PREDICTING SEDIMENT ROUTING ON THE SANDY RIVER, OREGON FOLLOWING THE REMOVAL OF THE MARMOT DAM

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Abstract The 14-meter-tall Marmot Dam was removed from the Sandy River, OR in October 2007. Its removal exposed nearly 730,000 m^3 of impounded sand and gravel to the river for erosion and transport downstream. Prior to the dam removal a two-fraction 1-D morphodynamic model was run to understand the probable river response to the dam removal and the predicted changes in morphology associated with the dam removal were assessed to be acceptable. As part of a large monitoring effort to capture the morphologic changes in the Sandy River following the dam removal, we measured the evolution of the bed downstream of the dam over a multi-year time period. The predicted reach-averaged values from the model corresponded well to our field measurements. We observed two reaches with bed elevation changes less than that predicted by the model. These are attributed in one case to uncertainty in the transport and storage capacity of a difficult-to-access bedrock gorge 2.5 km below the damsite, and in another case to a large logjam-induced rapid causing extreme local relief between a bar and the channel. We find the performance of the 1-D model robust, but urge users to be familiar with the objectives and limitations of any sediment routing and morphodynamic model when interpreting the results.

INTRODUCTION

The Sandy River, Oregon, is nearly 80 km long and drains a 1300 km^2 watershed in the western Cascade mountain range on the western flanks of 3428-meter-tall Mt. Hood (Figure 1). It empties into the Columbia River upstream of Portland, OR and downstream of the lowest Columbia River dam (Bonneville Dam). In 1913 the Mt. Hood Railway and Power Company constructed the Marmot Dam, at river kilometer 48 as part of the Bull Run Hydroelectric Project (Taylor, 1998) creating for the first time a barrier between the Pacific Ocean and the Sandy River headwaters. The original dam was replaced in 1989 by a 14-meter-tall concrete dam (Stillwater Sciences, 2000b). In 1999 Portland General Electric [PGE] (the owning and operating utility) filed a notice of intent not to seek a new license for the project and to decommission the Marmot Dam (PGE, 2002).

Over the life of the dam it had trapped nearly 730,000 m^3 of sediment (mostly sand and gravel – 0.1 – 100 mm) (Stillwater Sciences, 2000b). A geomorphic assessment including numerical modeling of sediment transport and bed evolution (Stillwater Sciences, 2000a), was conducted and it was predicted the river would have the ability to erode, transport, and redeposit the reservoir sediment without creating significant problems for fish passage, fish spawning, or recreational boating. Using this assessment, the decision was made to remove the dam with only minimal excavation of the sediment and to use the river to redistribute the remaining impounded sediment.

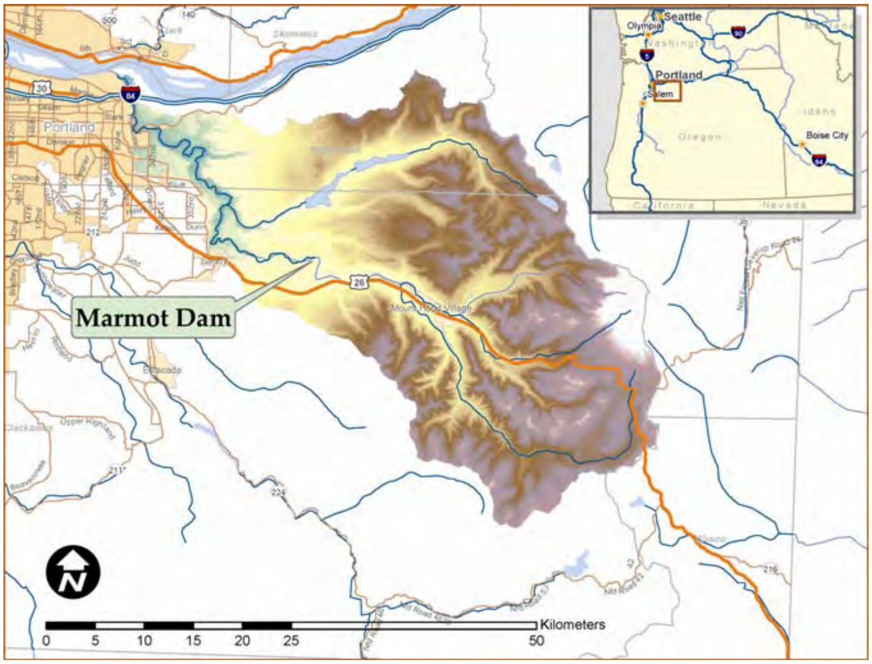

Figure 1 Overview of the Sandy River Basin and the Marmot Dam location.

