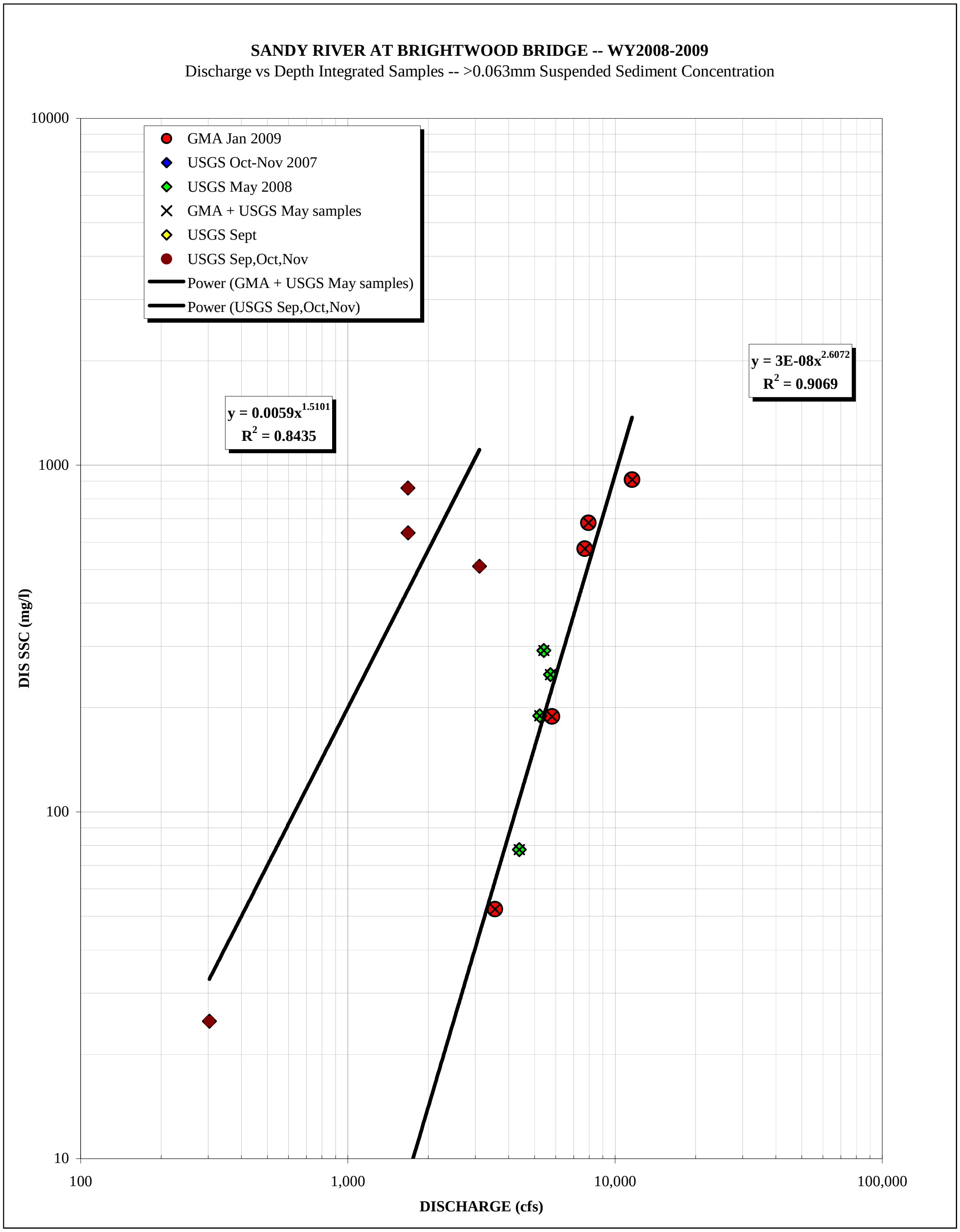

Figure 27 - Suspended Load Measurements - Coarse Fraction

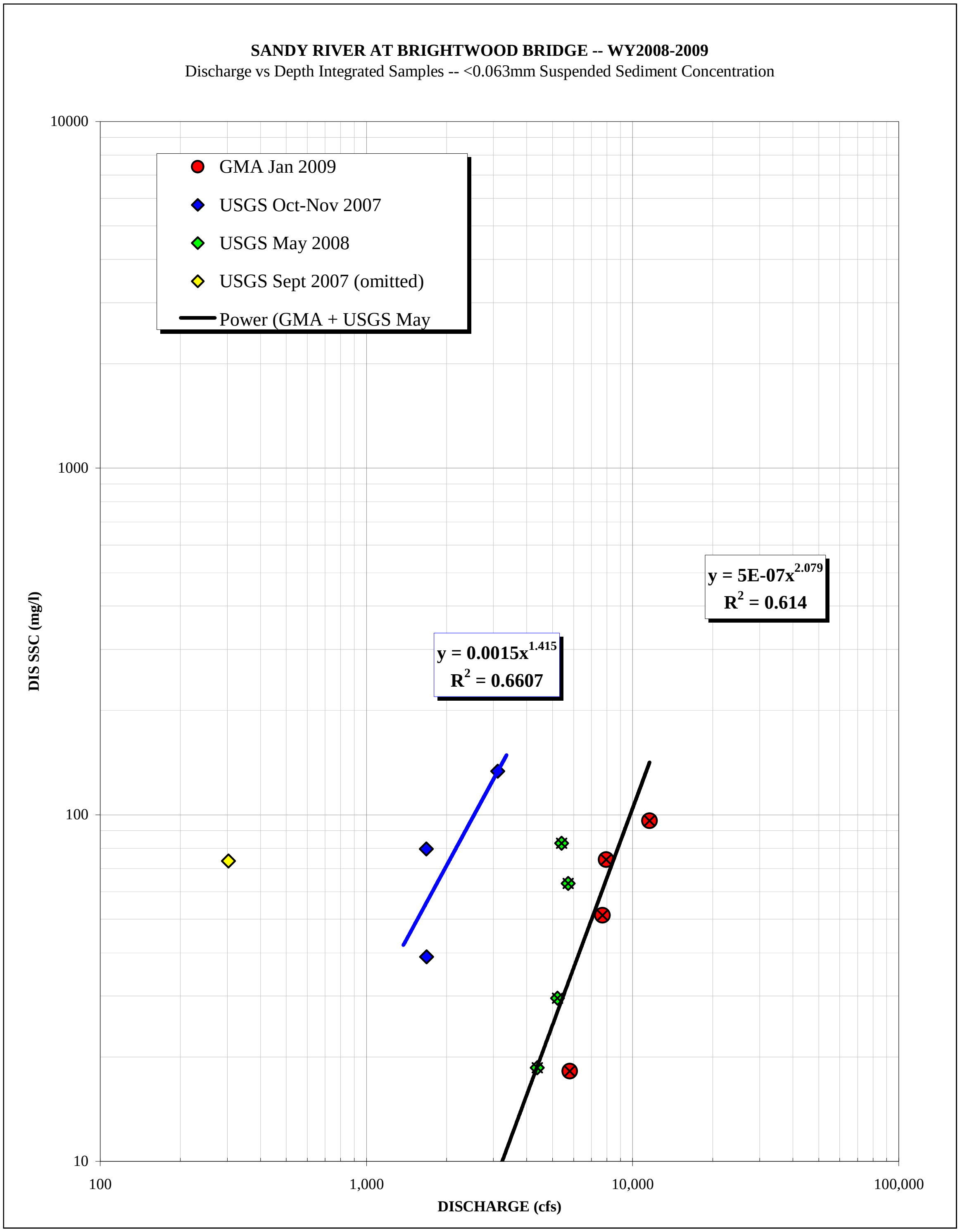

Figure 28 - Suspended Load Measurements - Fine Fraction

3.5. BEDLOAD

GMA collected five bedload samples in January 2009 to complement the six WY2008 USGS samples. The highest flow sampled was 7,380 cfs (209 cms) on January 8, 2009 with a corresponding instantaneous bedload discharge of 2,412 tons/day (2,188 Mg/day). Data collected in both water years are summarized in Table 3.

Loads were computed for two fractions: >2mm ("gravel") and <2mm ("sand"), each in the English system of units, later converted to metric. Regressions were examined for both fractions and for Total bedload (Figure 29, Figure 30, Figure 31). As in the case with suspended load, October bedload data shows higher transport than the rest of the data.

In order to examine the effect of excluding or omitting these October outliers, loads were computed two ways:

1. Omitting the October samples altogether.
   a. A regression was developed using USGS November 2007 sample and the GMA January 2009 data and applied to the entire water year for <2mm and >2mm.
   b. Equations by size class:
      i. <2mm: $BLD = 2E\text{-}08Q^{2.7799}$
      ii. >2mm: $BLD = 3E\text{-}15Q^{4.5495}$
   c. Results by size class:
      i. <2mm bedload: 13,493 tons (12,241 Mg)
      ii. >2mm bedload: 5,161 tons (4,682 Mg)
      iii. Total Bedload 18,655 tons (16,924 Mg)

2. Shifting the "dominant" equation by eye to fit the October data and computing separately for this period (through the end of the first major winter storm, November 28 13:00 hrs).
   a. Fall Period, equations by size class:
      i. <2mm: $BLD = 8E\text{-}07Q^{2.7799}$
      ii. >2mm: $BLD = 5E\text{-}13Q^{4.5495}$
   b. Equations for the balance of the year are provided in Scenario #1 above.
   c. Results by size class:
      i. <2mm bedload: 34,480 tons (31,280)
      ii. >2mm bedload: 26,564 tons (24,098 Mg)
      iii. Total Bedload 61,044 tons (55,378 Mg)

Method #2 predicts a load over three times larger than Method #1. With a transport threshold of 350 cfs for the fine fraction, Method #2 shows continuous transport for the sand fraction, as the Sandy River did not drop this low in WY2007. While an important transport phenomenon occurred in October 2007, without more data to confine the very high rates measured in October, we provide the totals in Method #1 as our best estimate for bedload transport in WY2007, though this estimate is likely low. The load totals from suspended sediment and bedload computations are combined to reflect their respective sediment budget components (gravel/sand/fine -- see Section 3.6).

