Simulating dam removal with a 1D hydraulic model: Accuracy and techniques for reservoir erosion and downstream deposition at the Chiloquin Dam removal

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ABSTRACT

Hydrodynamic models are often used to reduce uncertainty regarding the outcomes of dam removal, though the accuracy of these models is not regularly evaluated post-removal. With the goal of improving understanding on the accuracy and limitations of making predictions of sediment dynamics following dam removal, we compare predicted and observed sediment erosion and deposition in the reservoir and downstream for the Chiloquin Dam removal. Results from a 1D (HEC-RAS) hydraulic and sediment transport analysis (Yang equation) are compared to pre- and post-removal bathymetric and sediment surveys. Observed bathymetric changes indicate minimal response in both the reservoir and the downstream reaches to the removal, due in part to the low water year and the low volume of sediment stored in the reservoir following drawdown. Model simulations overpredicted erosion in the reservoir and downstream relative to what was observed, likely due to a combination of limited field documentation of resistant hardpan and to issues in model stability. Magnitude and potential sources of error are presented and suggestions are made regarding data needs and potential modeling approaches in future dam removal studies.

INTRODUCTION

Sediment management is one of the central issues in the design and implementation of dam removals (Downs et al. 2009), and hydrodynamic models are frequently used to reduce uncertainty regarding the sediment. A handful of models specific to dam removal (Cantelli et al. 2007, Cui et al. 2006a, Cui et al. 2006b), as well as more general hydrodynamic applications (HEC-RAS, MIKE 11, GSTARS), are available for simulating responses of rivers to the erosion and downstream pulse of reservoir sediments generated by dam removal. For example, simulation outputs of HEC-RAS (Brunner 2008), a 1D longitudinal hydraulic model, have been coupled previously with HEC-6 sediment transport calculations for the Chiloquin Dam removal to investigate whether fine sediment from the reservoir would deposit in riffles, key spawning areas, and at the location of the new pumping plant (Bauer and Randle 2005). Cui and Wilcox (2008) describe the application of DREAM, a 1D cross-sectionally and longitudinally averaged sediment transport model, at the Marmot Dam removal site to investigate potential aggradation and suspended sediment concentrations under various flow and sediment management scenarios.

Other studies (Cheng 2005, Downs et al. 2009, Roberts et al. 2007, Wyrick et al. 2009) present additional examples of various applications of hydrodynamic models in the study of dam removal, and Cui and Wilcox (2008) present a thorough overview of the key issues in modeling dam removal.

However, a number of challenges exist in implementing both dam removal specific and more general hydrodynamic models for the application of dam removal. For example, some (Ferguson and Church 2009) have rightly criticized the use of 1D models in non-uniform rivers due to the spatial and temporal variability of sediment dynamics across and down rivers. The spatial and temporal variability of channel dynamics associated with dam removal challenges the assumptions and limitations of 1D models and introduces a number of issues regarding data requirements and model interpretation. Therefore, this paper presents a case study analysis of applying HEC-RAS 4.0 to the Chiloquin Dam removal to:

- Simulate locations, depths, and sizes of deposition in the Sprague River for the water year following removal
- o Investigate how 1D models may used in the context of dam removal

Study Site Description. The 4050 square kilometer drainage area of the Sprague River is on a volcanic plateau east of the Cascade Range in south-central Oregon (Figure 1). The basin is more than half public lands (56 %). The remainder of the basin is private forest (24 %), rangeland (11%), or irrigated agriculture (6%) (NRCS 2005).

The Chiloquin Dam was located on the Sprague River about 0.87 miles upstream from the confluence with the Williamson River (Figure 2, Table 1). Downstream from this point the Williamson River enters Upper Klamath Lake. The dam was constructed in a bedrock canyon of volcanically derived rock in 1914 for irrigation diversion. The reasons for removal of the dam in 2008 included safety concerns of the deteriorating structure and the barrier it presented to fish passage for endangered shortnose and Lost River suckers, among other species.