DAM REMOVAL AND MONITORING

At the time it was removed, the Marmot Dam was one of the largest dams (in terms of dam height and sediment stored) to be removed. Its size and the fact that so much sediment would be moved by fluvial erosion led many to participate in the monitoring of geomorphic changes in the river. Researchers from several academic institutions (Johns Hopkins University, Oregon State University, Portland State University, and the National Center for Earth-surface Dynamics) partnered with federal (US Geological Survey, US Forest Service, Bureau of Reclamation), state (Oregon Watershed Enhancement Board), and local (Sandy River Basin Watershed Council) agencies as well as PGE to mount an intensive multi-year data collection effort documenting changes in the Sandy River morphology due to the dam removal. Previous studies of dam removal and subsequent channel change (Cheng and Granata, 2007; Doyle et al, 2003), have been on smaller dams, in lower gradient streams, with smaller grain sizes.

In order to capture the changes in the Sandy River a variety of data were collected. Measuring changes in the forms of the river bed, banks, and bars were done by repeated surveys. Several sets of surveys were generated from on-the-ground measurements using GPS and total station surveying equipment beginning in 2005. An additional topographic dataset includes airborne non-bathymetric Light Detection and Ranging [LiDAR] measurements taken in 2006, 2007, and 2008. These topographic datasets together provide detailed topography and bathymetry within 2 km of the dam several times throughout the year. They provide detailed topography and bathymetry at three locations (river km 38, 34 and 28) on an annual basis. And they provide detailed topography (but not bathymetry) along the entire river on an annual basis. In addition to the form of the river bed, its grain size was of interest. In the reservoir deposit, and in the immediate downstream of the dam, both surface grain size counts and subsurface bulk samples were taken. At several downstream locations multiple grain size measurements were made over several years. In addition to the quantitative measurements, there is a plethora of photographic data from the Sandy River. High resolution aerial photographs (0.25 m resolution) are available from 2006, 2007, and 2008. At several locations in the 20 km downstream of the dam there are semi-annual repeat photographs taken from monumented locations, and for the first year after the dam removal, five fixed-position digital cameras recorded the reservoir erosion with time lapse photography at intervals as fine as 15 minutes. To compliment the measures of changes in the river, measurements of water and sediment flux were made. A gauging station has been in operation near the dam site for over 90 years, there is a long-standing gauge 20 km downstream of the dam, and a newly installed gauge 10 km upstream of the dam. Sediment transport (both bedload and suspended load) measurements were made during the first two years after the dam was removed, upstream of the dam, immediately below the dam, and at three locations downstream (10, 18 and 38 km) (Major et al, 2008). Taken together this dataset of topography, grain size characterization, water discharge, sediment flux, and photographs provide an excellent record of the erosion of the impounded reservoir sediment and the development of the river downstream of the dam.

Figure 2 Paired photographs taken from the same location 50m below the dam looking upstream (A&B) and downstream (C&D) before removal (A&C) in July 2007 and after removal (B&D) in July 2009.

The removal process took place during the low-water season of 2007. In June and July 2007, a small earthen-cofferdam was constructed 70 meters upstream of Marmot Dam. Using the cofferdam, a diversion canal, and pumps, the Marmot Dam's concrete face was dewatered and mechanically removed. A small amount of sediment (approximately 23,000 m^3) was removed mechanically, leaving the rest available for fluvial erosion. The cofferdam was designed to fail in a flow exceeding 70 cms, which could be expected to arrive in the mid-autumn as the fall and winter rains commenced. The cofferdam breach occurred on October 19th, 2007. Approximately 48% of the impounded sediment was eroded during the first winter, with an additional 7% being eroded out during the second winter (Figure 2) (Major et al, 2010). Near the damsite, the deposition took the form of several meters of bed aggradation (Figure 3), with the magnitude of the deposition greatly falling off within the first 2 km downstream of the dam (Figure 4).