Grain size analysis of bedload samples were completed in the GMA Coarse Sediment Lab in Arcata, California. An example lab form and size-distribution curve are provided in Table 4 & Figure 32. Sieve analyses reveal samples to be mostly (57-80%) sand or finer, with a fairly consistent D50 ranging from 1.2 to 1.7mm (Table 4). The intermediate axis of the largest particle sampled was 124mm (#2009-03).

Sandy River at Brightwood Bridge
Bedload Sampling Summary -- GMA WY2009, USGS WY2008

Sample Number	Date & Mean Time	Streamflow Average Discharge (cfs)	<2 mm (tons/day)	>2mm* (tons/day)	2-8 mm (tons/day)	8-32mm (tons/day)	> 32 mm (tons/day)	Sum of Partials (tons/day)
SRRB-BLM2009-01	1/6/09 10:47	6,530	1,332	1,006	428	239	339	2,338
SRRB-BLM2009-02	1/6/09 12:59	7,380	1,460	951	461	155	335	2,412
SRRB-BLM2009-03	1/9/09 11:46	5,869	547	239	68.4	20.8	150	786
SRRB-BLM2009-04	1/10/09 12:04	3,695	142	67.3	30.4	15.2	21.7	209
SRRB-BLM2009-05	1/10/09 12:35	3,625	139	34.5	24.4	2.00	8.05	174
USGS-BLM2008-01	10/19/07 17:20	1,515	1,037	180	178	2.44	0.00	1,217
USGS-BLM2008-02	10/19/07 17:50	1,515	600	222	220	1.64	0.00	823
USGS-BLM2008-03	10/20/07 13:25	1,748	1,102	304	299	4.22	0.00	1,405
USGS-BLM2008-04	10/20/07 14:00	1,783	416	182	180	1.79	0.00	597
USGS-BLM2008-05	11/17/07 12:10	3,157	167	13.7	13.6	0.18	0.00	181
USGS-BLM2008-06	11/17/07 12:30	3,178	185	35.4	31.3	4.18	0.00	220

*>2mm is not included in Total
Values not rounded according to Porterfield (1972)

Table 3 - Bedload Sampling Measurements

WY2009 Brightwood Bedload Samples -- Grain Size Analysis Results

Sample	2009-01	2009-02	2009-03	2009-04	2009-05 *
Date	01/06/2009	01/06/2009	01/09/2009	01/10/2009	01/10/2009
Discharge (cfs)	6,530	7,380	5,869	3,695	3,625
Fraction (mm)					
D5	0.5	0.5	0.5	0.5	0.5
D16	0.7	0.8	0.7	0.7	0.7
D25	0.9	0.9	0.8	0.9	0.8
D35	1.2	1.2	0.9	1.1	0.9
D50	1.7	1.6	1.3	1.4	1.2
D65	2.9	2.4	1.8	1.9	1.5
D75	7.7	4.5	3.2	2.7	1.8
D84	26.7	21.2	58.8	14.0	2.4
D90	43.8	96.1	71.7	32.4	3.8
Dmax	92	124	92	48	71

