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Upstream Geomorphic Response to Dam Removal: The Blackfoot River, Montana

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UPSTREAM GEOMORPHIC RESPONSE TO DAM REMOVAL:
THE BLACKFOOT RIVER, MONTANA

By

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As dam removal is increasingly used as a tool to restore rivers, developing a conceptual and field-based understanding of the upstream fluvial response is critical. Using empirical data and modeling, I investigated the spatial and temporal pattern of reservoir sediment erosion and upstream channel evolution of the Blackfoot River, MT, following the 8 m base level reduction caused by the removal of Milltown Dam. Field data collected include surveys of channel bed topography and water surface elevation profiles which were integrated into a flow modeling approach. Headward erosion extended 4.5 km upstream of the dam site during the first five months following the dam removal. In the lower 1.8 km of the reservoir, up to 3 m of highly mobile silt and sand was evacuated. Upstream, the river incised into a coarse deltaic sediment deposit (D_{50} 70mm) in the upper reservoir. The analysis of erosion through the hydrograph shows that the channel incised up to 2 m in some locations and maximum volumetric erosion of 260,000 m^3 was reached several days after the flood peak (286 m^3/s, 3.5 year return interval). Net erosion following the dam removal, accounting for both scour and deposition, was 150,000 m^3 across the 5 km study reach. The modeling-based water surface elevation analysis revealed the intra-hydrograph pattern of erosion that otherwise would have been missed by comparing pre- and post-removal cross section topography. The post-removal evolution of the lower Blackfoot was heavily influenced by confinement of the channel and the above average discharge. Widening was associated with areas of local aggradation, whereas narrowing was associated with degradation—a finding similar to those from previous flume experiments.

Key words: Dam removal, reservoir sediment erosion, upstream geomorphic response, base level, large woody debris.

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I. INTRODUCTION

Caught at the crossroads of declining ecosystem services, decaying infrastructure, and increasing interest in ecological restoration, the U.S. has entered into an era of dam removal (Doyle et al. 2008). Dam removal is perhaps the largest of available options to restore rivers, but in many cases has a significant potential to restore or enhance ecosystem services valued by society (Graf 2002, Pizzuto 2002). Despite decades of dam removal practice, there are few detailed studies performed before and after such projects are completed to enhance our understanding of river response (Doyle et al. 2002). From planning stages to execution, perhaps the most critical element to dam removal projects is the fate of sediment stored behind a given dam (Shuman 1995, Cui and Wilcox 2008). The fate of reservoir sediment can be the costliest and least certain component of a dam removal, and is therefore of interest to scientists and policy-makers (Cui and Wilcox 2008). Reservoir sediments may be a source of contamination, interact with certain life history stages of aquatic organisms, or affect adjacent communities. Furthermore, the questions surrounding the evacuation of reservoir sediment is coupled with the how a channel upstream of a given dam will evolve.

This study will focus on the upstream sediment dynamics including erosion of reservoir sediment and the evolution of the newly reclaimed Blackfoot River above Milltown Dam. The Milltown Dam removal is part of the larger > $100 million dollar multi-year Superfund remediation effort. While significant resources were allocated to feasibility studies to prepare for the dam removal and mechanical excavation of contaminated sediments, significant questions surrounding the fate of reservoir sediment and the upstream response of rivers remain for scientists and policy-makers to consider in future dam removals. For example, in the first spring runoff following the removal of the dam, 180,000 m^3 of contaminated sediments eroded from the upper portion of the Clark Fork arm of Milltown reservoir (Wilcox et al. 2008). The 180,000 m^3 is equivalent to ~4500% of the volume predicted to be eroded from the upper reservoir area by the pre-removal modeling efforts (Envirocon 2004). The spatial component of the upstream response was not captured by the modeling efforts applied to the problem of predicting reservoir sediment erosion to manage contamination.

Fluvial Sediment Dynamics and Base Level

Building a dam creates a reservoir where sediment transport capacity is greatly reduced. Annual sediment loads supplied from upstream hill-slope and fluvial processes are trapped by the low velocity slack-water behind a dam, filling the reservoir with sediment over time (Graf 1999, Graf 2002). When a dam is removed, the sediment balance tips in the opposite direction: the system's capacity to transport sediment is increased while having a large supply in the reservoir sediment deposit. Dam removal reactivates sediment supply to downstream river reaches in a sediment pulse (or series of several pulses) as the reservoir deposit erodes. The post-removal sediment pulse may be orders of magnitude higher than typical seasonal sediment flux in a given river system, because of the potentially large reservoir sediment deposit and the unique geomorphic context which can lead to flux of large volumes at high transport rates (Major et al. 2008).

The concept of base level is useful in placing upstream geomorphic response to dam removal into a theoretical context. Given upland watershed processes and climate operating within normal levels of variability, rivers tend toward an equilibrium base level, defined as the level below which a river cannot down-cut (Leopold and Bull 1979). Base level is considered to be a downstream control on rivers, a reduction of which will cause upstream degradation or incision (Knighton 1998). Base level changes can occur over geologic time scales through tectonically driven uplift which may create landscapes in a transient state (Crosby and Whipple 2006, Bishop 2005). The rapid decrease in water surface elevation caused by dam removal can be considered as a change in local base level (Doyle et al. 2002). Such a case may constrain the upstream fluvial response to a shorter time scale than in other physiographic settings, such as in bedrock systems. For example, a study of upstream migrating incision into networks of bedrock channels found climate-driven base level fall propagated knickpoints upstream over 18,000 years (Crosby and Whipple 2006).

Base level may change due to naturally occurring processes at the confluence of two rivers through altered climate and discharge (Leopold and Bull 1979) or changes in incision rates at the main-stem river (Crosby and Whipple 2006). Base level for streams flowing into lakes can be set by long-term fluctuations in lake level driven by climatic variations (Galay 1983, Figure 1).

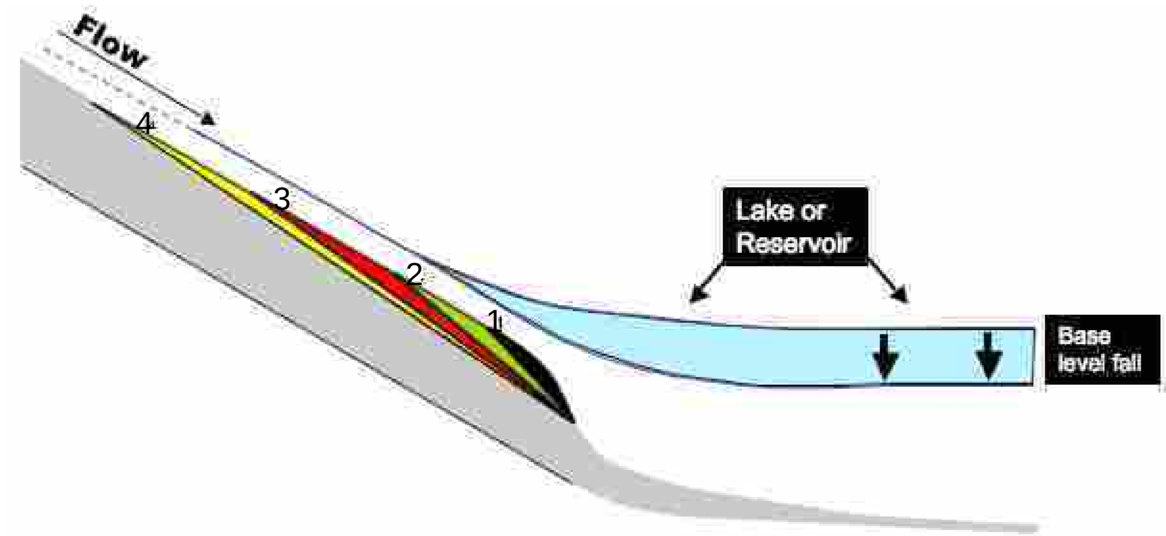


Figure 1. Idealized diagram of base level fall from a reduction in lake or reservoir elevation. Progression of upstream erosion through time (t = 1 through 4). Adapted from Galay 1983.

Furthermore, changes in sea level and anthropogenic disturbances such as water diversion, dam construction, reservoir regulation and dam removal are additional drivers of base level change. In the case of dam removal, the base-level drop reduces the downstream control on the stored reservoir sediment (Doyle et al. 2002) and will initiate upstream geomorphic response such as incision and headward migrating knickpoints (Larue 2008). Other potential responses include changes in slope, surface sediment textures, roughness, sinuosity or lateral channel migration resulting in altered aquatic and associated riparian habitats (Leopold and Bull 1979). Furthermore, the literature has been summarized to predict that the effect of base level fall will be most pronounced when it occurs rapidly and the upstream channel is confined (Knighton 1998).

Conceptual Model of Reservoir Sediment Erosion and Channel Evolution

Channel evolution following base level reduction has been explored both in the field and laboratory by several authors (Begin 1981, Schumm 1984, Simon and Hupp 1987, Begin 1988, Doyle et al. 2002, Doyle et al. 2003, Cantelli et al. 2004). Channel evolution models (CEMs) that originate in empirical studies of incised sand-bed channels have been applied to dam removal (Doyle et al. 2002, See Figure 2). Accordingly, headward migrating channel degradation increases bank height above a lowering bed surface, leading to channel widening driven by bank failure (which is controlled by bank angle, height, and sediment cohesion properties). Sediment contributed to the channel from widening (bank failure) can mitigate the effects of degradation, or where critical discharged for downstream transport of bank material is reached, greatly increase the total amount of sediment evacuated from a given stream reach (Doyle et al. 2002). Flume experiments on dam removal found erosional narrowing to occur during the initial incision into the reservoir deposit (Cantelli et al. 2004, Cantelli et al. 2007). As the flume channel rapidly incised into the reservoir sediment deposit, the channel actually narrows before widening.

Following perturbation of the system through base level change, it would be expected that fluvial response would lead to some state of equilibrium. One field study described upstream channel response to base level rise approaching a new equilibrium state with a similar slope to the pre-perturbation channel. The development of an upstream sediment wedge resulting from dam construction extended 1.5 km upstream after 25 years and adjusted to 83% of the initial slope (Van Haveren et al. 1987, Knighton 1998). In the case of dam removal, it may be possible that post-removal channel equilibrium would reach a slope similar to pre-dam conditions at a different mean bed elevation following degradation.

It has also been shown that in some sand-bed systems, upstream channel evolution following base-level fall is governed by the migration rate of a knickpoint (Doyle et al. 2002). A knickpoint is a point of dramatic slope increase in the longitudinal profile of a stream inclusive of small rapids through the spectrum to a vertical waterfall (Brush and Wolman 1960, Crosby and Whipple 2006). Knickpoints migrate upstream over a variety of timescales depending on the individual case, and are often formed by base level fall. A knickpoint may maintain its shape and move upstream as a stepped knickpoint. Alternatively, it may get longer and less steep if the top of the knickpoint erodes faster than the base, creating a rotating knickpoint (Stewart 2006). Flume experiments investigating "blow and go" removal of a dam with results up-scaled to gravel-bed rivers support the rotating knickpoint phenomena (Cantelli et al. 2004). Field observations of low-head dam removals in sand bed, low gradient systems in the mid-west found both stepped and rotating knickpoints migrating upstream through reservoir sediment deposits (Doyle et al. 2003, Cheng and Granata 2007, Evans 2007, Major et al. 2008). Furthermore, knickpoint form is also controlled by how the sediment eroded from the face moves downstream. Stewart (2006) proposed that knickpoints may evolve in four possible modes following dam removal: 1. rotating with diffusion, 2. rotating with dispersion, 3. stepped with diffusion, or 4. stepped with dispersion (Figure 3). As the literature covering fluvial response of fine-bed channels to base level reduction is more developed, there is some disagreement on what form a knickpoint will take in gravel bed rivers. Furthermore, it is possible for erosion of reservoir sediment to occur without the formation of a knickpoint. In the removal of Saeltzer Dam on Clear Creek, California, headcutting was not observed in the coarse sediment exposed to high discharge (Cui and Wilcox 2008).

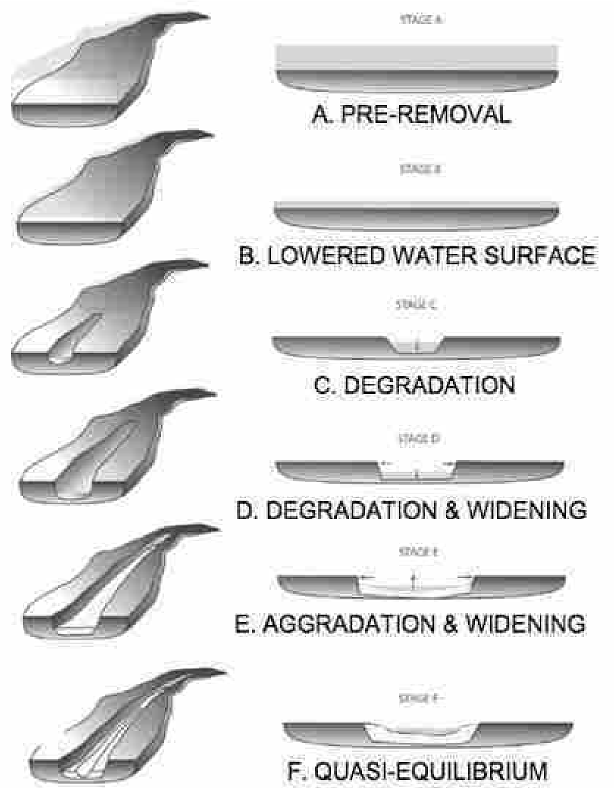


Figure 2. Channel evolution model for upstream response to dam removal from Doyle et al. 2003, based on incising channels. Modifications for larger reservoir and mixed sediment composition of reservoir deposit may be needed for this study.

Studies applying a diffusion model showed that base-level reduction may cause degradation along the length of the channel equal to the amount of base level fall, maintaining a stream with the same slope (Begin 1988, Knighton 1998). Application of these results to the Blackfoot this would predict degradation on the order of 8 m (Begin 1988). It was noted that heterogeneous sediment and armoring could produce different results. The BFR has both heterogeneous sediment, and complications of variable roughness (bedrock, large woody debris, rip-rap banks, and bridge piers). Additionally, the diffusion model results may be inappropriate for application to large unconfined alluvial rivers that can alter sinuosity and roughness preventing the signal of base level fall from migrating far upstream (Knighton 1998), but perhaps more applicable to the constrained BFR channel.

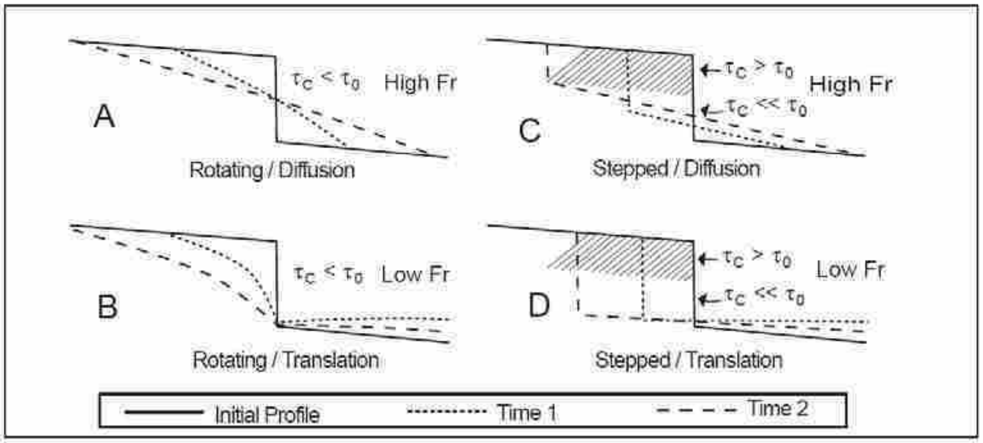


Figure 3. Four potential knickpoint migration patterns proposed by Stewart (2006). Sediment transported downstream is predicted to move via diffusion at high Froude (Fr), and translation at low Fr (from Stewart 2006).

Recent studies of dam removal have centered on low gradient sand-bed, with the exception of the removal of Marmot Dam from the Sandy River in Oregon. Marmot Dam was removed from the Sandy River, a tributary to the Columbia River, on October 19, 2007. Of the 730,000 m^3 of sand and gravel stored behind the dam, 100,000 m^3 eroded within 48 hours of the dam breaching through a combination of headward and lateral erosion of the unconsolidated banks of the newly incised channel (Major et al. 2008). A knickpoint formed at the coffer-dam, which migrated 500 meters in the 48 hour time period. The combination of a steep channel (0.006 - 0.009 m/m) and a discharge of 30% above the mean annual discharge allowed for rapid incision of the channel into the reservoir sediment deposit.

II. THE PROBLEM

The primary objectives of this study are to better understand (1) the spatial and temporal pattern of reservoir sediment erosion, (2) how a gravel-bed river channel evolves upstream of a dam removal. In light of the literature reviewed, I would like to explore the applicability of channel evolution models to a confined, mountain gravel-bed channel. The Blackfoot is a confined, gravel-bed mountain river which flowed into the reservoir behind Milltown Dam from 1907 to 2008. In the Blackfoot arm of Milltown

Reservoir, a fine (silt-sand) deposit accumulated in the lower portion and a coarse deltaic deposit pro-graded downstream in the upper end of the reservoir (additional study site information is detailed in the following section).

I hypothesize that two distinct phenomena will be seen in the upper and lower Blackfoot reservoir reflecting erosion of two bed sediment types. The fine sediment deposit in the lower reservoir will erode rapidly during the rising limb of the first hydrograph these sediments are exposed to. Investigation of the processes initiated by dam removal in mountain gravel bed rivers may enhance our understanding of how rivers respond to such actions. In the case of dam removal leading to a rapid increase in sediment transport capacity with a large sediment supply, I hypothesize that cross sectional area (A) is the dominant variable changing through the first hydrograph expected to erode reservoir sediments. The comparison of observed water surface elevations (WSE_{obs}) to modeled elevations (WSE_{model}) will be used to reveal the process of reservoir sediment erosion through the 2008 hydrograph.

Furthermore, I would like to explore whether reservoir sediment erosion following dam removal can be described by an exponential decay function, where erosion is a function of time and a decay constant (α). Furthermore, roughness and grain size are the key factors that will control the decay constant (α) in the case of the BFR due to the limited lateral migration potential and existence of features that will contribute to roughness (large woody debris, bedrock, etc.). The data set gathered in this study provides the opportunity to test the ability of an exponential decay function to describe reservoir sediment erosion.

Three different approaches were devised to elucidate the surface textural response and the pattern of reservoir sediment erosion in the BFR following the removal of Milltown Dam: (1) a surface sediment texture analysis, (2) a net morphological change analysis, and (3) an analysis of the upstream response through the 2008 spring runoff. A combined flow modeling and field measurement approach was devised to understand the intra-hydrograph patterns of erosion patterns following the breaching of Milltown Dam. By exploring this method, I hoped to achieve a higher temporal resolution to fill in the gap between the two base flow topographic surveys.

III. STUDY SITE

The Blackfoot River (BFR), MT, is a tributary to the Clark Fork River (CFR) and drains an area of 5,931 km^2 (Figure 4, Rothrock et al. 1998). The BFR flows through glaciated meadows in the upper watershed, moving downstream through conifer forest and wetlands, open ranch and timbered areas, then between steep forested slopes with some narrow canyon sections in the lower river before it meets the CFR (Figure 5). The lower BFR is naturally confined to a narrow active zone bounded by steep mountains and canyon walls on either side of the channel. Adjacent development and road projects have further confined the river in some reaches.

Milltown Dam was constructed in 1907 at the confluence of the Blackfoot and Clark Fork Rivers. One hundred years later, in March of 2008, the dam was breached allowing the BFR and CFR to flow freely, exposing more than 100 years of accumulated reservoir sediment in the BFR to river erosion. The Milltown project is unprecedented in size and complexity. The 20 m high, 200 m long dam stored approximately 4.6×10^6 m^3 of sediment in the reservoir, which filled during a 300-500 year flood in 1908. Mine tailings were transported downstream by the 1908 flood largely filling Milltown reservoir with sediment. Decades later, Milltown Reservoir became the nation's largest EPA Superfund site (EPA 2004). The removal of Milltown Dam has garnered substantial attention because of the presence of contaminated sediments in the Clark Fork arm of Milltown Reservoir, but river erosion of uncontaminated sediments from the Blackfoot arm has provided an opportunity to examine upstream geomorphic response.

In addition to Milltown Dam, a second and smaller dam influenced the lower BFR. The Stimson Dam, 2 km upstream of Milltown Dam was constructed in 1884 to supply power to the adjacent lumber mill, and to catch harvested timber floated down the Blackfoot during log drives (Figures 6, 7). The two dams created distinct backwater effects. The Stimson Dam converted the lower BFR into a reservoir-tailwater reach. Approximately 20 years later the creation of Milltown reservoir flooded the Stimson reservoir (Milltown water surface elevation surpassed the elevation of the Stimson reservoir at high discharge). The net result after 1907 was an increase in the base level at the mouth of the BFR, altering local geomorphology, hydrology and ecology in ways typically associated with dam construction (e.g., Dynesius and Nilsson 1994, Graf 1999, Ward and Stanford 1995). Furthermore, the human-induced recruitment of large woody debris to the channel from logging operations upstream left a legacy of > 10,000 individual logs in the lower 3 km of the BFR (Figure 6). At the time of the dam removal, the large woody debris was located on the bed and buried in the coarse reservoir sediment deposit in the upper reservoir.