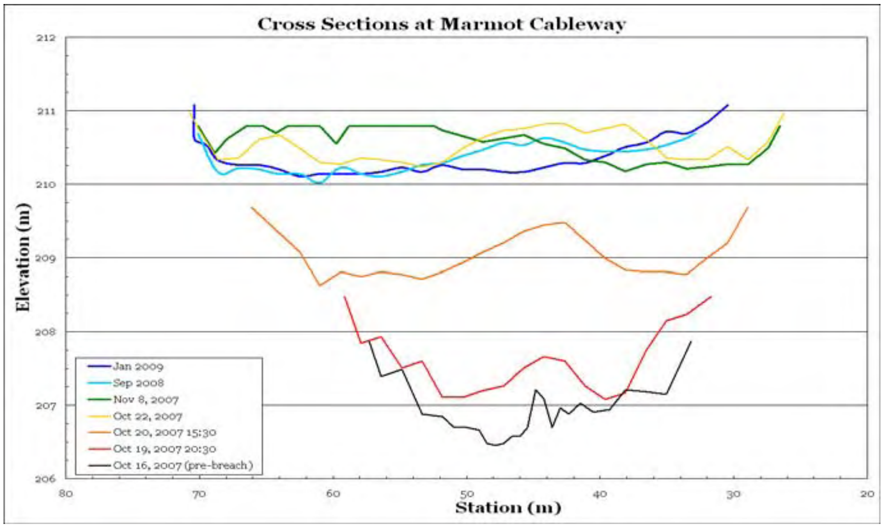

Figure 3 Repeat cross sections at the Marmot cableway. The aggrading channel bed is evident in this series. Note some erosion between September 2008 and January 2009.

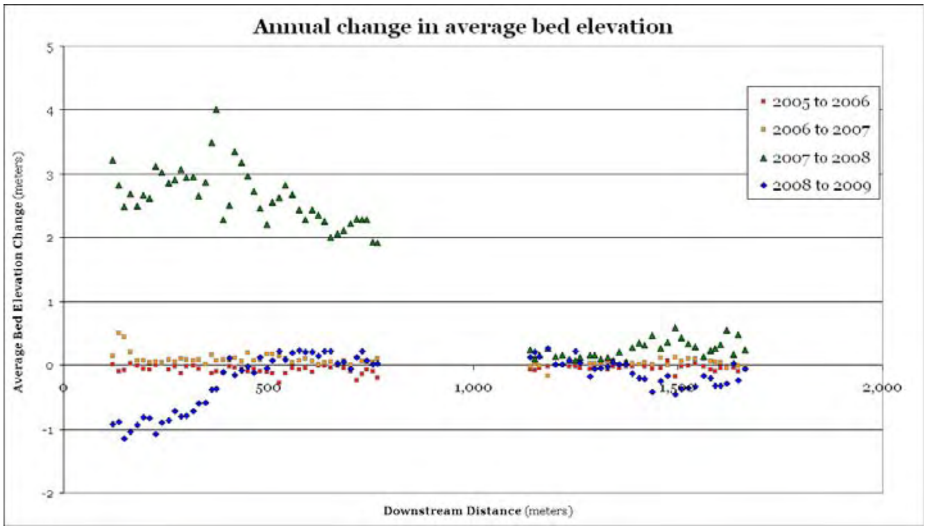

Figure 4 Longitudinal profiles [averaged at a cross section] for annual change in bed elevation

MODELLING SEDIMENT ROUTING

Predicting the evolution of an alluvial river bed requires predicting both the transport as well as the erosion and deposition of sediment. The only numerical modeling done before the dam removal was a two-fraction 1-D model by Stillwater Sciences (Stillwater Sciences 2000a; Cui and Wilcox, 2008). This model was a direct predecessor of their Dam Removal Express Assessment Model [DREAM] (Cui et al, 2006a & b). It calculates flow using a standard backwater calculation and a quasi-normal flow assumption for higher Froude numbers. Roughness is a function only of grain size, and sediment transport is calculated using a Parker surface based transport function for gravel and a Brownlie model for sand. Sediment continuity is enforced with a memoryless active layer formulation.