* analysis skewed by single particle skipping 3 size classes

Table 4 - Bedload Sample Grain Sizes

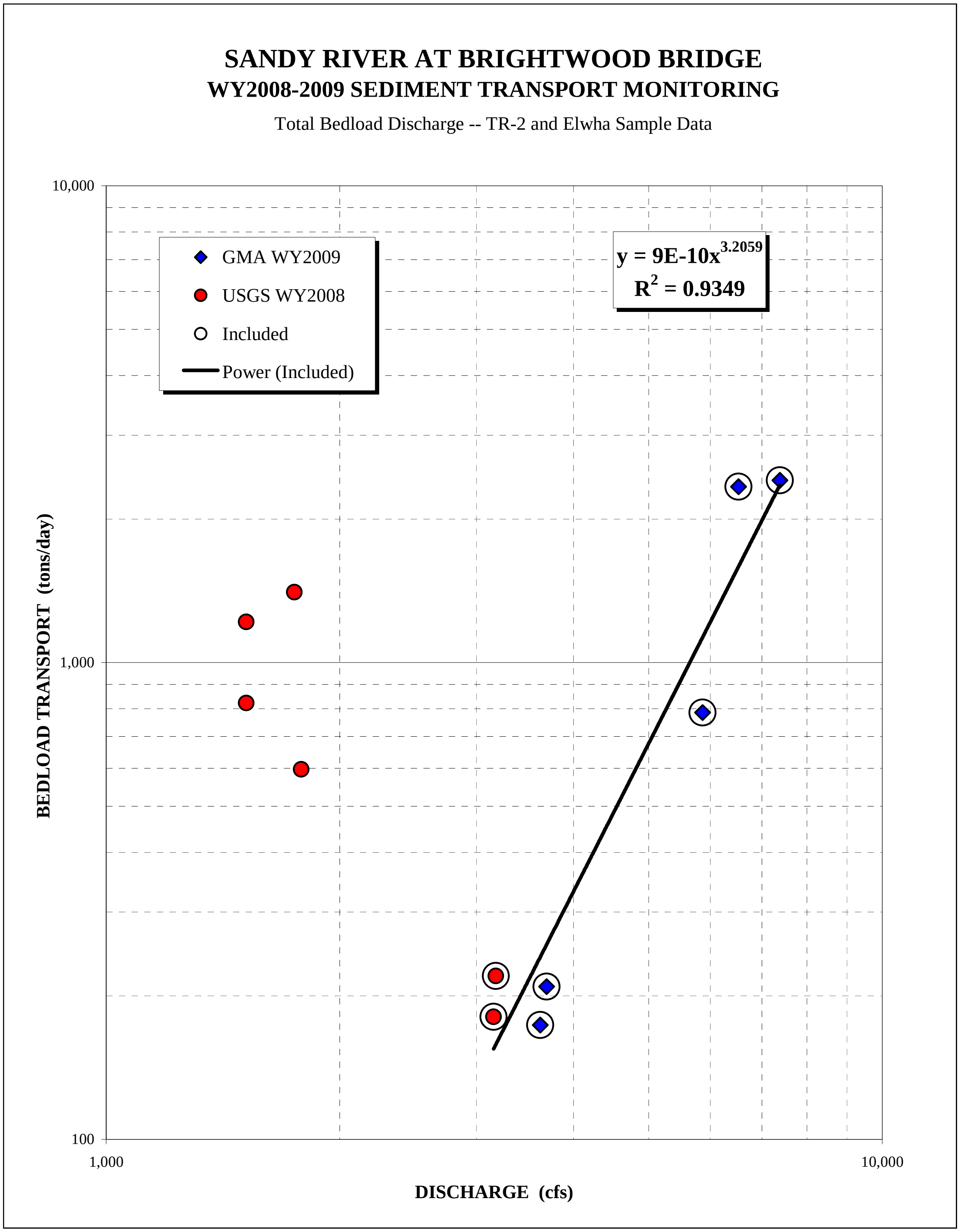

Figure 29 - Bedload Measurements - Total Load

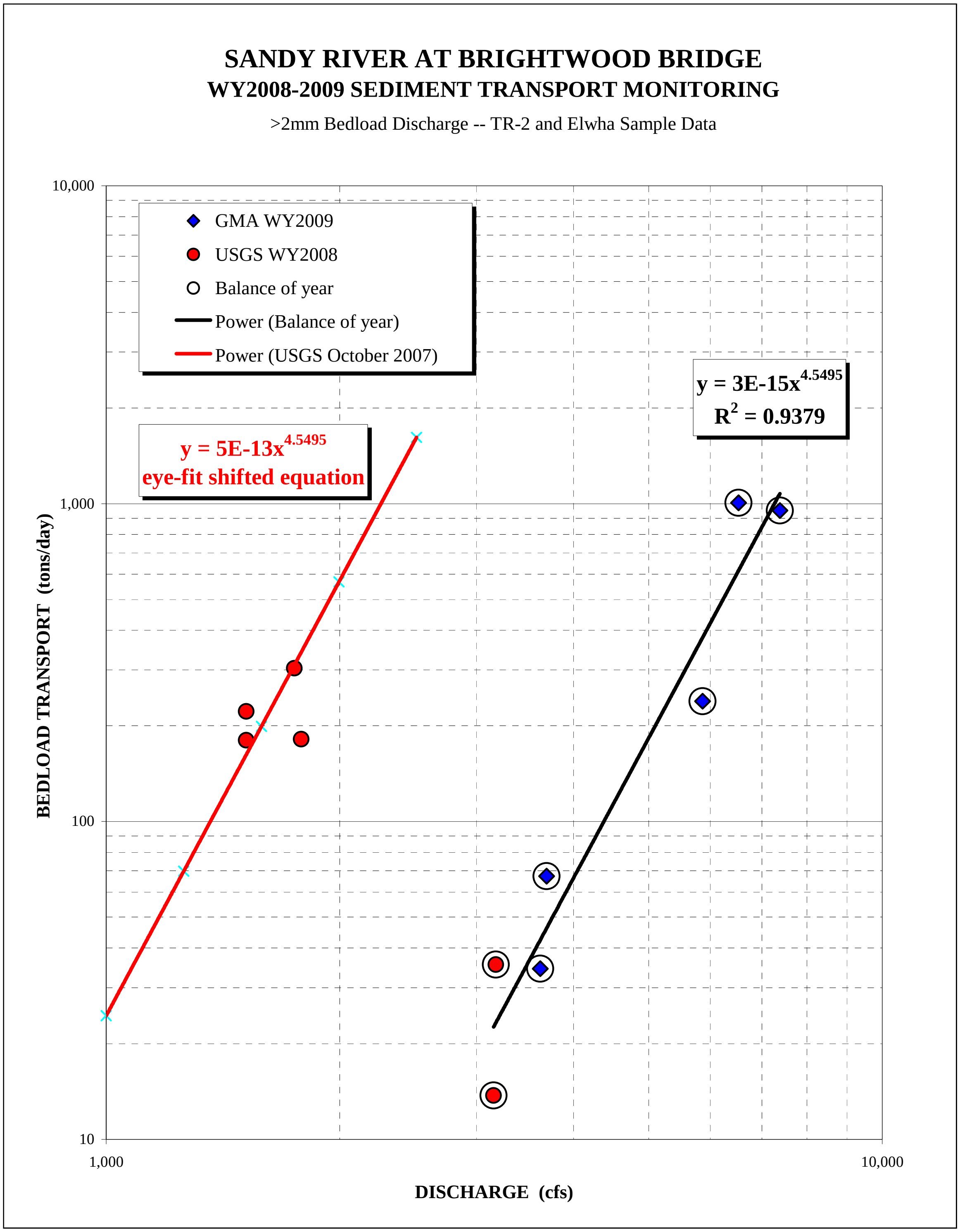

Figure 30 - Bedload Measurements - Coarse Fraction

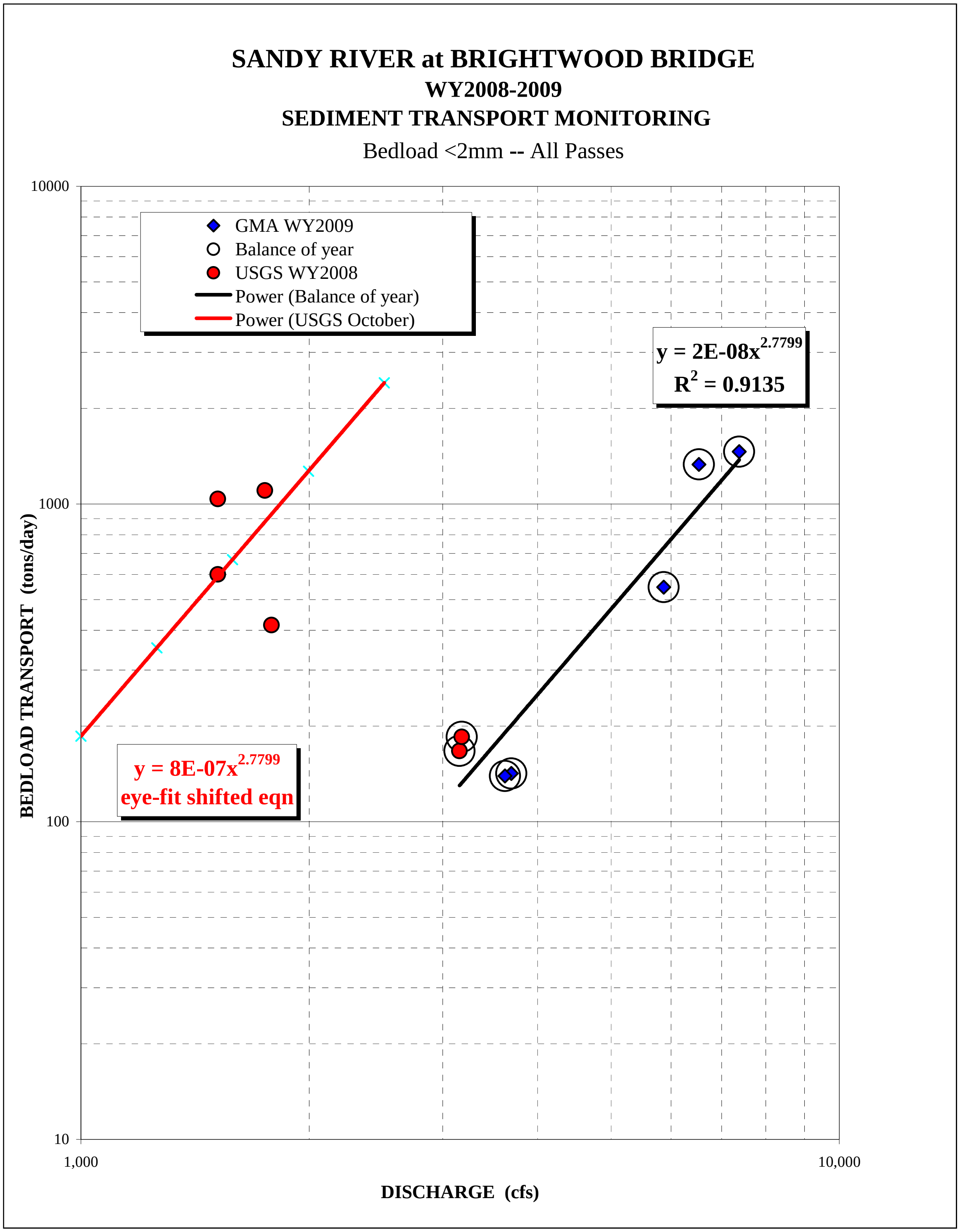

Figure 31 - Bedload Measurements - Fine Fraction

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WY2008 06/25/2008

PARTICLE SIZE ANALYSIS

River:	Sandy River	Sample #	2009-03
Location:	Sandy River at Brightwood Bridge	Date Collected:	01/09/2009
Crew:	S. Pittman, C. Podolak, L. Cornelius	Method of Collection:	Bridge

Bedload Measurements

Begin Time	11:35	Start Station (ft):	35
End Time	11:58	End Station (ft):	107
Begin SH	-1.6	Interval (ft):	18
End SH	-1.65	# Verticals:	5
Station bottom time (sec):	30	Sampler Type:	TR-2
Pass # of #:	1/1	Bag # of #:	1/1

Bulk Samples

Description	
Sampler	
Surface/Sub-surface	
Bag # of #	

Date Processed:	26 Jan 2009
Processed by:	EO
Entered by:	BC
Checked by:	BC

UNITS G

------------------ WEIGHT -----------

Sieve	Finer than	Gross	Tare	Net 1	x Multiplie	Final Net	%	Cum%<
256						0.0	0.0%	100.0%
180	256					0.0	0.0%	100.0%
128	180					0.0	0.0%	100.0%
90	128					0.0	0.0%	100.0%
64	90					1727.5	15.0%	100.0%
45	64					460.0	4.0%	85.0%
31.5	45					0.0	0.0%	81.0%
22.4	31.5					26.0	0.2%	81.0%
16	22.4					94.0	0.8%	80.7%
11.2	16					74.5	0.6%	79.9%
8	11.2					109.5	1.0%	79.3%
5.6	8			2.3	38.6	88.8	0.8%	78.3%
4	5.6			4.0	38.6	154.5	1.3%	77.5%
2.8	4			6.0	38.6	231.8	2.0%	76.2%
2	2.8			13.6	38.6	525.3	4.6%	74.2%
1	2			89.0	38.6	3437.8	29.9%	69.6%
0.85	1			30.5	38.6	1178.1	10.3%	39.7%
0.5	0.85			80.1	38.6	3094.0	26.9%	29.4%
0.25	0.5			7.3	38.6	282.0	2.5%	2.5%
0.125	0.25			0.1	38.6	3.9	0.0%	0.0%
0.063	0.125			0.0	38.6	0.0	0.0%	0.0%
Pan	0.063			0.0	38.6	0.0	0.0%	0.0%
TOTAL:				233		11487.64	100.00%	

Sample Dry Wt 11500 - Total Processed Wt 11488 = Net Loss: 12.4

% of Sample: 0.11%

Splitting: Gross Split 9000 - Tare 0 = Net Split 9000

Split at 5.6 mm — Split Wt. = 233

Split/Net = 0.025888889

Multiplier (inverse Split/Net) = 38.62660944

D_{max}	
B-axis (mm)	92
Mass (g)	1044.5

PARTIAL TRANSPORT

≤2 mm	2-8 mm	8-32mm	> 32 mm	Sum
7,995.71	1,000.43	304.00	2,187.50	11,487.64

Table 5 - Bedload Grain Size Analysis

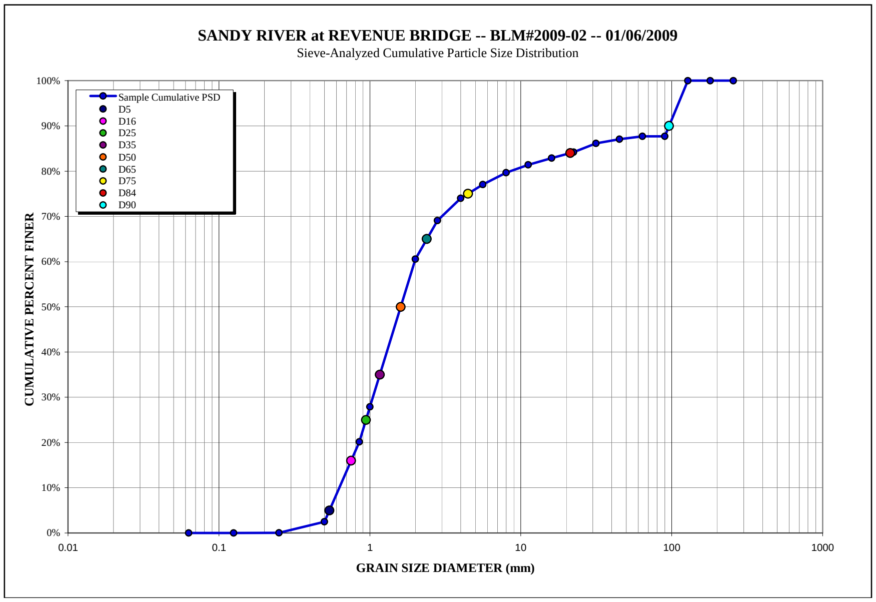

Figure 32 - Bedload Grain Size Distribution

3.6. BUDGET

The computed annual load for WY2008 at Brightwood / Sleepy Hollow is the input into the sediment budget reach (Table 6). The computed annual load for WY2008 at the Revenue Bridge sampling site (GMA, 2008) is the other flux component to the sediment budget. We are contributing these two calculations to the group effort to compute a two-fraction sediment budget for WY2008. Initial computations show between 600,000 and 680,000 Mg (661,000-750,000 tons) of sediment eroded from the reservoir in the first year (roughly half sand and half gravel), and between 155,000 and 225,0000 Mg (170,000-248,000 tons) of sediment was deposited between the dam site and the head of the gorge (roughly 10% of which was sand and 90% gravel). The final budget will be published in another forum by the group of collaborators.