The BFR reservoir provides a unique case as it has two spatially distinct sediment deposits: silt and sand up to 3 m deep in the lower 2000 m of the reservoir (Envirocon 2004), and a coarse gravel-cobble deltaic deposit at the upstream end of the reservoir prograding downstream (typical form of reservoir deltaic sediment deposits, Figure 8). The lower 2500 m of the reservoir is the most confined, with maximum confinement in a 500 m section where a rip-rap bank narrows the channel against a bedrock wall. The staged removal of Milltown dam has lowered the reservoir water surface elevation, and base level controlling the upstream channels, from 2006-2008. In 2006, the reservoir was drawn down by 4m to begin the mechanical removal of contaminated sediment from the CFR arm of the reservoir. The March 2008 breaching of Milltown dam lowered the local base level by an additional 5 m. Studies commissioned by the EPA and state agencies estimated 150,000 – 229,000 m^3 of reservoir sediment accumulated in the BFR over the life of the dam (Envirocon 2005).

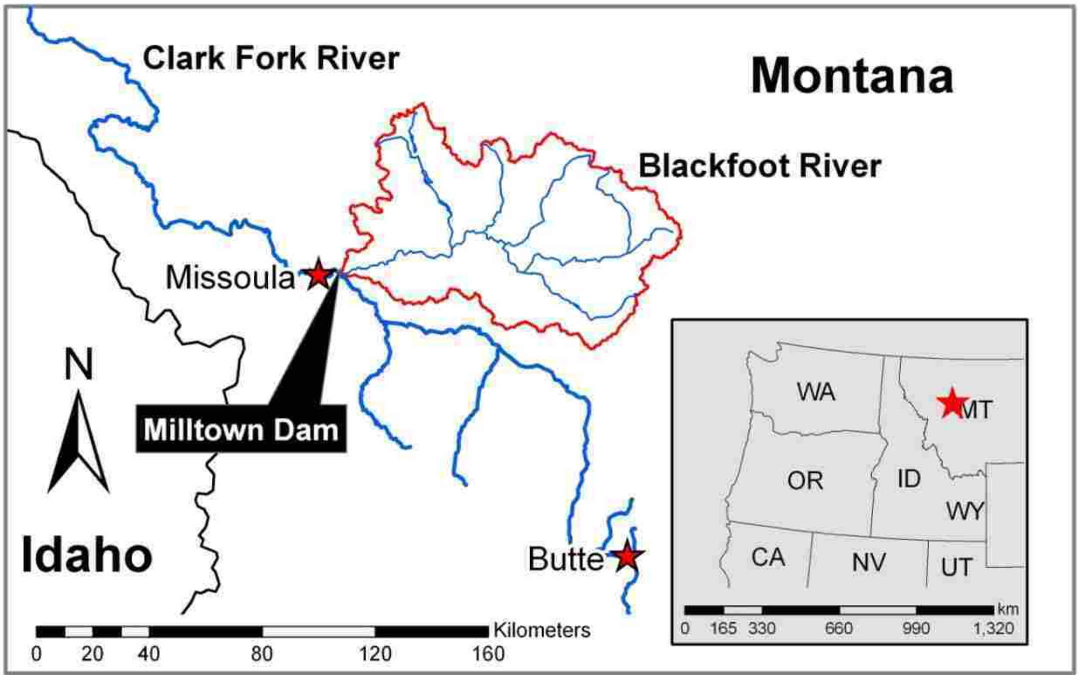


Figure 4. Overview map of the upper Columbia River basin in Western Montana. The Blackfoot watershed is outlined in red and meets the Clark Fork River West of Missoula and immediately upstream of the former site of Milltown Dam.

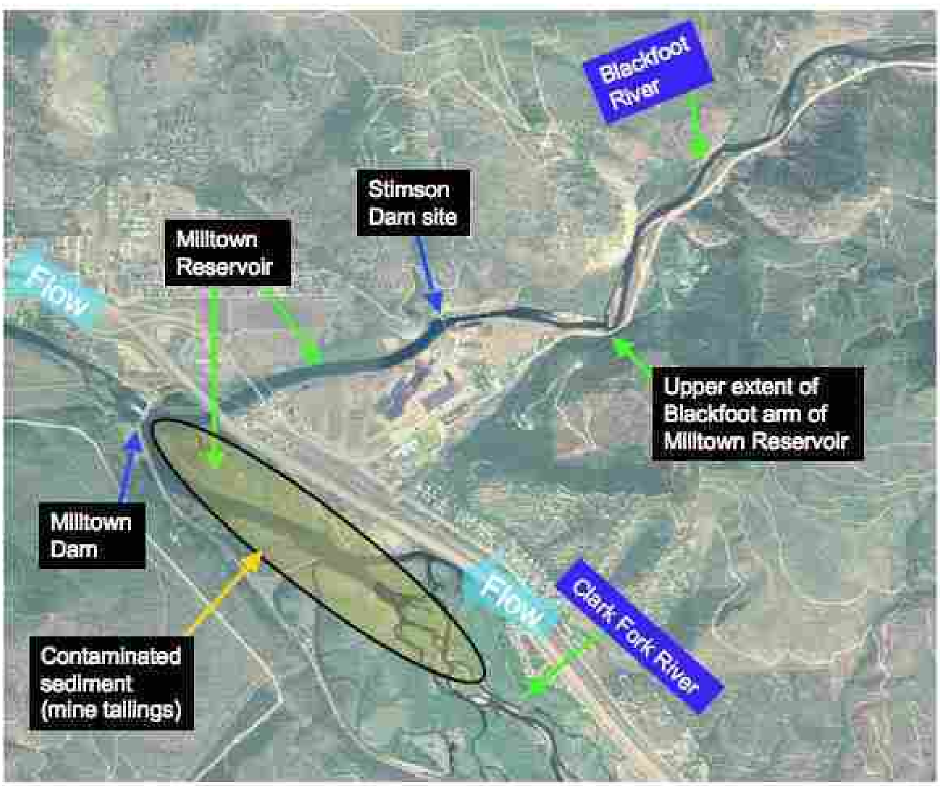


Figure 5. Aerial photo of the Milltown Dam area. Locations of Milltown and Stimson Dams indicated, in addition to location of contaminated sediment removed as a part of superfund remediation program in the Clark Fork arm of Milltown Reservoir. NAIP 2004.

Figure 6. River of wood: cut timber fully covering the Blackfoot River in Bonner adjacent to the Stimson Mill following the 1908 flood (The Montana Collection, Mansfield Library, The University of Montana).

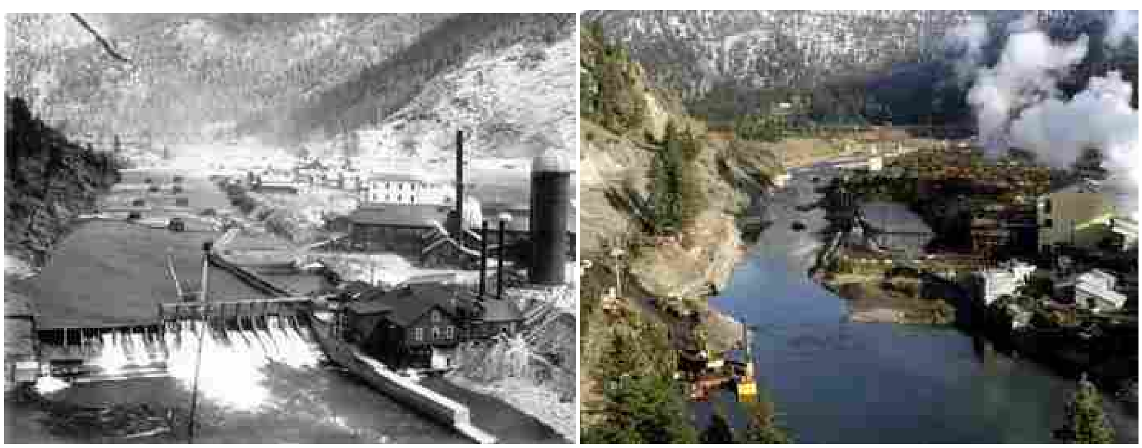


Figure 7. Photographs of the Stimson Dam site on the BFR in the early 1900's (left) and after its removal in 2005 (right). Photos: Montana Environmental Information Center.

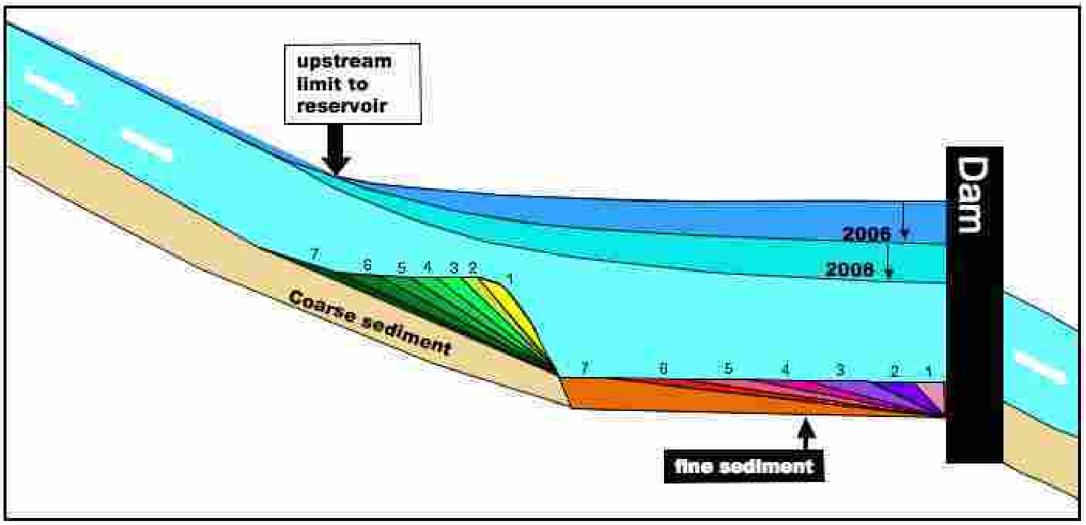


Figure 8. Conceptual diagram of headward erosion of the two distinct reservoir sediment deposits and evolution of water surface elevation from 2004 through the Milltown Dam breach in 2008.

IV. METHODS

To investigate the upstream response of the BFR following the removal of Milltown Dam, three approaches were used: (1) a surface sediment texture analysis, (2) a Spring –Fall 2008 net morphological change analysis, and (3) an analysis of erosion through the 2008 spring runoff. To achieve a higher temporal resolution that fills in the gap between the two base flow topographic surveys, a combined flow modeling and field measurement approach was devised to analyze the pattern of reservoir sediment erosion.

In order to evaluate morphological changes, I measured cross sections throughout the study reach. The BFR-CFR confluence is located in the middle of the Superfund remediation and dam removal site with active construction equipment and crews working at the time this study was done. This made some of the lower river inaccessible for field data collection. The study reach for this project began 900 m upstream of the dam site and extended to 5 km upstream of the dam. Approximately 6 km upstream of the dam, the BFR changes from a gravel-cobble, alternating pool riffle channel to a plane-bed channel with cobbles and boulders. Focusing field efforts on the lower 5km of the BFR was logical given this distinct change in channel type above 6 km and limited time to survey in the Spring of 2008. Cross sections were established in areas that could be surveyed at base-flow ($Q < 17$ m^3/s).

Conventional cross section surveying techniques (total station, survey-grade GPS) were used. Cross sections were surveyed using a Leica Total Station TPS300 and Trimble Real Time Kinematic (RTK) GPS units (R7, 5800 receivers) with maximum horizontal and vertical precision of GPS data of 0.003 – 0.03 m. Seven cross sections were established within the area influenced by Milltown Reservoir in addition to six cross sections upstream (Figure 9). Wade-able cross sections were surveyed in riffles and tail-outs of pools. Boat-based surveys were done in areas that were too deep to wade and had suitable surfaces for setting static line anchors. Cross section data were used to develop longitudinal thalweg profiles.

The response of surface sediment to the change in base level was evaluated using pebble counts or soil cores done in the Spring and Fall of 2008. Wolman 100-particle counts (Wolman 1964) were used where surface texture was > 2mm, and a soil corer in the fine deposit in the lower reservoir where individual grains were smaller than 2 mm (mean D_{50} of 0.2 mm). Bed sediment from the fine reservoir deposit was sieved and the < .5 mm fraction was analyzed using a laser diffractometer (Malvern Mastersizer particle size analyzer). Grain size data were used to assess changes in bed surface texture and grain mobility throughout the study reach at a variety of discharges. Grain mobility was calculated for the two reservoir deposits: the fine deposit in the lower 1.8 km, and the coarse deposit in the upper reservoir. The 2003 Wilcock and Crowe sediment transport function in the Bedload Assesment in Gravel-bedded Streams (BAGS) software was used (Pitlick et al. 2007). I used BAGS to assess grain mobility throughout the study reach, to develop an understanding of where and when particles started moving. BAGS calculates sediment transport rates and incipient motion using six substrate and surface-based transport models. The Wilcock and Crowe 2003 surface-based equation was selected due to its ability to model transport of both fine (<2mm) and coarse sediment. Among the six models in BAGS, Wilcock and Crowe 2003 best represents the influence of sand on gravel transport (Wilcock et al. 2001, Wilcock and Crowe 2003). Reach-average grain size data were combined by averaging percent-finer-than intervals from individual grain size distributions.

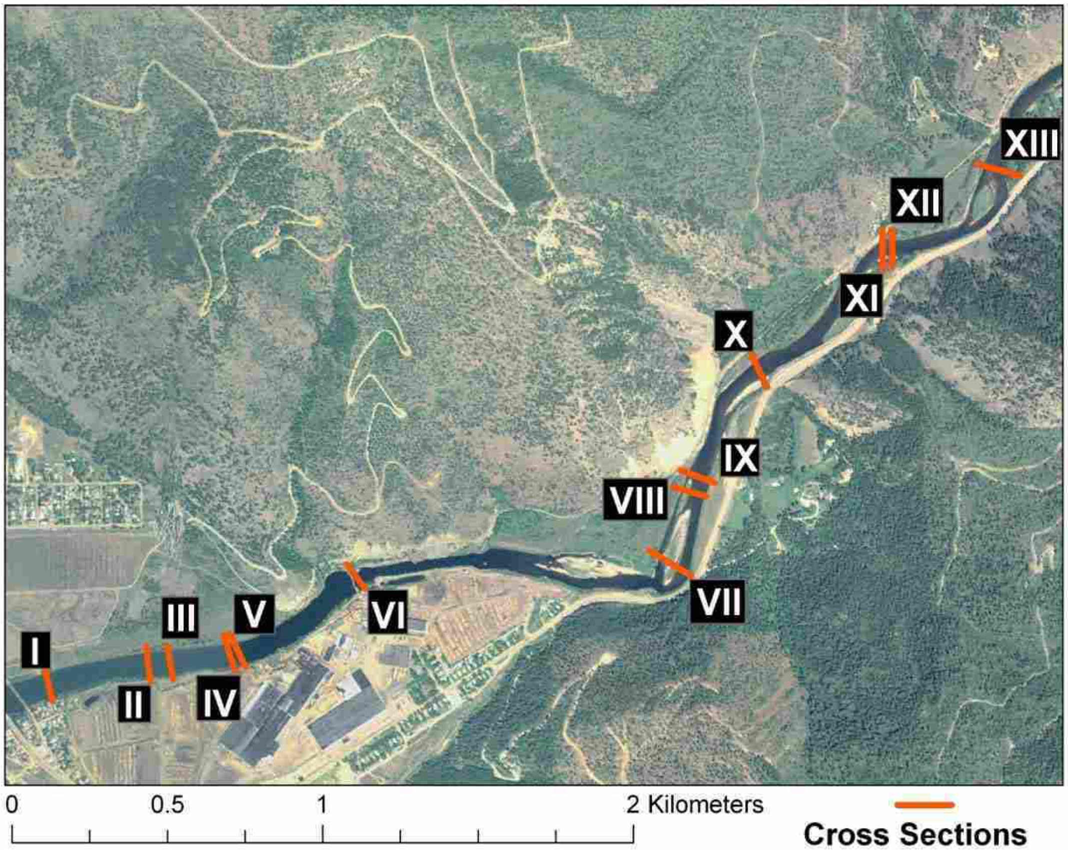


Figure 9. 2004 USDA NAIP aerial photo of the study area. Cross section locations denoted respectively by red lines.

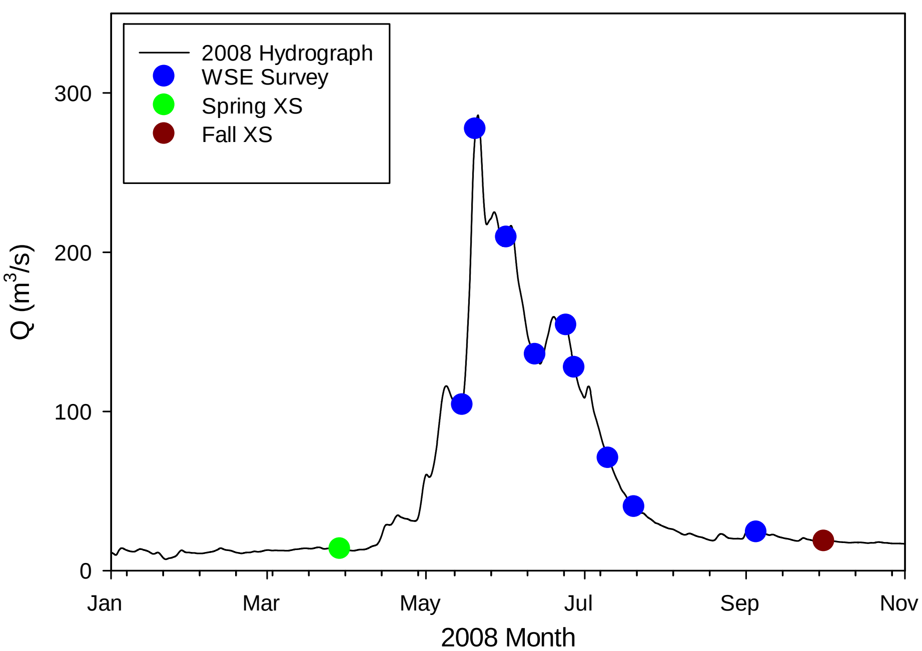


Figure 10. 2008 hydrograph for the Blackfoot River. Closed points show water surface elevation (WSE) survey dates, and open dots show repeat cross section survey dates at base flow.

Water Surface Elevation (WSE) Analysis

In order to evaluate spatial and temporal patterns of reservoir sediment erosion, an approach using flow modeling and water surface profile surveys was used. Water surface profiles were surveyed in the lower 4 km of the BFR throughout the 2008 Spring runoff. RTK-GPS units were used to survey water surface profiles at both left and right wetted edges of the channel when possible (Figure 10). This analysis was performed to supplement the morphological change analysis from Spring 2008 to Fall 2008. The proxy for erosion using this approach is the deviation of a modeled water surface elevation from the observed elevation, from which local scour or deposition can be calculated (Figure 11).

In order for the analysis based on observed water surface elevations to be applied to erosion, I reviewed the relationship between channel height and other physical parameters for a given channel. I used the discharge form of the Manning equation:

$$Q = \frac{Ah^{2/3}S^{1/2}}{n} \qquad (1)$$

where Q is discharge (m^3/s), and is a function of flow area, *A* in (m^2); average depth, *h* in (m); slope, *S* in (m/m); and roughness, Manning's *n*, (dimensionless). By rearranging equation (1), *h* can be solved for:

$$h = \left[\frac{Qn}{AS^{1/2}}\right]^{3/2} \qquad (2)$$

Channel height (*h* in relation to a datum or WSE) can fluctuate due to changes in discharge, slope, roughness, and area. Based on equation 2, three potentially dynamic variables, n, A, and S control *h*. In order for changes in WSE from the modeled WSE to be used in analyzing the pattern of erosion the primary dynamic variable would have to be *A*. Changes in WSE in a reach where erosion of reservoir sediments is expected, and confinement of the channel would prevent widening, degradation would conceivably cause an increase in A and a lowering of WSE.

HEC-RAS Modeling

HEC-RAS is used for 1-dimensional hydraulic modeling of natural and altered systems (HEC 2008). The purpose of using HEC-RAS in this study was to evaluate the temporal and spatial patterns of erosion in the BFR. The HEC-RAS Steady Flow Analysis tool was employed to model steady flow through input channel geometry and boundary conditions at a variety of discharges in the 2008 hydrograph taken from the USGS station Blackfoot River near Bonner MT (Gauge #1234000, Table 1). A calibration process using both known water surface elevations at pre-erosion discharges, and an analysis of results as a percentage of mean flow depth was done before using output water surface elevations for analysis. These modeled data were then compared to observed WSE through the 2008 hydrograph. The subsequent analyses of the deviations of observed WSE from the modeled WSE ($\Delta WSE = WSE_{obs} - WSE_{model}$) through space and time was performed to reveal the process of sediment erosion from Spring 2008 to Fall 2008.