A numeric model of sediment routing is meant to capture the essential processes and patterns. In the case of the Marmot Dam modeling at the upstream boundary there was both variability (water discharge) and uncertainty (sediment load) (Stillwater Sciences 2000a). To incorporate the variability in the water discharge, the model was run with three different hydrographs drawn from wet, dry, and average water years contained in the 69-year discharge record. Rates of sediment input at the upstream boundary were estimated based on a combination of model testing and values derived from other basins in the Cascades. The actual hydrograph for the first year following the dam removal was somewhere in between the wet and the dry years used to constrain the model (Figure 5). It had peaks similar to the dry-year hydrograph but had more frequent events as well as a long duration snowmelt event in May and June. In addition to the variability in the water input condition, there was great uncertainty in the sediment supply boundary conditions. The values used for the model were approximately 23,000 Mg of gravel and 230,000 Mg of sand, which were reasonably close to the post-removal field measured values. Calculations made based on measurements of suspended load and bedload transport from October 2007 through May 2008 indicate that the gravel load is 40,000 mg and the sand load is nearly 500,000 Mg.

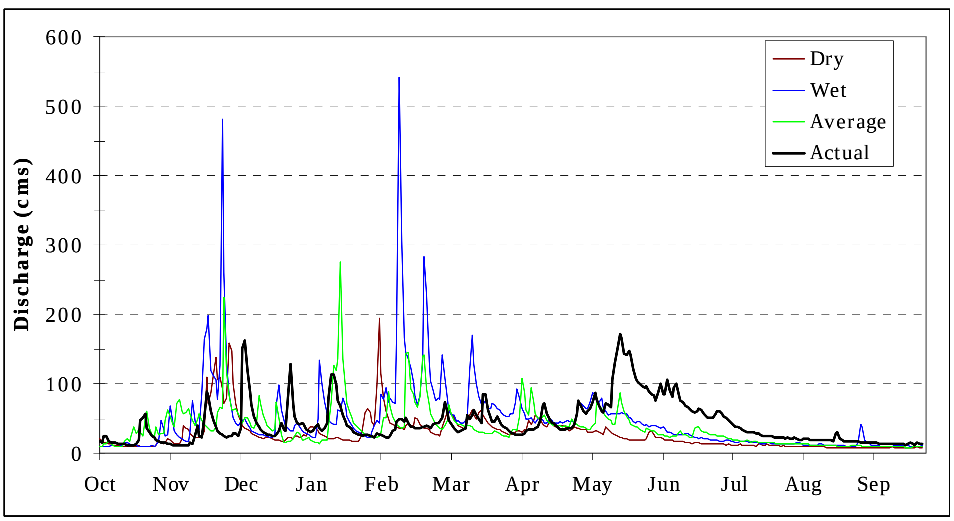

Figure 5 Hydrographs for discharge at the dam site - dry, wet, and average conditions used for the model inputs, as well as the actual daily discharge at USGS station 14136500.

The results of the pre-removal modeling are shown with field measurements superimposed (Figure 6). Downs et al (2009) also provide a brief review of the predicted and measured results. At the large scale, the 1-D sediment routing model predicted the location and magnitude of the deposition – several meters in the reach immediately below the dam and very little in the lower reaches. The one-dimensional two-fraction sediment routing model predicted the changes in river morphology over a 50-km river reach with very little field-gathered data. In trying to advance the predictive ability of the community, it is instructive to look at the areas where the model and the measurements diverge.