WY2008 Sediment Load Totals for Sandy River at Brightwood Bridge

Load Component Computational Fraction	Suspended Sediment * <.063mm	 >.063mm	Bedload * <2mm	 >2mm	TOTAL
Tons	34,300	101,700	13,500	5,160	154,660
Metric Tons	31,100	92,300	12,200	4,680	140,280

Sediment Budget Component	Gravel	Sand	Fine	TOTAL
Tons	5,160	115,200	34,300	154,660
Metric Tons	4,680	104,500	31,100	140,280

* Values rounded, Porterfield 1972

Table 6 - Sediment Budget Inputs

4. DISCUSSION

4.1. DOWNSTREAM DEPOSITION

In the first year after its removal, more than one hundred thousand tons of sediment deposited within 10 km (6 mi) downstream of the Marmot Dam site, generally following the pattern predicted by Stillwater Sciences (Figure 33). This represents 120% of the volume that entered the reservoir reach and 1/3 of the total amount eroded in a slightly drier than normal water year. Despite this amount of deposition, the sediment did not cause fish passage issues nor did it drown out known spawning or rearing sites. Additionally, the basic form of the river and its bar configuration did not change.

In our downstream sites, the annual changes in bed elevation fell within the measurement uncertainty, and could not be attributed to the Marmot Dam removal. Within the near-dam reach, much of the eroded sediment only traveled several hundred meters. Two possible explanations of this localized deposition are (1) the low discharges during WY2008 and (2) a potential sediment 'deficit' downstream of the dam. The discharge which moved sediment within the first 60 days after the cofferdam breach were small compared to the flows experienced in WY2009 (Figure 4). This long profile was initially marked by a locally steep slope in the vicinity of the cofferdam (Figure 34). The steep local slopes combined with the moderate discharge likely provided enough transport capacity to move large grains a short distance (several hundred meters) but no further downstream. An analysis of surveys from summer 2009 should show changes due to the larger flows in WY2009. Second, the long profile and observations of the reach downstream of the dam (Figure 36), suggest that the reach immediately downstream may have experienced degradation over the life of the dam. Filling in this 'deficit' of sediment and bringing the reach back to its undammed profile, would account for some longer term storage immediately below the dam. If this is in-fact the case, much of the sediment deposited in the near-downstream reach could be expected to move no further, even when subjected to higher discharges.

The gravel deposition has been limited to the near-dam reach and it has shown two different forms. Podolak & Wilcock (2009b) found that within several hundred meters of the dam site, the deposition was spread across the entire channel and of a magnitude that exceeded even the largest clasts (> 1m). Further downstream (but still above the gorge) the deposition took the form of localized deposits on the top of existing bars (Podolak & Wilcock, 2009b). In the downstream sites (Revenue, Cedar Creek, and Oxbow Park) there was no measureable gravel deposition. There was however, sand deposited in these reaches, increasing the fraction of sand present on the surface by nearly 10% in all reaches (Figure 25 [upper]). Even at the moderate flows of WY2008, the river appears to have had the competence to transport sand well downstream and deposit it throughout the lower reaches – a phenomenon confirmed in the sediment transport observations from October 2007.

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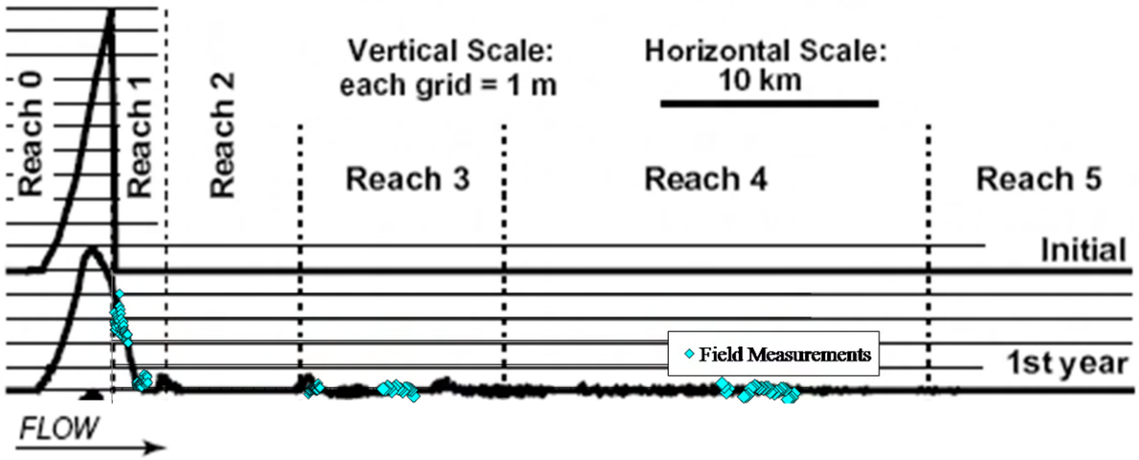

Figure 33 - Measured annual elevation changessuperimposed on pre-removal predictions (from Downs et al, 2009)

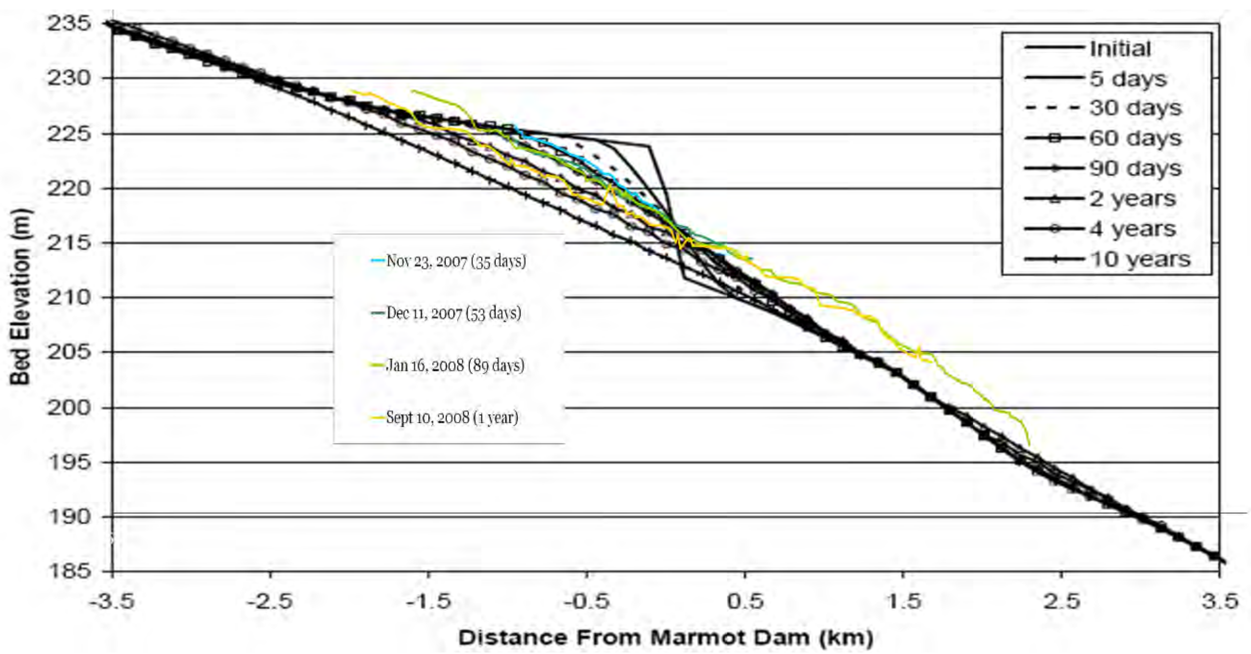

Figure 34 - Long Profile Evolution in the vicinity of the Marmot Dam Site. Black lines are predicted long profile evolution (Downs et al, 2009). Colored lines are elevations from USGS surveys.

4.2. DOWNSTREAM FINING

The Sandy River shows downstream fining typical of gravel-bed rivers. The river experienced an increase in sediment supply as a result of the dam removal. However, the supply consisted of stored river-transported material, and was not of a composition that differed significantly from the normal annual sediment load, as might be expected for a fine sediment input from a landslide, fire, or change in land use. Although the surface sand fraction at-a-site increased by ~10%, because the grain size of the 'augmentation' and 'normal load' were similar, there was no change in the downstream fining – the rate of increase of sand, and the rate of decrease in the gravel size fraction (in the downstream direction) did not change (Figure 25). Much of the gravel from the dam removal has not made it into the lower reaches, however based on GSD measures of the deposit in the near-dam reach it appears that the new deposit fits into the overall downstream fining pattern.

