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LiDAR Assessment of Sediment Transport Related to the Removal of the Marmot Dam, Sandy River, Oregon

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LIDAR ASSESSMENT OF SEDIMENT TRANSPORT RELATED TO THE REMOVAL OF THE MARMOT DAM, SANDY RIVER, OREGON

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ABSTRACT

LIDAR ASSESSMENT OF SEDIMENT TRANSPORT RELATED TO THE REMOVAL OF THE MARMOT DAM, SANDY RIVER, OREGON

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Four Aerial LiDAR survey were used to examine the impacts of the 2007 removal of the Marmot Dam on the Sandy River, Oregon. Geomorphic Change Detection software was used to answer three project goals: 1) to investigate how the dam removal affected sediment distribution in the lower reach of the river, several km downstream of the dam, 2) to determine whether the pulse of sediment from the dam removal created a detectable, successive downstream accumulation of sediment through time, and 3) to assess the effect of natural high-flow events on the sediment distribution related to the dam removal. The results showed that a sediment pulse could be identified and tracked up to 13 km downstream from the former dam, but below that the pulse could not be detected from normal river processes. A majority of the sediment deposited from the dam release moved downstream as a result of high-flow events during winter months.

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CHAPTER I

INTRODUCTION

In the contiguous United States there are roughly 2.5 million dams, most of them major rivers (National Research Council, 1992; The Heiz Center, 2002), and 80% of them will be reaching their 50-year life expectancy in the coming decade (FEMA and USACE, 1996). Recent studies of dams have documented their negative impact on riverine systems such as starving downstream habitats of new sediment, and producing unnatural water temperatures and flows that can be detrimental to aquatic life (Williams and Wolman, 1984; Hunt, 1988; Graf, 1999, 2005, 2006; Schmidt and Wilcock, 2008; Walter and Merritts, 2008). Because few large dams have been removed to date, little is known about the effects to the river during and after a dam removal (Burroughs et al., 2009; Major et al., 2011). The major concern with large dam removals is the release of the impounded sediment, which can reach 10^1-10^6 m^3 (Heinz Center, 2002; Major et al., 2011).

The response of a river to a dam removal is commonly site-specific (Doyle et al. 2003), but there are some similarities. Impounded unconsolidated sand and finer sediment tends to undergo vertical erosion until the original bed surface is reached, at which point channel widening dominates (Burroughs et al. 2009; Doyle et al. 2003; Downs et al. 2009; Rumschlag and Peck 2007; Wildman et al. 2007). This process is similar to the evolution of the impounded sediment behind the former Marmot Dam on the Sandy River, Oregon (Major et al. 2011). Deposition of the released sand to gravel sized bedload sediment generally occurs within a few km from the dam (Burroughs et al. 2009, Doyle et al. 2003, Downs et al. 2009, Rumschlag and Peck 2007).

In October 2007 the Marmot Dam on the Sandy River, Oregon (Figure 1) was removed releasing 438,000 m^3 of the estimated 750,000 m^3 of impounded sediment into the river reach downstream of the dam (Major et al. 2011). Prior to and after the removal of this dam, a collaborative effort among multiple government and private agencies allowed for an unprecedented collection of data, including repeat total-station surveys of

Figure 1: Images of Marmot Dam before and after removal. A: Former Marmot Dam, photo taken in 2007 (photo courtesy of Portland General Electric). B: Site of the former Marmot Dam site in the foreground, looking upstream toward the emptied reservoir in the background (photo taken by Carl Matzek)

the channel geometry, suspended sediment and bedload transport during dam removal and the acquisition of five sets of high-resolution aerial LiDAR (Light Detection and Ranging) (O'Connor and Major, unpublished data, 2011). This variety of pre- and post-removal monitoring efforts substantially increased our direct observations of the overall impacts a dam removal could have on a river system of this type.

The current study used the repeated LiDAR surveys to quantify the depositional locations, volume and migration of the sediment by the dam removal, as well as to determine the general spatial and temporal patterns of sediment storage and erosion in the Sandy River, Oregon over this time period. Four sequential LiDAR data sets from 2007 - 2011 were analyzed: 1 before the dam removal and three after. The 2006 LiDAR survey was not used in this study because the Digital Elevation Model (DEM) had an unknown vertical scale that could not be corrected in time for the completion of the analysis. The three main goals of this research project were: 1) to investigate how the dam removal affected sediment distribution in the lower reach of the river, several km downstream of the dam, 2) to determine whether the pulse of sediment from the dam removal created a detectable, successive downstream accumulation of sediment through time, and 3) to assess the effect of natural high-flow events on the sediment distribution related to the dam removal. Each set of LiDAR images brackets high-flow events, including natural floods as well as the removal of the dam. The largest flood occurred in 2011 and was the 3rd largest peak discharge on record at 64,000 ft^3/sec (1,736 m^3/sec), (Figure 2). The investigation focused on sites where deposition or erosion

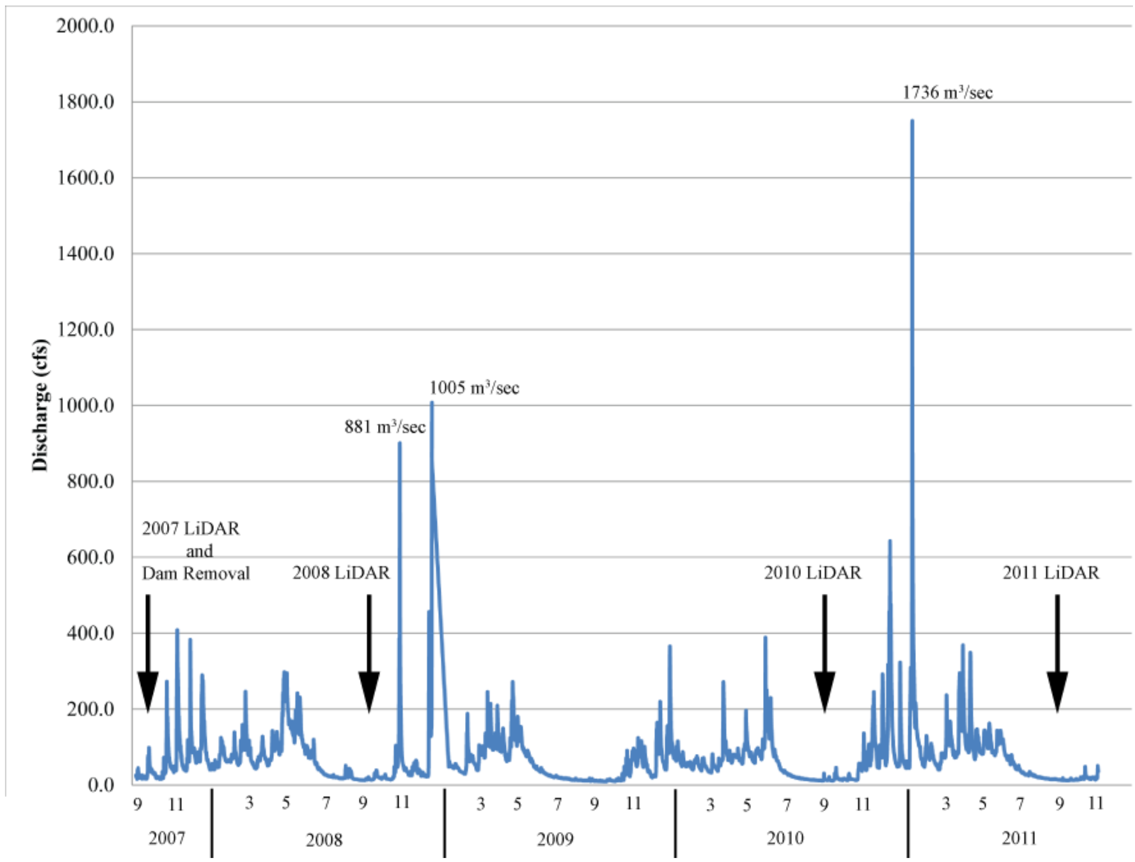

Figure 2: Timeline showing the annual peak hydrograph for the duration of the study (October 2007-October 2011). Arrows show dates of each of the 4 LiDAR survey acquisitions in relation to the peak flows during the study period.

typically occurs during high-flow conditions, such as reaches of decreasing slope, point bars and channel expansions.

Study Area

The Sandy River is a high-gradient river that heads on the western flank of Mt. Hood and flows into the Columbia River near Portland, Oregon (Figure 3), draining 1,300 km^2 (Major et al., 2011). A majority of the sand and gravel carried by the river originates near the base of Mt. Hood in Late Pleistocene to Holocene glacial deposits and volcanoclastic deposits (Crandell, 1980; Cameron and Pringle, 1986; Pirot et al., 2008; Pierson et al., 2011). Marmot Dam was located 52 km upstream from the Columbia River

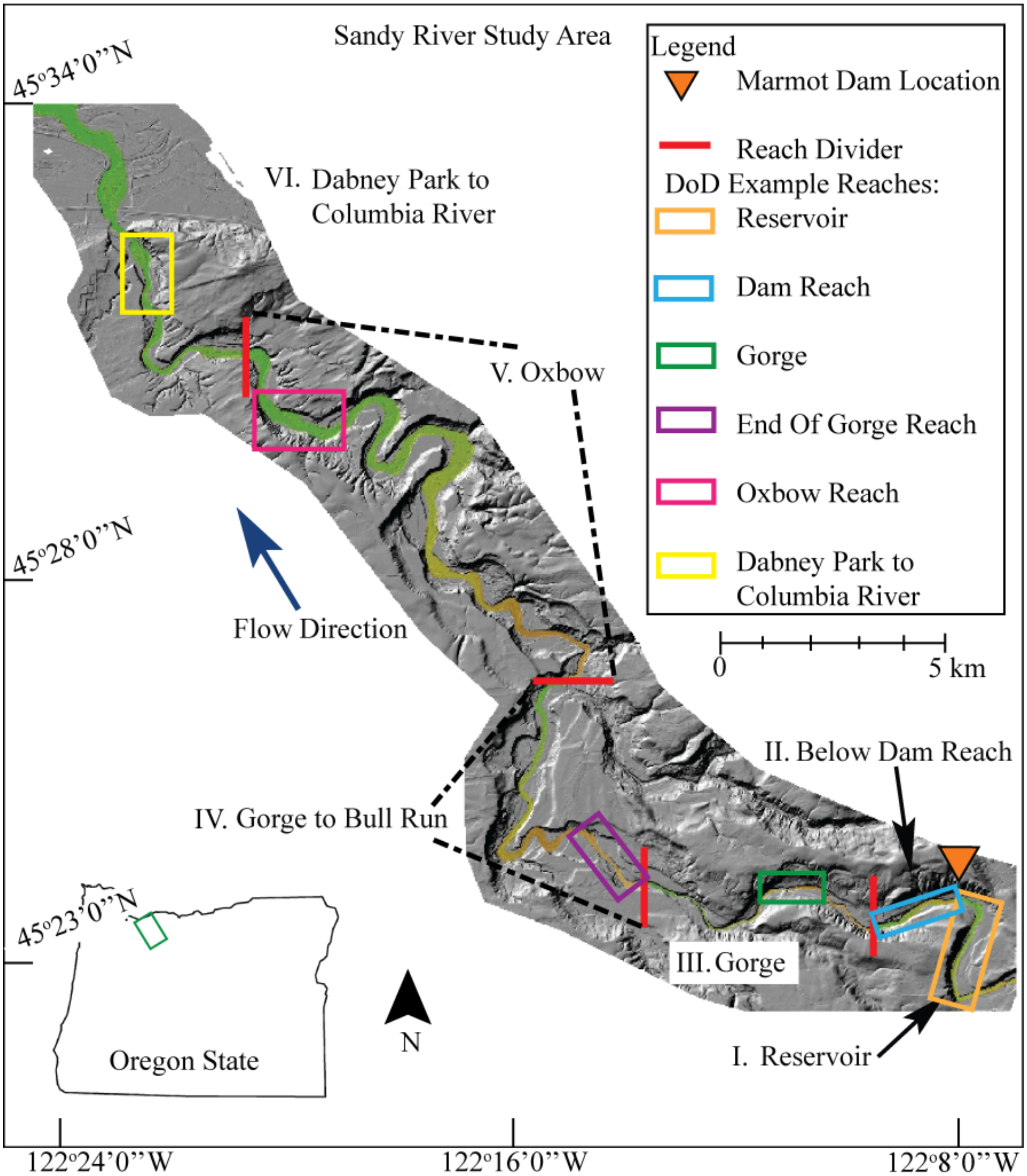

Figure 3: Map of the study area on the Sandy River in northern Oregon and the locations of the reach divisions used in the LiDAR analysis. The colored rectangles are locations of the DEM of Difference (DoD) example maps for each reach used in this paper.

confluence and stood 15 meters tall by 50 meters wide (Major et al. 2011). Sediment had filled the structure to nearly 14 meters allowing roughly 1 meter of standing water behind the dam (Major et al. 2011). This containment structure diverted water to a nearby river channel for use in generation of electrical power. Constructed in 1989 by Portland General Electric, the dam was structurally sound but in 2004 the operating license expired. Faced with the high cost of maintenance and upgrading the fish passage, Portland General Electric decided to demolish the dam and restore the river to its natural state. After the removal of Marmot Dam, water within the basin flowed freely from the headwaters to the mouth of the river for the first time in over 100 years (Major et al. 2011).