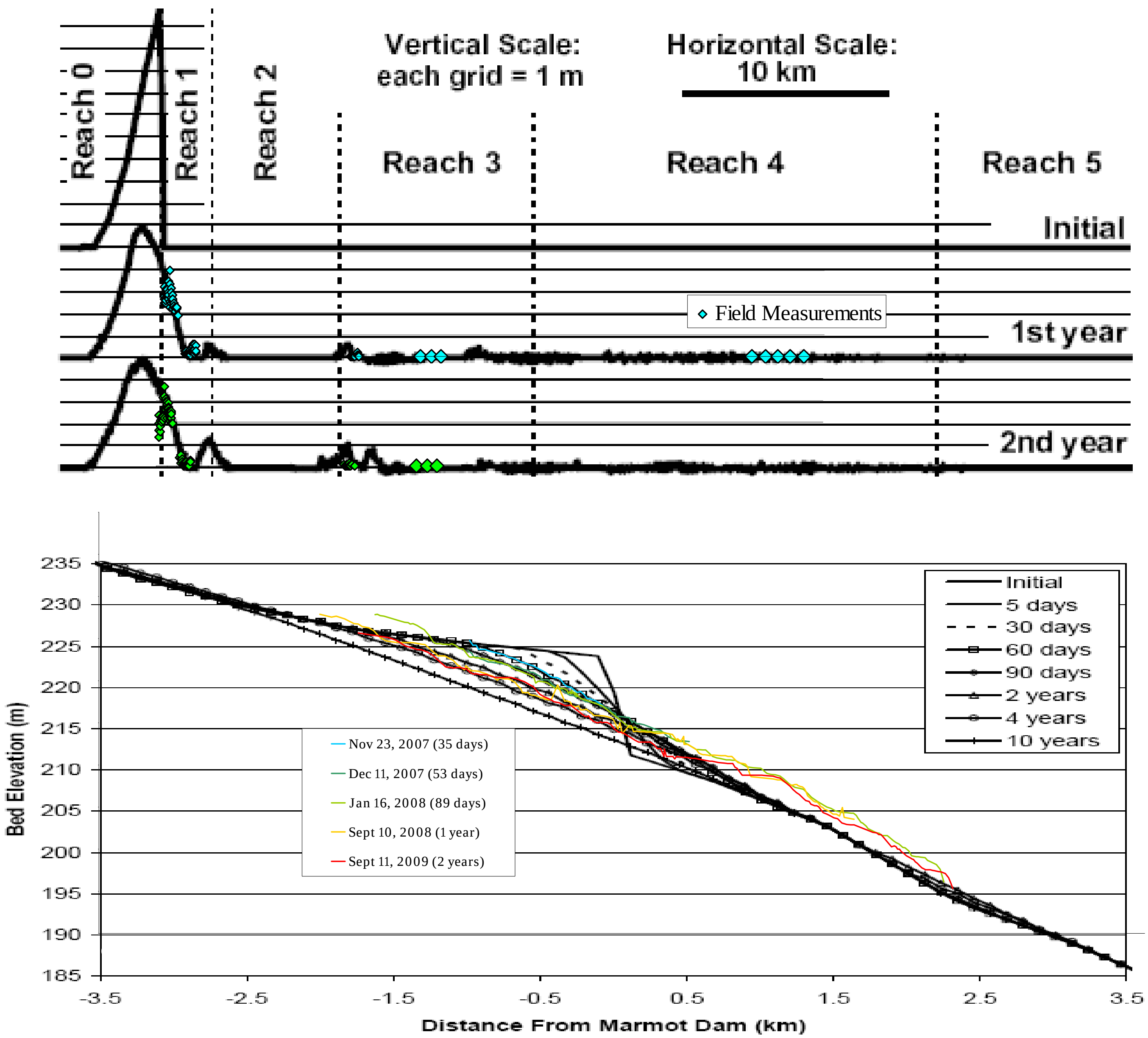

Figure 6 Results of numerical modeling from Cui and Wilcox (2008). Longitudinal profiles [averaged at a cross section] for a) annual change in bed elevation, and b) bed elevation

DISCUSSION

Below the dam there is a 2.5 km reach of wide alluvial river with floodplains and vegetated bars. At the bottom of the alluvial reach is a 6.5 km narrow bedrock gorge. In the alluvial reach the mean valley width is 2-4 times the river width, while in the gorge the ratio is 1:1. There are two surveyed reaches (immediately above and below the Sandy River Gorge – reach 2 in Figure 6) in which the actual deposition is less than the predicted deposition (Figure 7). In both the reaches there is an increase in width creating a zone of decreased transport capacity and the model predicts deposition. In a qualitative assessment of depositional potential along the river, Stewart and Grant (2005) predicted that there would be deposition below the gorge, but that it would be mediated by the increase in shear stress approaching the Revenue Rapid (at the end of the exit reach). Both reaches have gravel bars and islands as evidence of previous deposition.