4.3. TRANSPORT MEASUREMENTS

Empirically based sediment transport studies generally focus on the peak events which transport most of the sediment in a given year. As evidenced by the Brightwood and Revenue WY2008 sampling data, the Sandy River apparently exhibits periods of relatively high transport at relatively low flows. Since sediment discharge is a function of water discharge (the same rate at a higher flow results in more sediment transported), and since the abnormally high rates were observed at lower flows, one would assume that such anomalies are of little importance in the annual sediment load. However, since low flows occur between all the winter storms, elevated transport rates during low flows can conceivably drive the annual sediment load as much as the peak events, as evidenced by the computation gaming described in Section 3. No data were collected at Brightwood between November 2007 and May 2008 and the peaks were not adequately sampled. Our 2009 effort sought to fill the gaps in the USGS dataset bay sampling flows approximating the 20087 storm peaks. Post-processing revealed however, that sampling low flow periods would have greatly increased the accuracy of annual load computations. The lesson learned is that the Sandy River, through mechanisms we do not fully understand, is capable of moving high sediment loads during relatively low flow periods, since these flows occur for a very long time. A low-flow sampling program in WY2008 or the use of a surrogate such as continuous turbidity (GMA showed a very strong turbidity-SSC correlation at Revenue in WY2008) would have reduced the uncertainty in sediment load estimates considerably.

4.3.1. Upstream Boundary Comparisons to Estimates

The Marmot Dam was assessed to have impounded 750,000 m^3 of sediment (Stillwater Sciences, 2000a) prior to its removal. Uncertainty in the average annual sediment flux into the reservoir resulted in characterizing the impounded sediment as “a maximum of 20 years of annual average sediment flux yield and possibly much less” (Stillwater Sciences, 2000a, p.12), or “about 10 years of average annual sediment flux” (Major et al, 2008, p. 241), or nearly 30 years worth based on the estimated background flux rate (Stillwater Sciences, 2000b). The calculated annual load for WY2008 at Brightwood / Sleepy Hollow was 140,000 Mg (155,000 tons) (Table 6), which translates into a volume equivalent to one tenth of the impounded sediment.

In order to assess the volume of sediment delivered in WY2008 relative to the average value, an inquiry into the WY2008 discharge record compared to the complete discharge record is required. The USGS gauge near Marmot Dam (14137000) has a 97-year record of daily average discharge, and a 20-year record of 30-minute discharge. Due to the rapidly aggrading cross section at the Marmot gauge following dam removal, WY2008 was gauged upstream at the USGS Brightwood gauge (14113650), and downstream in the Revenue reach. Comparisons between concurrent discharge records from upstream, downstream, and at Marmot Dam, show the three stations have discharges within several percent of one another and functionally, provide the same record. Thus, despite minor tributary contribution, statistics derived from the 97 year record at Marmot are applicable to the other stations. The exceedance probability of the daily mean discharges for WY2008 is nearly identical to the mean for the 97-year record (Figure 35). When comparing the 30-minute discharges against the 20-year record, WY2008 appears to be slightly wetter than the mean. However, despite being wetter in terms of total discharge, WY2008 has fewer than average flows greater than 150 cms (5300 cfs). By some measures (total discharge) it was a wetter than average year, and by others more germane to bedload transport (total peak discharge, and flows above several hundred cubic meters per second) it was less effective at moving bedload.

It would be dubious to claim to know an average annual sediment flux based on so few sediment transport measurements, however it seems plausible that the average annual sediment flux is higher than the pre-removal estimates, that WY2008 was average to slightly below average in terms of annual sediment flux, and that the impounded sediment represented less than 10 years worth of average annual flux.

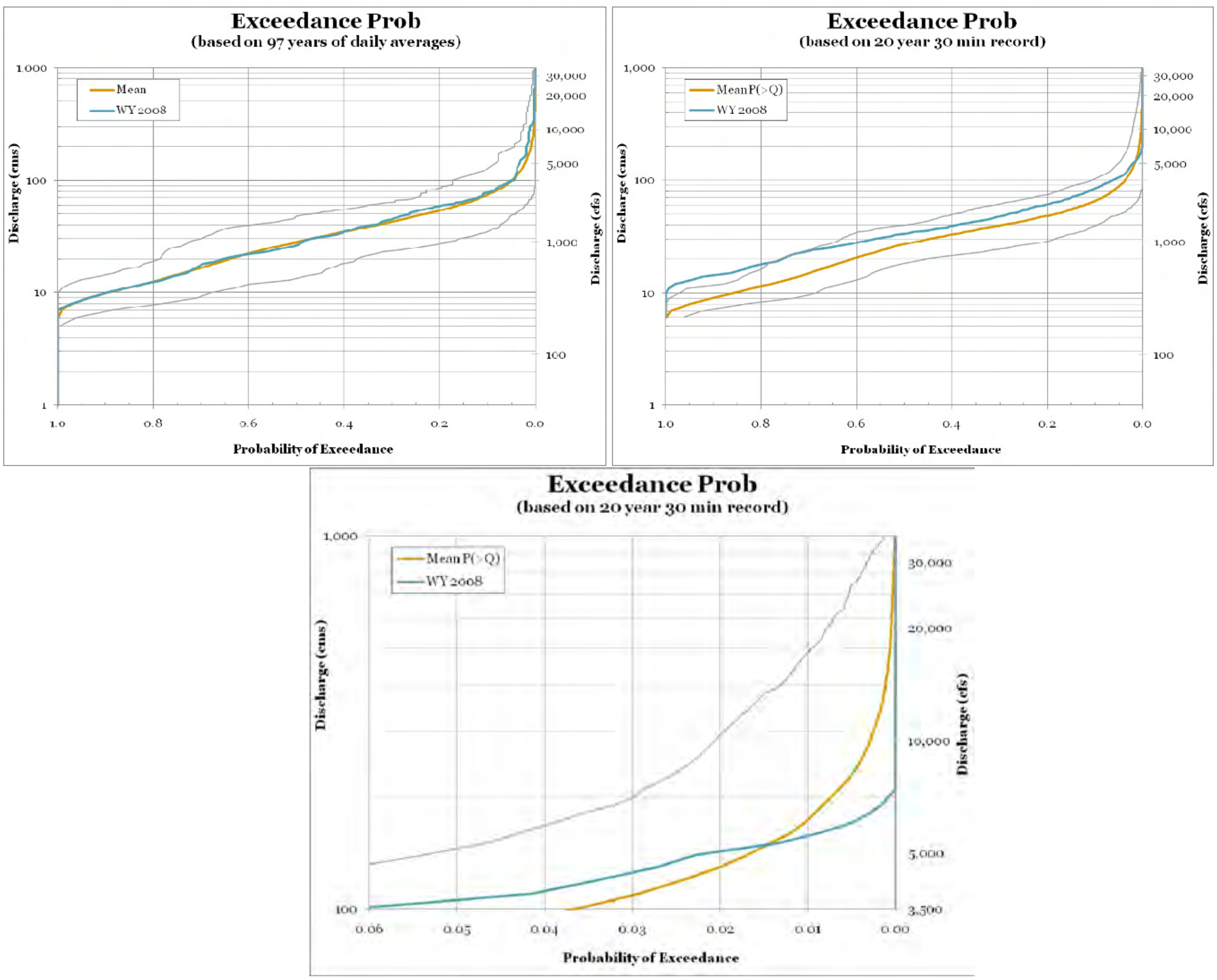

Figure 35 - WY2008 discharge comparisons with the 97-year record of daily mean flow (top left), and the 20-year record of 30 minute discharge (top right). WY2008 had fewer large discharges (lower figure). The grey bars trace the maximum and minimum exceedance probability values from the respective records.

4.4. Budget

The reach immediately below the dam (which was gravel-bedded with coarse-grain-dominated bedforms) received an increased amount of gravel transport and deposition. This led to an increase in bed elevation, particularly on top of existing gravel bars (Podolak and Wilcock, 2009a&b). Between Revenue Bridge and Dabney Park (RK 39.1 – 14.5 [RM 24.3 - 6]), the bed and bedforms are gravel-dominated with increasing sand content below Oxbow Park (Stillwater Sciences, 2000a). While there is some small-scale sand deposition on the lateral margins (Stewart and Grant, 2005), gravel forms the structure of the bed and bedforms. In this reach, the gravel load was not significantly elevated by the removal of the Marmot Dam, and the lack of significant bed and bedform change is not surprising. Finally, the lower reaches where the sand could have presumably deposited were not included in this study, so it is unknown whether the elevated sand load deposited in the lower Sandy River or was transported through to the Columbia River.

A key component of uncertainty to be addressed in the computation of the sediment budget is the Sandy River Gorge (RK 45.9 – 39.4 [RM 28.5 – 24.5]). It is a steep and narrow gorge, which went unmeasured prior to the dam removal. The steep walls and general east-west orientation make aerial photography and GPS usage on the water difficult. The depths, velocities, and rapids create logistic difficulties for surveys through the gorge. Consequently, there is very little baseline information in the gorge. Both Stillwater Sciences (2000a) and Stewart & Grant (2005) propose that there is limited storage capacity in the gorge. Anecdotal evidence from boaters before and after the dam removal report that there are some small new deposits on the channel margins, and that some pools appear to be storing additional sediment. Rough assessment of pool areas from one set of aerial photographs suggest that there is approximately 50,000 m^2 (60,000 yd^2) of pool area. While, there are no measures of pool depths before and after the removal, using the pool residual volume approach from Stewart and Grant (2005) we find it unlikely that more than 45,000 Mg (50,000 tons) could be accommodated in the gorge.