CHAPTER II

METHODS

This project used high-resolution aerial LiDAR to study the effects of the removal of the Marmot Dam on the Sandy River. Even though there are countless LiDAR datasets in existence, using it exclusively for a comprehensive analysis of sediment transport in a river is still an emerging practice (Brasington et al. 2003; Notebaert et al. 2009; Wheaton et al. 2010). This investigation built on a method developed by Wheaton and others (Brasington et al. 2003; Notebaert et al. 2009; Wheaton et al. 2009; Wheaton et al. 2010; Milan et al. 2011) and applied it to a full-length river analysis. The Geomorphic Change Detection software (Wheaton et al. 2010) was coupled with ArcGIS to quantify the sediment erosion and deposition shown on the LiDAR-derived DEM.

LiDAR involves the projection, reflection and collection of many laser beams to measure distances between the laser and the target surface. It is becoming a commonly used method for collecting high-resolution geomorphic information. To document changes related to the Marmot Dam removal, Watershed Sciences, an aerial LiDAR company based in Corvallis, Oregon, was commissioned to acquire the LiDAR surveys from 2006 to 2011. The LiDAR flights took place within the last week of September and the first week of October when the river was at low flow levels and the greatest amount of land surface was exposed above the water level. Watershed Sciences did all the post-processing of the point clouds and produced 1-meter DEMs for this project.

The 52 km of river channel covered by the LiDAR surveys was separated into 6 separate divisions for analysis: Reservoir, Below Dam, Gorge, Gorge to Bull Run, Oxbow, and Dabney Park to Columbia River (Figure 3). Local changes were initially documented within each reach and then tied into the entire study area of the river. The divisions were based on locations where the longitudinal slope changed and variations in bedform characteristics were reported in Major et al. (2011). Polygon layers for the Sandy River floodplain were created with ESRI ArcGIS© software and extracted from the DEM to process only those areas affected by the river processes.

Geomorphic Change Detection (GCD) software (v.5) was used to quantify the change in volume for each set of DEMs, and is a free add-on for ArcGIS 10 designed by Dr. Joe Wheaton, North Arrow Research, and ESSA Technologies. GCD is used to calculate the volume change between two different repeat topographic surveys to create a DEM of Difference (DoD) (Wheaton, 2010). The program is primarily designed to help address the uncertainty found in all digital elevation models by identifying possible locations of error and propagating those errors through the differencing. Accounting for the uncertainty with a survey-specific error variable allows the user to determine whether low-magnitude change is real change versus noise in the signal; one way to do this is to build an error model for the survey or project.

An error model was built for the dam reach and part of the reach below the gorge to better understand potential sediment transport or storage in the reaches closest to the former dam site. To apply the error model, each DEM was loaded into GCD as a multi-method survey to allow a mask to be superimposed on the DEM with specific error values. The error mask was created in ArcGIS as a multi-category polygon layer in which each category was assigned an error value related to the type of surface it was during the time of LiDAR acquisition (Figure 4). Three surface categories were used: 1) Bare land

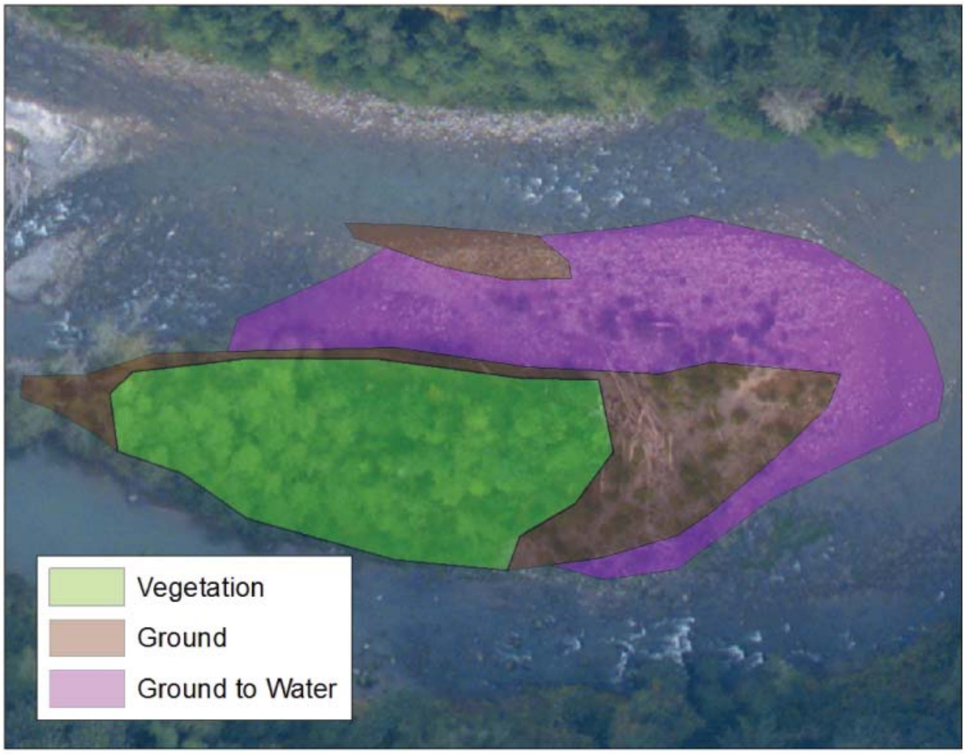

Figure 4: Example of the error model applied to a sediment bar. Each shaded polygon was assigned a specific vertical error uncertainty used for the error propagation model in GCD. Error values were based on project reports provided by Watershed Sciences.

in both surveys, 2) Land-to-water or water-to-land transition between surveys, and 3) heavily-vegetated surfaces. For each of the three categories an error value was assigned to each survey dataset based on reported bare surface and vegetated errors given in each of the final project reports (Watershed Sciences 2007, 2008, 2010, 2011). Each of the three error categories were merged into one error mask and applied to its respective DEM, which were then differenced.

DEM of difference (DoD) maps were created for all six river sections (Figure 3) using DEM pairings of the years 2008-2007, 2010-2008, and 2011-2010 to cover the entire study period. Each time step was differenced to track any possible progressive downstream changes that could be related to the dam removal. DoD maps were also created from the 2011-2008 and 2011-2007 pairs. The 2011-2008 DoD compares the surface elevations for the entire post-dam removal period, from one year after the dam removal to the last LiDAR survey and the 2011-2007 DoD pair spans the entire study period, from before the dam removal to most recent survey.

During the acquisition of the LiDAR in 2007 and 2010 the river discharge was higher than 2008 and 2011 producing a higher water surface (Table 1). The higher

Table 1: Discharge and Stage Data

Year	Discharge (ft)	Discharge (m)	Stage Height (m)	Stage Height Difference (m)
2007	832	23.6	2.57	0.15
2008	488	13.8	2.42	
2010	523	14.8	2.46	0.04
2011	484	13.7	2.44	0.02

Table 1. Discharge and Stage data from gaging station 14142500 on the Sandy River at the confluence of the Bull Run River. The stage height differences are all normalized to the water-surface elevation in 2008. This normalization was done to reduce the influence of the different water-surface elevations on the calculations of the volume of sediment erosion and deposition based on changes in surface elevations.

discharge and water-surface elevation during the 2007 and 2010 LiDAR surveys falsely exaggerated the calculated amounts of erosion and deposition within the channel. The ability to address the variation in stage and discharge of the water in the multiple surveys was a major concern in determining the accuracy of the DoD volume estimates. To lessen the effect of the added water height, the two higher stages (2007 and 2010) were normalized to the similar 2008 levels.

The stage and discharge readings from the USGS gauging station 14142500 at the confluence of the Bull Run River located at the boundary of the Gorge to Bull Run Reach and the Oxbow Reach (Figure 3) at the time of LiDAR acquisition were used to determine the difference in water-surface elevations among the years. The length of each reach and average width of the wetted channel were multiplied to calculate the surface area of the water, and the difference in the heights of the discharges of the pair was multiplied to get a volume of water. The calculated volume was then either subtracted or added to the erosion or deposition value depending on the DoD pairing. For the 2010-2008 pairing the higher stage in 2010 (Table 1) produces a greater deposition than actually happened; the deposition value was normalized. The discharge for 2008 and 2011 were within 4 cfs (0.11 m^3/sec) of each other should not support a 2 cm rise in the water surface (Table 1) but were normalized to keep everything standard.

The calculated changes in sediment volume based on the LiDAR with the normalized water-surface stage for the dam reach were compared with the sediment volumes calculated from total-station surveys by Major and others (2011) for the same reach and time period. The calculated sediment volumes using the two methods were within ~5% percent of each other, lending confidence to the application of the stage-normalization method to the DoD calculations for the downstream reaches with similar channel characteristics and flow dynamics.

The LiDAR reflects off the river-water surface and does not reveal the subaqueous channel bathymetry. To determine whether the water surface was the major determining factor for a positive or negative net change in sediment volume, a second set of DoD calculations for the Below Dam Reach and the upstream 2 km of the Below Gorge reach were created using only the subaerially exposed sediment bars and river banks that were above the water surface when the LiDAR was acquired. The surfaces used included all possible areas affected by high-flow events. The above water surface DoDs were also created to closely monitor the growth and development of sediment bars and to produce accurate estimates of the volume of sediment storage and transport through these two reaches. Polygon layers were created for each survey pair (2008-2007) and then were extracted from the full-channel DEMs already created. These subaerial polygons were only created for the Below Dam Reach and the first 2 km downstream from the gorge in the Gorge to Bull Run Reach (Figure 3). The subaerial DoDs for these two reaches matched the patterns of net deposition or erosion produced by the full-channel calculations, but with a slightly smaller volume of change because the river bed was excluded. The normalized net volume estimates might still be exaggerated slightly by the water surface, but this method serves as a first-order adjustment to more accurately estimate the volume of change. The results for the dam reach were then compared with total-station ground surveys and sediment budgets completed between 2007 and 2009 (Major et al. 2011, Podalak 2011) to calibrate and evaluate the effectiveness of the GCD program and error models.

CHAPTER III

RESULTS

The previously mentioned normalized volume calculations will be used throughout the remainder of the thesis unless a normalized value was not applicable. Refer to Table 2 for all calculated values both, raw and normalized. High resolution DoD images for the entire Sandy River study area can be found in the Appendix.

Reach I: The Reservoir

Initial erosion within the reservoir reach occurred during the breaching of the dam in October 2007. Results of a total station survey concluded that, during the initial dam breach, an estimated 125,000 m^3 was eroded in 60 hours as the river carved into the impounded sediment, widening to the full reservoir width and migrating upstream ½ km from the dam (Major et al. 2011). During the next 12 months, the knick point migrated upstream 2 km (Figure 5) and eroded farther into the sediment bringing the total to nearly 474,000 m^3 (Table 2). The next span of time (2010-2008) bracketed two high flow events (Figure 2). The DoD for this period shows a net sediment gain of ~32,000 m^3, with erosion occurring as well (Table 2). This calculation does not coincide with the net loss of 43,000 m^3 presented in Major et al. (2011). The final time interval (2011-2010) bracketed a large the large flow in 2011 (Figure 2). The entire reservoir experienced a net erosion of 285,000 m^3 during this 1-year period. Near the dam site, the main channel occupied a new location along the eastern bank of the bedrock-confined valley; previous channels had occupied the center of the valley with only secondary branches reaching the eastern wall (Figure 5).