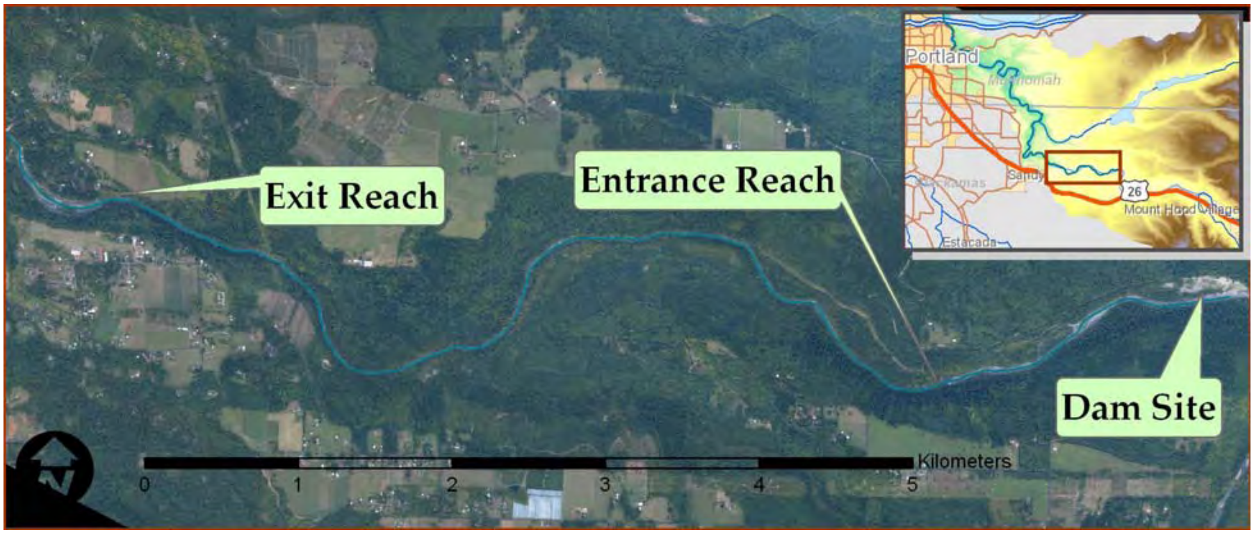

Figure 7 Sandy River Gorge & monitoring reaches immediately above and below.

However, in neither the entrance nor the exit reaches has there been any measurable deposition (Figure 6). Stillwater Sciences (2000a), Stewart and Grant (2005), and many others, including the authors of this paper, felt that there was no significant room for sediment storage in the gorge and it that it would effectively function as a 'pipe' for sediment between the upper and lower alluvial reaches. A sediment budget constructed with sediment flux measurements at the dam site and at the exit to the gorge, along with volume differences calculated from surveys of the depositional reaches finds that several tens of thousands to one hundred thousand metric tons of sediment was likely stored in the gorge during the first year. A combination of relief, valley orientation, and significant rapids in the gorge created a condition where there is a paucity of survey data (manual or GPS) or remote sensing (due to sun angles and non-bathymetric LiDAR) to describe the pre- and post-removal bed conditions in the gorge. The routing model had predicted that sediment would reach the gorge, but that it would move quickly through and deposit on the downstream end. The sediment is likely present in the gorge reach, however it is moving downstream much more slowly than expected. The filtering effect of the gorge should also have an effect on the magnitude of the downstream deposition by slowly metering out the sediment instead of having it all arrive as one slug. The lack of predicted sediment deposition downstream of the gorge can be explained by the uncertainty introduced by the transport capacity of the Sandy River gorge.