The total volumes of sediment flux upstream and downstream and are well constrained, as are the reservoir erosion volumes. The sand vs. gravel breakdown is well known at the boundaries, and in the reservoir deposit, however it is possible that the erodeding sediment did not have the same sand/gravel breakdown as the entire deposit due to selective transport processes, thus skewing the relative percentages measured at the downstream boundary. Despite the best efforts to collect all the necessary data, some uncertainty remains in the change in storage values. Our estimates of the total sediment storage in the gorge are likely high, however, the total volume stored is still of the same order of magnitude as that stored between the dam and the gorge. Additionally, our estimates of the sand/gravel breakdown of the sediment stored in the gorge probably err on the sandy side and underestimates the relative amount of gravel.

4.5. First Year Lessons

At the end of the first year of post-removal monitoring we have learned several lessons about the monitoring the response of the Sandy River to the removal of the Marmot Dam.

4.5.1. Geomorphic Observations

1) A one-dimensional morphodynamic model, coupled with professional qualitative assessment can capture the overall pattern and timing of erosion and deposition associated with a dam removal like the Marmot Dam. The predictions of the areal extent of significant bed change proved to be quite accurate.
2) Measuring the transport and deposition in at least a two-fraction framework was important to capture the disparate sand and gravel 'stories'.
3) A water year with below normal peak flows had the ability to mobilize and redistribute a large sediment volume containing large grain sizes.
4) Sediment transport rates varied through the season not only below the damsite (as expected), but at the upstream boundary, where variability in ambient conditions proved to be a large source of uncertainty.
5) Surveys & LiDAR at with ≈ 1 pt/m^2 density, coupled with large (0.25 – 1 meter) grain sizes, cannot resolve elevation changes much below several tens of centimeters.
6) In areas below the main depositional reach, bed elevation changes were very localized. Full topographic surveys were much more effective at capturing the areas of erosion and deposition than a method of widely spaced cross sections.

4.5.2. Monitoring Dam Removals

1) A collaborative monitoring effort without a dedicated organizational structure is possible with cooperative partners.
2) The lack of baseline data for the bedrock gorge downstream of the dam has hampered both predictions and monitoring efforts.
3) Where adequate reception was available, RTK GPS was a much more efficient way to capture bathymetry, however, high local relief combined with valley orientation can make RTK GPS nearly unusable and favor a more traditional total station survey method.
4) Choosing multi-year study reaches which require ongoing landowner permission without a financial / contractual access agreement, leaves one open to the chance of loosing access to a crucial site.
5) General interest and resources were relatively abundant for the first year monitoring due to widespread publicity, but maintaining a similar level of effort for a multiple-year monitoring program has been challenging.

5. APPLICATIONS

As this year's project was an interim step within a larger project, the lessons learned inform not only others' work, but our follow-on work. We have been actively modifying our research plans for the following year and sharing the data we have collected thus far in a variety of forums.

5.1. Recommendations for 2009-2010 Monitoring

After the completion of the 2007-2009 monitoring, several changes were made to the monitoring plan for the following (and final) year. With the upstream (Brightwood-Sleepy Hollow station) better constrained, the sediment sampling plan for 2009-2010 was to sample below the former dam site. Landowner permissions were obtained which would allow sampling several hundred meters below the winter 2007-2008 sampling site (see GMA 2008). Second, preliminary reconnaissance suggested that despite the large winter flows in WY2009, the Oxbow Park and Cedar Creek reaches experienced minimal change to the bars and river bed. The summer 2009 monitoring plan was modified to emphasize data collection in the reach near the former dam site at the expense of data collection in the lower reaches.

5.2. Shared Results

The Marmot Dam removal generated media coverage not only locally and regionally, but also nationally. There was an interest among the river restoration community, as well as the geomorphology community to learn lessons from the dam removal and subsequent sediment redistribution. To this end, the NCED/JHU/GMA team has been actively sharing and reporting the data and findings of this project. All the reports and presentations listed below are available at: www.jhu.edu/marmot.

5.2.1. Monitoring Team

All data collected by the OWEB-funded researchers has been freely shared with all the researchers monitoring the Marmot Dam removal – primarily USGS scientists from the Cascade Volcano Observatory and the Oregon Water Science Center. Reciprocal data sharing by these same scientists has provided us with a plethora of additional survey and sediment transport data.

5.2.2. Local Community

The Sandy River Basin Watershed Council arranged a presentation on July 29, 2008, in the City of Sandy for anyone who was interested in the research being conducted on the dam removal. We presented our work and a summary of preliminary findings to an enthusiastic audience. Many attendees were well informed on the previous work that had been done on the river, and were interested to discuss the changes that had been observed.

5.2.3. Regional Scientists & Practitioners

In November, 2008, we presented the OWEB-funded work to the US Forest Service Pacific Northwest Regional Watershed and Aquatics Program Managers meeting, in Hood River, Oregon. In February, 2010, the research was presented in an oral presentation at the River Restoration Northwest Symposium, where it was well received.

5.2.4. National Scientists & Practitioners

In addition to sharing the findings and research on a local and regional stage, the project has also been a frequent topic at national-level meetings. There were poster presentations at the 2008 and 2009 annual meetings of the American Geophysical Union (Devillier et al, 2008a; Podolak et al, 2008; Podolak and Wilcock, 2009b). At the annual meeting of the American Geological Society, the Marmot Dam was the central focus of an invited presentation (Podolak and Wilcock, 2009a) as well as a field trip (which Podolak was a co-leader). The NCED interns who worked on the project produced a group report and presentations given at the University of Minnesota (Devillier et al, 2008b). Further, the Marmot Dam was presented by Podolak as a case study to a series of working groups tasked by Federal Advisory Committee on Water Information Subcommittee on Sedimentation to create dam removal analysis guidelines for sediment.

Finally, we are currently coauthoring a manuscript for national-level publication bringing together our data collection efforts with the other collaborators in the monitoring effort. This will include the complete sediment budget and will be referenced in next year's annual report to OWEB.

6. FIGURES

Figure 36 - Panoramic Photographs from Dam Reach. For photo locations see Figure 8.

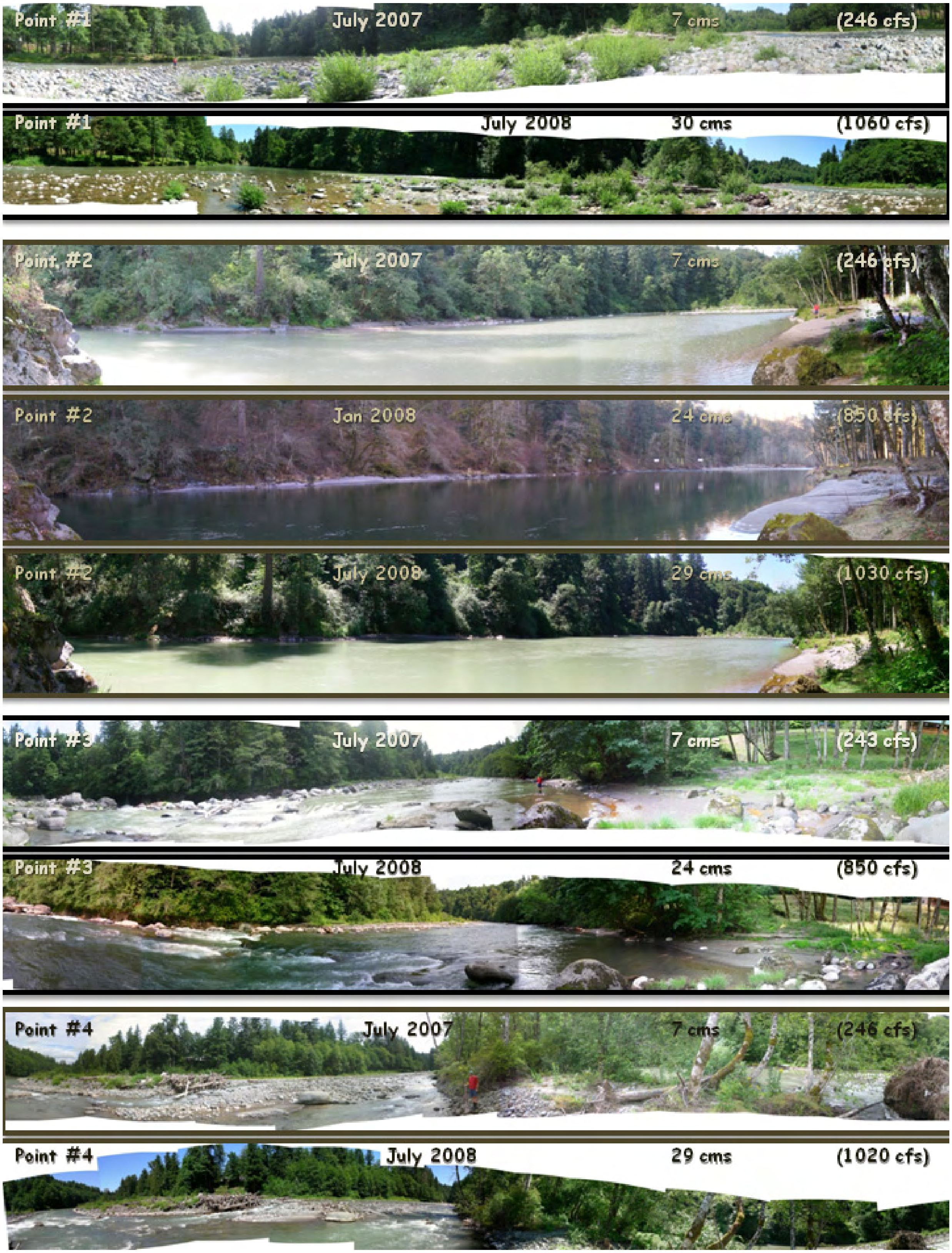

Figure 37 - Panoramic Photographs from Revenue Reach. For photo locations see Figure 9