Table 2: DoD Summary For All Reaches Of Study Area
* Values in thousands of meters *

Reach Number		I	II	III	IV	V	VI
Reach Name		Reservoir	Below Dam	Gorge	Gorge to Bull Run	Oxbow	Dabney Park to Columbia
2008-2007	Erosion	491	24	117	96	607	374
	Normalized	474	16	94	45	461	282
	Deposition	54	126	51	94	219	199
	Net	-420	110	-43	49	-242	-83
2010-2008	Erosion	159	27	43	109	473	202
	Deposition	196	168	397	465	1,092	677
	Normalized	191	166	391	451	1,053	653
	Net	**32**	**139**	**348**	**342**	**580**	**451**
2011-2010	Erosion	367	176	389	453	1,156	661
	Normalized	362	173	383	439	1,117	637
	Deposition	76	27	52	111	474	285
	Net	**-286**	**-146**	**-331**	**-328**	**-643**	**-352**
2011-2008	Erosion	329	56	74	185	826	404
	Deposition	76	49	91	199	762	544
	Normalized	74	48	88	192	742	531
	Net	**-255**	**-8**	**14**	**7**	**-84**	**127**
2011-2007	Erosion	756	19	34	197	1,054	520
	Normalized	755	18	31	190	1,035	508
	Deposition	68	112	129	208	602	485
	Net	**-687**	**94**	**98**	**18**	**-433**	**-23**

Note. DoD summary for all reaches of the Sandy River and all the DoD year pairings. Net losses are highlighted in red and net gains are in blue. Shaded rows are normalized to the 2008 and 2011 discharge and height of the water level.

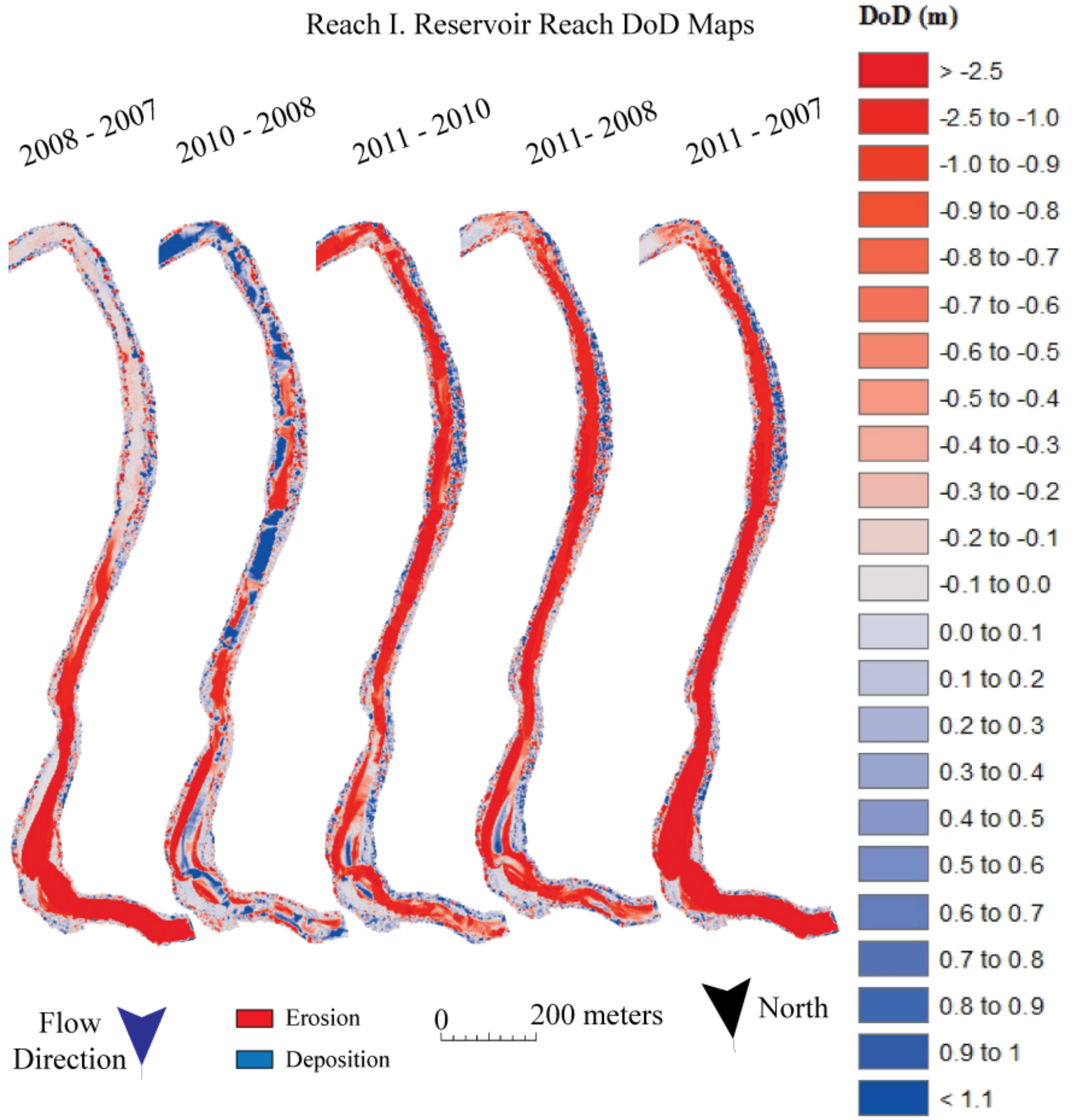

Figure 5: DoD maps for the former reservoir reach located behind the former Marmot Dam showing the change in vertical elevation of the ground surface between LiDAR surveys. Some of the apparent change within the channel is due to higher water levels in 2007 and 2010; values were resolved in data table 2.

The cumulative post-dam-removal DoD from 2011-2008 and the DoD from the entire study period of 2011-2007 both show a net loss of sediment from the reservoir: 253,000 m^3 and 690,000 m^3 respectively through the end of the study period.

Reach II: Below the Dam

The 2 km reach directly below the Marmot dam extends to the head of the bedrock gorge and was the primary site for sediment deposition related to the dam removal. Within the first year after dam removal (2008-2007), the LiDAR showed a deposition of 110,000 m^3 of sediment. The sediment deposition created a large sediment wedge 4 meters high at the dam site that pinches out roughly 1.5 km downstream (Major et al. 2011). In this reach most of the valley floor was raised from the outwash of sediment from the dam (Figure 6). Multiple large sediment bars were created immediately downstream of the dam during the breach and remained above the water surface during the subsequent LiDAR surveys (Figure 6). Sediment deposition covered the upper surfaces and sides of several existing bars farther downstream toward the entrance to the gorge. In the 2010-2008 DoD the reach experienced a net gain of ~140,000 m^3 (Table 2), with deposition occurring mainly on bars farther downstream and in the channel bottom. The sediment bar on the upper end of the sediment wedge had started to erode but still remained above the low-flow water surface. In the 2011-2010 DoD there was deposition on bars throughout the 2 km reach, but overall a net loss of 147,000 m^3 occurred. Based on the DoD volume calculations there was a net gain of 102,000 m^3 of sediment that still remained in the reach at the end of the study period, four years after the dam was removed (Table 2).

Using the categorized error model described earlier in the methods (Figure 4), the banks and sediment bars were analyzed without the water surface to quantify the amount of sediment deposited above the low-flow water surface (Figure 7) and compare the volumes and patterns of sediment erosion and deposition with the results from the full channel DoD (Figure 6). The sediment bar and full channel DoDs showed the same pattern of net gain or net loss for each year pairing, but the volumes were different (Table 2 and 3). The sediment bar DoD spanning the dam removal (2008-2007) only recorded a net gain of 55,000 m^3 (Table 2) compared to the 110,000 m^3 (Table 3) calculated with the full channel DoD and 105,000 m^3 by Major and others (2011). In the following years, the volume estimates for the sediment bars DoD (Figure 7) were much lower, only accounting for ~20,000 m^3 of deposition and erosion (Table 3).

Reach III: The Gorge Reach

The 8 km long bedrock gorge was thought to have experienced little deposition from the dam breach (Major et al. 2011) due to the higher flow velocity and virtually no river banks on which sediment could accumulate, but no field evidence could be collected to support the idea. During the dam breach, very little difference in suspended sediment was measured upstream and downstream of the gorge (Major et al. 2011). The cumulative post-dam period, 2008-2011, shows a net gain of 14,000 m^3 of sediment.

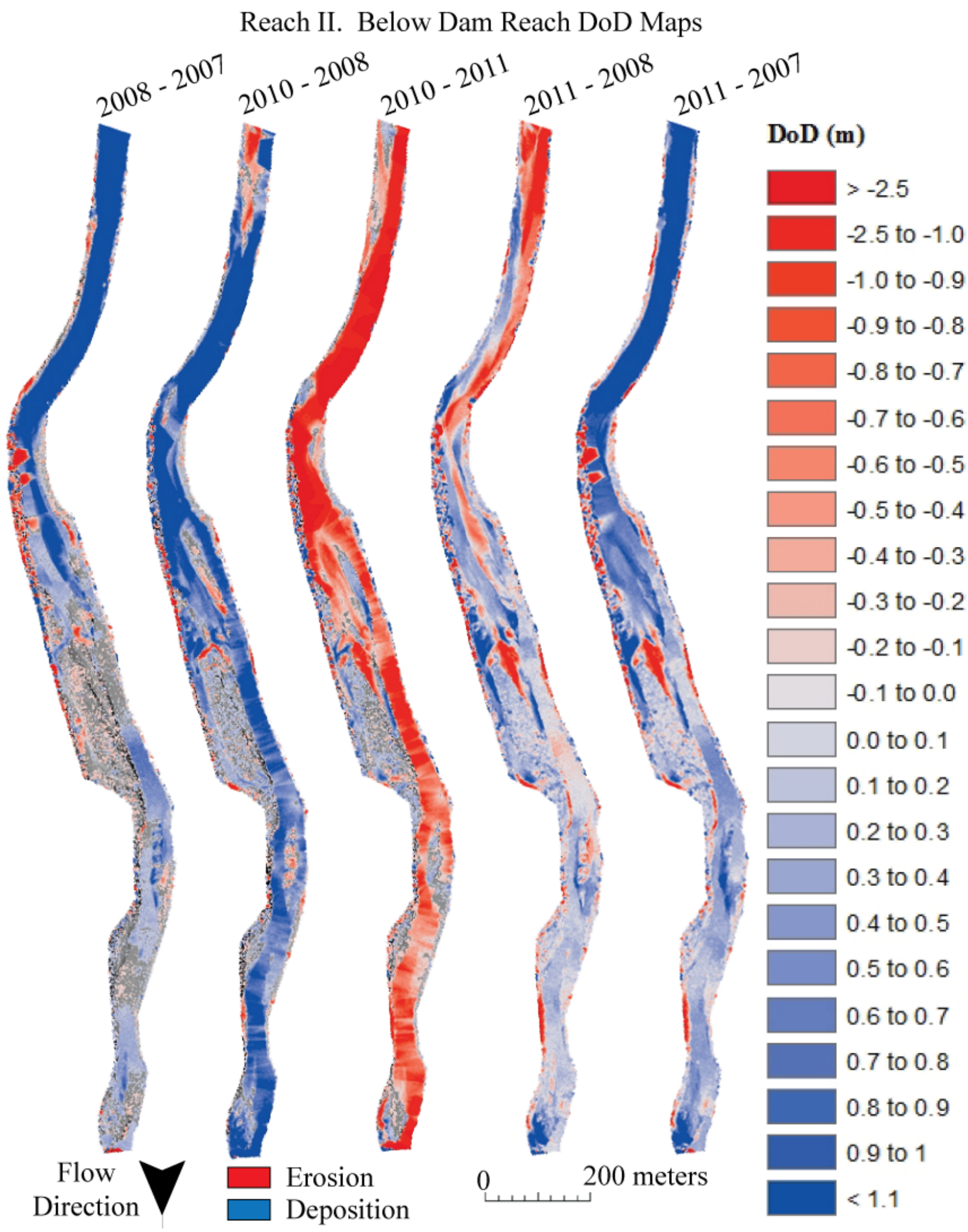

Figure 6: DoD maps for the 2 km Below Dam reach directly below the former Marmot Dam showing the change in vertical elevation of the ground surface between LiDAR surveys. Large volumes of deposition from the dam removal are visible within the reach. Some of the apparent change within the channel is due to higher water levels in 2007 and 2010; values were resolved in Table 2.