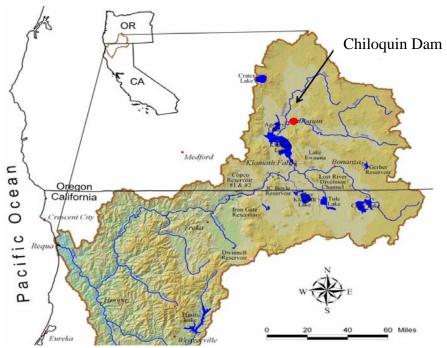


Figure 1. Location map (courtesy of Mike Neumann, BOR)



Figure 2. Chiloquin Dam from downstream prior to removal (left) and post removal (right).

Table 1. Dam and reservoir characteristics

Dam height: 3.35m	Dam length: 67m	
Reservoir width/river width: 1.8	Reservoir volume to mean annual river	
	flow: 0.000142	
Sediment Volume: Estimated 49,000	Sediment Composition: Silt and clay	
- 61,000 tons	(39%), sand (52%), and gravel (9%)	
(Randle and Dariao 2003)	(Randle and Dariao 2003)	

METHODS

Field Data. Field data from multiple sources were collected both as input to the model and for comparison with model outputs (Table 2). Three types of equipment were utilized for the topographic/bathymetric surveys: Real Time Kinetic (RTK)

Global Positioning System (GPS) for riffles, Acoustic Doppler Current Profiler (ADCP) for pools, and Light Detection and Ranging (LiDAR) for the floodplains. The RTK GPS surveys were performed with a Topcon Hiper Lite + (for 2008) and a Topcon GR-3 (for 2009) by Oregon State University (OSU), including the reservoir and cross sectional surveys of the downstream riffles. Coordinates of these surveys were post processed by submitting base station logs to the Online Positioning User Service (OPUS) as static and translating the associated points relative to the base station correction (NGS, 2009). The ADCP data was collected and processed by the Denver Technical Services Center of the Bureau of Reclamation (BOR) using a Teledyne RD Instruments 1200 kHz Workhorse Rio Grande ADCP and a Trimble 5800 RTK GPS (BOR, 2006). The ADCP data consisted of a longitudinal profile of the thalweg and zig-zags across the channel to represent cross sections. The LiDAR data was collected and processed by Watershed Sciences for the Klamath Tribes (Watershed Sciences and MaxDepth Aquatics, 2005). The LiDAR bare earth model point spacing was approximately 0.5 m, and extended more than 1 km from the main channel within the study area.

The sediment sampling for the study area consisted of pebble counts and grab samples. Pebble counts were performed at each cross section in the riffles by OSU (Wolman, 1954), and grab samples were performed within each pool by BOR. Initial values for Manning's n were estimated in the field in 2009 using Cowan's method (1956). The nearest (7 km upstream of the reservoir) USGS gage on the Sprague River (#11501000 near Chiloquin, OR) provided the flow series and temperature for the model.

Table 2. Sources of model input data

Component	Channel unit	Method	Years	Source
Topography/	Riffles	RTK GPS	2008, 2009	OSU
bathymetry	Pools	ADCP	2007, 2008, 2009	BOR
	Floodplain	Bare earth model from LiDAR	2004	Klamath Tribes
Sediment	Riffles Pools	Pebble counts Grab samples	2008, 2009 2008, 2009	OSU BOR
Temperature, discharge	All	USGS gage #11501000	2009 water year	USGS
Manning's n	All	Estimated	2009	OSU

Model Details. The modeled area stretches from 460 m upstream from the dam to 1.2 km downstream, encompassing the reservoir, two riffles, and two pools. Riffle and reservoir cross sections were evenly spaced within each particular channel unit dependent on its length, ranging from 20 to 180 m, while pool cross section locations were picked for point density and geomorphic significance, i.e. at the head, tail, and maximum depth. Several interpolated cross sections were added to the model to increase stability at abrupt channel transitions in elevation and width. The model was calibrated for low flows by adjusting the main channel Manning's n for each cross

section until the modeled water surface elevation was within 0.1 m of the observed water surface elevation.