While the gorge can help to explain the lack of deposition at the downstream end of the gorge, the lack of deposition above the gorge needs another explanation. Podolak and Wilcock (2009a & b) have demonstrated the non-uniform depositional patterns in the reach between the dam and the gorge. Much of the deposition past the first 700 meters is not spread uniformly across the reach but is concentrated on the top of existing bars and except in the immediate vicinity below the dam, there has been limited deposition measured in the thalwag. When the relief in a cross section is such that the bar tops are inundated to a sufficient depth at bedload-transporting flows, the bar tops can grow in elevation. The reach just above the gorge has a prominent rapid with large (>1m) clasts built up in a matrix of large tree trunks – know as the '64 Logjam (Figure 8). Immediately below the rapid there is a bedrock constriction rapidly narrowing the river to 1/3 of its width. The relief in this section is extreme with nearly 4 meters between the thalweg elevation and the bar top. In this reach, even at high flows much of the river and the sediment can be contained in the narrow and high energy deep channel on the left side of the bar. This bar and cross section can be compared to one with a similar planform located 1 km upstream (Figure 9). The relief in this section is much more subdued and the entire bar is wetted during high flows. In contrast to the '64 Logjam bar, this upper bar has received an average of 2.5 m of deposition (Figure 4), most of it occurring on top of the existing bar features (Wilcock & Podolak, 2009a). While these two bar features have similar average widths and average slopes, the local effects create two different responses. The reason for the lack of predicted deposition immediately above the gorge is not uncertainty with the gorge, but a large logjam producing a locally high slope and a high relief, high-energy channel around a bar – or in short, very local conditions.

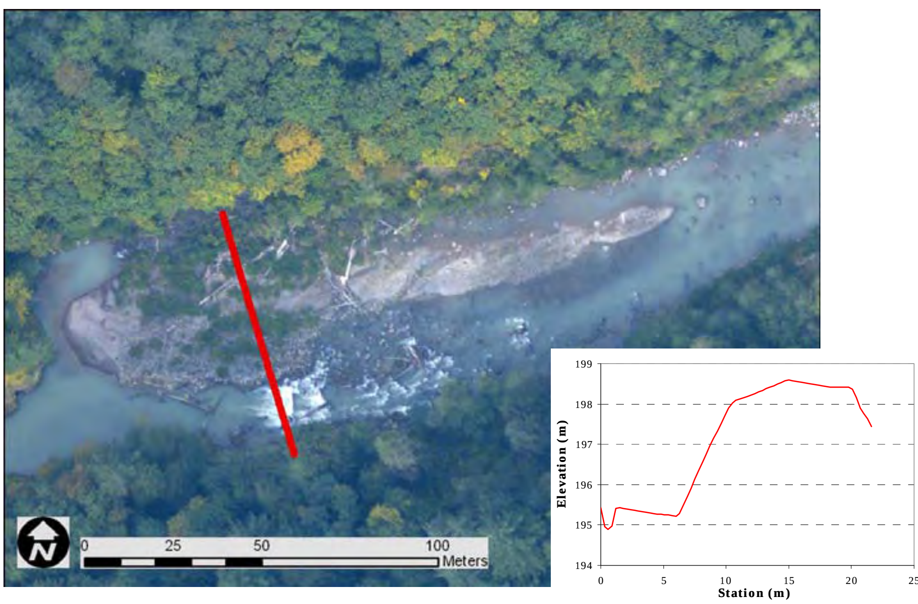

Figure 8 Features immediately above the gorge entrance. Note the relief in the cross section -- nearly 4 meters