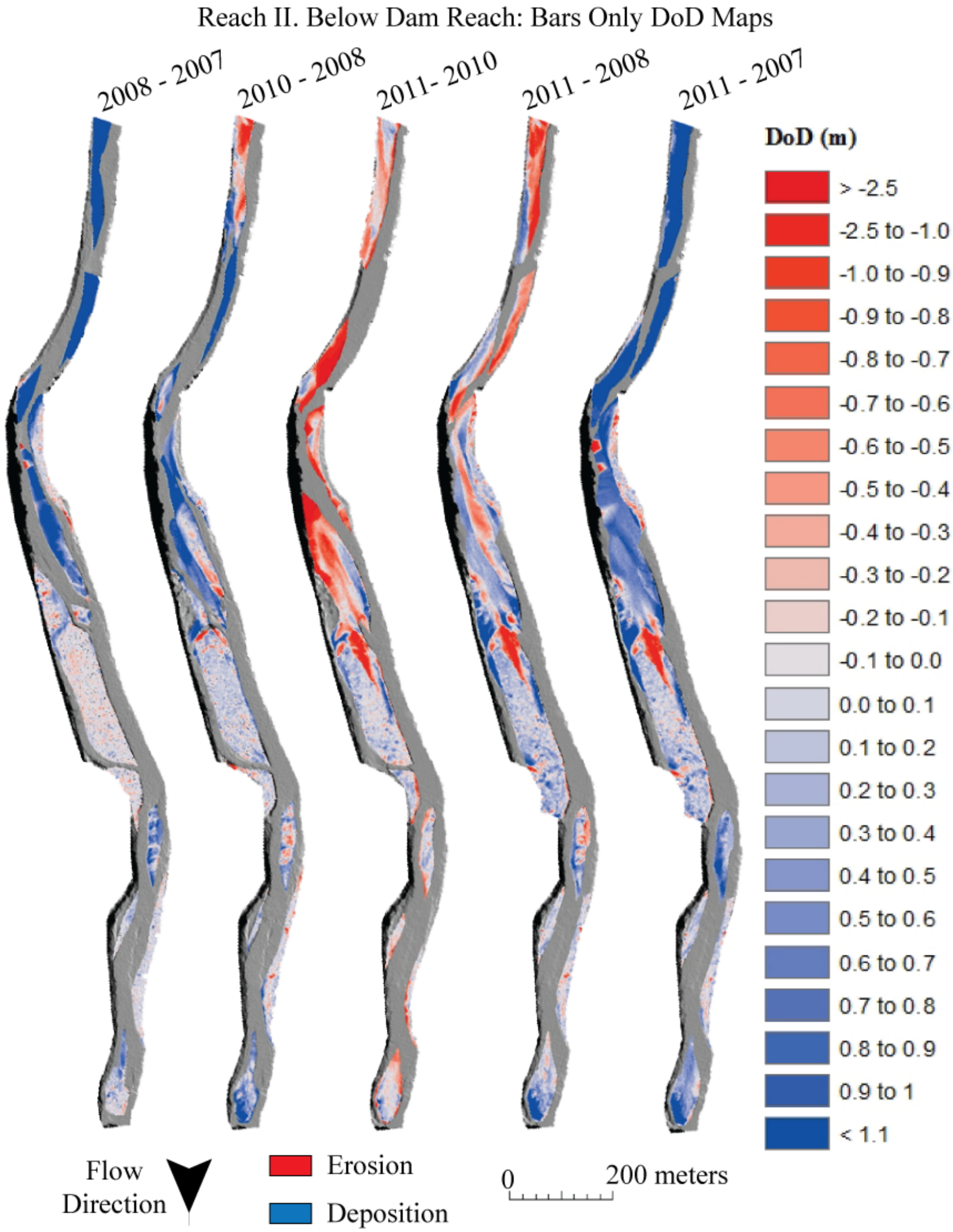

Figure 7: DoD maps for the sediment bars within the 2 km Below Dam Reach. The water surface was removed and the remaining surfaces were differenced to examine how much of the change occurred above the water surface, and to determine how much the water surface influenced the volume estimates.

Table 3: DoD Summary for Sediment Bars Only
* Values in thousands of meters *

Below Dam Bars					
DEM Pair	2008-2007	2010-2008	2011-2010	2011-2008	2011-2007
Erosion	3 ±1	9 ±3	31 ±6	20 ±5	6 ±2
Depostion	58 ±26	30 ±7	6 ±1	20 ±4	73 ±29
Net	**55 ±24**	**21 ±5**	**-25 ±5**	**0 ±1**	**67 ±27**
End of Gorge Bars					
DEM Pair	2008-2007	2010-2008	2011-2010	2011-2008	2011-2007
Erosion	2 ±1	3 ±1	7 ±1	5 ±1	6 ±2
Depostion	2 ±1	10 ±2	8 ±1	8 ±2	14 ±6
Net	**0 ±1**	**7 ±2**	**1 ±1**	**3 ±1**	**8 ±3**

Note. DoD summary of sediment bars and banks within the Below Dam Reach and the Gorge to Bull Run Reach using the categorized error model. These surfaces were above the water level during each LiDAR survey.

Based on inspection of the DoD and aerial photographs most of the deposition appears to be located near large boulders and sharp bends in the channel. According to the DoD calculations where a high water surface was included (2008-2007, 2010-2008, 2011-2010) a majority of the change occurred only in the channel and might be a result of the channel geometry combined with higher flow, not actual deposition or erosion.

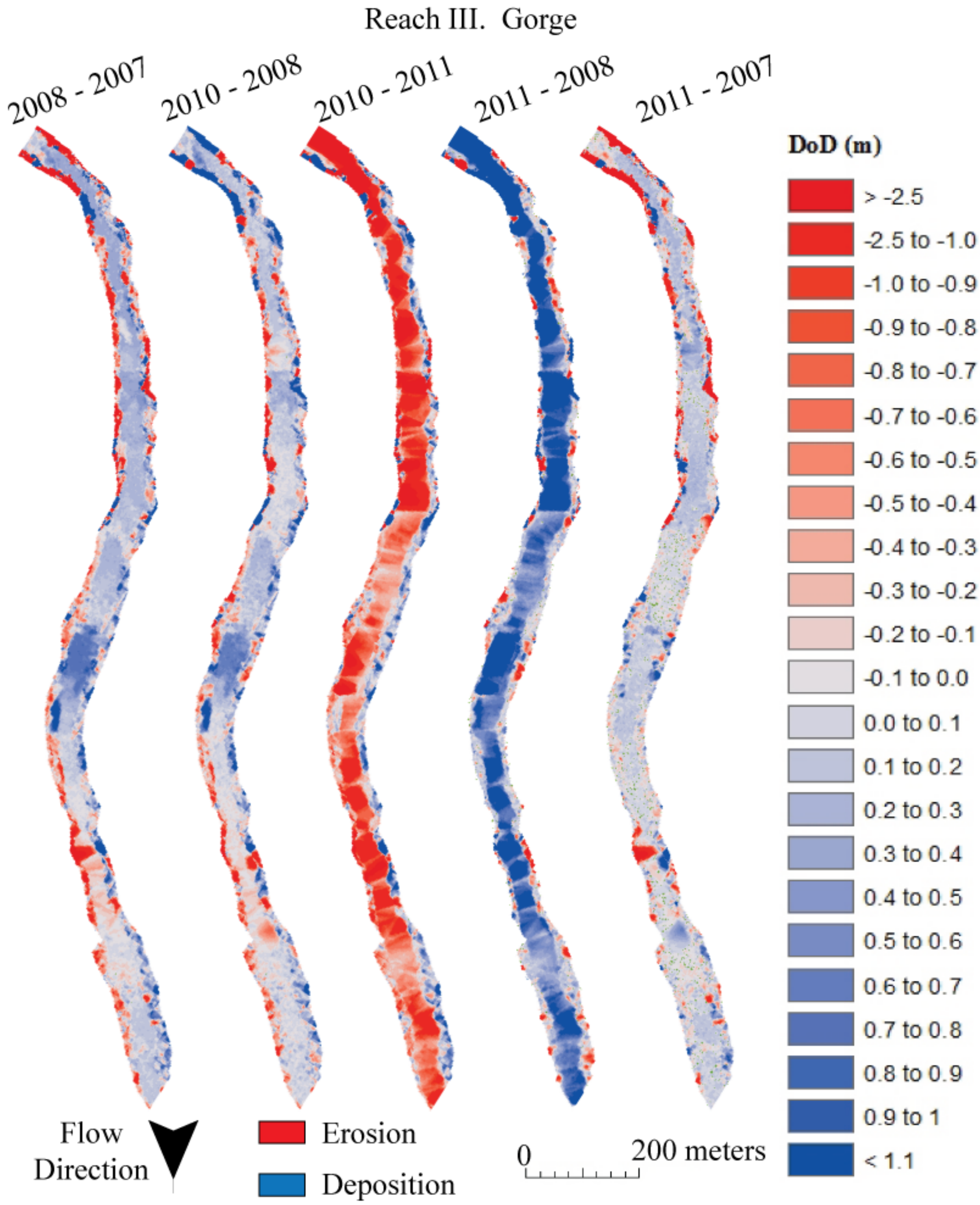

Figure 8: DoD maps of the full channel for a portion of the Gorge Reach showing the deposition and erosion within the Gorge. Some of the apparent change within the channel is due to higher water level in 2007 and 2010; values were resolved in data Table 2.

Reach IV: Gorge to Bull Run River

Below the Gorge to the confluence of the Bull Run River is a 9.5-km alluvial reach that was considered a possible location for sediment deposition from the dam removal (Major et al. 2011). During the 2008-2007 period spanning the dam removal, there was no major change apparent in the DoD (Figure 9; Table 2). The DoD for 2010-2008 showed a net increase of 355,000 m^3 in sediment volume (Table 2), some of which might be due to the higher water surface in 2010. A visibly significant amount of sediment was deposited on the tops and banks of the initial sediment bars downstream from the gorge, in some cases creating completely new sediment bars (Figure 9). Further downstream, there was minor deposition on a few bars and along the insides of meander bends with accompanied erosion on the outer bank of the bends and along some sediment bars (Appendix IV). During the 2011-2010 DoD, there was an overall loss of sediment to the reach, but some bars experienced substantial deposition on the downstream ends. Most notably, the bars immediately downstream of the gorge showed continued deposition and some grew together to form a single large bar. The post-dam period (2011-2008) had fairly balanced erosion and deposition throughout the reach, but ultimately, had a net deposition of 14,000 m^3. The entire study period (2011-2007) showed a net gain of 11,000 m^3, with most of the deposition occurring on a few major bars, including those at the mouth of the gorge (Figure 9).