Quasi-unsteady flow analysis is used within HEC-RAS to simulate river hydraulics and sediment transport. The quasi-unsteady flow analysis approximates a flow hydrograph by a series of steady flow profiles associated with corresponding flow durations. Flow, stage, temperature, and sediment loads are held constant over each specified flow duration. The flow duration is then divided into computation increments, with constant flows but changing bed geometry and hydrodynamics. Finally, computational increments are divided into bed mixing time steps, where the mixing layers may be rearranged, thus adjusting the sediment transport capacity (Brunner 2008). Determining the appropriate flow, computational, and mixing steps can be a critical element of dam removal modeling, as it may strongly influence the stability of the model.

For our simulations, the quasi-unsteady flow consisted of a flow series (October 1, 2008 to August 15, 2009) for the upstream boundary condition and normal depth for the downstream boundary condition. The input data for the flow series was compiled from average daily discharge and unit (30 minute interval) discharge such that flow did not change more than 10 % between entries (Table 2). The slope for the normal depth (0.6 %) was the average of the slopes of the left and right water surfaces for the four most downstream cross sections, which encompassed a riffle. To achieve model stability, 7 days of constant flow (4.3 cms) and temperature (15 °C) were added to the beginning of the flow series, and the computation increment was adjusted down to 0.05 hours.

The Yang (1973) sediment transport equation was applied, using Exner 5 (Thomas 1982) as the sorting method and Rubey (1933) as the fall velocity method. Sediment data was entered into user defined grain classes as ½ phi unit classes (from 2 to 1024 mm). Sands (63µm to 2mm) and fines (less than 63 µm) were differentiated manually by hand texturing in the field and entered separately into the model. The erosive boundaries were set to a max depth, ranging from 0.5 to 2 meters, as estimated depths to hardpan for each cross section. Sediment parameters which were adjusted from the default included: specific gravity (to 1.75 from the default of 2.65) and bed exchange iterations per time step (to 25 from the default of 10). Specific gravity was estimated from the average of 8 sand samples taken below the dam site (in riffles 1 and 2) in October of 2009. We used a flow load rating curve for the upstream sediment boundary condition. This curve was develop from a) suspended sediment concentration vs. discharge relationships and b) the ratio of suspended load to bedload, developed between February 2004 and June 2006 on the Sprague River system (Graham Matthews and Associates 2007).

Error Analysis. Observation error for these channel surveys was a result of measuring a continuous feature with discrete points using instruments (RTK GPS, LiDAR, and an ADCP) with measurable uncertainties. The observation errors can be important to provide context for the modeled and observed changes. Error estimates for the ADCP and LiDAR data were based upon values reported elsewhere (Watershed Sciences and MaxDepth Aquatics, 2005; Wilson et al., 1997). Repeat surveys of cross sections were performed to measure our ability to consistently

represent the bathymetry using the RTK GPS, providing context for year to year comparisons. The error between repeat surveys was calculated as differences in channel area and bed elevations by interpolating points on each curve such that there was an interpolated point to match each observed point at each station, and calculating and compiling the differences for each cross section. Differences between the repeat surveys may be due to rod placement relative to particles (Chappell et al. 2003), operator point choice on a heterogeneous surface, and instrument error (Downward 1995).

RESULTS

Summary of observations and errors. Discharge for 2008-2009 was consistently below the historic median for the 85-year record, and in most months (all but March-June) below the 25th. The 2009 water year was very dry with few substantial rainfall events early in the season.

One year following removal, little reservoir erosion was observed (Figure 3). The limited erosion of reservoir sediments is likely explained by a) substantial removal of fine sediments during drawdown, re-establishing the riffle-pool channel before the structure was removed, and b) a lack of flows adequate for transporting coarser material. It is important to note that the pre-removal survey represents the post-drawdown channel when the reservoir was accessible and not the historical reservoir condition. Downstream of the dam, we observed limited deposition in the first riffle and in the second pool (Figure 3). Because our surveys were only performed annually during the low water period, these results do not reflect the patterns of deposition and scour that may have occurred throughout the winter.