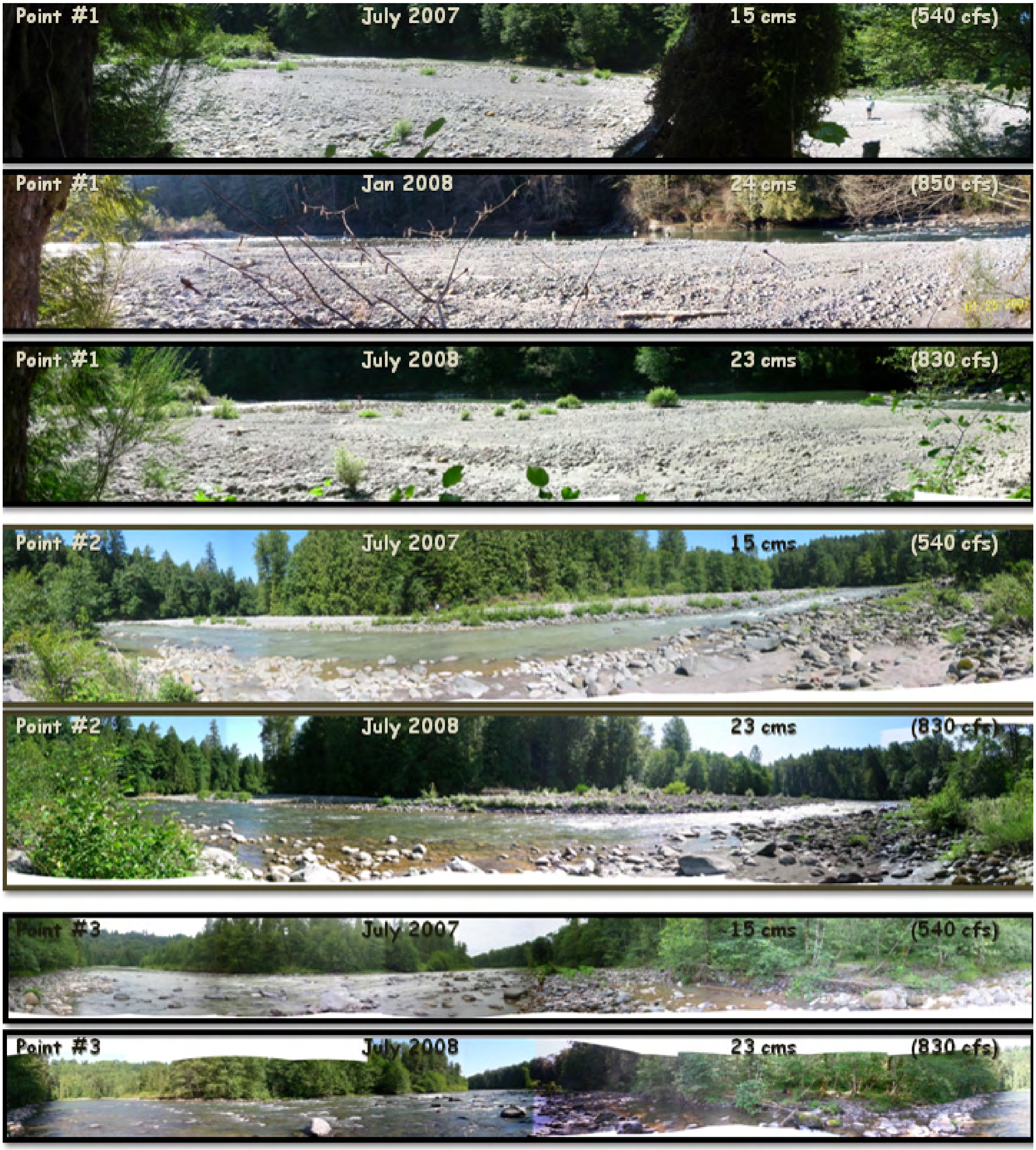

Figure 38 - Panoramic Photographs from Cedar Creek Reach. For photo locations see Figure 10.

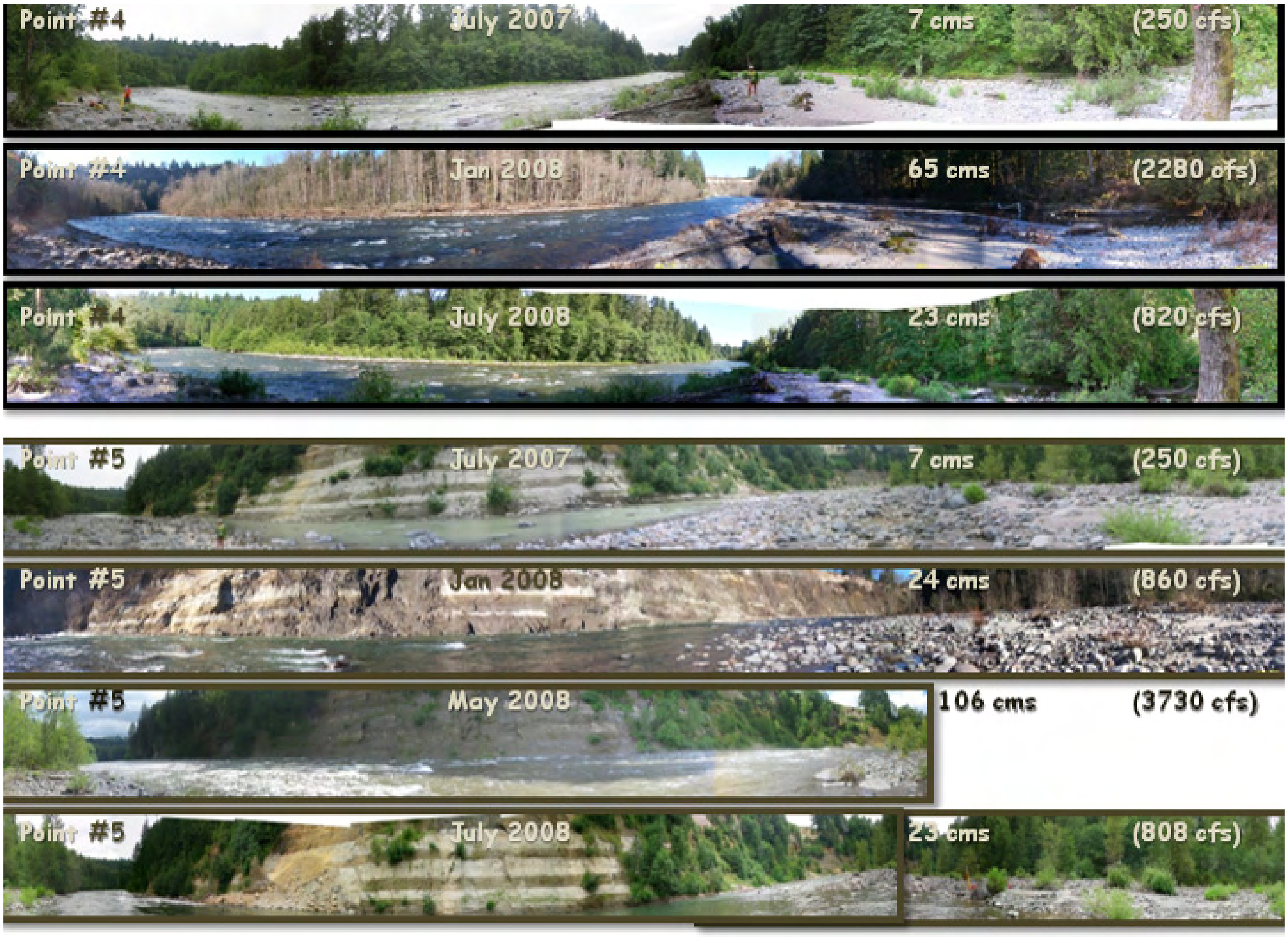

Figure 38 (con't)