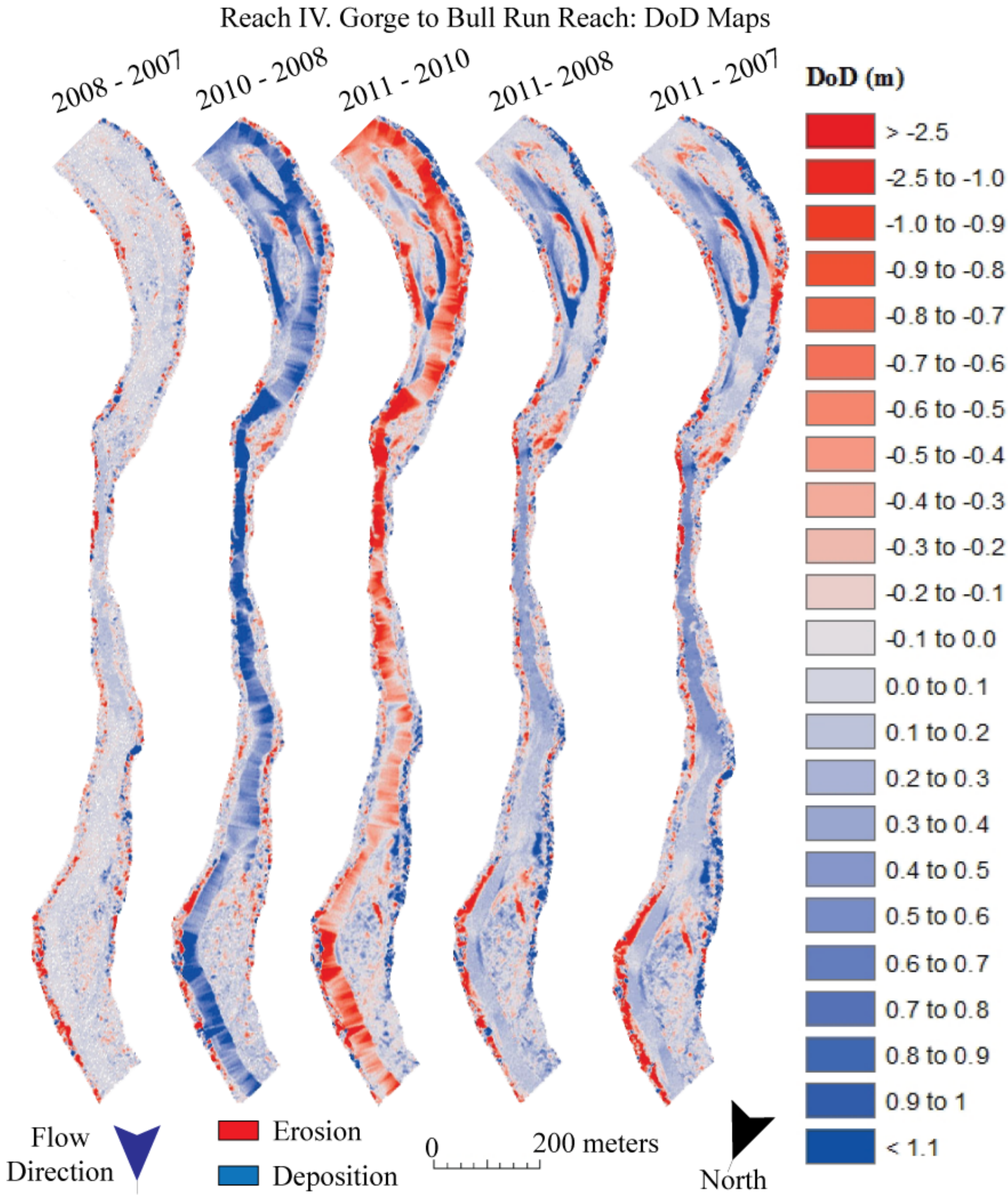

Figure 9: DoD maps of the full channel for the first 2 km of the Gorge to Bull Run Reach showing the deposition on sediment bars near the mouth of the gorge that is evidence for a sediment pulse coming from the former Marmot Dam removal. Some of the apparent change within the channel is due to higher water level in 2007 and 2010; values were resolved in data Table 2.

In this reach, the subaerially exposed bars and banks in the 2 km sub-reach immediately downstream of the gorge where the most change occurred were analyzed separately using the categorized error model explained in the methods (Figure 4). Between 2007 and 2008, these areas had a negligible net loss of 179 m^3, but during the next few years sediment started to enter the reach (Figure 10). The 2008-2010 DoD showed a deposition of 10,300 m^3 (Table 3), but due to some erosion, had a net gain of 7,500 m^3 (Figure 10). Over the next set of years (2010-2011), another 8,200 m^3 was deposited on the bars but the effects of the large flood in 2011 also eroded some previously deposited sediment resulting in a net gain of 1,300 m^3 (Figure 10). The result was a gross gain of ~18,500 m^3 since 2008 and a net gain of 8,880 m^3 (Table 3).

Reach V: Oxbow

The 19-km Oxbow Reach starts at the confluence of the Bull Run River and ends just upstream of Dabney Park (Figure 3). The reach shown in Figure 11 is a representative sample of what occurred within the entire Oxbow Reach and is located roughly 17 km downstream from the start of the reach (Figure 3). From 2007-2008, this reach experienced a net loss of 242,000 m^3 of sediment (Table 2), but only a few bars changed by a noticeable amount (Figure 11). There was some bank erosion in a straight section (Figure 11) with some deposition occurring on downstream ends of bars. In the 2010-2008 DoD, there was an overwhelming depositional signal, most of the deposition was coming from the channel, but there were many bars and banks that were covered in new sediment. Bank erosion was prevalent in the sharp bends followed by high amounts of deposition downstream or on opposite sides of the channel (Figure 11).

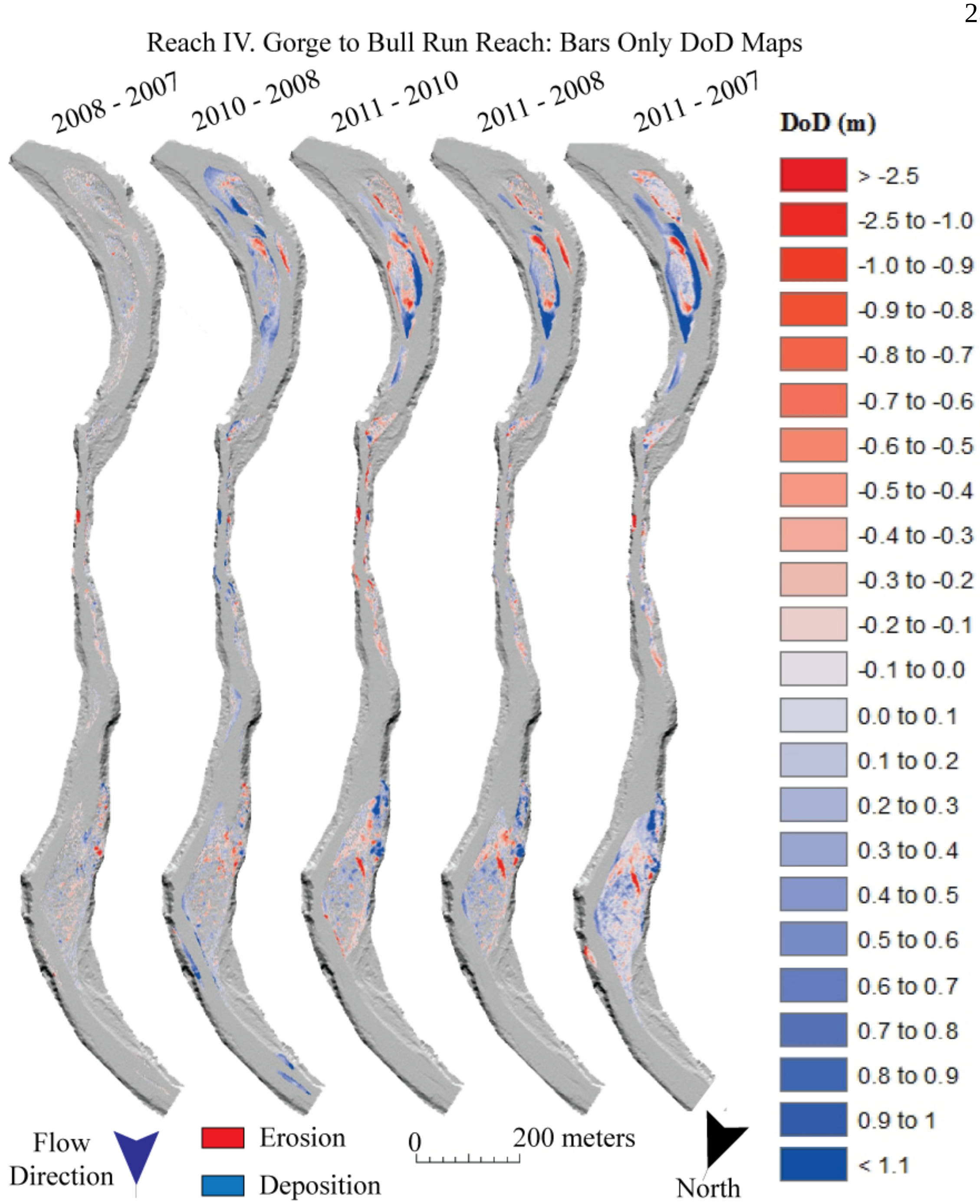

Figure 10: DoD maps for the first 2 km of the Gorge to Bull Run Reach with the water surface removed to more easily show the sediment deposition on the bars immediately downstream from the gorge that is attributed to the sediment pulse from the Marmot Dam removal.

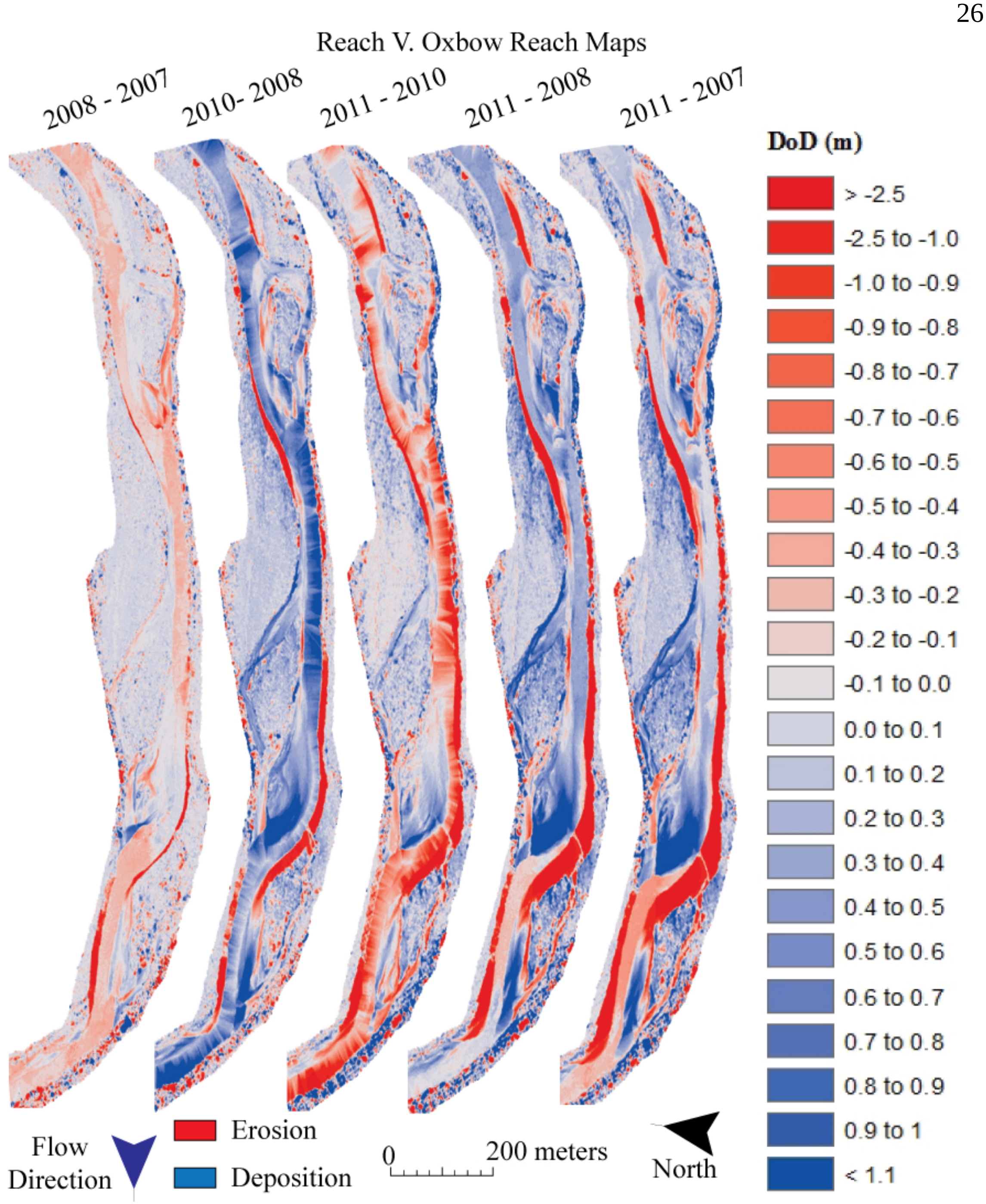

Figure 11: DoD maps for a 2.5 km section of the Oxbow Reach. The DoD depicts erosion and deposition throughout the reach during the study period, with no discernible downstream migration of a pulse of sediment following the Marmot Dam removal. Some of the apparent change within the channel is due to higher water levels in 2007 and 2010; values were resolved in Table 2.

Following the high-flow event in January of 2011 the 2011-2010 DoD has a strong erosional signal with a net loss of 643,000 m^3 (Table 2). There was considerable cut bank erosion on most bends in the reach, most notably in the straight section shown in Figure 11. The locations of erosion and deposition are most clearly illustrated on the two cumulative DoDs (2011-2008 and 2011-2007). The entire channel has migrated a full channel width in the meander near the downstream end of the reach (Figure 11) during the study period. There is no discernible, systematic downstream migration of a sediment pulse through this reach following the dam removal.