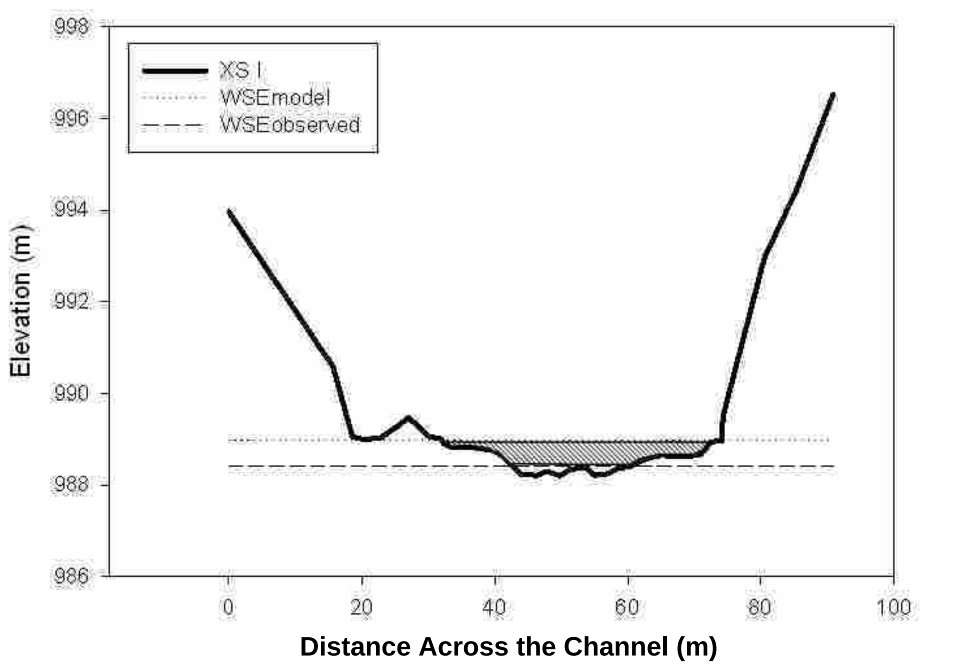


Figure 11. Pre-erosion cross sectional topography for Cross Section I. Dotted line is WSE_{model}, dashed line is WSE_{obs}. Erosion of the shaded cross sectional area between the two lines is the hypothesized mechanism causing a deviation between the observed and modeled water surface elevations.

ΔWSE was later used to calculate change in area (ΔA, or net erosion at a cross section) and then used in the spatial and temporal analyses of reservoir sediment erosion through the hydrograph.

The model river network was set up using the HEC GeoRAS 4.1.1 add-in for ArcGIS 9.3 and split into two separate reaches, cross section I to VI and cross section VII to X. Cross sections XI to XIII were upstream of the extent of repeat water surface elevation surveys, and therefore not used in the HEC-RAS analysis. The model river network represents the lower 3.8 km of the BFR. From Arc, the model network was exported and brought into the HEC-RAS interface. Expansion and contraction coefficients were set to recommended values of 0.1 and 0.3 respectively (HEC 2008). The model was calibrated to measured pre-erosion WSEs at base-flow when the Spring 2008 survey was done using n values within the range expected for gravel-bed rivers (Table 1). Flows ranging from 12 – 277 m^3/s were routed through the network using the steady flow analysis tool in order to model WSE at each cross section. Downstream boundary conditions were set to known pre-erosion WSEs at Spring 2008 base-flow.

To evaluate changes in channel width, HEC-RAS was used to model a 1.5 year return interval flow (187 m^3/s) through both Spring and Fall 2008 model networks. Channel widening is of interest as the literature depicts widening as a common theoretical and observed upstream response to dam removal.

Model Parameters		
Cross Section	*Distance Upstream of Milltown Dam (m)*	HEC-RAS *n*
*XIII	4877	
*XII	4389	
*XI	4359	
X	3784	0.026
IX	3367	0.03
VIII	3320	0.04
VII	3076	0.06
VI	2014	0.065
V	1554	0.02
IV	1528	0.02
III	1330	0.03
II	1260	0.02
I	935	0.035

Table 1. Cross sections and distances upstream of Milltown Dam. Manning's n values input into HEC-RAS modeling framework.
*Cross section upstream of water surface elevation analysis reach.

Date	Q (m^3/s)
3/11/2008	13
3/17/2008	14
3/23/2008	14
3/29/2008	14
3/31/2008	13
4/1/2008	13
4/9/2008	14
4/12/2008	16
5/15/2008	104
5/20/2008	277
6/1/2008	209
6/12/2008	136
6/24/2008	154
6/27/2008	127
7/10/2008	71
7/20/2008	40
9/5/2008	24

Table 2. Discharges modeled through the Spring 2008 topography from USGS Blackfoot River near Bonner Station (#12340000).

Exponential Decay

Estimates of the temporal pattern of reservoir sediment erosion were used to test the applicability of an exponential decay function. Exponential decay functions are used to describe decay of a substance or material at a rate proportional to the initial quantity, based on time, and a decay constant. In the case of modeling sediment release following dam removal, the rate of decay of an initial quantity of reservoir sediment (or erosion) is hypothesized to follow an exponential decay as a function of a decay constant (α); time (t); and the initial volume of sediment (V_i). Analyzing the reservoir sediment erosion and fitting it to an exponential decay function may help address some key questions. For example, it is unknown what influences the decay constant (α): grain size, roughness, or channel geometry.

At any given time, t, the change in the volume of sediment ($\partial V/\partial t$) is a function of α, a decay constant and V_i, the initial volume of sediment such that (Q_s, the flux of sediment out of the reach, m^3/t, at a given time, t):

$$Q_s = \frac{\partial V}{\partial t} = -\alpha V = -\alpha V_i e^{-\alpha t} \qquad (3)$$

The decay constant, α, can also be viewed as a sediment transport constant, as the decay in this case is erosion (m^3).

V. RESULTS

In the first spring runoff following the removal of Milltown Dam, the fine sediment accumulated in the lower 1.8 km of the BFR was largely evacuated. The river incised into the coarse sediment deposit and transported gravel and cobbles to the lower reservoir and out of the study reach once the critical discharge was reached. In the lower reservoir area, gravel deposited as the BFR flushed out fines and re-established its channel while being supplied with coarse material. This reach developed alternating point bars with a series of mid channel bars (Figure 12).

Sediment Surface Texture and Mobility

Surface sediment texture coarsened by two orders of magnitude in the lower 1.8 km of the reservoir, and generally became finer upstream (Figure 13-17). The largest changes in grain size occurred in the lower reservoir, where median grain size increased by 10 to > 10,000 percent (Figure 16). Gravel and cobble (D_{50} 13-60 mm) deposited after the silt and sand deposit was evacuated from the lower reservoir area. Furthermore, sediment patches sampled at ≥ 4 km upstream showed little change from Spring to Fall 2008 (Figure 15).

The grain mobility analysis performed in BAGS shows that the silt-sand deposit was mobile at virtually all discharges. The fine deposit was likely scoured out of the study reach well before the peak discharge on May 20. Upstream, the coarse bed was mobilized at discharges ranging from 32 - 369 m^3/s (Figure 18).

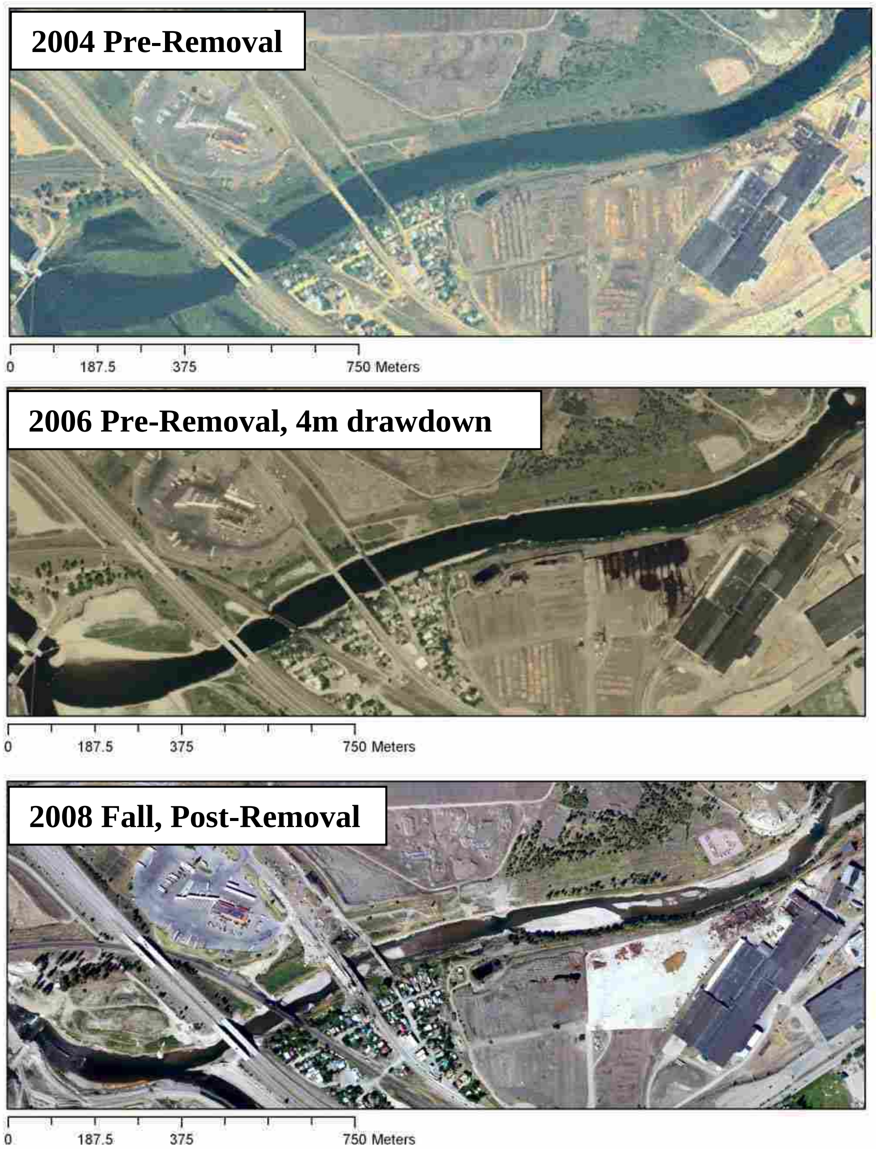


Figure 12. The lower 2 km of BFR in 2004, 2006 and 2008. The Milltown Dam site is located in the lower left of the image. NAIP 2004, 2006. Flow is from right to left.

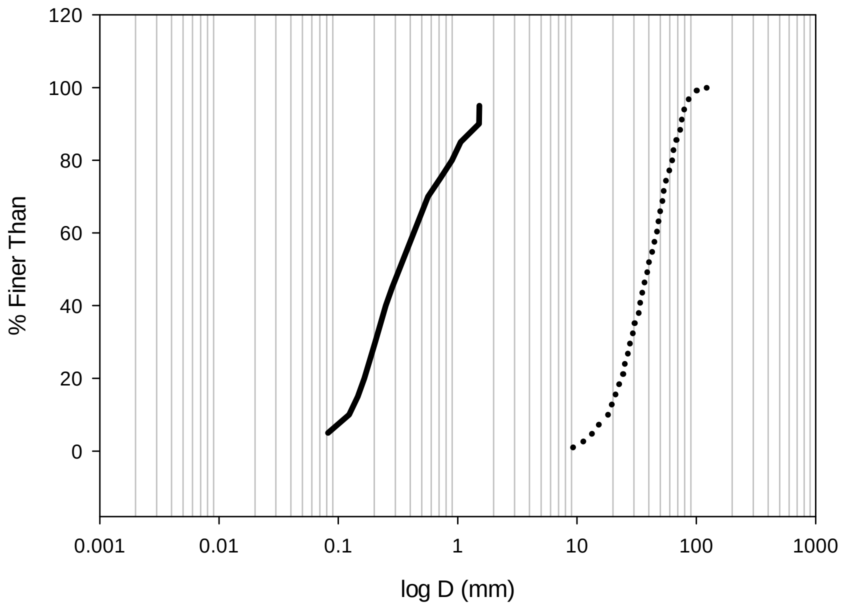


Figure 13. Mean surface textures for Spring 2008 (solid line) and Fall 2008 (dotted line) for the fine sediment reservoir deposit in the lower 1.8 km (XS I – V) of the study reach composed of silt and sand.

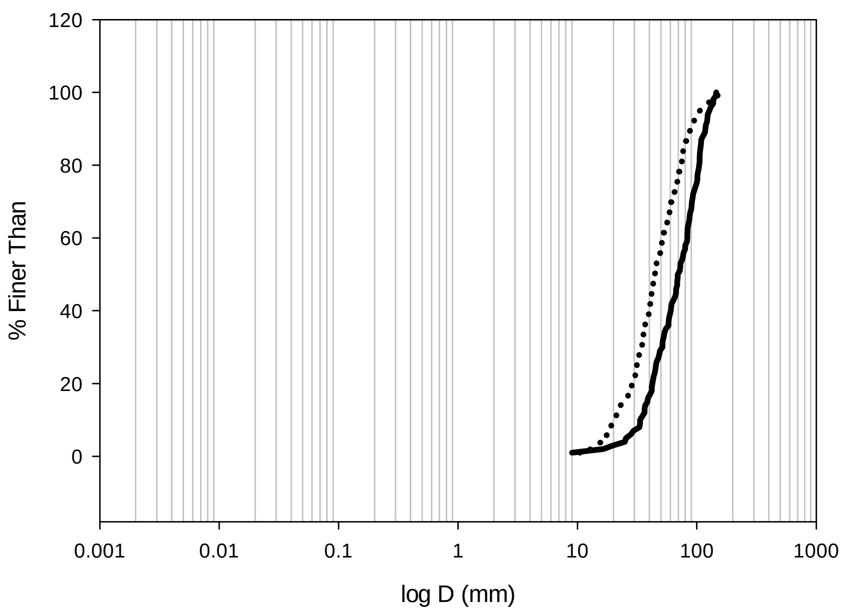


Figure 14. Mean surface textures for Spring 2008 (solid line) and Fall 2008 (dotted line) in a zone of local upstream fining (cross sections VII and VIII, 3.0- 3.8 km upstream of Milltown Dam).

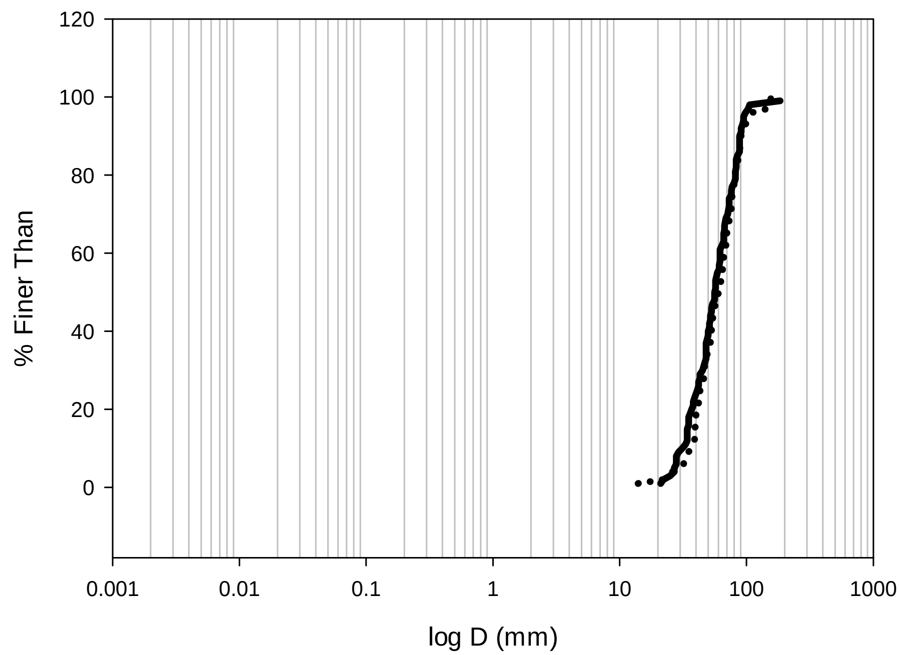


Figure 15. Mean surface textures for Spring 2008 (solid line) and Fall 2008 (dotted line) 4.4 km (XS XII) upstream of the dam site, where surface texture showed little response.

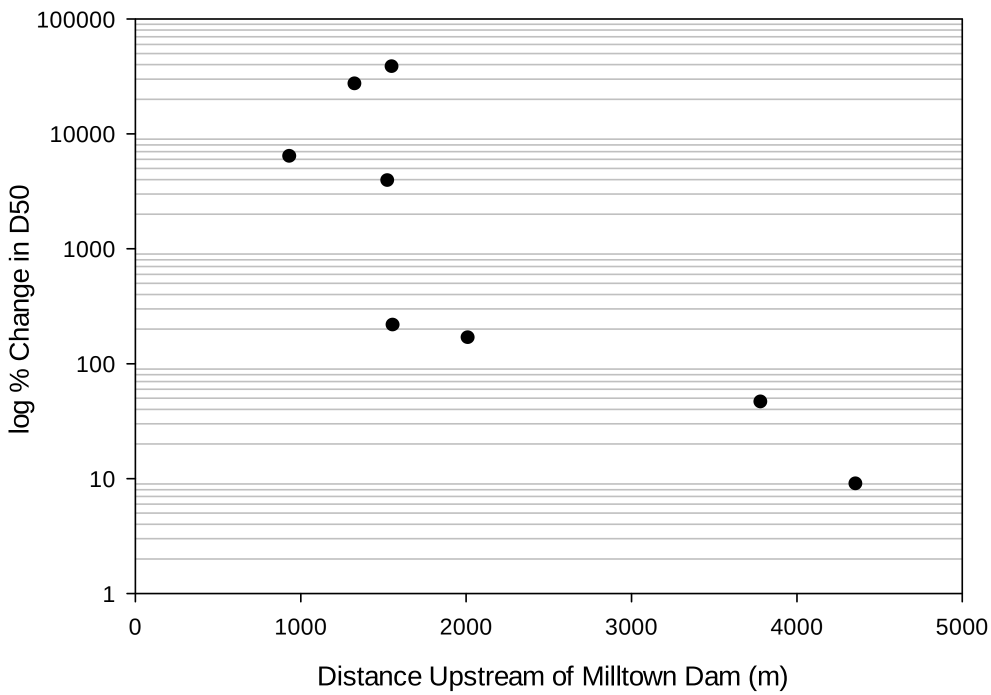


Figure 16. Percent change in the median grain size illustrating the coarsening of the bed in the lower reservoir. Fining (negative values) not depicted in this log-scale figure.

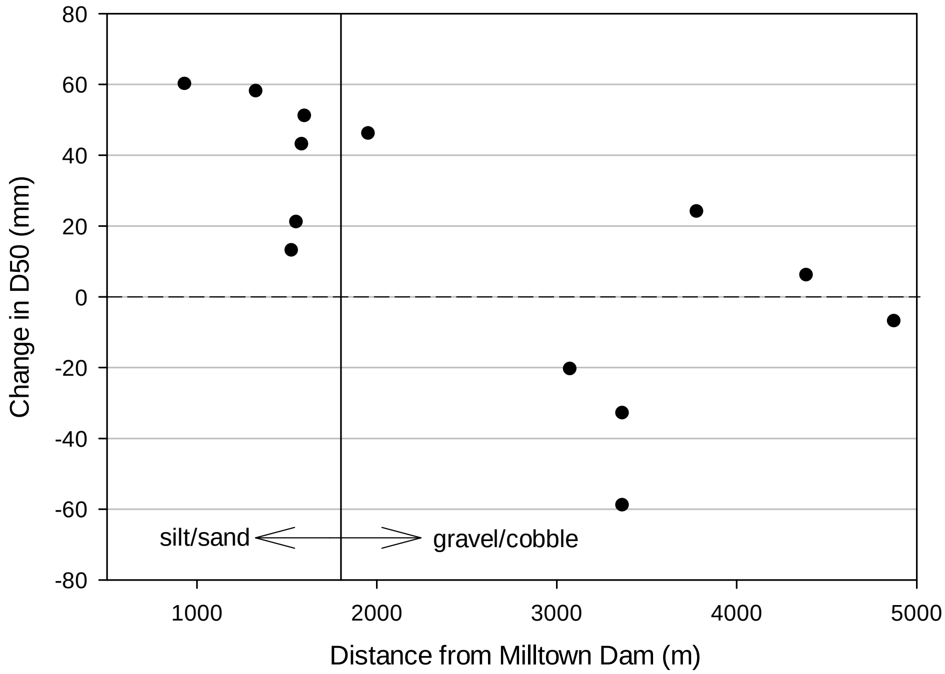


Figure 17. Change in bed surface texture (D_{50}) from Spring to Fall 2008. Vertical line at 1800m denotes gravel-silt/sand transition before the 2008 spring runoff. As of Fall 2008, entire study reach is gravel-cobble.

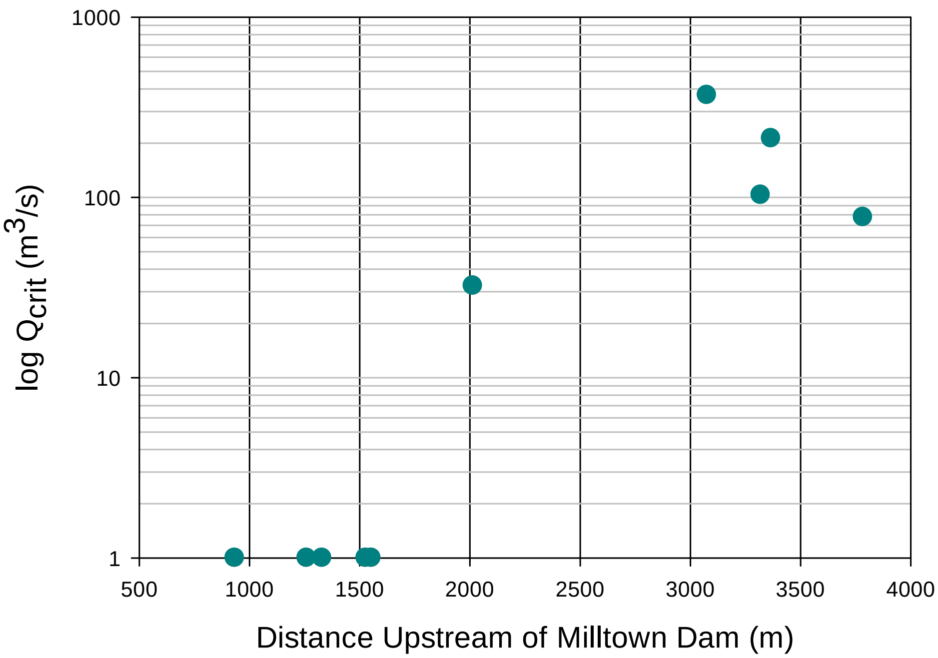


Figure 18. Q_{crit}, or discharge necessary to mobilize the Spring 2008 bed sediment shown by their distance from the Milltown Dam site. Fine sediment in the lower reservoir is mobile at all discharges, while higher discharges are needed upstream, where the bed consists of coarse material (gravel and cobble).