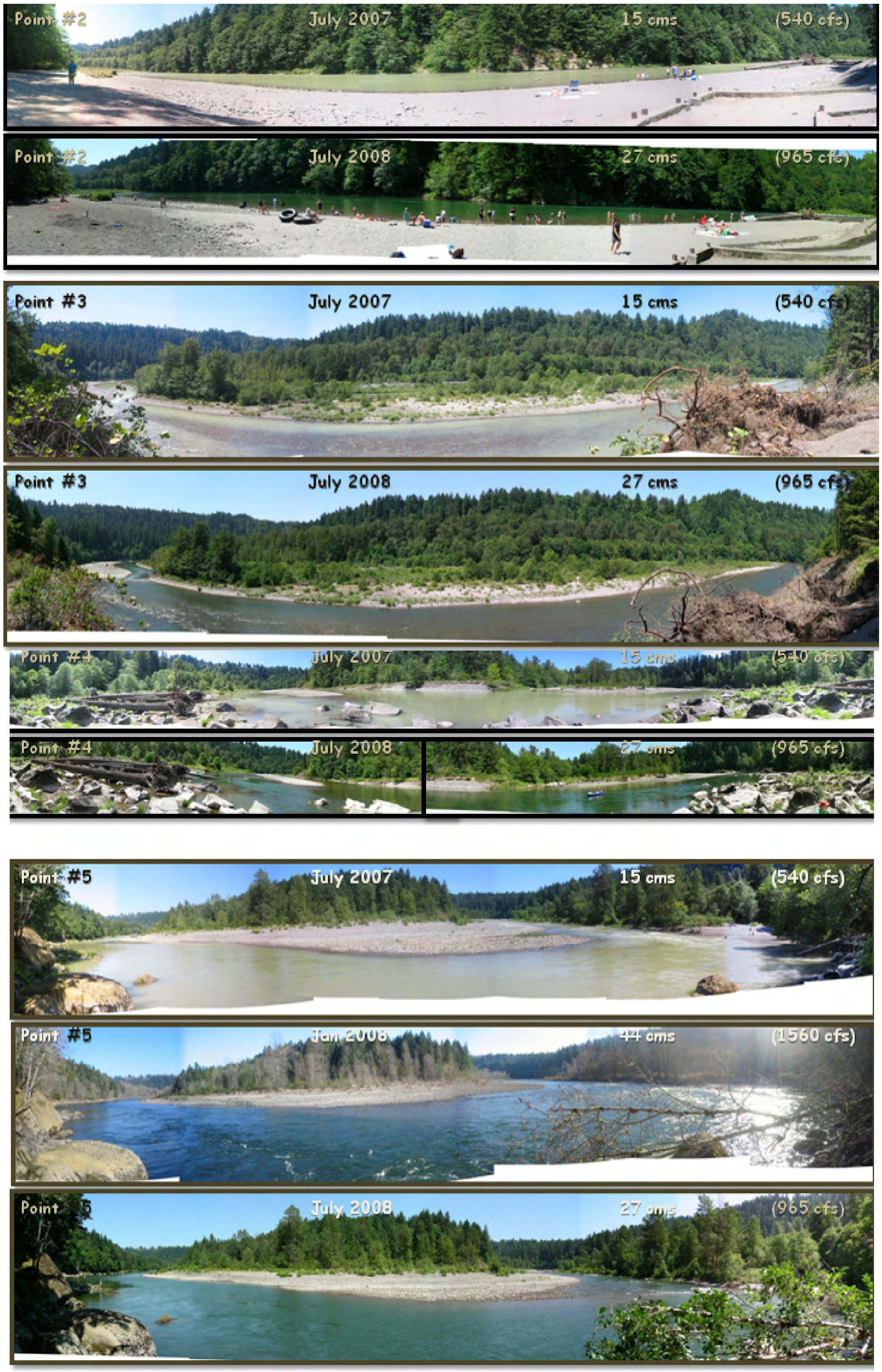

Figure 39 - Panoramic Photographs from Oxbow Reach. For photo locations see Figure 11.

7. REFERENCES

American Rivers, 1999, Dam Removal Success Stories: Restoring rivers through selective removal of dams that don't make sense. American Rivers, Washington D.C., 146 p.

Bauer, T., and Bountry, J., 2007, 2007 Profile Survey of the Sandy River for the Marmot Dam Removal, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO, 20 p.

Bruce McCammon Photography, 2009, Marmot & Little Sandy Dam Removal: Final Report, submitted to USDA Forest Service, Mount Hood National Forest, August 2009, contract number AG-046W-P-07-0099.

Buffington, J.M., and Montgomery, D.R., 1999, A procedure for classifying textural facies in gravel-bed rivers, *Water Resources Research*, v. 35, n. 6, pp. 1903-1914.

Cheng, F., and Granata, T., 2007, Sediment transport and channel adjustments associated with dam removal: field observations, *Water Resources Research*, v. 43, W03444, doi:10.1029/2005WR004271, 14 p.

Cui, Y., and Wilcox, A., 2008, Development and application of numerical models of sediment transport associated with dam removal, in Garcia, M.H., ed., *Sedimentation Engineering – Processes, Measurements, Modeling, and Practice.* American Society of Civil Engineers Manuals and Reports on Engineering Practice no. 110, pp. 995-1020.

DeVillier, K.N., Podolak, C.J., Wilcock, P.R., 2008a, Effects of the Marmot Dam Removal on Grain Size Distribution on the B Reaches of the Sandy River in Oregon, *EOS Trans. AGU*, (89)53, Fall Meet. Suppl., Abstract H43B-0997

DeVillier, K.N., Jurk, D., Palomo, C., Shin, T.A., Trifone, K., 2008b, River Processes in the Sandy River in Oregon: Team Marmot 2008, unpublished manuscript, National Center for Earth-surface Dynamics, Minneapolis, MN, 80 p.

Doyle, M.W., Stanley, E.H., and Harbor, J.M., 2003a, Channel adjustments following two dam removals in Wisconsin, *Water Resources Research*, v. 39, no. 1, 1011, doi:10.1029/2002WR001714, 15 p.

Doyle, M.W., Stanley, E.H., Harbor, J.M., and Grant, G.E., 2003b, Dam removal in the United States: Emerging needs for science and policy, *EOS, Transactions American Geophysical Union*, v. 84, pp. 29, 32 – 33.

Downs, P.W., Cui, Y., Wooster, J.K., Dusterhoff, S.R., Booth, D.B., Dietrich, W.E., Sklar, L.S., 2009, Managing reservoir sediment release in dam removal projects: An approach informed by physical and numerical modeling of non-cohesive sediment: *Intl. J. River Basin Management*, v. 7, n. 3, p. 1-20.

Edwards, T.K., and Glysson, G.D., 1999. Field Methods for Measurement of Fluvial Sediment, *Techniques of Water-Resource Investigation*, USGS Report number 03-C2. available online at: http://pubs.er.usgs.gov/usgspubs/twri/twri03C2

Esler, J., 2009, Going, Going, Gone – reflections on the retirement of the Bull Run hydroelectric project, *Open Spaces*, v. 9 no. 4, p. 21-25.

Federal Energy Regulatory Commission (FERC), 2003, Bull Run Hydroelectric Project (FERC Project No. 477-024) – Oregon, Final Environmental Impact Statement, FERC/FEIS – 0162F, Washington DC.

Graham Matthews and Associates (GMA), 2008, Sandy River Sediment Transport Monitoring Project, WY2008 Annual Report, prepared for Sandy River Basin Watershed Council. available online at: http://www/jhu.edu/marmot

Major, J.J., O'Connor, J.E., Grant. G.E., Spicer, K.R., Bragg, H.M., Rhode, A., Tanner, D.Q., Anderson, C.W., Wallick, J.R., 2008, Initial fluvial response to the removal of Oregon's Marmot Dam: *EOS, Transactions American Geophysical Union*, v. 89, no. 27, pp. 241 – 242. available online at: http://www.agu.org/pubs/crossref/2008/2008EO270001.shtml

O'Connor, J., Major, J., and Grant, G., 2008, The dams come down—unchaining U.S. rivers: *Geotimes*, v. 53, no. 3, pp. 22-28.

Pizzuto, J., 2002, Effects of dam removal on river form and process: *BioScience*, v. 52, pp. 683 – 691.

Podolak, C., Wilcock, P., and Pittman, S., 2008, First-Year Downstream Sediment Budget Following the Marmot Dam Removal from the Sandy River, Oregon, *EOS Trans. AGU*, 89(53), Fall Meet. Suppl., Abstract H43B-0996.

Podolak, C., and Wilcock, P., 2009a, The Formation and Growth of Gravel Bars in Response to Increased Sediment Supply Following the Marmot Dam Removal, *Geological Society of America Abstracts with Programs, Annual Meeting*, Portland, OR, 41(7), p. 573, abstract 225-4.

Podolak, C., and Wilcock, P., 2009b, The Formation and Growth of Gravel Bars in Response to Increased Sediment Supply Following the Marmot Dam Removal, *EOS Trans. AGU* 90(52) Fall Meet. Suppl., Abstract EP33A-0600

Portland General Electric (PGE), 2002, Decommissioning Plan for the Bull Run Hydroelectric Project. FERC Project No. 477, filed by Portland General Electric Company with the Federal Energy Regulatory Commission Office of Hydropower Licensing.

Stillwater Sciences, 2009, Post-dam-removal Channel Complexity Monitoring Survey Data Analysis, Sandy River, Oregon, 1st Year Following Dam Removal. Technical Memorandum, prepared for Portland General Electric, January 27 2009, Barkley, CA.

Stillwater Sciences, 2008, Pre-dam-removal Channel Complexity Monitoring Survey Data Analysis, Sandy River, Oregon. Technical Memorandum, prepared for Portland General Electric, February 27 2008, Barkley, CA.

Stillwater Sciences, 2000a, Evaluation of Geomorphic Effects of Removal of Marmot and Little Sandy Dams and Potential Impacts on Anadromous Salmonids, Technical Report, prepared for Portland General Electric, Barkley, CA.

Stillwater Sciences, 2000b, Numerical Modeling of Sediment Transport in the Sandy River, OR Following Removal of Marmot Dam, Technical Report, prepared for Portland General Electric, Barkley, CA.

Stewart, G., 2003, unpublished survey data, Oregon State University.

Stewart, G., and Grant, G., 2005, Potential Geomorphic and Ecological Impacts of Marmot Dam Removal, Sandy River, OR, prepared for Portland General Electric.

Taylor, B., 1998, Salmon and Steelhead Runs and Related Events of the Sandy River Basin – A Historical Perspective, Report, prepared for Portland General Electric.

Walther, S., Marcus, W., Fonstad, M., 2009, Bathymetric mapping using remote sensing on the McKenzie River, Oregon, *EOS Trans. AGU* 90(52) Fall Meet. Suppl., Abstract H51A-0739

Watershed Sciences, 2006, LiDAR Remote Sensing Data Collection: Sandy River, Oregon, Submitted to: Portland General Electric: Portland, OR.

Watershed Sciences, 2008, LiDAR Remote Sensing Data Collection: Department of Geology and Mineral Industries, Oregon Department of Forestry, Puget Sound LiDAR Consortium. Submitted to: Puget Sound Regional Council.

Watershed Sciences, 2009, LiDAR and True-Color Orthophotographs, Airborne Data and Processing: Sandy River, Oregon, Submitted to: Stillwater Sciences, Berkeley, CA

Wolman, M.G, 1954. A Method of Sampling Coarse River-Bed Material, *Transactions, American Geophysical Union*, v. 35, no. 6, p. 951 – 956.