Reach VI: Dabney Park to the Columbia River

The remaining 10 km of the Sandy River from Dabney Park to the Columbia River is the lowest-gradient reach of the study area (Figure 3) and the only reach with a predominantly sand-bed channel. The DoD spanning the time of the dam removal (2008-2007) showed a net loss of sediment, the majority of which occurred on a few cut banks and some in the delta before the Columbia River (Figure 12). Scattered erosion and deposition also occurred on some of the major bars. In the subsequent 2010-2008 DoD, most of the sediment bars experienced deposition, while erosion was common along both the inner and outer banks at river bends (Figure 12). During 2011-2010, deposition continued on most of the sediment bars, even though the DoD showed an overall net loss. The cumulative post-dam DoDs (2011-2008) indicate a net gain of sediment after normalizing for the water-surface elevation (Table 2) but the cumulative study period shows a net loss of sediment (Table 2).

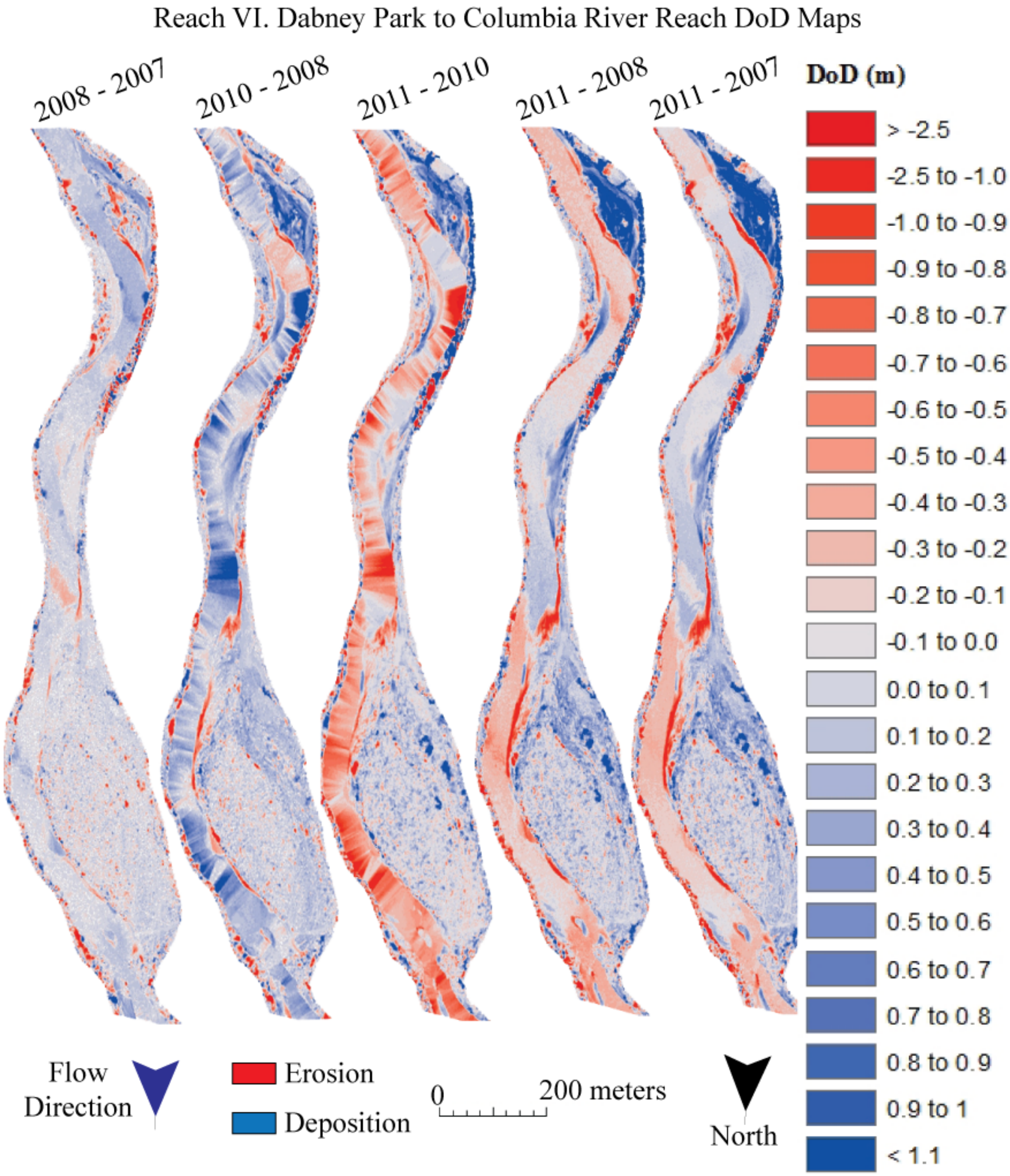

Figure 12: DoD maps for a 2-km section of the Dabney Park to Columbia River reach, the final reach of the Sandy River before it enters the Columbia River. In this reach there was consistent deposition during the study period (2007-2011), but no observed pulse of sediment moving through the reach. Some of the apparent change within the channel is due to higher water levels in 2007 and 2010; values were resolved in Table 2.

Cumulative deposition over the study period occurred on a majority of the large sediment bars and along some sections of the river bank.

Summary of Results

The gross erosion, deposition and net change during each DoD pairing is graphically represented in Figures 12 and 13 using the normalized sediment volumes (Table 2) where applicable. The bar graph can be used to compare the mean vertical change among the channel reaches. For example, the sediment deposition in the Below Dam Reach II was roughly 30% that in the Oxbow Reach V (Table 2), but when these volumes were spread over the length of the reach, the vertical change was much greater in the shorter Below Dam Reach II (Figures 12 & 13).

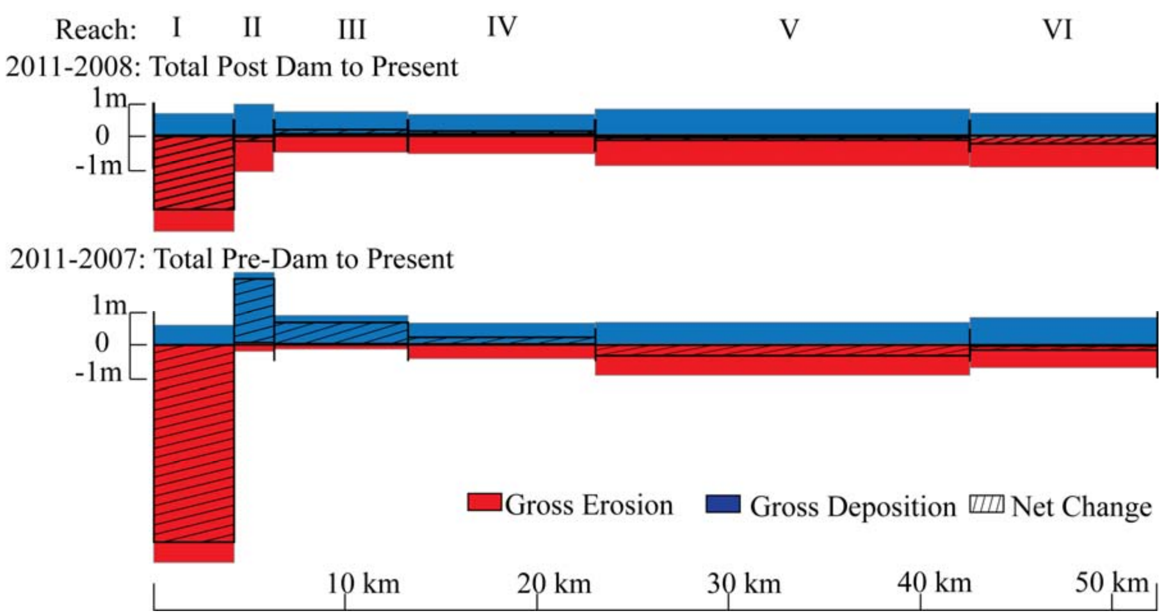

Figure 13: Gross deposition, erosion and net change of each DEM pair during incremental time periods for the Sandy River from the former Marmot Dam Reservoir to the Columbia River. The volumes of sediment from Table 2 (normalized where applicable) were divided by the length and average width of the channel in each reach to show the average vertical change in each section. Reach Labels: I. Reservoir, II. Below Dam, III. Gorge, IV. Gorge to Bull Run, V. Oxbow, VI. Dabney Park to Columbia River.

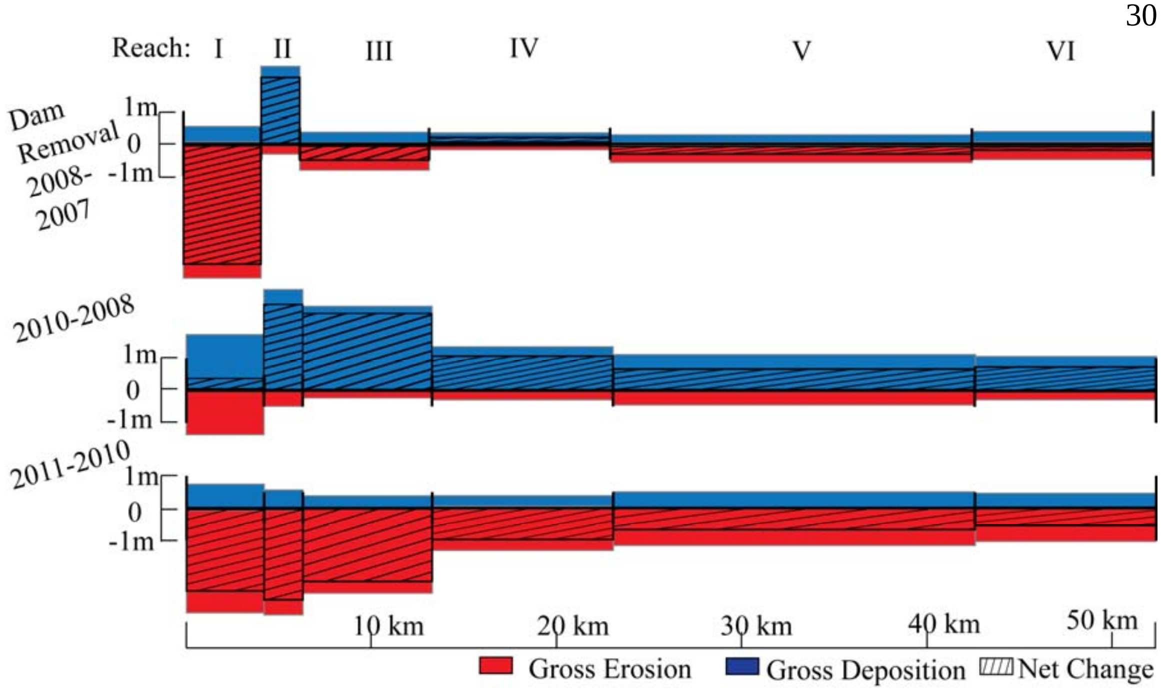

Figure 14: Cumulative gross deposition, erosion and net change for the total post-dam period (2008-2011) and the entire study period (2007-2011) for the Sandy River from the former Marmot Dam Reservoir to the Columbia River. The volumes of sediment from Table 2 (normalized where applicable) were divided by the length and average width of the channel in each reach to show the average vertical change in each section Reach Labels: I. Reservoir, II. Below Dam, III. Gorge, IV. Gorge to Bull Run, V. Oxbow, VI. Dabney Park to Columbia River.

CHAPTER IV

DISCUSSION

Reach I: The Reservoir Reach

Incision of the reservoir progressed rapidly after the breach of the coffer-dam: within 60 hours over 125,000 m^3 of sediment was removed, within 2 months 40% of the sediment in the reservoir was evacuated, and after 2 years nearly 60% of the total reservoir (425,000 m^3) was eroded (Major et al. 2011). Since 2009, two particularly high discharge events occurred during December and January in 2010 and 2011, resulting in more erosion within the former reservoir. The channel continued to widen and incise throughout the entire 3 km reach from 2007 to 2011, which is apparent by the lowering of the channel itself (Figure 5).

The DoD pair of 2010-2008 produced a net gain of sediment, even though the downstream half of the reservoir experienced predominantly erosion. The deposition occurred on some bars in the upstream portion and two near the end of the reach. The apparent net gain could have occurred when the channel migrated eastward within the bedrock-confined valley, resulting in a large volume of sediment deposited within the former channel after the reservoir pool drained.