Net Morphological Change Analysis

Although no knickpoint was observed, the comparisons of pre- and post-removal cross section data show that an incisional pulse extended 4.5 km upstream of the Milltown Dam site (and 2 km above of the upper extent of the reservoir, Figure 19, 20). It is possible that a knickpoint did develop, but was not detected by the methods employed in this study. Bed lowering was found from the lower reservoir 4.5km upstream, with the exception of local net aggradation at 1.5 km where a pool filled. The maximum bed lowering occurred at cross section VII (3 km) where a vegetated bar was eroded, the channel incised and the main channel thalweg migrated 80 m across the active zone (Figures 21, 23). Due to the confined nature of the lower BFR, minimal channel widening occurred based on the analysis of channel widths at a 1.5 year flood discharge. Alternatively, the mean change in channel width observed was narrowing by 3.1 m. Maximum narrowing of 16.8 m occurred at cross section VII, 3 km upstream of the dam site (Figure 22). The comparison of pre-erosion (Spring 2008) and Fall 2008 cross sectional topography reveals the net change in cross sectional area. Based on the spring and Fall 2008 topographic surveys, I estimated that net volumetric erosion from the 2008 runoff was 150,000 m^3.

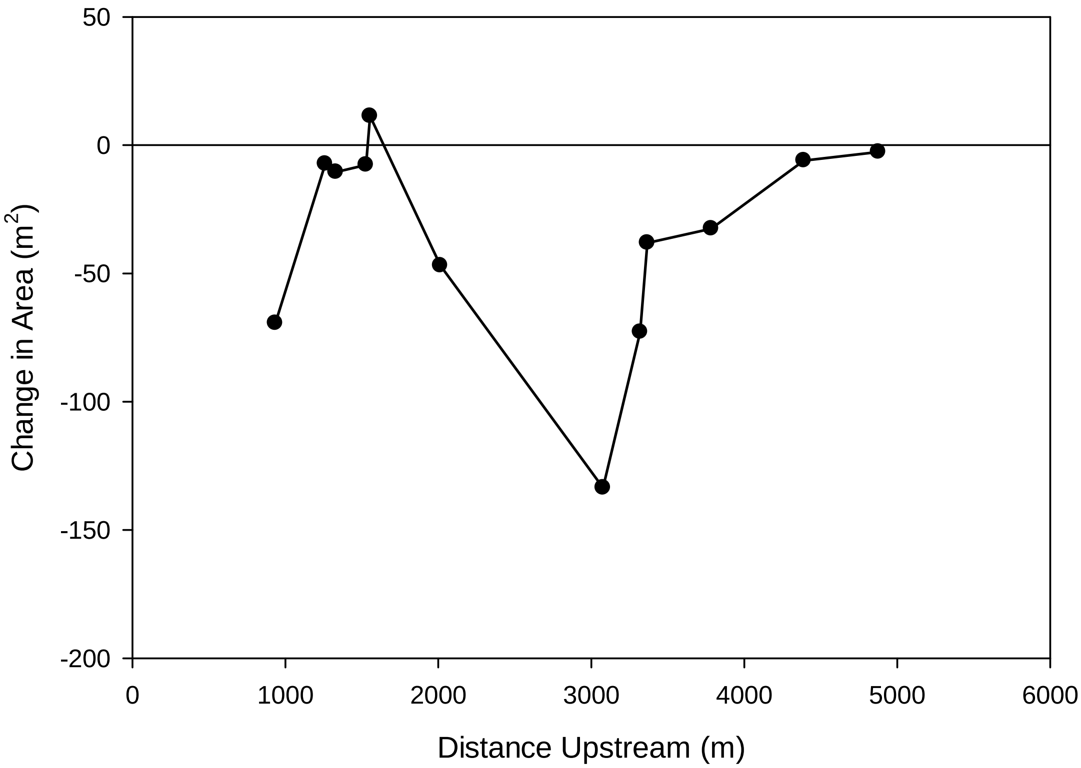


Figure 19. Spring-Fall 2008 change in cross sectional area (based on repeat cross section surveys) shown versus distance upstream of Milltown Dam (x). Negative and positive changes in cross sectional area show local scour (-) and deposition (+). The geomorphic response extended 5 km upstream of the dam, and 2 km beyond the upstream limit to the reservoir.

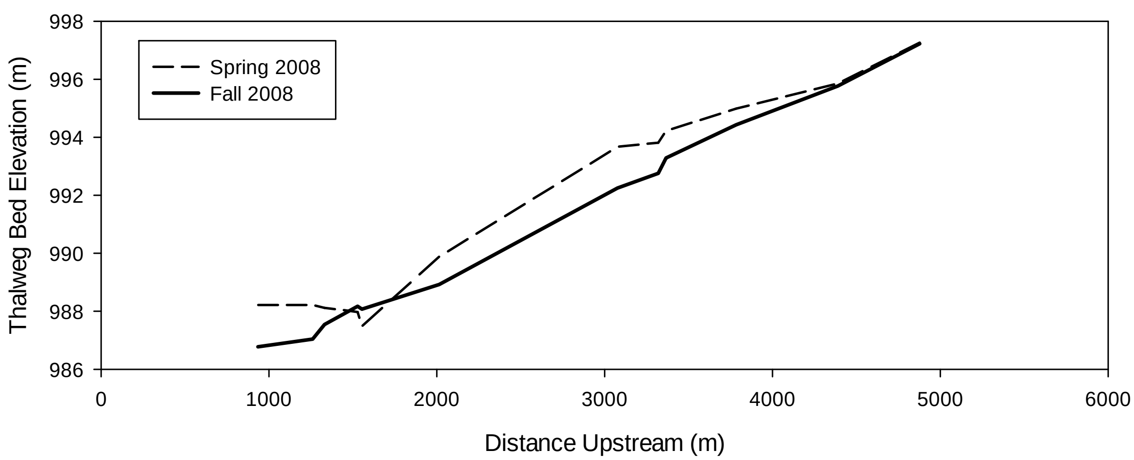


Figure 20. Longitudinal profile showing Spring and Fall 2008 bed elevations based on repeat cross section surveys. Headward erosion extended 4.5 km upstream.

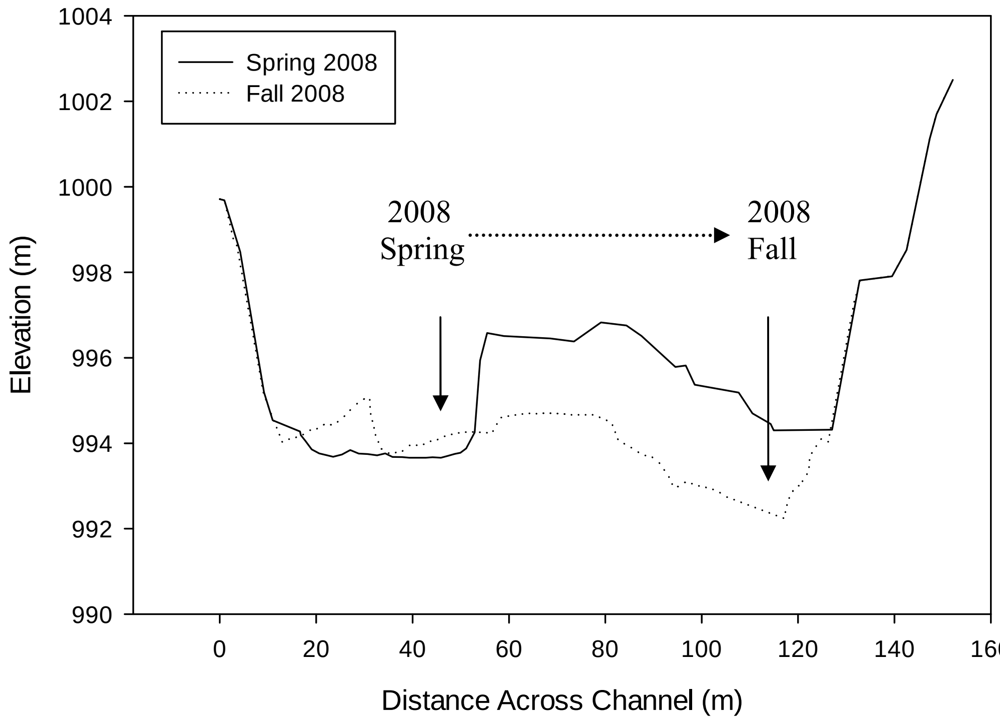


Figure 21. Spring 2008 (solid line) and Fall 2008 (dotted line) cross sections shown for Cross section VII. At this site, 3 km upstream of the dam, bed lowering of up to 2m was observed. The thalweg migrated 80 m across the active channel.

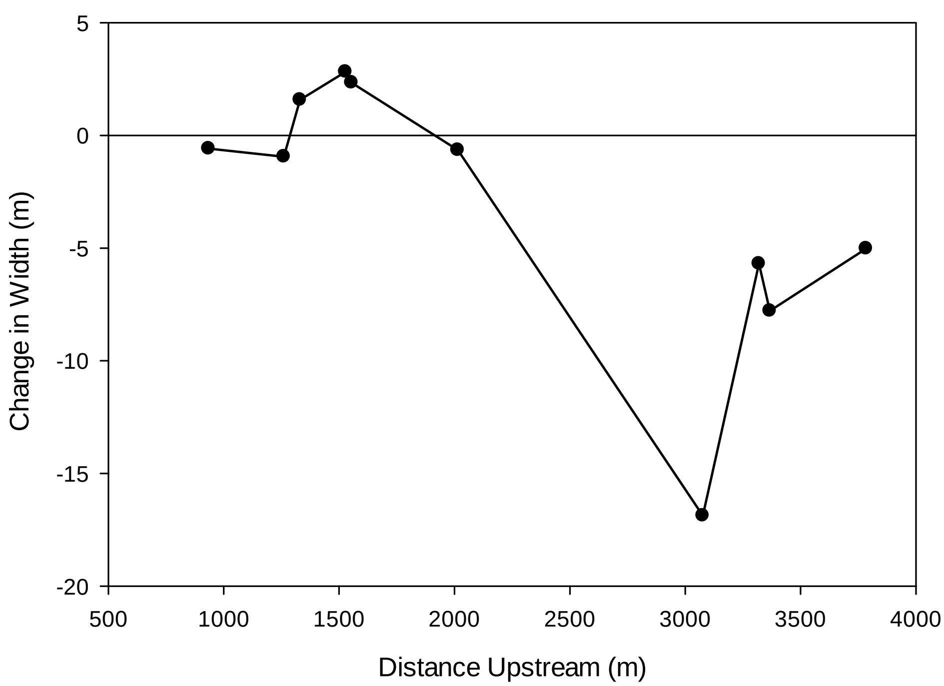


Figure 22. Distance upstream of Milltown Dam plotted against change in channel width from Spring to Fall 2008 at 1.5 year return interval flow (187 m^3/s).

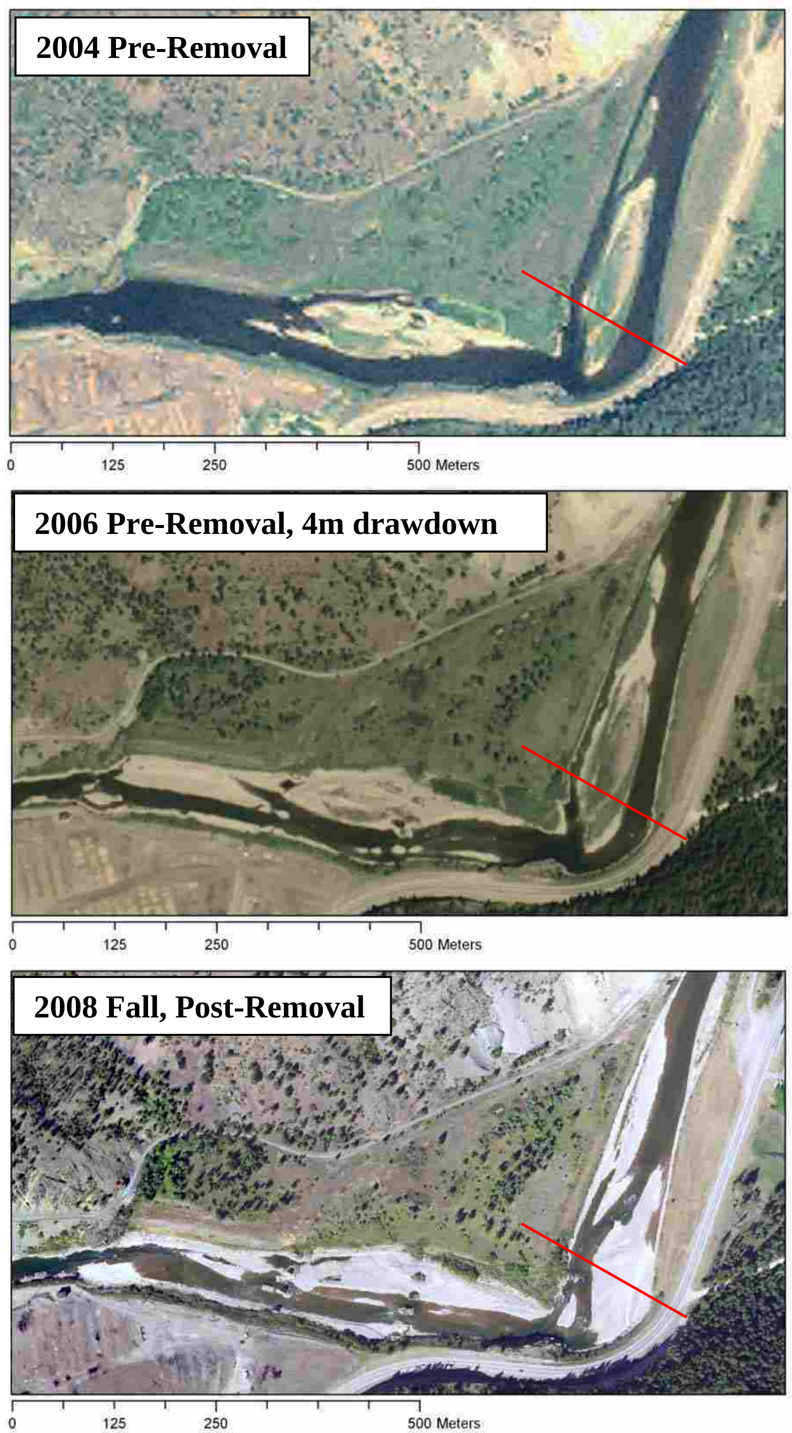


Figure 23. Time series aerial photography of the reach located 2 – 3.5km upstream of Milltown Dam. NAIP 2004, 2006. Red line is cross section VII—downstream end of the vegetated bar that was eroded in the Spring 2008 runoff. Flow is from top right to bottom left.

ΔWSE Analysis

Figure 24 shows the spatial and temporal patterns of reservoir sediment erosion using the flow modeling method. The pre-erosion condition was effectively modeled and shown using the WSE analysis. The ΔWSE approach shows that the entire modeled 3.7 km reach eroded at some point. It appears that both erosion and deposition happened concurrently at different locations in time and space. Figure 25 shows that modeled volumetric erosion occurred rapidly during the rising limb of the hydrograph, peaking close to June 11. This point of maximum modeled bed lowering occurred just after the peak of the 2008 hydrograph. The flow modeling approach developed to quantify reservoir sediment erosion throughout the 2008 hydrograph showed a similar spatial pattern of erosion seen in the pre-erosion (Spring) and Fall base-flow morphological comparison (Figure 19, 24). At the log jam complex 1.5 km upstream, the ΔWSE failed to capture the net aggradation, as the increase in roughness caused by the log jams was not modeled in HEC-RAS. The temporal pattern of erosion shows that significantly more erosion may have occurred than can be captured by the net volumetric change. The HEC-RAS results indicate that the maximum erosion occurred on June 1, eleven days after the peak in the hydrograph, by which time a total of 260,000 m^3 had been eroded from the lower 4.5 km of the BFR (Table 2, Figure 25). After the BFR returned to base-flow in the fall, the net volumetric change was 72,000 m^3 as of 9/5/08 (Q= 24 m^3/s). Based on the flow modeling approach, the peak erosion of 260,000 m^3 on June 1 represents 115% - 174% of the initial volume of reservoir sediment stored in the BFR arm of Milltown Reservoir (Envirocon 2005). Longitudinal profiles derived from water surface profiles surveyed are shown in Figure 26, for comparison with the pre-removal reservoir WSE.

The 8 m base level reduction is evident in the evolution of the water surface through the 2008 hydrograph.

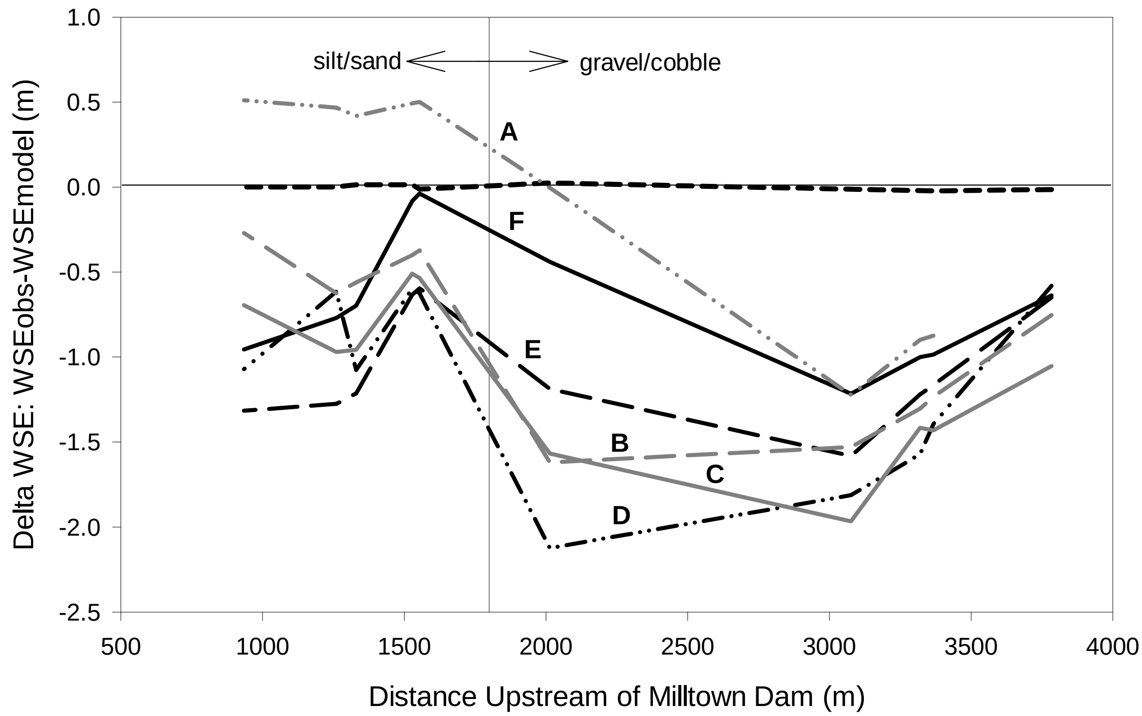


Figure 24. ΔWSE curves throughout the hydrograph plotted against distance upstream. The bold dashed calibration line shows WSE_{model} fits the WSE_{obs} at Spring 2008 baseflow. A, the gray dash-dotted line, is the earliest date and associated discharge modeled. F, the solid black line, is the latest discharge modeled, from 9/5/08. Note the vertical line representing the gravel-sand transition in the Spring of 2008.

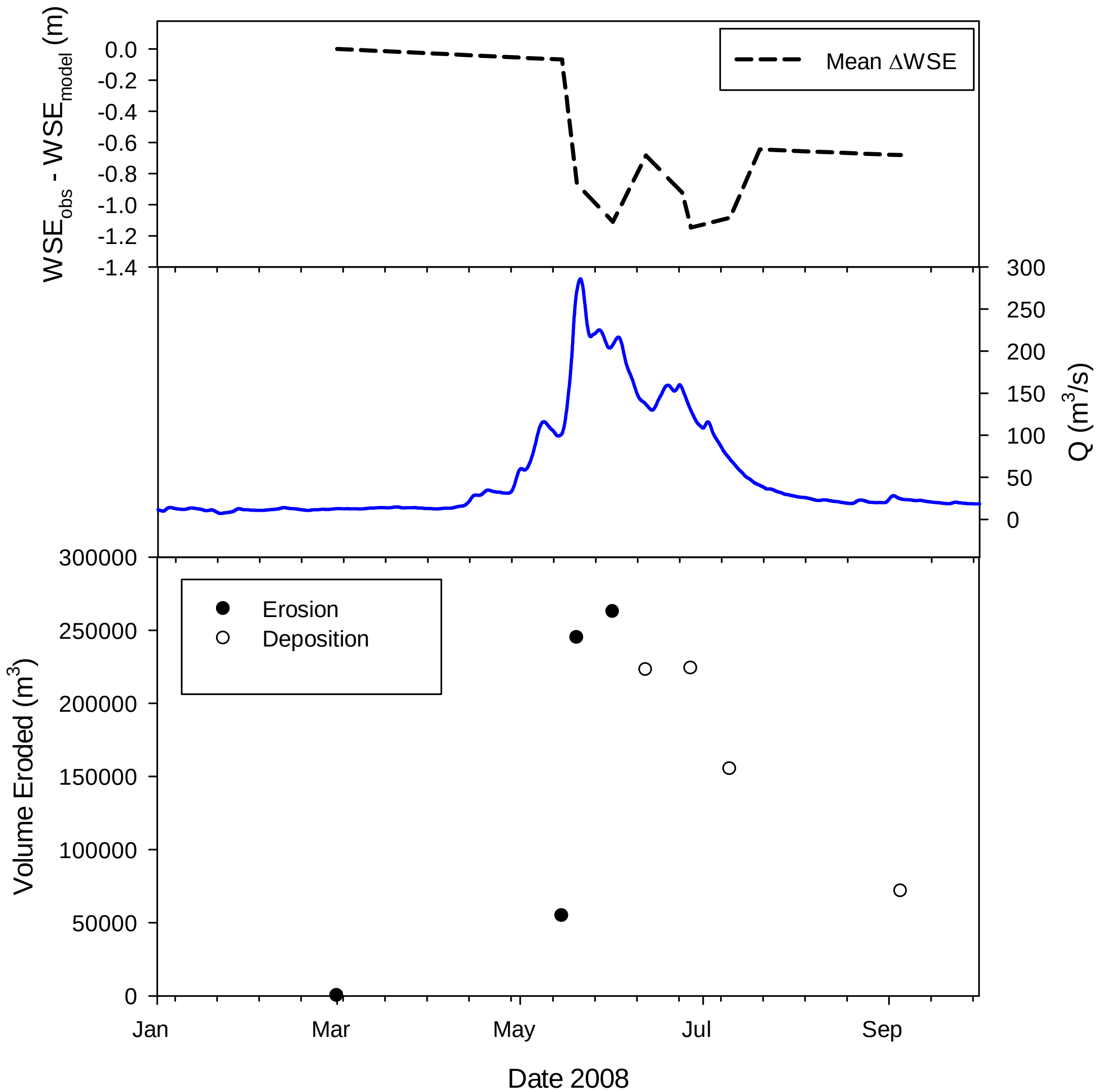


Figure 25. Mean ΔWSE, 2008 hydrograph and volumetric erosion through the hydrograph. Solid points show increasing erosion, and white points show sediment deposition during the falling limb of the hydrograph.