The majority of the observed erosion or deposition both in the reservoir and downstream was within error bounds. The level of error varied across survey techniques, with the ADCP measurements adding larger errors (\pm 0.2 m) than GPS measurements (\pm 0.1 m).

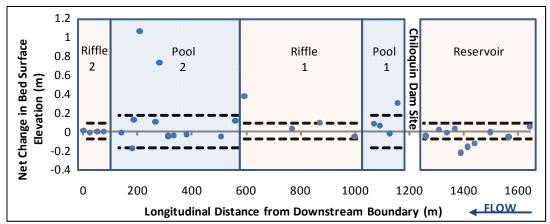


Figure 3. Measured erosion and deposition at cross sections 1 year following the removal of Chiloquin Dam. The dotted lines represent measurement error.

Observed vs. modeled changes. In comparing observed changes to predicted changes in average bed elevation (Figure 4), the sediment model overpredicts erosion

in both the reservoir and in channel below the dam. Most notably, the model erroneously eroded the bottom of the second large pool downstream. The failure of the model to capture the deposition in the pools may be related to the

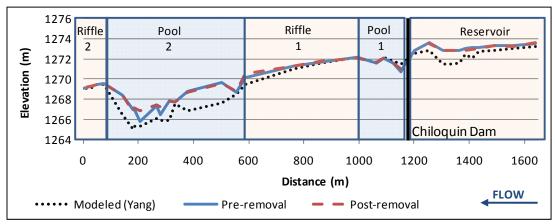


Figure 4. Observed and modeled average bed elevations by cross section relative to distance from the downstream boundary.

hardpan layer that exists near the surface in some areas of this reach. This hardpan is resistant to erosion but highly variable in depth and exposure, making it difficult to model accurately, particularly in deep pools (8-10m) where detailed mapping of exposed hardpan is not feasible.

While limited volumetric changes were observed in the reservoir, nearly all cross sections in the reservoir were observed and modeled to coarsen as finer material was evacuated post-removal (Figure 5). However, the model greatly overestimates the grain size for the reservoir relative to observations, particularly at the cross section 130 m upstream from the dam. This cross section is located at the major slope break, transitioning from 0.0009 to 0.0131, between the reservoir and the downstream channel. The model is consequently simulating a local increase in shear stress and transport capacity across this point. However, grains of this size do not move into or through the reservoir, illustrating that model results at the reservoir-river transition must be interpreted with caution.

Some fining of the surface grain size distributions was observed in both riffles downstream of the dam, while little change was observed in the pools. This pattern was not well predicted by the model simulations, as very limited fining was simulated for riffles and pool 2 appeared to coarsen.

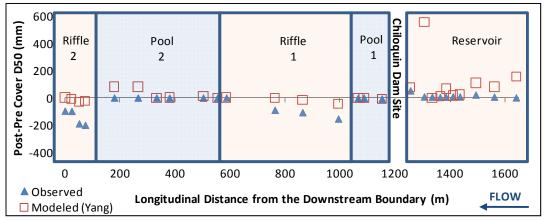


Figure 5: Observed and modeled change in D50 over the 2009 water year.

Reservoir erosion. Between the post-drawdown and post-removal surveys, we observed relatively little erosion from the reservoir: small amounts of lateral erosion 80m upstream from dam, and minor vertical incision midway (200m upstream of dam) through the reservoir (Figure 6). Loss of silt and sand from the active channel within the former reservoir was visibly apparent (a historic bridge structure buried for many years in the sand was unearthed). The model results predict greater erosion of the reservoir sediment than was observed, incising the pre-removal channel roughly uniformly, as expected with a 1D hydraulic model (Figure 4). This figure is characteristic of most of our modeled cross-sections, with relatively uniform increases and decreases in bed surface, that result from the averaging of hydraulic conditions across the channel in 1D models.