The only incremental time period that showed a net increase in elevation and sediment volume in the Reservoir Reach was 2008-2010. The rise in surface elevations over this period was probably partly due to the higher discharge and water-surface elevation during the 2010 LiDAR survey (Table 1). The apparent depositional volume produced by an average 4-cm stage increase (Table 1) across the water surface was subtracted from the 2010-2008 sediment-volume change, but this normalization might not have accounted for the entire effect of the higher water stage. Based on field observations and LiDAR assessment there still appears to be remaining sediment from the former dam within the channel that could be mobilized. The large flood in January of 2011 (64,000 cfs, 1,736 m^3/sec, Figure 2) was the most erosive period within the reservoir since the initial draining of the reservoir. During the high flow event between the 2010 and 2011 LiDAR surveys the channel incised 1 to > 2.5 meters into the existing channel bottom throughout the entire 3 km reach. Even taking into account the minimum 2 cm height difference of the water surface between the two surveys there was considerable incision during the 2011 flood event.

Reach II: Below Dam Reach

The 2 km reach directly below the former Marmot Dam to the entrance of the bedrock gorge was the primary site for a majority of the sediment deposition related to the removal of the dam. Half of the estimated 65,000 m^3 of sediment eroded within the first 60 hours was deposited within the first 1.5 km downstream of the former dam (Major et al. 2011). The valley bottom was raised 4 meters near the dam and tapered off 2 km downstream (Major et al. 2011). Over the next few months the reservoir continued to release sediment, and one year after the dam breach 105,000 m^3 was deposited within the 2 km reach (Major et al. 2011). Most of the deposition occurred within the first kilometer below the dam (Figure 6). Most of the deposition occurred within the channel itself, with very little on the banks of the river. This pattern is probably a result of very steep valley walls and narrow floodplain.

High-flow events in the winter months of 2008 and 2009 deposited more sediment into the reach, mainly within the first ½ km downstream of the former dam (Major et al. 2011). However, in the 2010-2008 DoD there was erosion within the first ½ km on the bars within the channel and may have happened between field observations by Major and others in 2009 and the LiDAR survey in October of 2010. During these storm events the flow was high enough to overtop the sediment bars, depositing new sediment on the top of the bars and eroding along some banks (Figure 6). The large storm event in January of 2011 (Figure 2) removed an estimated 173,000m^3 of sediment from the reach (Table 2). Most of the erosion occurred within the channel; only up to a few decimeters of sediment were eroded from the bars that were visible above the water surface during the 2010 and 2011 surveys (Figure 6). The 2011-2008 cumulative DoD (Figure 6) indicates a net decrease of only ~7,000 m^3 during the 3-year period after the dam was removed (Table 2), although the sediment flux into and out of this reach was significantly greater during individual incremental time periods. This calculation is reliable because the discharges during both LiDAR surveys were nearly identical, thus any vertical change in the water surface could be considered a removal or addition of sediment. According to the 2011-2007 DoD (Figure 6) a net gain of 101,600 m^3 occurred since pre-dam-removal conditions (Figure 14).

Within the 2-km Below Dam Reach, approximately half of the initial 110,000 m^3 net gain within the first year after the dam removal was recorded by the sediment bars exposed above the water surface in the 2008-2007 DoD (Figures 6 and 7). The sediment bars near the dam site covered ~60% of the surface area of the sediment wedge described by Major et al. (2011). Preexisting bars >1.5km from the dam had minimal amounts of deposition during the first year, which might have been a result of the discharge at the time of the dam breach being insufficient to overtop the bars and deposit sediment.

The evolution of the sediment wedge is most apparent during the last three LiDAR surveys. Sediment bars in the upstream end of the reach eroded laterally and elongated downstream, while deposition on the downstream bars in this reach increased. By 2010 erosion had begun on the upstream end of the reach; it continued in 2011 and progressed downstream (Figures 6 & 7). Field work by Major and others (unpublished data, 2011) suggests that a majority of the coarse sediment stayed within the 2-km dam reach, which is consistent with other research indicating that coarse sediment released from a dam removal decreases dramatically downstream from the dam (Kibler et al., 2011).

One of the main objectives of this study was to determine whether a sediment pulse related to the Marmot Dam removal could be documented as it moves through the river system. A pulse of sediment can either progress downstream via dispersion or translation, or some combination of the two (Lisle et al. 2001, Sklar et al. 2009), but dispersion is the dominant mode of transporting a sediment pulse even when combined with translation (Lisle et al. 1997; Cui et al. 2003; Lisle, 2008). With dispersion, the mass of sediment is gradually removed and spread downstream, whereas translation refers to the propagation of the entire mass of sediment (Sklar et al., 2009). Considering that 90%

of the original volume of the sediment wedge deposited during the dam removal is still located in the same place, the pulse must be moving through dispersion. A sustained flow regime up to 2.5 times greater than the discharge required for sediment entrainment is considered the most favorable condition to move a large mass of sediment via dispersion (Humphries et al. 2012). During the spring snowmelt season and winter rains between October 2007 and spring of 2008, the Sandy River was able to reach these conditions for brief windows of time allowing for dispersion of the sediment downstream. Much larger flows are required for the complete translation of a sediment pulse (Humphries et al. 2012). A few such flows occurred during the study period, such as the flood in January, 2011 with a peak discharge of 64,000 cfs (1,736 m^3/sec) (Figure 2). After this large flood, the sediment wedge downstream from the dam was still in place and had only been reshaped slightly (Figures 6 & 7). This observation supports the interpretation that a majority of the boulder and gravel-sized sediment deposited within the 2-km dam reach has stabilized and could potentially remain for years to come. The sand-sized sediment released from the dam, however, is readily mobilized during high flows and is continually being dispersed downstream into the gorge and beyond.

Reach III: The Gorge

The 13-km gorge on the Sandy River is bedrock-confined with virtually no floodplain. The stream gradient is much steeper than in the other 5 study reaches. Given the channel geometry and the steep profile, the flow hydraulics within the gorge are not directly comparable to the rest of the study area. The procedure employed to normalize the volume calculations was applied to this reach, but based on the channel geometry and flow conditions the correction for the water surface may not be enough to accurately account for the entire volume generated by the higher water surface. The 2010-2008 and 2011-2010 DoD shows a large volume of deposition followed by erosion. The channel geometry in the Gorge is narrower than the other channels and would create an even higher water height during increased flow discharge compared to the other channels. This even higher increase in stage would produce the high volumes seen in 2010-2008 and 2011-2010 (Table 2). The discharge in 2007 was higher than 2010 (Table 1) and should have produced higher volumes within the Gorge but for some reason didn’t (Table 2). This discrepancy may suggest that a large volume of sediment was deposited in the gorge between 2008 and 2010. However, the net accumulation of sediment in the Gorge for the entire study period (2007-2011) as well as the cumulative post-removal period (2008-2011) is consistent with the cumulative patterns for the adjacent reaches (Table 2; Figure 4)

Reach IV: Gorge to Bull Run

Within the first 0.5 km downstream from the bedrock gorge, near Revenue Street Bridge (Figure 3), the Sandy River enters a low-gradient, gravel-bed channel where deposition occurred after the dam removal. The 2008-2007 DoD of the Below Gorge Reach showed minimal signs of change within the first 2 km of this reach, but the following 2010-2008 and 2011-2010 periods recorded sediment coming into the reach from the gorge. The 2010-2008 DoD showed an appearance of sediment on the bars and banks immediately downstream of the gorge.

To better understand the volume of sediment coming into the system, the subearial river banks and sediment bars in the first 2 km of the Below Gorge reach were analyzed separately without the water surface within the channel (Figure 10). The appearance of sand after the 2011 flood can be readily detected in a comparison of Google Earth images from 2010 and 2011, as previous low-growing vegetation was either completely removed or covered by sand in the later image (Figure 15). The inflow of sediment into the reach below the gorge is most likely sourced from the upstream reaches like the Gorge or the Below Dam Reach.

A fair amount of erosion occurred within the Below Dam Reach during 2008-2010, and this sediment probably passed through the gorge and was deposited on the first bars downstream, at the upstream end of the Gorge to Bull Run Reach (Table 2; Figures 8 and 9). The absence of new sediment in the 2008-2007 DoD followed by deposition after the 2008 LiDAR survey is interpreted as a sediment pulse related to the removal of the dam and propagating downstream over the course of 2 years. Downstream of the first 2 km in this reach, the sediment pulse could not be distinguished from sediment that was reworked by normal river processes. The influx from the dam removal might have extended farther downstream, but it was overwhelmed by the background of natural sediment transport in the river. In the DoD images farther downstream within the Gorge to Bull Run Reach there is no sudden appearance of a large volume of sediment equivalent to that at the upstream end of the reach. Repeat ground surveys between 2008 and 2009 (Bauer,2009; Podolak, 2011) were unable to detect any change in the river channel related to the dam removal downstream of Revenue Bridge (Figure 3). The lack of evidence during the ground survey suggests that the sediment pulse entered the reach during the high flows during the winter of 2010, nearly 3 years after the removal of the Marmot Dam.

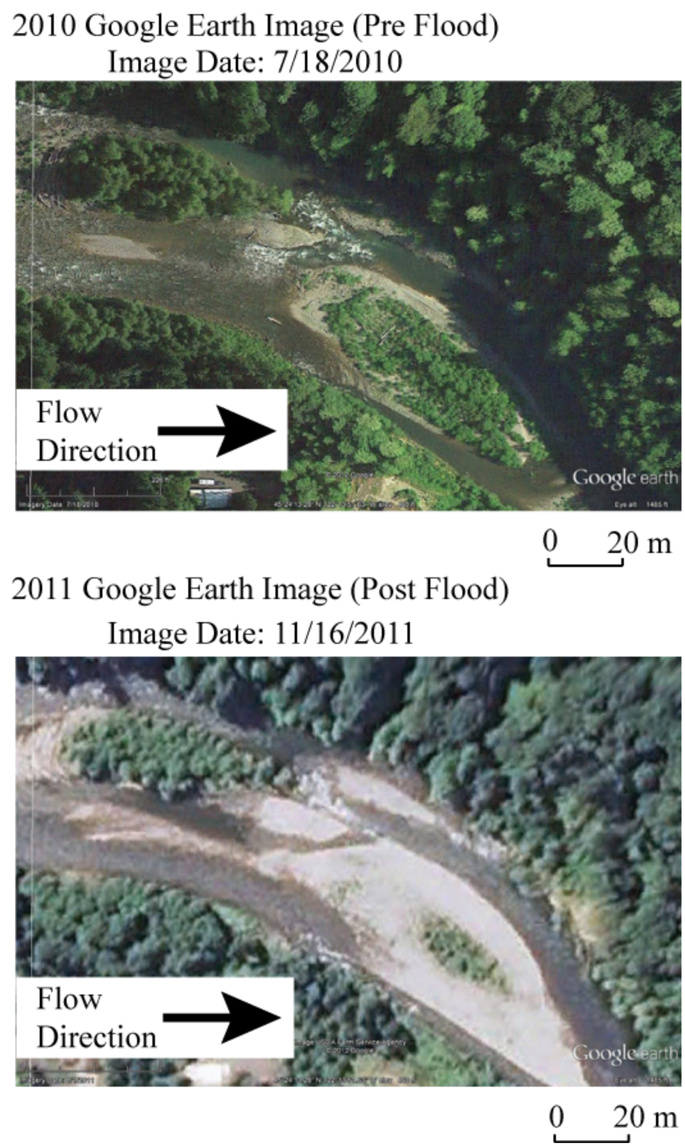

Figure 15: Google Earth images of the first sediment bar downstream from mouth of the gorge. Top image is from 2010 before a large flood and bottom image is from 2011 after the large flood.

Remaining Reaches of the Sandy River

The downstream reaches below Revenue Bridge to the Columbia River showed no detectable change related to the Marmot Dam removal; however, they were vigorously active with local erosion and deposition. The 2008-2007 DoD time frame was the least active for the entire study period with only minor changes throughout the downstream reaches. Large volumes of sediment transport were recorded for these reaches, but considering the longer lengths of the reaches (9 - 20 km) compared to the 2-km Below Dam Reach, they were relatively low-magnitude changes (< 0.5 meters vertical change). The Oxbow reach was the most active reach throughout the entire study period, 2007-2011, with continuous erosion and deposition in the meander bends and downstream of them, as shown in the representative 2-km example sub-reach (Figure 11). The downstream reaches all tended to follow the same net gain or loss of the upstream Below Dam and Gorge to Bull Run Reaches, but with larger volumes of sediment.