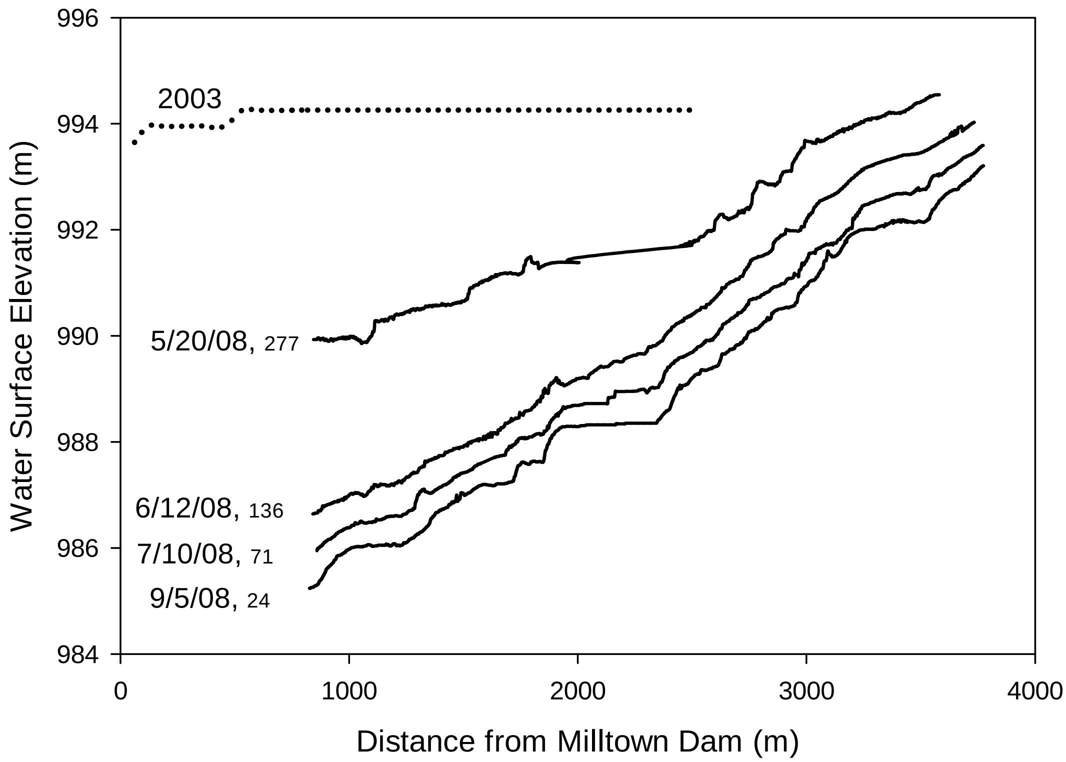


Figure 26. Water surface profiles throughout the 2008 hydrograph shown with the 2003 reservoir water surface. Dates for water surface profiles surveyed in 2008 listed with discharge (m^3/s).

Exponential Decay

The exponential decay hypothesis was tested by fitting two exponential decay functions to match volumetric erosion estimates. Decay curves that fit ΔWSE and net morphological change analysis erosion estimates had α values of 0.06 and 0.0058 respectively (Figure 27). First, to show the peak erosion of 260,000 m^3 as of June 11, 2008, an exponential decay curve was fit to the modeled data (before deposition occurred) using an α value of 0.06. This is a rapid rate of decay in comparison to the more gradual erosion shown by the curve fitted to the net morphological change of 150,000 m^3. Fitting the decay functions to these data shows a range of predictions for the full evacuation of the stored reservoir sediment in the BFR: 2 - 17 months.

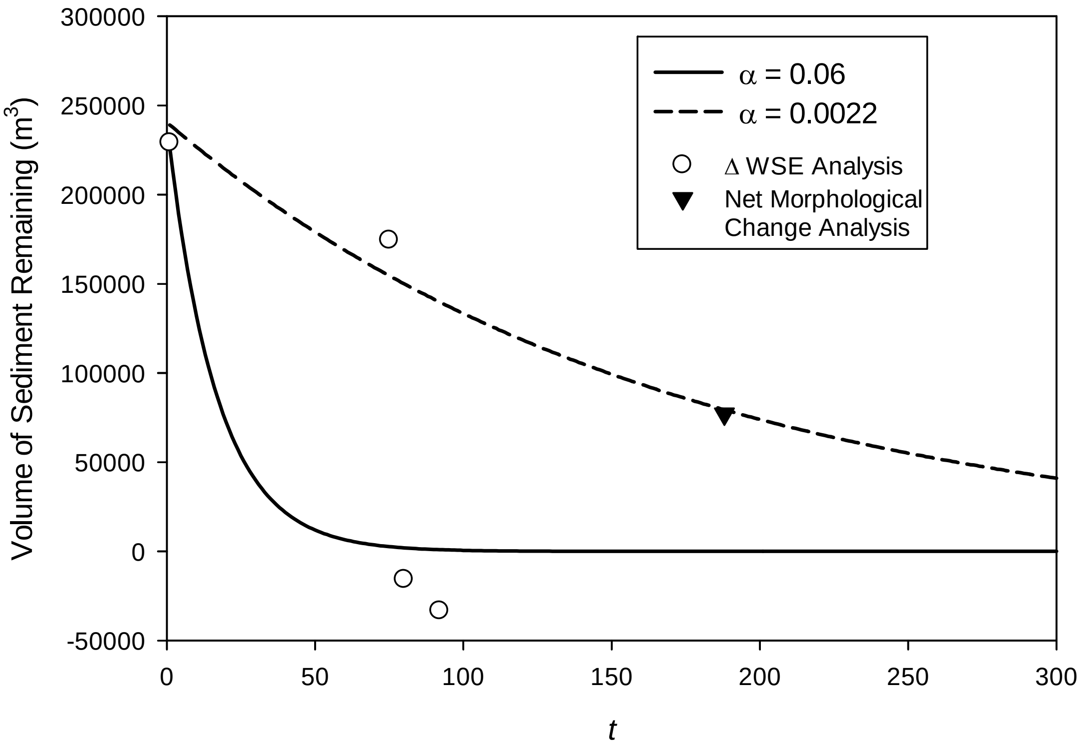


Figure 27. Exponential decay functions fit through the ΔWSE and net morphological change estimates of volumetric erosion. The pattern of erosion in the time period examined does not appear to exponential. However, subsequent years may prove that erosion may show an exponential decay pattern.

Decay Constant α	**% Eroded (t, days)**	
	50%	**95%**
0.0059	118	518
0.06	12	65

Table 3. Estimated time (*t*, days) for the reservoir sediment deposit to decay using three different values for α, ranging from < 3 months to several years.

VI. SENSITIVITY ANALYSIS

In order to evaluate the appropriateness of using a ΔWSE analysis to detect local scour or aggradation, a sensitivity analysis was performed to evaluate the potential contribution of changes in Manning's *n* and *S* (slope) to the ΔWSE calculations. The main purpose of the sensitivity test was to determine how much of ΔWSE could be accounted for by changes in S and n without eroding or depositing sediment to drive changes in cross sectional area (*A*). For assessing the sensitivity of WSE to slope, repeat calculations were performed using equation (2), holding all other variables fixed. To test WSE sensitivity to roughness, repeat runs of the Steady Flow Analysis in HEC-RAS was done. The parameters *S* and *n* were incrementally varied from 2%-100%, and the resulting change in *h* was calculated as a percentage of ΔWSE for a given cross section.

The sensitivity analysis shows that WSE is not sensitive to changes in roughness, and slightly more sensitive to changes in slope. A doubling of slope contributed 20% ΔWSE for most stations evaluated, and up to 50% for only a few (Figure 28). Doubling *n* could only account for a maximum of ~10% ΔWSE. Although the sensitivity test results illustrate the complexity of using WSE changes to assess bed sediment dynamics, they indicate that changes in *S* and *n* cannot solely explain the fluctuations in WSE.

As changes in roughness is shown to have a minimal effect on the WSE analysis results, the potential dilution of the results by changes in slope were computed at two discharges (24 and 127 m^3/s) in order to express the accuracy of the ΔWSE. Figure 29 illustrates the potential contribution of a 100% increase in slope to the ΔWSE analysis. Generally, a doubling of slope could only explain a fraction of the total deviation between observed and modeled WSE. However, at cross section IV, a 100% increase in slope actually overwhelms the effect. Repeat topographic surveys showed that the channel aggraded at cross section IV.

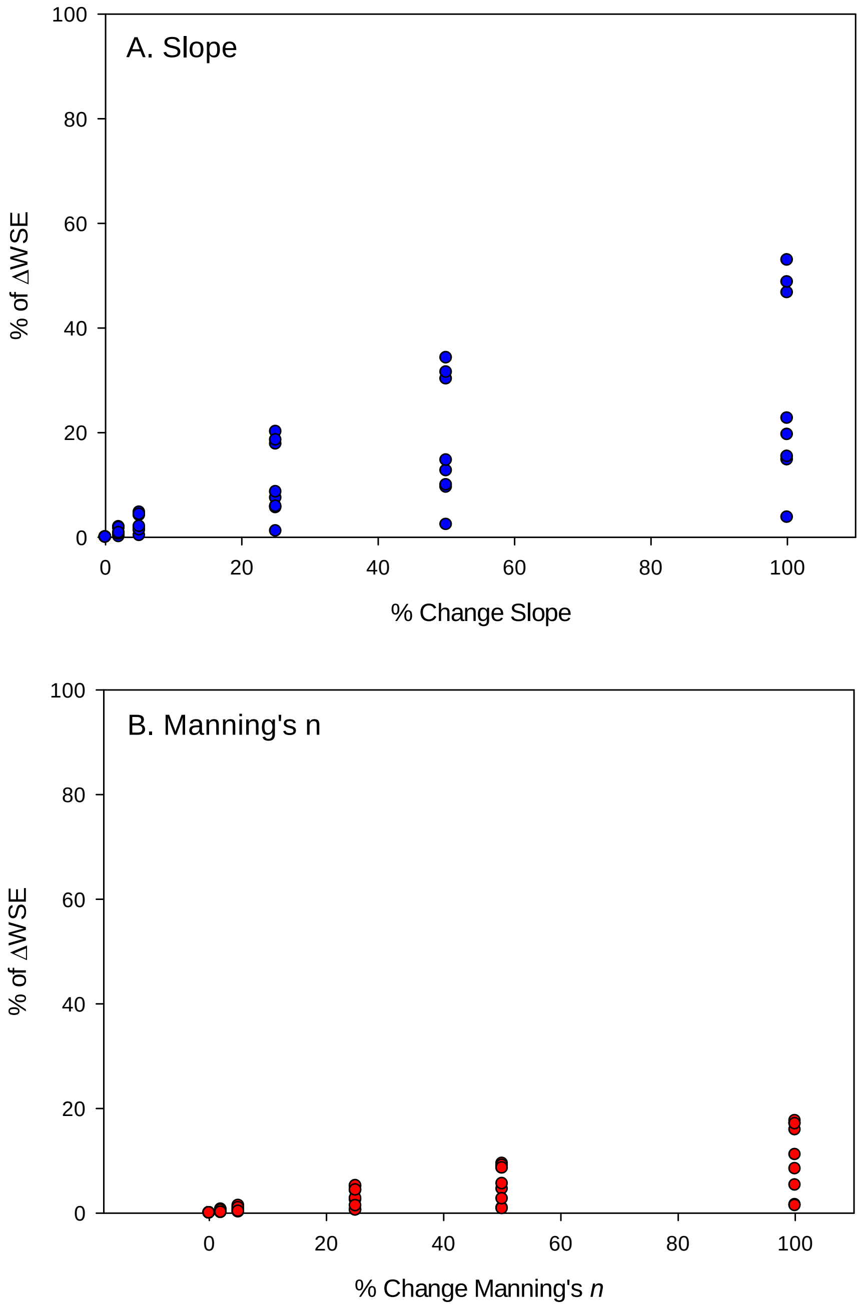


Figure 28. Sensitivity analysis of *h* to changes in A. Slope, and B. Manning's n. A 100% increase in Manning's n could account for ~10% of ΔWSE, while a 25% change in slope may account for 20% of ΔWSE.

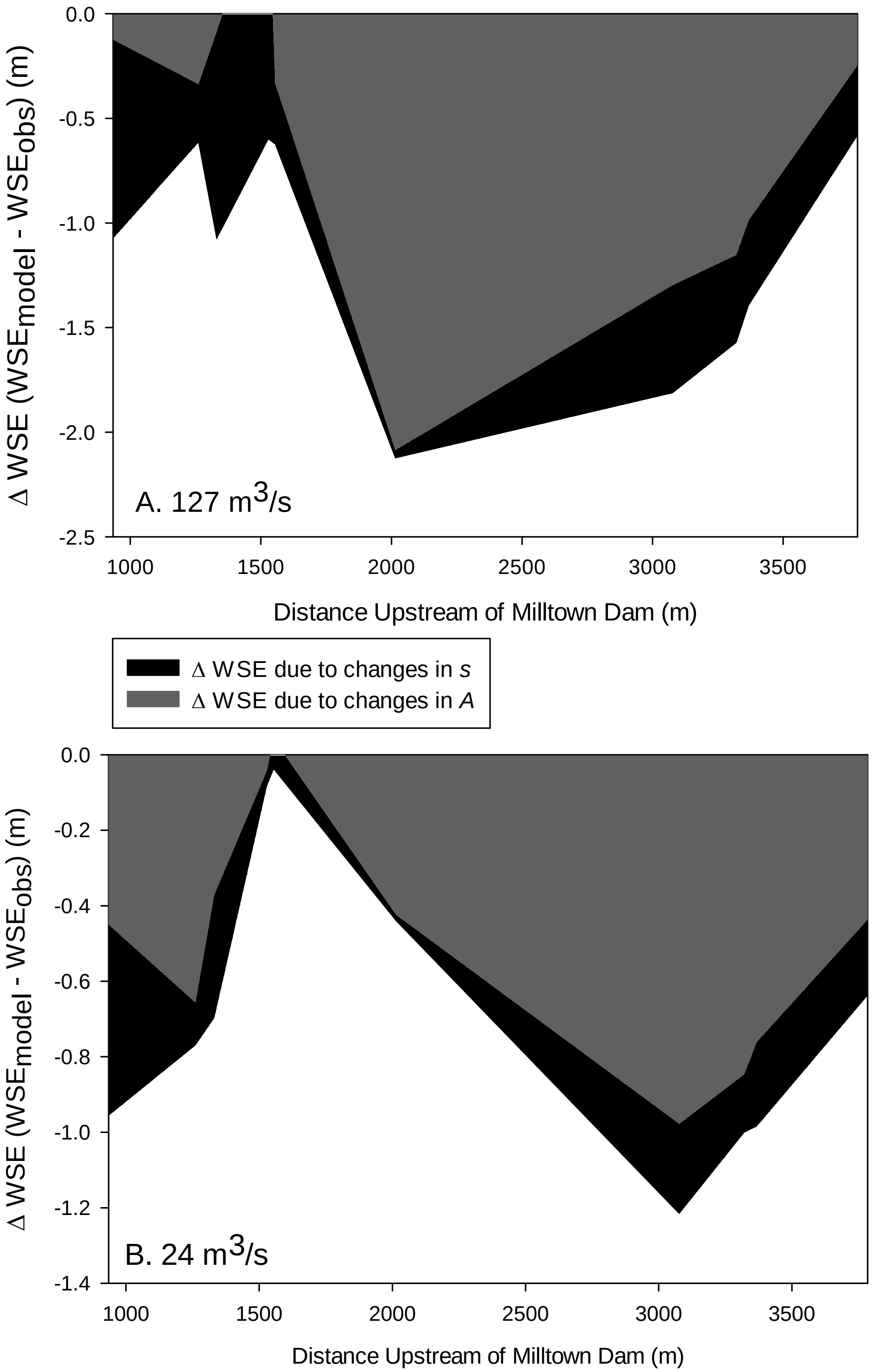


Figure 29. ΔWSE with sensitivity analysis results incorporated for (A) 6/27/08 (Q = 127 m^3/s) and (B) 9/5/08 (Q = 24 m^3/s). The potential maximum dilutive effects of a 100% change in slope is illustrated by these two ΔWSE analyses. The black area represents the proportion of ΔWSE that can be explained by a 100% change in slope. The black and grey areas added together represent the total ΔWSE.

VII. DISCUSSION

Net Morphological Change vs. WSE Analysis

The ΔWSE and flow modeling approach to tracking the process of reservoir sediment erosion through the 2008 hydrograph generated a similar pattern to that observed in the morphological comparison derived from spring and fall topographic surveys. The modeling approach reveals more information about how much erosion may have happened between the spring and fall topographic survey dates. Headward erosion lowered the bed and was followed by aggradation during the falling limb of the hydrograph. The final base-flow erosion estimate from the modeling approach under-predicts volumetric erosion in comparison with the estimate derived from the topographic surveys (72,000 m^3 vs. 150,000 m^3). Quantifying changes in fluvial bedforms from observed water surface elevations is somewhat of a simplification of complex interacting variables (*n, S, A*). Furthermore, it is possible that the modeling-based approach behaves differently at different points in the hydrograph. During the Spring 2008 flood peak (286 m^3/s on 5/21/2008), the ΔWSE analysis could lead to over-prediction of volumetric erosion, while at low discharge (i.e. 24 m^3/s on 9/5/08) the volumetric erosion may be under-predicted. Perhaps the resulting temporal analysis should be used more as a range in volumetric erosion, rather than a single estimate. Furthermore, the sensitivity analysis results show that where ΔWSE is small or near zero, a doubling in slope overwhelms any signal that can be extracted from the WSE analysis. The above average discharge and significant erosion throughout the reach made changes in cross sectional area the largest driver of ΔWSE.

Furthermore, the WSE method may have missed some of the erosion in the lower reservoir due to the potential rapid changes in slope and roughness in the fine sediment reservoir deposit. The calculated changes in cross sectional area can only be estimates in cases where the WSE_{obs} was lower than the original minimum bed surface. Computing ΔA for such cases becomes more of a low-bound estimate rather than an exact calculation. This is a potential explanation for the deviation between the Fall 2008 base-flow volumetric erosion estimate (based on WSE) and the calculation from repeat cross section surveys, 72,000 and 150,000 m^3 respectively. The model-based calculation represents a lower bound, as the ΔWSE may represents other geomorphological changes in addition to a potential increase of cross sectional area (scour).

The volumetric erosion estimates based on the net morphological change and the ΔWSE approach are consistent with those derived from observed bedload measurements. Bedload was sampled at the bottom of the study reach on two days before the peak (5/17, 5/18/2008) and two after the peak (5/26, 5/27/2008). Transport rates ranged from 41 – 1500 m^3/day. A rating curve based on the bedload samples taken during the 2008 hydrograph suggest evacuation of 150,000 to 300,000 m^3 using bedload : washload ratios of 1:5 and 1:10 respectively (Johnsen 2009).

The total volumetric change calculated through the hydrograph reaches its peak during the falling limb (Figure 25). This is consistent with hysteresis found in sediment transport, where transport rates are higher on the falling limb due to a lag time in the creation and destruction of bed roughness elements (Figure 30, Lee et al 2004, Kuhnle 2006). Hysteresis seen in the BFR is likely due to the time taken for material eroded from the coarse sediment deposit to transport out of the reach. The maximum volumetric change, as seen on June 1 (Figure 25), would only reflect the evacuation of the coarse material once it was flushed out of the study reach.