Downstream deposition. In cross section, the 1D model generally missed localized and isolated deposition observed downstream, such as along riffle margins. Our surveys indicate some deposition occurred in the first riffle below the former dam. This deposition occurred both within the channel and along the margins and between larger clasts, as noted by the changes in D50 (Figure 4). However, overall topographic changes in riffle 1 remained small between our surveys (Figure 3), which is consistent with model simulations (Figure 4) for this riffle. It is likely that most sediment was transported through the downstream reaches during the fall and winter flows, despite their low magnitudes. Throughout the winter, undocumented deposition occurred in this first riffle (315m downstream of dam), evident from the repeated burial of USGS antennas by sand, which were placed along the channel margins directly downstream of the dam site for monitoring fish movement (Scott Vanderkoi, personal comm.).

Pool surveys indicate that some sediment has deposited in the pool directly below the dam site, with greater deposition at the larger pool further downstream (Figures 3, 4). This suggests that sediment released from the reservoir during drawdown and following removal is rapidly moving downstream despite the low flows over the winter. Sediment transport simulations predict deposition for the first pool as a uniform increase in bed elevation across the pool. For the second pool, the bed was predicted to erode (Figure 4), likely due to inaccurate (user) estimates of the erodible depth due to the irregular exposure of resistant hardpan and to abrupt changes in slope that result in near-critical depth just upstream of the second pool.

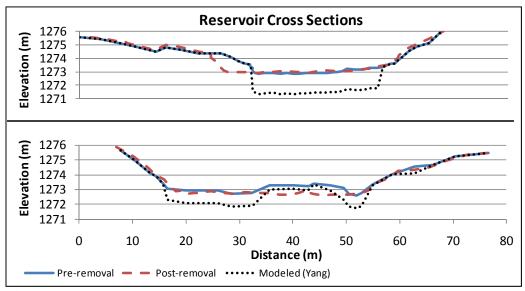


Figure 6. Reservoir cross sections approximately 80 m (top) and 200 m (bottom) upstream from Chiloquin Dam.

DISCUSSION

Models of the Chiloquin dam removal are limited in their ability to capture the small levels of erosion and deposition that were observed, particularly those changes that occurred along the margins. Model simulations overpredicted erosion in most areas, with a maximum of nearly 2m error in the second pool downstream. We believe these errors are primarily due to model instability associated with abrupt changes in slope that create near-critical flows, and to inaccurate (user) estimates of the variable depth for the resistant hardpan layer in the channel.

Appropriate modeling. HEC-RAS may be useful for modeling the erosion and deposition following dam removal in some systems, where larger net changes occur and average bathymetric and sediment changes are adequate, rather than prediction of detailed geomorphic patters. In using HEC-RAS and other hydraulic models for simulating dam removal, users should consider assumptions of 1D hydraulic and sediment models and the temporal and spatial resolution of the model when interpreting the results. For example, users should consider appropriate questions and scales (e.g. reach-averaged) for this class of models, such as:

- Annual rates: Timing and rate of degradation from reservoir
- Amounts: Volume or mass of reservoir sediment to be eroded, volume or mass of sediment deposited downstream, sediment concentrations downstream
- Extents: Average depth of bed incision/aggradation with distance downstream
- Spatial characteristics: Grain size distribution of surface layers, locations of potential downstream depositional zones, average bed profiles

Modeling the reservoir. Our results illustrate some of the errors associated with predicting changes across the channel using 1D models. Thus, appropriate questions

for 1D models will focus on average depth changes, as opposed to specific cross-sectional changes. This may be critical to the study of dam removal, where consideration of geomorphic processes (knickpoint retreat, incision, and widening, Grant et al. 2008) driving dam removal responses is needed. In our system, the vertical transition between the reservoir and the downstream channel was small and no large incision process occurred, making the assumption of uniform erosion across the channel more acceptable. For larger dams with coarser sediment and a greater vertical transition between the reservoir and downstream river, this assumption is likely not valid, and will require thoughtful consideration of how to simulate the vertical and lateral channel changes predicted in many dam removals. A number of approaches may allow modeling more complex reservoir erosional processes using HEC-RAS:

- *RAS 4.0*: Simulate upstream and downstream reaches independently (Cui and Wilcox 2008), using the output of reservoir erosion as the upstream boundary condition for the downstream reaches.
- RAS 4.1: Simulate Schumm et al's (1984) channel adjustment model, adjusting erodible limits and critical shear stress between stage II and III to simulate widening (Thomas 2005). The model would be allowed to incise a narrower channel down to the critical bank height. The user then widens the erodible limits to allow lateral erosion of banks. The final width and location of the channel may be predicted by historical photos, and by the width of the channel upstream of the reservoir.
- *RAS 4.2*: Will include an erosional model (Cantelli et al. 2007) that simulates a "pivot point," located near the center of the delta front, around which erosion and deposition occur.

For any of these approaches, users must consider whether their systems match the underlying conceptual models (Schumm 1973, Cantelli et al. 2007).

Model stability. In considering any manipulation of the model to better represent the complex hydraulics of dam removals, model stability becomes an important concern. While HEC-RAS can perform supercritical flow calculations, it often drives instability in the hydraulics and sediment transport calculations. This is often due to "unrealistic" hydraulic gradients and vertical adjustments generated in simulating a dam removal. However, a number of computational adjustments may be considered to improve model stability, including:

- *Computation increments*: Because flow and bed geometry are updated at different increments, stability issues occur with large computational increments because the bed geometry is not updated frequently enough. However, decreasing computation increments greatly increases simulation run time.
- *Boundary conditions*: Model stability is sensitive to definition and stability of upstream and downstream boundary conditions, including errors in boundary data (e.g. flow-load curve).
- *Hydraulic averaging*: While averaging hydraulics between cross sections is commonly used to increase model stability, it may not be appropriate for dam removal scenarios where cross sections represent important transitions. Instead,

- adding cross sections to allow the water surface to adjust vertically over a series of cross sections may be more appropriate.
- *Erodible limits*: Sediment transport functions are highly sensitive to local changes in channel hydraulics, creating instabilities in the model. Thus, selecting and adjusting limits that are representative of the field conditions can be important in the calibration of dam removal models.

A sensitivity analysis, not reported here, found our model stability and predictions to be most responsive to changes in the sediment upstream boundary condition and the choice of sediment transport equation.

Input data. In addition, some issues with model stability can sometimes be avoided by considering data requirements for the modeling effort prior to dam removal to ensure adequate data are collected. Thus, we recommend that monitoring plans include efforts to document:

- *Bathymetry*: Adequate XS density based on the variability of the channel hydraulics (Samuels 1989) and thorough mapping of resistant bed materials (e.g. bedrock, hardpan) if present and near the surface.
- *Stage and discharge*: Water surface elevations at higher, sediment transporting flows are critical to calibrating the model.
- Suspended and bed sediment loads: Suspended sediment concentrations and bedload (if a substantial portion of total load) observations are expensive but important measures for establishing boundary conditions and for model calibration.
- *Observation error*: Replicate samples (sediment, bathymetry) provide some context for errors in data relative to errors in the models.

Further, it is important acknowledge that observation error associated with stitching together multiple datasets or inadequate coverage of key model inputs requires substantial time to rectify and can contribute to substantial model error.

CONCLUSION

The removal of Chiloquin Dam appears to have had limited geomorphic impact on the Sprague River. The changes were small and consequently difficult for any hydrodynamic model to predict accurately. However, this work highlights some of the primary values, considerations, and challenges of using 1D models to predict dam removal responses. As more refined models are developed and evaluated, the basic principles of using quality data, considering model assumptions and limitations, and establishing appropriate model questions and expectations will continue to be important.

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