The consistently large volume of erosion and deposition fairly evenly distributed throughout the downstream reaches during the study period (2007-2011) suggests that the dam removal in fact had little detectable impact >2.5 km downstream of the gorge (12 km from the former dam). Erosion occurred on upstream ends of bars and along cutbanks, and deposition occurred on the downstream ends of bars and pointbars, as would be expected. The pattern of erosion and deposition distributed longitudinally through the reach supports the interpretation that it represents reworking of sediment within the channel system, rather than the arrival of a discrete sediment pulse. Erosion and deposition were present in the same DoDs, in contrast to the Gorge to Bull Run Reach where deposition occurred in the absence of erosion within the same reach.

In summary, the effects of the Marmot Dam Removal were documented with the LiDAR analysis in both the Below Dam Reach and the Gorge to Bull Run Reach. The downstream-thinning, 2-km sediment wedge produced during the dam breach in the Below Dam Reach still remained 4 years after the removal of the Marmot Dam and is visually represented in Figure 13 and 14. A possible sediment pulse was detected 12 km downstream from the former dam in the Below Gorge Reach and was tracked to a point 2.5 km below the mouth of the gorge. The observed patterns of erosion and deposition in the reaches of the Sandy River farther downstream were distributed throughout the channel and flood plain following the years of high flows on the Sandy River. The Reservoir Reach experienced a net decrease in sediment over the entire study period spanning the dam removal (2007-2011), as expected. The 3 reaches immediately downstream of the dam experience a net increase, which is likely due to the transfer of sediment from the reservoir into the initial portion of the river channel downstream. The sediment pulse related to the Marmot Dam removal could not be directly traced through the furthest downstream reaches. This is due to the overwhelming influence of the high flow events and their ability to cause natural processes of sediment redistribution within the river system.

Areas of Uncertainty in the Results

The largest source of uncertainty within this project was normalizing for the high water surface. A greater discharge most likely would not produce the exact same water column each year due to the bed surface of the channel constantly changing. The volume of water was also calculated using the assumption of a constant channel width in each reach division along with a constant depth of water. Using an excel spreadsheet I was able to determine how much the change in the height of the water surface affected the volume produced in the DoD. The volume of sediment was not affected past the significant figures until a 70% error of change in water surface was applied. An error of 50% for the stage height is unlikely and would have been stated within the USGS data retrieved during the project. This gives some validity for the normalizing procedure as an initial method to account for some of the water column.

Other sources of uncertainty lie within the survey data itself. Each LiDAR survey has its own vertical accuracy and the production of each DEM was completed by Watershed Sciences, Inc. The water surface in each DEM that was used for the differencing was created using some ground control points and an algorithm designed by Watershed Sciences Inc. Stretching that surface over the entire length of the river could easily produce some areas that were inaccurate. These uncertainties are a possible source of error for any study using digitally-generated ground surfaces. The exact volume of sediment change within each reach contains some uncertainties. However, based on the overall patterns and other measures of the validity of the results, I am confident in the accuracy of the net gain or loss of sediment and general magnitude of the change.

Things to Consider for Future Projects

To further reduce the uncertainty with the water surface during each of the LiDAR surveys, water height and discharge measurements should have been taken at multiple locations throughout the length of the river. Had the water surface issue been addressed earlier, I would have removed it from all of the DEMs and only analyzed above water surface areas as in Figures 7 and 10. Removing the water surface from the calculations would have given a minimum net change but the calculated volumes would have been more accurate because the water in the DEMs was a partially an artificially generated surface. Unfortunately removing the water surface was too time intensive to be completed for the entire river in this project. Future projects could refine the results by taking some of these issues into consideration.

CHAPTER V

CONCLUSIONS

This study tracked sediment transport related to the removal of the Marmot Dam with four sets of high-resolution aerial LiDAR surveys using the Geomorphic Change Detection software (GCD v.5) created by Joe Wheaton at Utah State University and Philip Bailey from Arrow North Research. Within the 2-km reach directly below the former dam, the LiDAR analysis with GCD closely matched sediment volumes calculated from total-station field surveys (Major et al. 2011) completed over the three years following the dam removal. Approximately 110,000 m^3 of deposited sediment was calculated in this reach using the GCD software and LiDAR; total-station surveys completed by the USGS and a private consulting company estimated deposition of ~105,000m^3 of sediment within the 2-km reach in the first year following the dam removal (Major et al. 2011). With the use of LiDAR and GCD it was possible to extend this initial work by calculating the sediment flux through multiple reaches over the four year study period.

One of the primary concerns with the removal of the dam was the immediate and long-term impact that a large input of sediment would have on the river system (Esler, 2009). The increased sediment load from a potential sediment pulse propagating downstream over multiple years could have a negative impact on the environments of aquatic life (Wheaton, 2010). The majority of the sediment wedge composed of gravel and sand-sized sediment that was deposited immediately after the dam breach is largely intact after four years and multiple large flow events. The base of the sediment wedge has not changed since its deposition; only finer sand/silt sediment has been removed from the surface. There has been some dispersion of the sediment downstream through the 13-km bedrock gorge and into the reach directly below. The appearance of the sediment pulse downstream from the gorge sometime after the 2008 LiDAR acquisition and before the 2010 LiDAR survey indicates that the Sandy River was still reacting to the influx of sediment into the river from the dam removal. The 2 km stretch of river directly downstream from the gorge had continual net deposition during the post-dam period 2008-2011. This pattern was even stronger when only the sediment bars within the first 2-km were isolated from the water and analyzed. The sediment pulse, however, is not distinguishable from normal river processes beyond the 2.5-km stretch below the gorge.

The robust set of LiDAR data also provided the ability to study how the river stores and transports sediment on an annual to biannual scale. The majority of the river downstream from the gorge did not show an obvious lasting impact from the dam removal, but did show a detailed record of sediment storage and transport. The Sandy River is a very active river that transports high amounts of sediment on a yearly basis (Major et al. 2011). Deposition primarily occurred on sediment bars within the channel and locations where the channel was in contact with its floodplain. Many cut banks were heavily eroded during the study period, in some cases meters of bank were eroded between two successive surveys. Most of the intensive erosion occurred during large winter floods in 2009 and 2011. The information provided from the lower reaches could be helpful in determining long-term sediment budgets for the river and planning for locations of possible hazards such as bank failure or flooding.

With many dams becoming outdated in the U.S. (Burroughs et al. 2009), the importance of monitoring is critical for understanding future implications to the river. Repeat LiDAR surveys are one way to accomplish that. This study demonstrated that 1-meter DEMs from aerial LiDAR combined with the use of the GCD software can accurately estimate erosion and deposition resulting from a dam removal, and that a sediment pulse could be detected and tracked downstream for 13 km. The results presented in this study support the utility of LiDAR and the GCD software as an effective tool to quantify the geomorphic response to a dam removal.

REFERENCES CITED

Bailly, J.-S., Coarer, Y.L., Languille, P., Stigermark, C.-J., and Allouis, T., 2010, Geostatistical estimations of bathymetric LiDAR errors on rivers: Earth Surface Processes and Landforms, v. 35, p. 1199-1210

Bauer, T.R., 2009, Profile survey of the Sandy River for Marmot Dam removal. US Breau of Reclamation Report SRH-2009-44, 1. *www.usbr.gov/pmts/sediment/projects/index.htm*

Brasington, J., Langham, J., and Rumsby, B., 2003, Methodological sensitivity of estimates of coarse sediment transport: Geomorphology, v. 53, p. 299–316.

Burroughs, B.A., Hayes, D.B., Klomp, K.D., Hansen, J.F., and Mistak, J., 2009, Effects of Stronach Dam Removal on Fluvial Geomorphology in the Pine River, Michigan, United States: Geomorphology, v. 110, p. 96–107.

Cui, Y., and Parker, G., 2005, Numerical Model of Sediment Pulses and Sediment-Supply Disturbances in Mountain Rivers: Journal of Hydraulic Engineering, p. 646-656

Downs, P.W., Curi, Y., Wooster, J.K., Dusterhoff, S.R., Booth, D.B., Dietrich, W.E., and Sklar, L.S., 2009, Managing reservoir sediment release in dam removal projects: An approach informed by physical and numerical modelling of non-cohesive sediment: International Journal of River Basin Management, v. 7, no. 4, p. 433–452.

Doyle, M.W., Stanley, E.H., and Harbor, J.M., 2003, Channel adjustments following two dam removals in Wisconsin, Water Resources Research, v. 39, no. 1.1011-1026

Doyle, M.W., Stanley, E.H., and Harbor, J.M., 2002, Geomorphic Analogies for Assessing Probable Channel Response to Dam Removal: Journal of the American Water Resources Association, v. 38, no. 6. p. 1567-1579

ESRI (2012) ArcGIS Desktop v. 10.1

Heinz Center, 2002, Dam Removal, Science and Decision Making: The John H. Heinz Center for Science, Economics, and the Environment. www.heinzctr.org

Humphries, R., Venditti, J.G., Sklar, L.S., and Wooster, J.K. Experimental evidence for the effect of hydrographs on sediment pulse dynamics in gravel-bedded rivers: Water Resources Research, v. 48, doi: 10.1029/2011WR010419. P. 1-15

Kibler, K., Tullos, D., and Kondolf, M., 2011, Evolving Expectations of Dam Removal Outcomes: Downstream Geomorphic Effects Following Removal of a Small, Gravel-Filled Dam: American Water Resources Association, v. 47, no. 2. p.408-243

Lisle, T.E., and Cui, Y., 2001, The Domiance of Dispersion in the Evolution of Bed Material in Waves in Gravel-Bed Rivers: Earth Surface Processes and Landforms, v. 26, p. 1409–1420.

Major, J., J., O'Connor, J., Podolak, C., Keith, M., Grant, G., Spicer, K., Pittman, S., Bragg, H., Wallick, J., Tanner, D., Rhode, A., and Wilcock, P., 2011, Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam: U.S. Geological Survey Professional Paper 1972,.

Milan, D.J., Heritage, G.L., Large, A.R.G., and Fuller, I.C., 2011, Filtering spatial error from DEMs: Implications for morphological change estimation: Geomorphology, v. 125, no. 1, p. 160–171, doi: 10.1016/j.geomorph.2010.09.012.

Notebaert, B., Verstraeten, G., Govers, G., and Poesen, J., 2009, Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology: Earth Surface Processes and Landforms, v. 34, p. 217–231.

Podolak, C., 2011, Observations of the Sandy River following the January 16th, 2011 High Flows: Unpublished work.

Rumschlag, J.H., and Peck, J.A., 2007, Short-term Sediment and Morphologic Response of the Middle Cuyahoga River to the Removal of the Munroe Falls Dam, Summit County, Ohio: Journal of Great Lakes Research, v. 33, p. 142–153.

Sklar, L.S., Fadde, J., Venditti, J.G., Nelson, P., Wydzga, M.A., Cui, Y., and Dietrich, W.E., 2009, Translation and dispersion of sediment pulses in flume experiments simulating gravel augmentation below dams: Water Resources Research, v. 45, doi: 10.1029/2008WR007346 p. 1-14

Watershed Sciences, 2007, LiDAR Remote Sensing Data Collection: Sandy River, Oregon. p. 1-27

Watershed Sciences, 2008, LiDAR and True-Color Orthophotographs, Airborne Data Aquisition and Processing: Sandy River, Oregon. p.1-31

Watershed Sciences, 2010, Airborne LiDAR Project Report, Sandy River ARRA LiDAR Project. p. 1-30

Watershed Sciences, 2011, LiDAR Remote Sensing Data Collection, Department of Geology and Mineral Industries OLC Sandy. p.1-25

Wheaton, J.M., Brasington, J., Darby, S.E., Merz, J., Pasternack, G.B., Sear, D., and Vericat, D., 2010, Linking geomorphic changes to salmonid habitat at a scale relevant to fish: River Research and Applications, v. 26, no. 4, p. 469–486, doi: 10.1002/rra.1305.

Wheaton, J.M., Brasington, J., Darby, S.E., and Sear, D.A., 2009, Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets: Earth Surface Processes and Landforms,, p. n/a–n/a, doi: 10.1002/esp.1886.