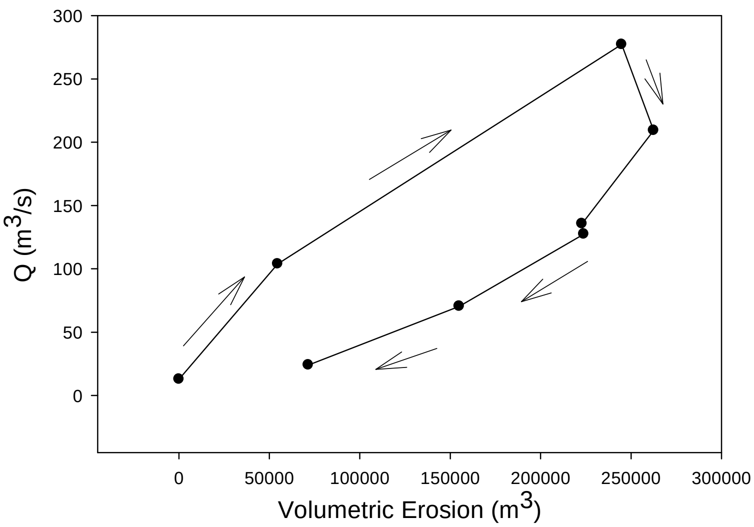


Figure 30. Hysteresis seen in volumetric erosion plotted against discharge (Q). This finding is consistent with sediment transport studies documenting similar patterns of hysteresis in sediment transport (Kuhnle 2006).

Erosion Predictions vs. Observations

During the Milltown Superfund Remediation initial stages, a subcontracted engineering firm modeled erosion using HEC-6 (USACE 1993). Although HEC-6 is a 1-dimensional modeling framework which cannot model channel widening, it likely was an appropriate model for application to the confined lower BFR where the potential for channel widening is small. In feasibility studies, the reservoir deposit was estimated to be 150,000 - 229,000 m^3. A variety of bed and flow conditions were run in HEC-6 which produced a range of sediment transport estimates using the Ackers-White equation (Ackers and White 1974). The HEC-6 results were used to make predictions of total sediment transport over a four-year period, starting with the initial reservoir draw-down through the full removal of Milltown Dam. The peak erosion derived from the WSE analysis exceeds the range predicted by pre-dam removal studies done for Milltown. The 260,000 m^3 of erosion I estimated from the period of March – September 2008 accounts for 115% to 140% of the total HEC-6 erosion predicted to occur over a period of 4 years following the dam removal (Envirocon 2004).

Sediment: Texture and Mobility

Upstream, fining occurred in three out of four sites sampled. At cross section VII, this can be explained by the erosion of a high vegetated bar, reducing the variation in bed elevation (see Figure 22). Coarsening was expected at cross sections I and II resulting from incision however fining was observed. This may be because the patches re-sampled may not best represent the new cross section morphologies at these sites. Furthermore, it is important to consider how much the above average peak discharge—flood peak return interval of 3.5 years—may have contributed to the sediment transport versus the dam removal. It has been shown that because of the unique geomorphic context of dam removal and headward erosion, high rates of transport can occur at moderate discharge (Major et al. 2008). However, when discharge is high (~ bankfull discharge, $Q > 1.5 – 2$ year return interval) does more erosion occur, or just more sediment delivered from upstream?

Grain mobility assessed using the Wilcock and Crowe model in BAGS show that bed sediment in the upper reservoir was not likely mobilized below ($< 100\ m^3/s$, Figure 18). Alternatively, the fine material in the lower reservoir was mobile at all discharges which indicates that much of the sand and silt deposit likely was transported early in the 2008 hydrograph. This would suggest that during the rising limb of the hydrograph, below 100 m^3/s, large particles were not mobilized and supplied to the lower reservoir area. Conceptually, as larger particles are delivered to the lower reservoir, changes in local shear stress (in this generally less steep reach) could cause such particles to fall out of transport and armor the fine bed. It is likely that the time lag between incipient motion of coarse material, and it's eventual delivery to the lover 1.8 km of the reservoir, would have been large enough to allow for even more time for erosion of the fine sediment deposit.

Exponential Decay

Although the pattern of erosion observed in the BFR did not follow an exponential decay, testing the applicability of exponential decay to reservoir sediment erosion revealed some interesting questions and limitations. How should an exponential decay function (which by nature is decaying an initial volume) be used to model a complex process that involves both erosion and deposition? Ignoring sediment deposition, we could say that 95% of the reservoir deposit had been eroded 65 days following the dam removal (Table 3, Figure 26). However, this overlooks the complexity of a longer-term adjustment and erosion of coarse sediment from the upper reservoir, and from upstream reaches as headward erosion progresses. Should an exponential decay model be used to describe total export of sediment, or to approximate volumetric changes (i.e. erosion and deposition)? I did not contemplate how deposition would confuse the erosion signal and more generally how deposition of sediment is a process that cannot be predicted by a mathematical function that only decays (erodes). As shown in the HEC/WSE analysis results, deposition during the falling limb of the hydrograph strongly influenced the signal. Deposition of sediment in the study reach will be an integral part of the upstream response as the BFR nears a new equilibrium state.

My observations of the erosion in the BFR are limited to one spring runoff cycle. This is both a challenge within the year, and in a multi-year time frame. Erosion is not occurring during the greater part of a given year. Although it is possible that an exponential decay may summarize erosion over one year, it will show that erosion continues to happen when, in reality, discharge is not sufficient to mobilize bed sediment. This alone may indicate that exponential decay is inappropriate for this application. Tracking the erosion over a longer period of time (i.e. 2 - 5 years) may ultimately follow an exponential decay. However, the data showing erosion and deposition dynamics from Spring – Fall 2008 do not show a pattern of exponential decay.

Widening vs. Erosional Narrowing

It appears that in a confined channel, bed degradation may lead to channel narrowing, while zones of aggradation can drive widening. In the BFR, local degradation was observed to further entrench the channel, causing the width to decrease (evaluated at a 1.5 year flood discharge). The location of maximum bed degradation corresponds with maximum channel narrowing (cross section VII , 3 km upstream). The absence of widening in the analysis of channel width pre- and post-removal at a 1.5 year flood should be treated differently than widening as a mechanism of reservoir sediment erosion. I observed failing vertical or near-vertical, unconsolidated banks on the rising limb of the 2008 hydrograph (Figure 28). Widening certainly acted as a mechanism to erode reservoir sediment, as noted in other studies (see Figure 17, Doyle et al. 2003, Cantelli et al. 2004, Evans et al. 2007). Although the analysis of channel widths at a 1.5 year return interval (RI) did not show that significant widening had occurred in the study reach, the observations in the BFR do support the Doyle et al. 2003 proposed conceptual model for channel evolution following dam removal. Although the confined nature of the BFR set a boundary on potential lateral response, widening was one of the processes observed to evacuate reservoir sediment.

Furthermore, channel narrowing seen in locations with the greatest degree of bed lowering may support the Cantelli flume experiment results. As the data collected in this study do not match the spatial and temporal resolution of the collected in a flume environment, it is impossible to verify whether the accompanying numerical model is a good fit for the response of the BFR (Cantelli et al. 2007).

Knickpoint

Although no knickpoint was detected, it is clear that a pulse of erosion migrated upstream through the two distinct reservoir deposits. It is possible that two different and concurrent knickpoints may have formed at the downstream end of the two reservoir deposits and met as the lower knickpoint reached the upper. At the time of the dam breaching in March of 2008, a knickpoint was observed moving through the coffer dam and upstream to the confluence of the BFR and CFR. It is difficult to say exactly what happened when it hit the split of the two channels. The CFR side of the confluence led to a rip-rap bypass channel with an immobile bed. If a knickpoint did continue up the BFR, then it would have immediately run into a series of highway, railroad, and pedestrian bridges. These structures could have dissipated a knickpoint. The data do not show the existence of a knickpoint moving through either sediment deposit.

It is unclear which of the four knickpoints may have been present, if at all, in the BFR (see Figure 3). Given the presence of coarse material and abandoned bridge piers which stabilized certain parts of the bed, it is unlikely that a stepped knickpoint could have moved through the reach. It is possible that a rotating knickpoint with diffusion could have marched upstream, stopping 4.5 km upstream of the dam. Further data analysis may be possible to explore this possibility.

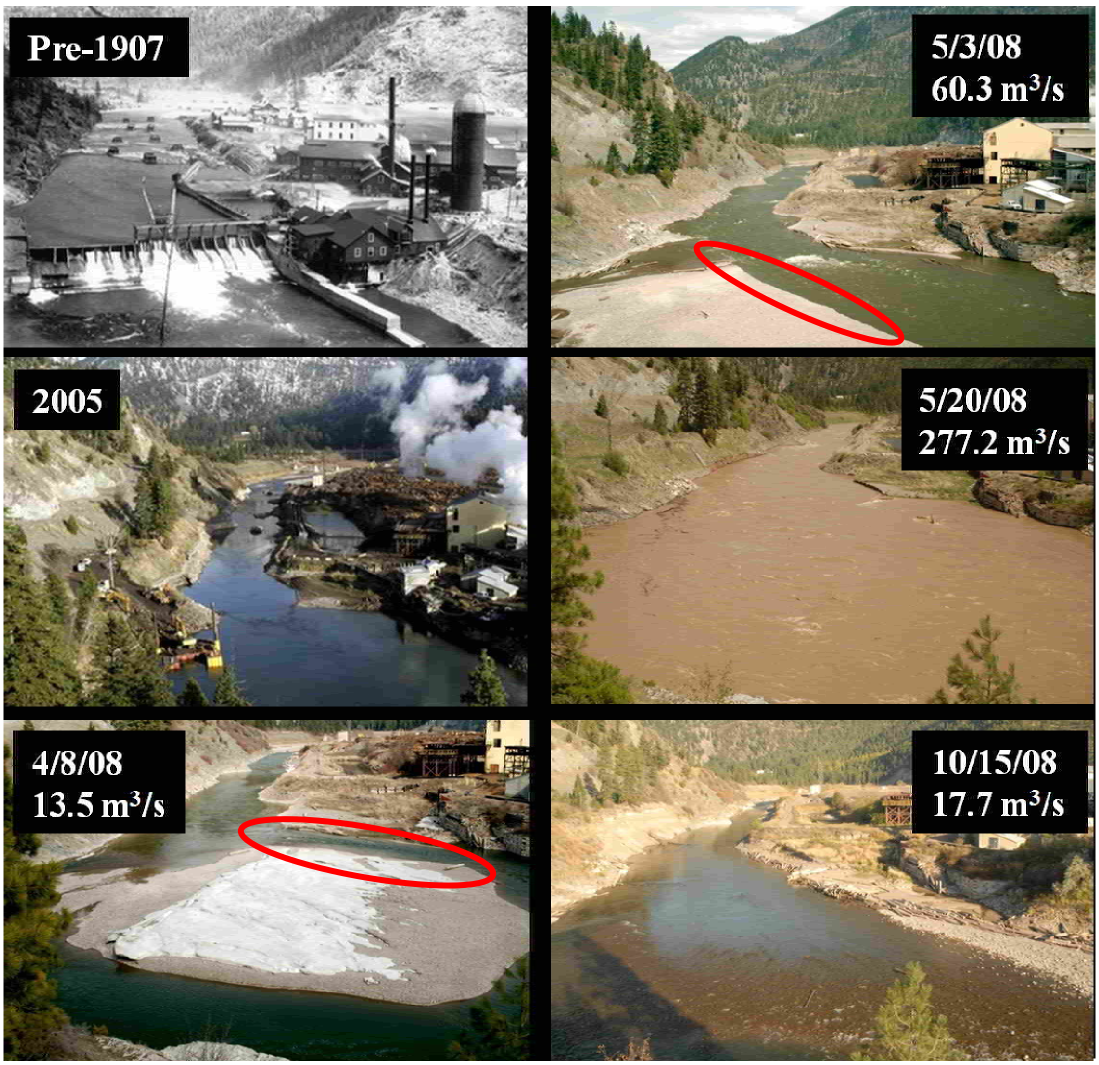


Figure 31. Repeat photography at the Stimson Dam site (2 km upstream of Milltown dam), where a large mid channel bar formed in the 2006-2008 period, and eroded in the 2008 runoff peak. The progression of 5/3/08 to 5/20/08 shows how the channel widened through th e mid-channel bar. The vertical bank (indicated by the red oval) made of unconsolidated coarse material contributed sediment to the channel for downstream transport.

Monitoring and Future Restoration

Tracking the adjustment of the BFR to the new base level condition should be a multi-year endeavor. The BFR will continue to be in a transient state over several years until it reaches a new equilibrium. Perhaps the most dramatic period of response will be the Fall 2008 - Fall 2009 period depending on the size of the spring flood peak. During the Fall of 2008, contractors hired by the Montana Department of Natural Resource Conservation removed individual logs and several old bridge piers. These objects had partitioned shear stress away from grains on the bed. As these elements of roughness are removed from the channel, more shear stress will act upon the bed sediments allowing the river to more efficiently transport sediment downstream.

The lower BFR is a naturally and anthropogenically constrained channel. Following the removal of Milltown Dam and the subsequent erosion of reservoir sediment, the bed has lowered and the river is entrenched to a greater degree. From a flood management perspective, this is a good thing as the possibility for a large spring runoff to overflow the banks and affect adjacent property is very low. However, longer-term restoration of the lower portion of the watershed could include giving back some adjacent property to the river corridor. The most dramatically altered section is adjacent to the Stimson Lumber Mill property where the channel has been pushed against a bedrock and scree slope by a steep rip-rap bank. This is also the location of polychlorinated biphenyl (PCB) contamination on the industrial property. After the remediation of the contaminated site, giving back some of the Stimson property to the river corridor would continue river restoration efforts started by the removal of Milltown Dam. The lower BFR is comprised of a sequence of riffles and pools. The 500 m stretch along the Stimson property is a narrow, high velocity section that is an anomaly in comparison to less impacted adjacent reaches. The bankfull channel width in the narrowed reach is ~18 to 30 m, compared to ~30 to 105 m in the 2km reach upstream. Furthermore, in the lower 1.8 km, vertical banks from 0.5 to 3 m tall remain on the northwest side of the channel. These banks could be viewed as a hazard to recreational users of the river. It is possible that some active management or restoration of those banks could be appropriate including bank setbacks and re-vegetation.

2006 Reservoir Drawdown and the Stimson Dam Removal

The upstream response of the BFR to the removal of Milltown Dam began before the March 2008 breach. The removal of Stimson Dam in 2005 followed by the 2006 3.4 m reservoir drawdown created the conditions to initiate the upstream response and the erosion of coarse reservoir sediment. As approximately 2 km of the BFR was still a part of Milltown reservoir from 2006 -March 2008, the fine sediment deposit remained intact in the reservoir reach. Although the BFR did begin its adjustment before I collected any data, I feel that my field efforts from Spring – Fall 2008 captured the majority of the response as the majority of the sediment remained in the study reach until after March

2008 with the additional 4.6 base level reduction (8 m total base level change from 2006 –March 2008). Any coarse sediment mobilized from the upper end of the reservoir (the portion of the river that began flowing after the 2006 drawdown) before 2008 could not have been transported below ~2 km above the dam. A 13 m deep scour hole below the Stimson Dam was filled with gravel and cobbles during the 2005-2008 period, as evidenced by field observations and comparisons with bathymetry data from

2003 (Envirocon 2004). It is possible that some incision into the reservoir sediment occurred, however monitoring of the BFR during this time period was not performed by Milltown contractors or others. The majority of sediment mobilized from the study reach during the 2005-2008 period can be viewed as a transfer within the reach.

Challenges

The analysis of erosion through the hydrograph was complicated by the challenge presented by surveying river bed topography at moderate-to-high discharges in medium-sized alluvial systems. Typical survey techniques are limited to flows at which cross sections can be waded or measured using a static line from which a small boat can be fixed. Boat based surveying techniques typically employed in large river systems were not well suited to the BFR. Without the installation of fixed cableways (such as at USGS gauging stations), other infrastructure, or specialized equipment, surveying at high flows is not possible. Furthermore, river hazards created by several thousand logs and other debris (mill saw blades, metal debris, bridge piers, and a submerged vehicle) made using motorized boat surveying techniques impractical at high discharges. Given such restrictions to surveying at high flows, only topographic data collected at base-flow conditions was available for analyzing the upstream response.

Comparison to other Dam Removals

In relation to recent dam removals documented by various investigators, the sediment release from the BFR following the removal of Milltown Dam presents a distinct case study. My results show that a large proportion of the reservoir sediment that accumulated in the lower BFR was evacuated in the first 5 months following the removal of Milltown Dam. Depending on the variety of estimates for both the amount of sediment stored, and my erosion estimates, 75% - 175% of the reservoir deposit eroded during the 5 month time frame of this study. Given that the BFR is still several years away from reaching a new equilibrium and will likely evacuate a significant volume of sediment during the 2009 Spring runoff period, the total volumetric export may greatly exceed the initial reservoir sediment deposit size.

Compared to published studies of dam removals in recent years, this represents one of the more rapid rates (if not the most rapid rate) of reservoir sediment flushing (Table 4, Figure 33). The studies summarized in Table 3 reported 4 – 14% of reservoir sediment flushed following the removal of dams from low gradient, fine sediment systems, with the exception of Marmot Dam which flushed a larger proportion of the coarse reservoir deposit (43% in 3 months). This comparison is not exhaustive given the variety of physiographic settings each dam removal was performed within. In order to enhance this comparison, it would be useful to explicitly account for discharge, grain size, slope, the initial volume of sediment at the time of dam removal, and the morphology of the reservoir sediment deposit at each of these dam removals.

<u>Marmot Dam</u> The removal of Marmot Dam from the Sandy River, OR, presents the most appropriate comparison given the similarity of the two systems: confined gravel-bed rivers. As described earlier, 100,000 m^3 of reservoir sediment was eroded following the breaching of Marmot Dam in 48 hours at moderate discharge (Q ~ 50 m^3/s, which is 30% above the mean annual flow of 38 m^3/s). A comparable discharge on the BFR would be 57 m^3/s (mean annual flow is 44 m^3/s). Peak discharge of 287 m^3/s was reached on

May 21, 2008, exposing the reservoir sediments to much higher discharge in comparison to the 48 hour period following the Marmot Dam removal.

The hydrology of the Sandy and BFR differ significantly. The Sandy's hydrograph is determined by large rain events and snowmelt from the Cascades. The Sandy River near Marmot, Oregon (USGS station # 14137000) typically shows a flashy pattern from Fall through June or July, spiking with rain events throughout that time. Peak discharge may occur in Fall, Winter or Spring due to the influence of both rain events and snowmelt. Alternatively, the BFR is a typical snowmelt driven river system with peak discharge typically occurring in May or June.

Two primary factors differentiate the conditions and response on the Sandy and Blackfoot Rivers: channel slope and the morphology of the reservoir sediment deposit. The Sandy River at Marmot Dam is a high gradient, confined channel (slope 0.06 - 0.09) and the sediment deposit extended up to the dam itself (Figure 32). Alternately, the lower BFR near Milltown Dam had a lower gradient (slope = 0.001-0.005) and an elongated reservoir sediment deposit with spatially distinct zones of fine and coarse sediment (see Figure 8). The less compact sediment deposit and the lower slope in the BFR made the response more dependent on high flows, whereas results from the Marmot Dam removal show that moderate discharge mobilized a large volume of sediment. The grain mobility analysis for the BFR shows that much of the coarse sediment would not have been mobile at 57 m^3/s, which is equivalent to the 30% of mean annual discharge that eroded 15% of the Marmot Dam sediment in only 48 hours. Furthermore, a knickpoint developed at the Marmot coffer dam site moved 500 meters upstream in the first 48 hours (Major et al. 2008). The morphology of the sand and gravel deposit included a steep slope at the downstream face of the coffer dam presented the conditions to initiate a knickpoint.

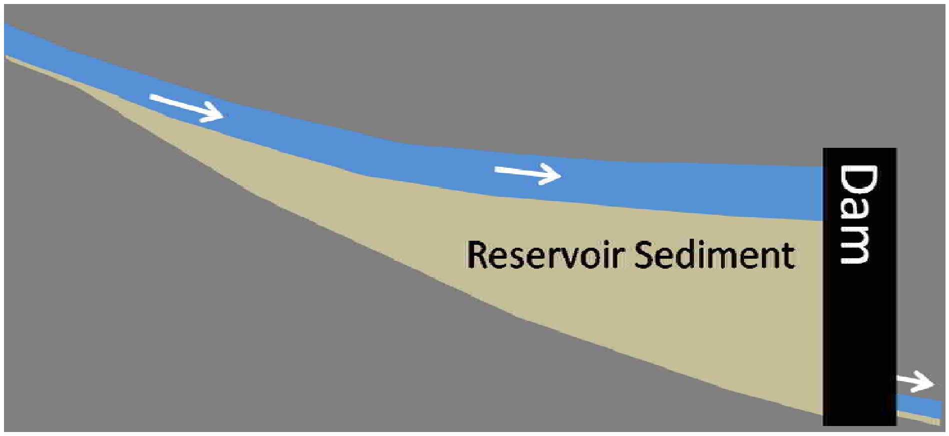


Figure 32. Idealized diagram of a coarse reservoir sediment deposit that extends up to a dam, tapering off upstream. This diagram shows the morphology of the deposit in the Marmot Dam on the Sandy River, for comparison to that found in the BFR (Figure 8).