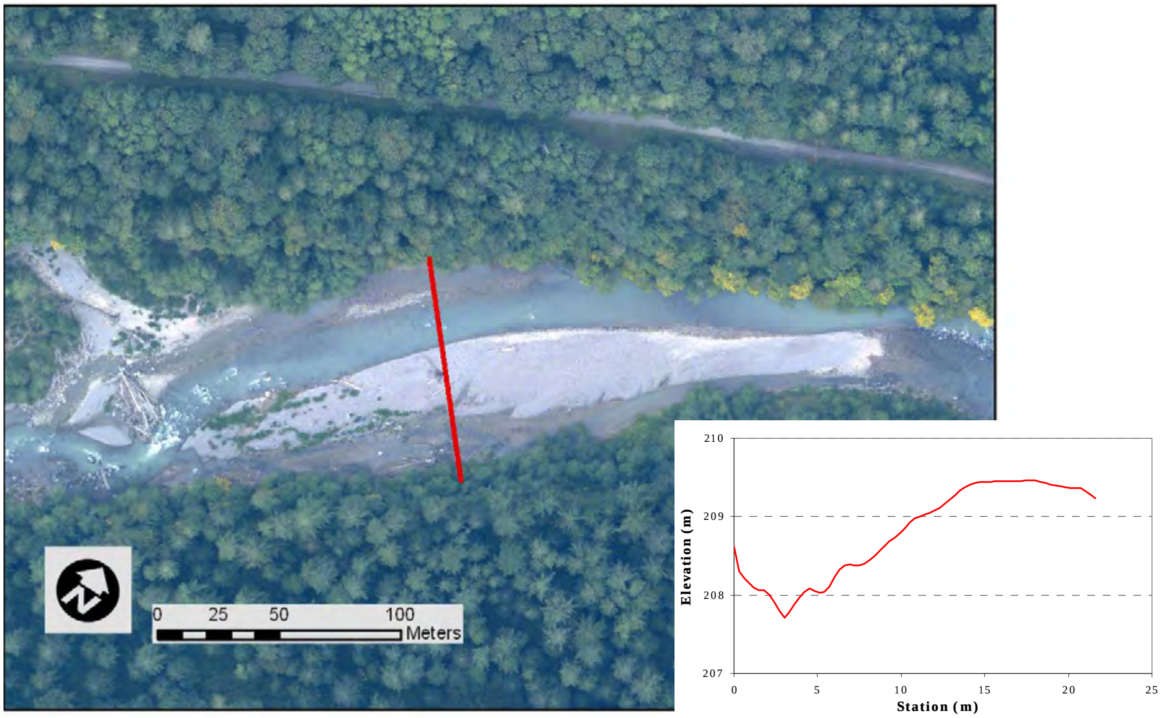

Figure 9 Depositional reach 900 m below the dam site and 1 km above the reach in Figure 8.

When assessing the performance of the model, it is tempting to focus on the places where it did not match what happened. This could lead one to draw the wrong conclusions from the comparisons. In the report containing the model results, Stillwater Sciences very clearly states that it "provides estimates of sediment transport rates and cross-section and reach-averaged depths of sediment deposits" (Stillwater Sciences, 2000a, p. 7). While we measured several areas where the local deposition was not as high as predicted, we also confirmed with field measurements that the magnitude of the deposition in the near vicinity of the dam was correct, the downstream extent of deposition was accurate, and in downstream areas where there was no predicted deposition, that there was in-fact none. In this light, we find that the model served its purpose to predict the broad temporal and spatial patterns of sediment transport and deposition.

CONCLUSION

The Marmot Dam removal provided not only an opportunity to measure the effects of a large dam removal, but also to test morphologic models in a field setting. The removal of the dam made available a volume of sediment equivalent to several years of the river's annual load to fluvial erosion and transport. The changes in the river bed were modeled during the planning process with a non-coupled two-fraction 1-D sediment transport model. This predicted the overall pattern and magnitude of deposition relatively accurately. There are several areas where the measured bed elevation change did not match the predictions. These can be attributed to uncertainty associated with a difficult-to-access narrow bedrock gorge for which virtually no bathymetric data existed, and to localized steep slopes associated with a logjam-induced rapid. In future problems of sediment routing through long reaches (50+ km) of river, a 1-D model seems appropriate, but when detailed responses (erosion or deposition on individual features of the bed) are required, a more detailed study must be undertaken to understand the distribution of bed changes within the 'reach average' value that a 1-D model calculates.

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