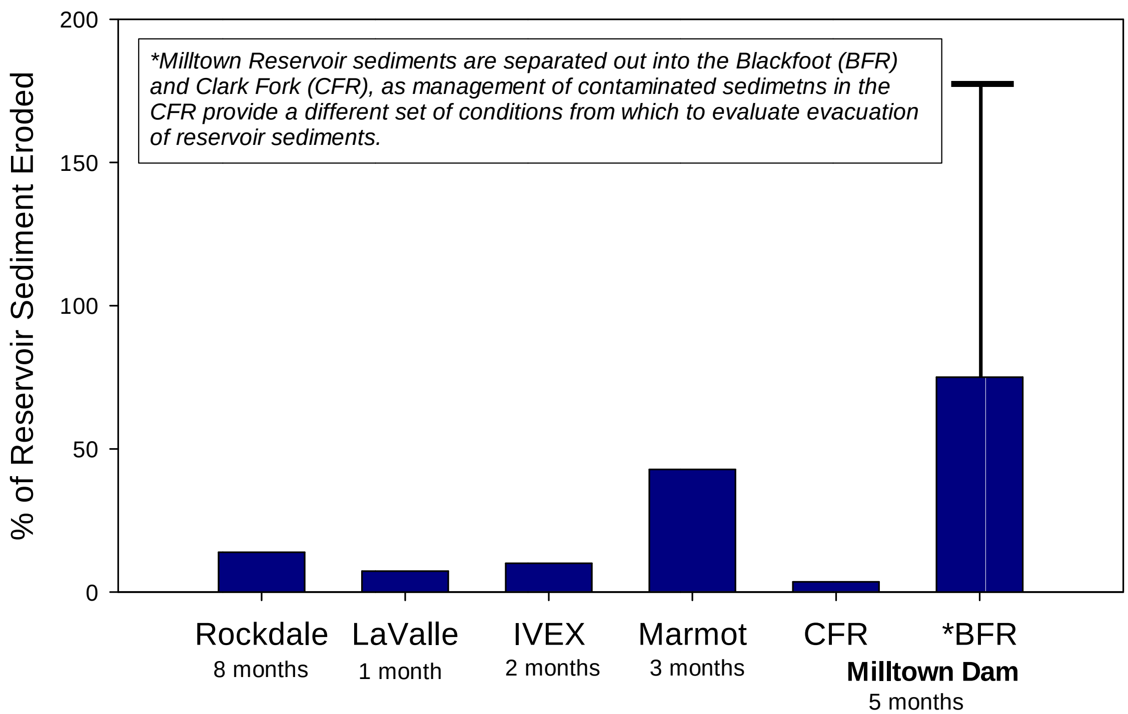


Figure 33. Proportion of reservoir sediment eroded following removal of the four respective dams from published studies documenting fluvial response (See Table 4). Range of estimates for total reservoir sediment (175,000 – 229,000 m^3) and erosion (150,000 – 260,000 m^3) for Milltown shown. Note: time period of observed sediment release shown for each dam.

Dam	River	Drainage Area (km^2)	Dam Height (m)	Reservoir Sediment	Reservoir Sediment Storage (m^3)	Sediment Evacuated (m^3/time)	Slope (m/m)	Observed Upstream Response	Knickpoint
[1]Rockdale Dam	Koshkonong (WI)	360	3.3	silt-sand	287,000	40,000 m^3/ ~8 months	0.0007	Headcutting	YES
[1]LaValle Dam	Baraboo (WI)	575	2	silt-sand	140,100	10,200 m^3/ ~1 month	0.0005	Incision into reservoir deposit, bed lowering	NO
[2]St. Johns Dam	Sandusky (OH)	3637	2.2	Sand-gravel	200,000	N/A	.0001	Decrease in slope after sand filled pools, zones of erosion and deposition upstream of dam	NO
[3]Saeltzer Dam	Clear Creek (CA)	720	4.6	Gravel-cobble	N/A	N/A	N/A	Incision, lateral erosion	NO
[4]IVEX Dam	Chagrin (OH)	692	7.4	Fine sediment	236,000	23,700-31,300 m^3/ 2 months	N/A	Incision, widening, Modified Doyle 2003 CEM	YES
[5]Marmot Dam	Sandy (OR)	1300	14	sand-gravel	730,000	100,000 m^3/48 hrs, 300,000 m^3/ 3 months	0.006 - 0.009	Headward and lateral erosion, bank failures, widening through reservoir deposit, Q ~50 m^3/s	YES
[6,7]Miltown Dam (CFR)	Clark Fork River	9430	20	Silt-sand	> 5,000,000	180,000 5 months	0.0012 – 0.0028	Widening, channel migration across historic floodplain, headward erosion 2.6 – 2.8 km upstream of the dam site	NO
Milltown Dam (BFR)*	Blackfoot (MT)	5931	20	silt-sand, gravel-cobble	175,000 - 229,000	150,000 - 260,000 m^3/ 5 months,	0.0012 - 0.005	Narrowing, headward erosion 4.5 km upstream of the dam in first 5 months, 3.5 year RI peak (287 m^3/s)	NO

*Excluding sediments accumulated in the Clark Fork Arm of Milltown Reservoir

Table 4. Review of detailed dam removal studies from around the U.S. Adapted from [1]Doyle et al. 2003, [2]Cheng and Granata 2007, [3]Ferry and Miller 2003, [4]Evans 2007, [5]Major et al. 2008, [6]Wilcox et al. 2008, [7]Brinkerhoff 2009 . IVEX was a dam failure that has been compared to “blow and go” dam removal. NOTE: although a knickpoint developed in the coffer dam at the time of the breaching of Milltown Dam, it is unclear what happened to it as it moved upstream and reached the complex of bridges in the lower BFR, and the entrance to the rip-rap bypass channel in the Clark Fork River.

Clark Fork Arm of Milltown Dam Intensive management of the contaminated sediments in the Clark Fork arm of Milltown reservoir prevented the CFR from responding naturally to the base level lowering. However, there are differences between the BFR and CFR that warrant some exploration and comparison of how each of these two rivers have responded. Unlike the confined BFR, the CFR is a broad, complex floodplain reach. Based on historical documents and hand-drawn maps, it has been shown that the ~5 km reach immediately upstream of Milltown Dam had a complex multiple channel plan-form with islands and bars (Woelfle-Erskine 2008). Furthermore, the reservoir sediment in the CFR is largely composed of the fine sediment that originated upstream and filled the reservoir following the 1908 flood.

In the months leading up to the breach of Milltown Dam, the CFR was diverted into a rip-rap bypass channel to keep the channel away from ongoing mechanical removal of contaminated sediments. Although much of the contaminated sediments in the CFR were protected by immobile banks and grade control, 180,000 m^3 of contaminated sediment was eroded from the upper portion of the reservoir as the channel migrated across the broad floodplain (Wilcox et al. 2008). Field observations show that some banks migrated more than 200 m in the first spring runoff following the dam removal. The unconfined alluvial valley that the CFR occupies illustrates how rivers will adjust their plan-form via channel migration given a new base level condition. Alternatively, in systems like the BFR or the Sandy River, the confinement of the channel forces the primary modes of adjustment to be slope and grain size.

The 180,000 m^3 that eroded in 2008 is a small proportion of the total reservoir sediment stored in the CFR (3-4 %). Due to the contamination of the CFR sediments, approximately one-third of the > 5,000,000 m^3 of reservoir sediment was mechanically excavated and was not available for river erosion. It is also possible that the wide alluvial valley setting would contribute to a slower rate (in comparison to the BFR) of reservoir sediment evacuation upstream of a removed dam. If a channel is unconfined and able to migrate, the migration rate of the channel would determine the rate at which the reservoir sediment would be eroded.

Implications for Other Systems

The results of this study should be considered in the context of the following controls on the upstream response:

- Slope (S)
- Discharge following the dam breach (Q)
- Grain size (D)
- Roughness (*n*)
- Initial volume of sediment (V_o)
- Confinement of the channel
- Morphology of the reservoir sediment deposit

Perhaps the most efficient way to encourage the evacuation of sediment behind a dam is to do so in a confined channel with sufficient slope and discharge. The comparison of the Marmot and Milltown Dam removals illustrates that a compact sediment deposit in a steeper channel required only moderate flows to flush sediment quickly. The shape of the sediment deposit was critical for providing the conditions to propagate a knickpoint upstream and evacuate sediment rapidly. Alternatively, the spread-out reservoir sediment deposit in the BFR lacked the steep slope and likely did not result in a headward migrating knickpoint. However, the BFR had sufficient discharge to achieve a rapid rate of reservoir sediment evacuation.

Roughness was a strongly interacting variable in controlling the geomorphic response of the BFR to the removal of Milltown Dam. In the lower reservoir, channel morphology, deposition, and surface texture response were strongly linked to the roughness (shear stress partitioning) caused by log jams that organized in the lower reservoir (Figure 31). The roughness in the channel is thought to have slowed the downstream transport of reservoir sediment f rom the lower reservoir area and increased habitat heterogeneity in the newly reclaimed BFR. The integration of natural or constructed logjams in an evolving reservoir after a dam removal could provide a useful tool to manage the ensuing sediment pulse, foster channel complexity, and increase habitat heterogeneity for aquatic organisms.

Figure 34. Lower BFR flowing for the first time since 1907 conversion to reservoir. Distinct sediment and vegetation banding shows phased reduction in base level, starting in 2006, and recently completed by the coffer dam breaching on March 28, 2008 (Photo taken 4/8/2008)

VIII. CONCLUSION

The observations and processes described in this study may be useful in other dam removals and human induced or natural reductions of base level in river systems. Observed water surface elevations can be used to approximate the erosion and elucidate patterns (spatial, temporal) through a known pre-disturbance topography. However, a more robust integration of changes in slope and roughness could help improve a flow modeling approach's ability to provide specific estimates in place of what I consider to be a range of estimates produced in this study. Furthermore, it appears that in a confined mountain channel, headward migrating erosion may drive channel narrowing, where bed lowering further entrenches the channel into the confined active zone. Narrowing was most pronounced at cross sections with the largest magnitude of incision or bed lowering. Alternatively, local sediment deposition may be a mechanism causing some widening in such systems.

In summary, following the removal of Milltown Dam, I observed the following response of the Blackfoot River:

- Headward erosion extended 4.5 km upstream of the dam site in the first 5 months following the removal of Milltown Dam.
- A large proportion of BFR reservoir sediment was evacuated in the first 5 months (a range of 75%-175% of estimated reservoir sediment deposit).
- ΔWSE analysis show that entire initial volume of reservoir sediment (V_o) eroded in the first 100 days following the dam breach.
- Response was influenced by confinement of the channel, shear stress partitioning by LWD, and above-average discharge (287 m^3/s, 3.5 year RI).
- The flow modeling WSE analysis seems to be a reasonable approach and provided insight into the pattern of erosion through the 2008 hydrograph.

Future Directions

A quantitative assessment of the effects of large woody debris on the BFR would help develop the important role of roughness in the geomorphic response. This could be done using the high resolution air photos acquired in the Fall of 2008, in combination with some existing methods to account for flow resistance from wood in channels (Wilcox et al. 2006). Furthermore, some of the water surface profile data could be further explored in an attempt to locate a knickpoint signal. Also, because the channel will likely continue adjusting over the next few years, repeating cross section surveys and acquisition of aerial photography will help show how BFR continues to evolve and reach a new state of equilibrium. Furthermore, acoustic backscatter or Laser In-Situ Scattering and Transmissometery sensors could be installed to measure suspended sediment exiting the lower BFR (Gray et al. 2003), for comparison with data sets from the USGS gauging station upstream (1234000), and the station downstream on the CFR (12340500).

REFERENCES CITED

Ackers, P. and White, W., 1975. Sediment Transport - New Approach and Analysis. JOURNAL OF THE HYDRAULICS DIVISION-ASCE, 101(NHY5): 621-625.

Begin, Z.B., 1988. Application of a Diffusion-Erosion Model to Alluvial Channels Which Degrade Due To Base-Level Lowering. EARTH SURFACE PROCESSES AND LANDFORMS, 13(6): 487-500.

Bishop, P., Hoey, T., Jansen, J. and Artza, I., 2005. Knickpoint Recession Rate and Catchment Area: The Case of Uplifted Rivers in Eastern Scotland. EARTH SURFACE PROCESSES AND LANDFORMS, 30(6): 767-778.

Brinkerhoff, D. 2009. Personal Communication.

Brush, L.M., Wolman, M.G., 1960. Knickpoint Behavior in Non-Cohesive Material: A Laboratory Study. BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA. 71: 59-74.

Buffington, J. and Montgomery, D., 1999. Effects of Hydraulic Roughness on Surface Textures of Gravel-Bed Rivers. WATER RESOURCES RESEARCH, 35(11): 3507-3521.

Cantelli, A., Paola, C. and Parker, G., 2004. Experiments on Upstream-Migrating Erosional Narrowing and Widening of an Incisional Channel Caused by Dam Removal. WATER RESOURCES RESEARCH, 40(3).

Cantelli, A., Wong, M., Parker, G. and Paola, C., 2007. Numerical Model Linking Bed and Bank Evolution of Incisional Channel Created by Dam Removal. WATER RESOURCES RESEARCH, 43(7).

Cheng, F. and Granata, T., 2007. Sediment Transport and Channel Adjustments Associated With Dam Removal: Field Oobservations. WATER RESOURCES RESEARCH, 43(3).

Clark Fork River Technical Assistance Committee. August 2008. http://www.cfrtac.org/sitehistory.php

Crosby, B. and Whipple, K., 2006. Knickpoint Initiation and Distribution Within Fluvial Networks: 236 Waterfalls in the Waipaoa River, North Island, New Zealand. GEOMORPHOLOGY, 82(1-2): 16-38.

Cui, Y., A. Wilcox. 2008. Development and Application of Numerical Modeling of Sediment Transport Associated with Dam Removal. In: M.H. Garcia, Ed.

Sedimentation Engineering. *ASCE Manual 110*. Reston, VA: American Society of Civil Engineers.

Doyle, M., Stanley, E. and Harbor, J., 2002. Geomorphic analogies for assessing probable channel response to dam removal. JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION, 38(6): 1567-1579.

Doyle, M., Stanley, E. and Harbor, J., 2003. Channel adjustments following two dam removals in Wisconsin. WATER RESOURCES RESEARCH, 39(1).

Doyle, M., Stanley, E, Havlick, D., Kaiser, M., Steinbach, G., Graf, W., Galloway, G., Riggsbee, J., 2008. Environmental Science - Aging Infrastructure and Ecosystem Restoration. SCIENCE, 319(5861): 286-287.

Dynesius, M., Nilsson, C., 1994. Fragmentation and Flow of River Systems in the Northern 3rd of the World. SCIENCE, 266(5186): 753-762.

Envirocon. *Milltown Reservoir Scour Evaluation Addendum 2 – Evaluation of Potential Infrastructure Impacts Associated with Dam-Removal Induced Scour and Effectiveness of Possible Countermeasures.* April 28, 2005.

Envirocon. *Milltown Reservoir Dry Removal Scour Evaluation, Addendum 1, Proposed Plan Updated Scour Evaluation*. October 7, 2004.

Envirocon. Remedial Design Data Summary Report #1, Milltown Reservoir Sediments Site. June 8, 2004.

EPA. *Biological Assessment of the Milltown Reservoir Sediments Operable Unit, Revised Proposed Plan and of the Surrender Application for the Milltown Hydroelectric Project (FERC No. 2543)*. August 2004.

Evans, J., 2007. Sediment Impacts of the 1994 Failure of IVEX Dam (Chagrin river, NE Ohio): A test of Channel Evolution Models. JOURNAL OF GREAT LAKES RESEARCH, 33: 90-102.

Ferry, M., Miller, P., 2003, The Removal of Saeltzer Dam on Clear Creek : An Update. Water Resources Center Archives, The University of California.

Graf, W., 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. WATER RESOURCES RESEARCH, 35(4): 1305-1311.

Graf, W., (Ed.) 2002. *Dam Removal Research: Status and Prospects*, H. John Heinz II Center for Science, Economics and the Environment., Washington, D.C.

Gray, J.R., Melis, T., Patino, E., Larsen, C., Topping, D., Rasmussen, P., Figueroa-Alamo, C., 2003. U.S. Geological Survey Research on Surrogate Measurements for

Suspended Sediment. Proceedings, Interagency Conference on Research in the Watersheds.

HEC-RAS 4.0. 2008. User's Manual. Hydrologic Engineering Center, US Army Corps of Engineers.

Johnsen, J. 2009. Personal Communication.

Knighton. D. 1998. "Fluvial Forms and Processes: A New Perspective." Oxford University Press, New York, NY.

Lane, E.W. 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. American Society of Civil Engineers Proceedings, 81, 1-17. Physical Monograph Series, Vol. 89, edited by J.E. Costa et al.

Larue, J., 2008. Effects of Tectonics and Lithology on Long Profiles of 16 Rivers of the Southern Central Massif Border Between the Aude and the Orb (France). GEOMORPHOLOGY, 93(3-4): 343-367.

Lee, K., Liu, Y. and Cheng, K., 2004. Experimental Investigation of Bedload Transport Processes Under Unsteady Flow Conditions. HYDROLOGICAL PROCESSES, 18(13): 2439-2454.

Leopold, L., and Bull, W., 1979. Base Level, Aggradation and Grade. PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY, 123(3): 168-202.

Major, J. J., J. E. O'Connor, G. E. Grant, K. R. Spicer, H. M. Bragg, A. Rhode, D. Q. Tanner, C. W. Anderson, and J. R. Wallick (2008), Initial Fluvial Response to the Removal of Oregon's Marmot Dam, EOS TRANSACTIONS. AGU, 89(27), doi:10.1029/2008EO270001.

Pitlick, J., P.R. Wilcock, J.P. Potyondy, P. Bakke, Y. Cui. 2007. Bedload Assessment in Gravel-bedded Streams. Stream Systems Technology Center, United States Forest Service, Department of Agriculture.

Pizzuto, J., 1994. Channel Adjustments to Changing Discharges, Powder River, Montana. GEOLOGICAL SOCIETY OF AMERICA BULLETIN, 106(11): 1494-1501.

Pizzuto, J. 2002. Effects of Dam Removal on River Form and Process. BIOSCIENCE. 52(8): 683-691.

Rothrock, J., Barten, P. and Ingman, G., 1998. Land Use and Aquatic Biointegrity in the Blackfoot River Watershed, Montana. JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION, 34(3): 565-581.

Shuman, J., 1995. Environmental Considerations for Assessing Dam Removal Alternatives for River Restoration. REGULATED RIVERS-RESEARCH & MANAGEMENT, 11(3-4): 249-261.

Stewart, G.B. 2006. Patterns and Processes of Sediment Transport following Sediment-filled Dam Removal in Gravel Bed Rivers. Dissertation. Oregon State University.

Van Haveren, B.P., W.L. Jackson, G.C. Lusby. 1987. Sediment Deposition Behind Sheep Creek Barrier Dam, Southern Utah. JOURNAL OF HYDROLOGY (New Zealand) 26:185-196.

Ward, J. and Stanford, J., 1995. Ecological Connectivity in Alluvial River Systems and its Disruption by Flow Regulation. REGULATED RIVERS-RESEARCH & MANAGEMENT, 11(1): 105-119.

Wilcock, P.R., Kenworthy, S.T. and Crowe, J.C., 2001. Experimental Study of the Transport of Mixed Sand and Gravel. WATER RESOURCES RESEARCH, 37(12): 3349-3358.

Wilcock, P.R. and Crowe, J.C., 2003. Surface-Based Transport Model for Mixed-Size Sediment. JOURNAL OF HYDRAULIC ENGINEERING-ASCE, 129(2): 120-128.

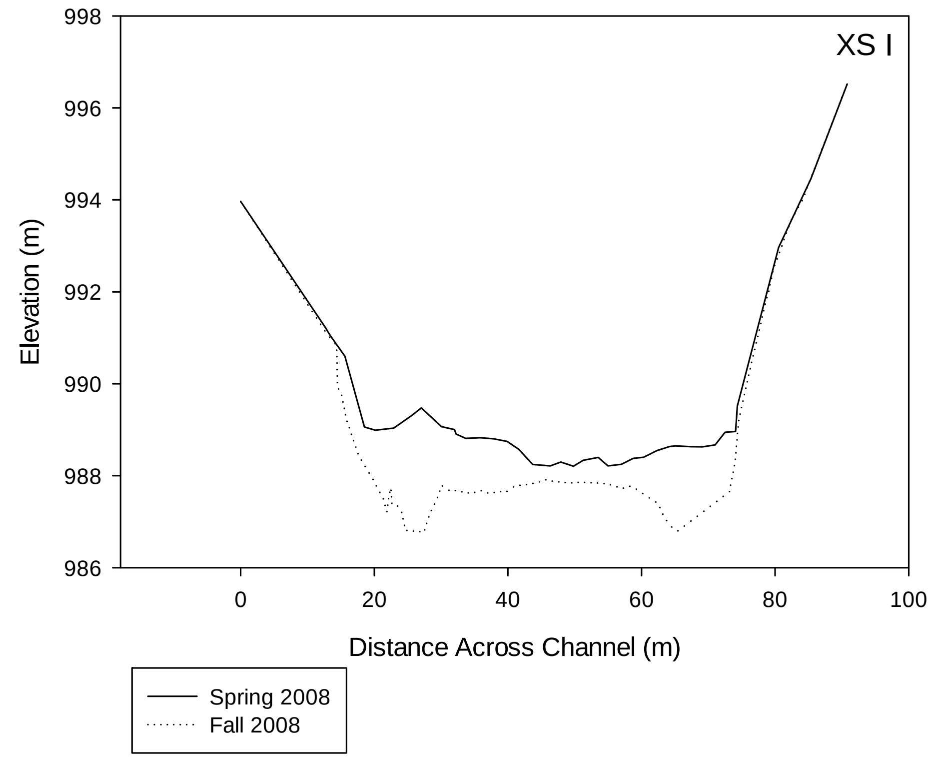
Wilcox, A., Nelson, J. and Wohl, E., 2006. Flow Resistance Dynamics in Step-Pool Channels: 2. Partitioning Between Grain, Spill, and Woody Debris Resistance. WATER RESOURCES RESEARCH, 42(5).

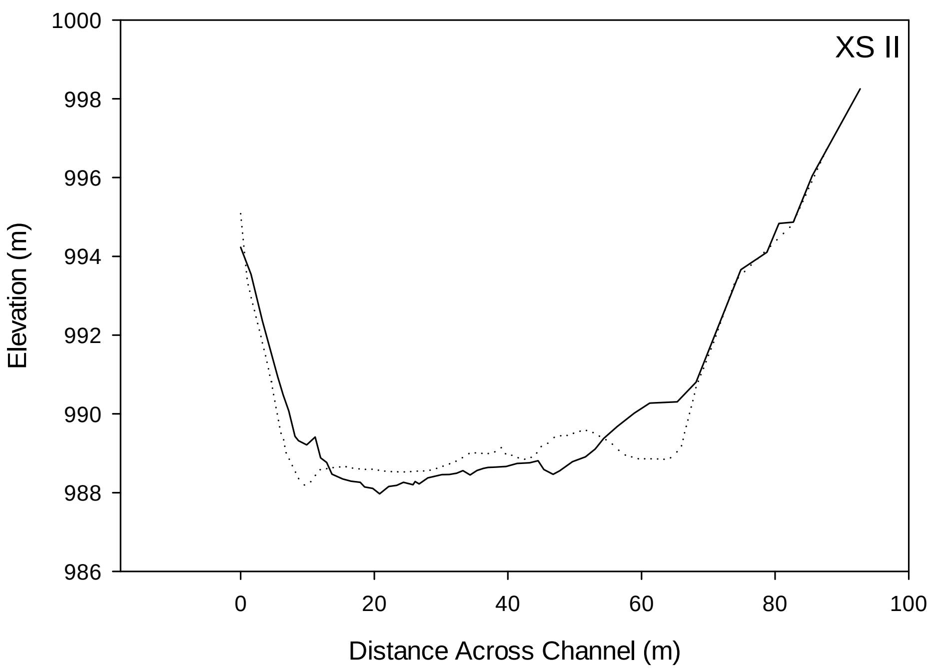
Wilcox, A. C., Brinkerhoff, D., Woelfle-Erskine, C., 2008. Initial geomorphic responses to removal of Milltown Dam, Clark Fork River, Montana, USA. *EOS Trans. AGU.* 89(53) Fall Meet. Suppl. Abstract H41I-07.

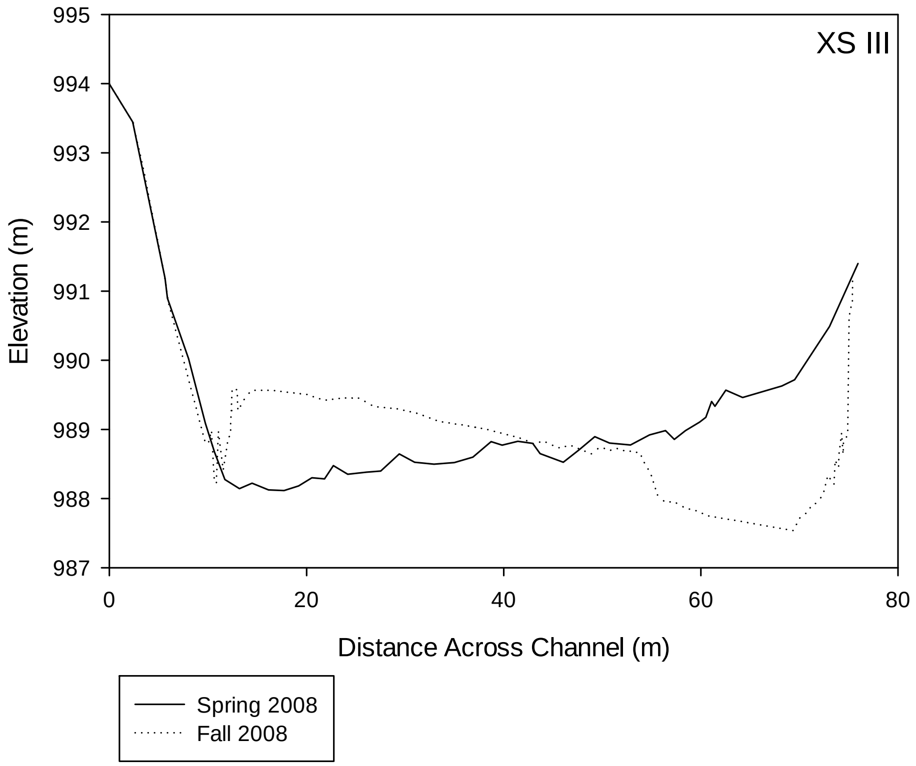
Woelfle-Erskine, C. 2009. History and uncertainty in post-Milltown dam removal restoration on the Clark Fork River, Montana. Honors Thesis, Department of Geosciences, The University of Montana.

Wolman, M.G., 1954. A Method of Sampling Coarse Bed Material. American Geophysical Union, TRANSACTIONS, 35: 951-956.

APPENDIX I: CROSS SECTIONS



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Elevation (m)
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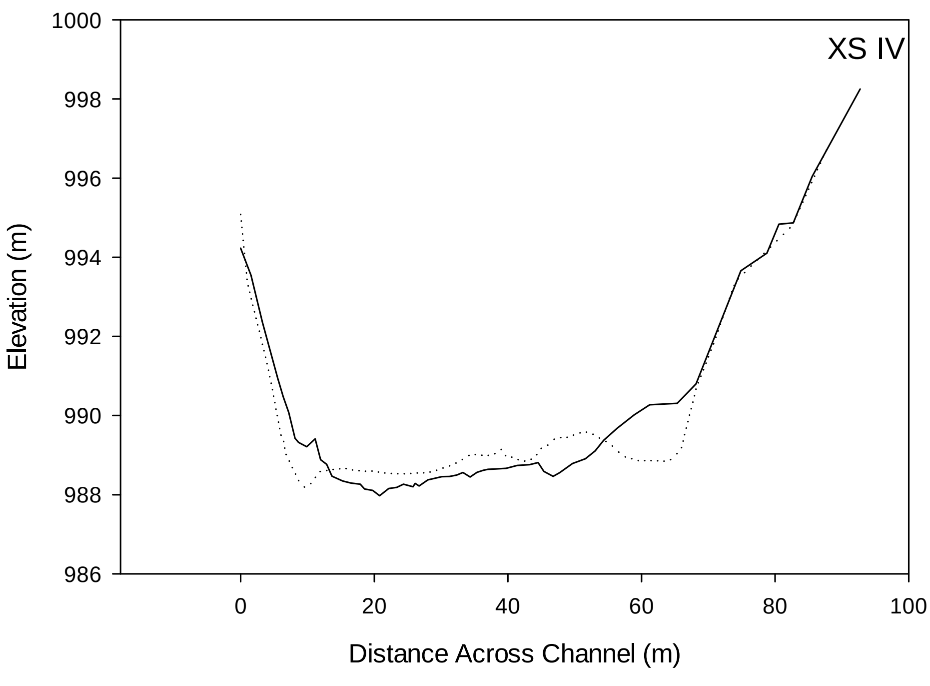
993
992
991
990
989
988
987
0
20
40
60
80
Distance Across Channel (m)
Spring 2008
Fall 2008


XS IV
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998
996
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20
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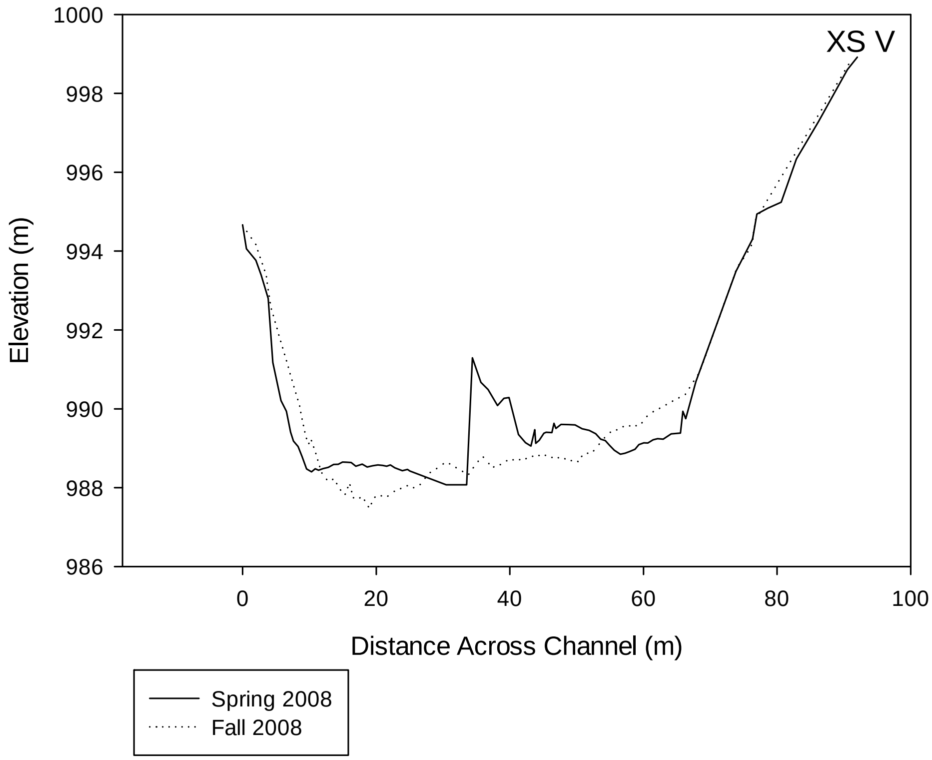
60
80
100
Distance Across Channel (m)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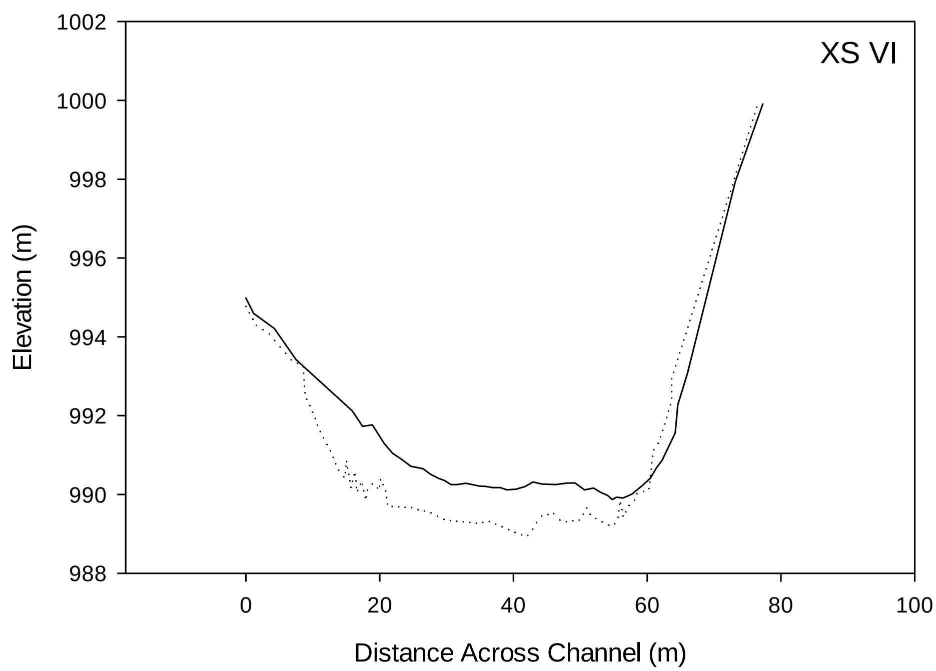
Distance Across Channel (m)
Spring 2008
Fall 2008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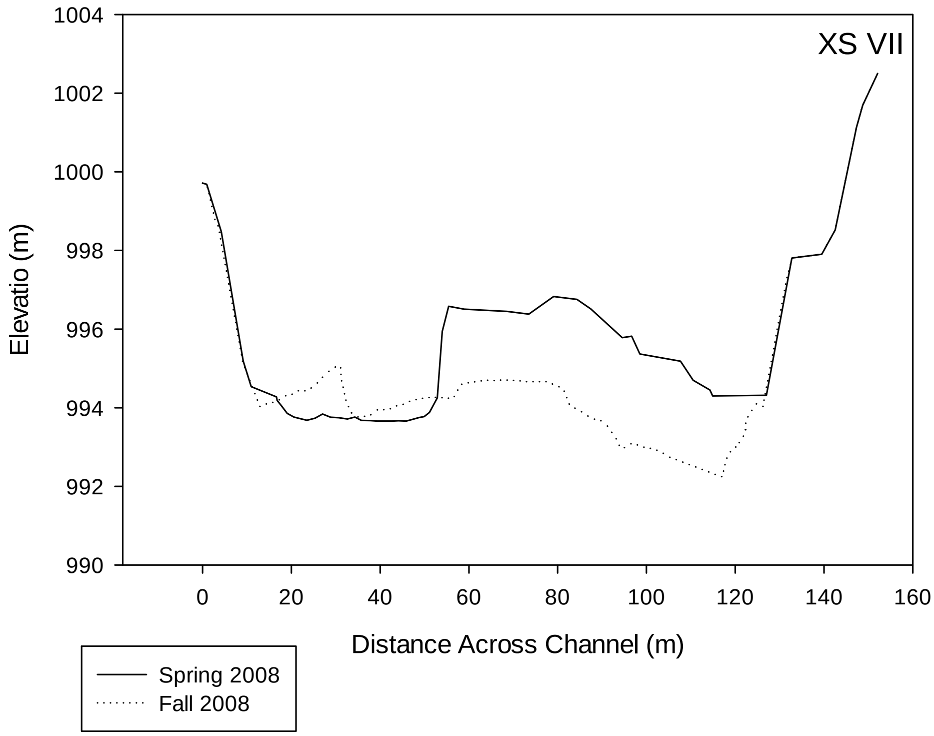
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Distance Across Channel (m)
Spring 2008
Fall 2008
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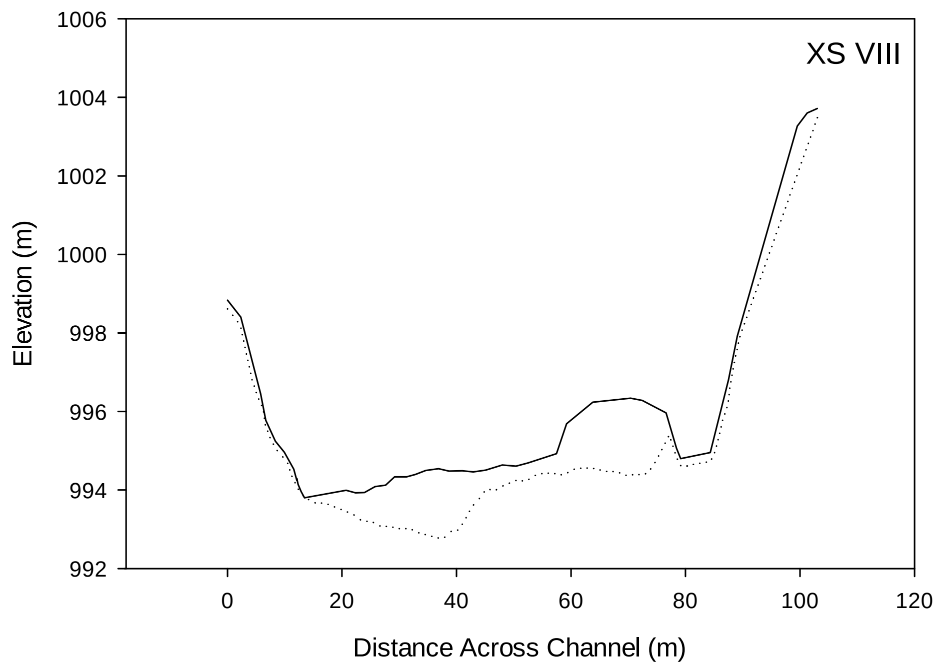
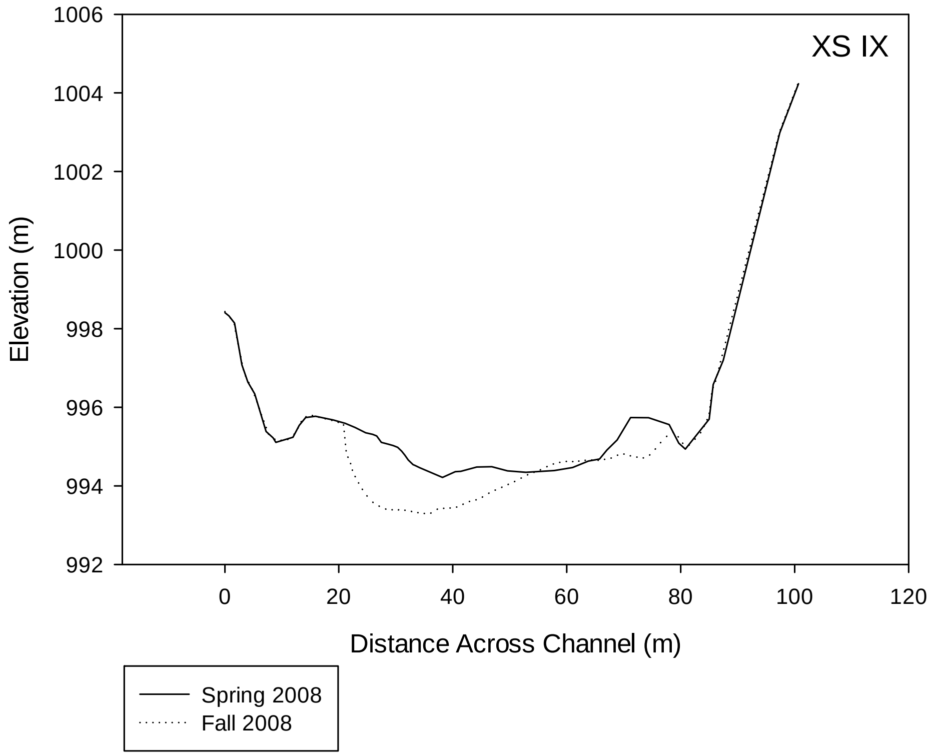
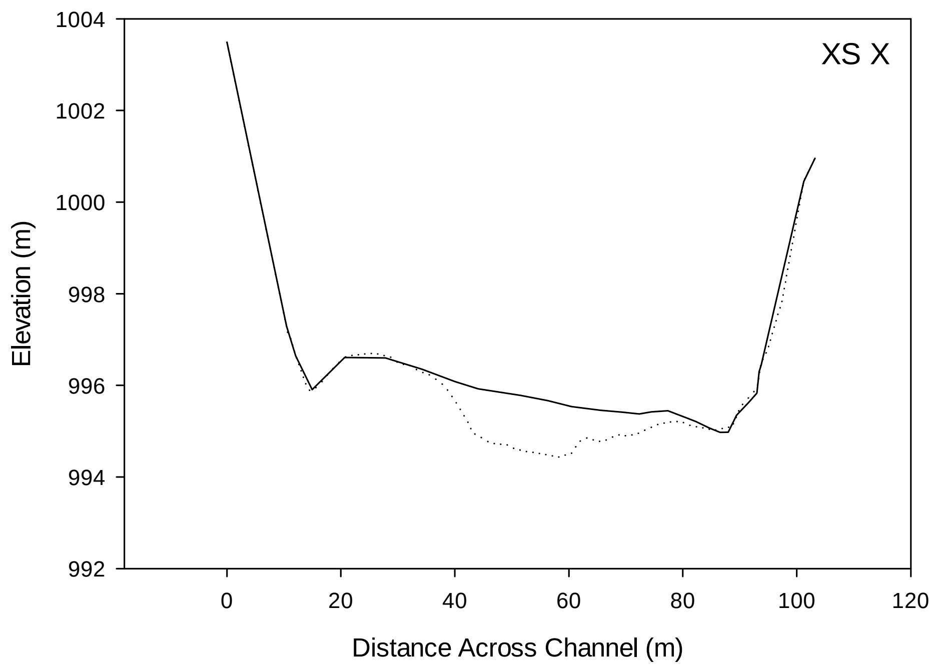
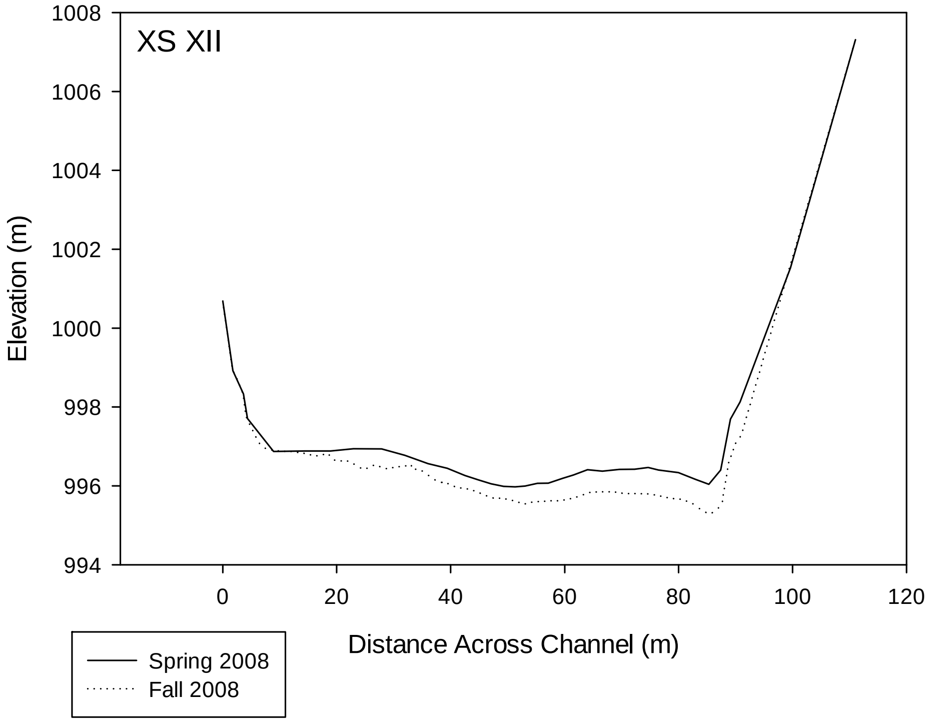
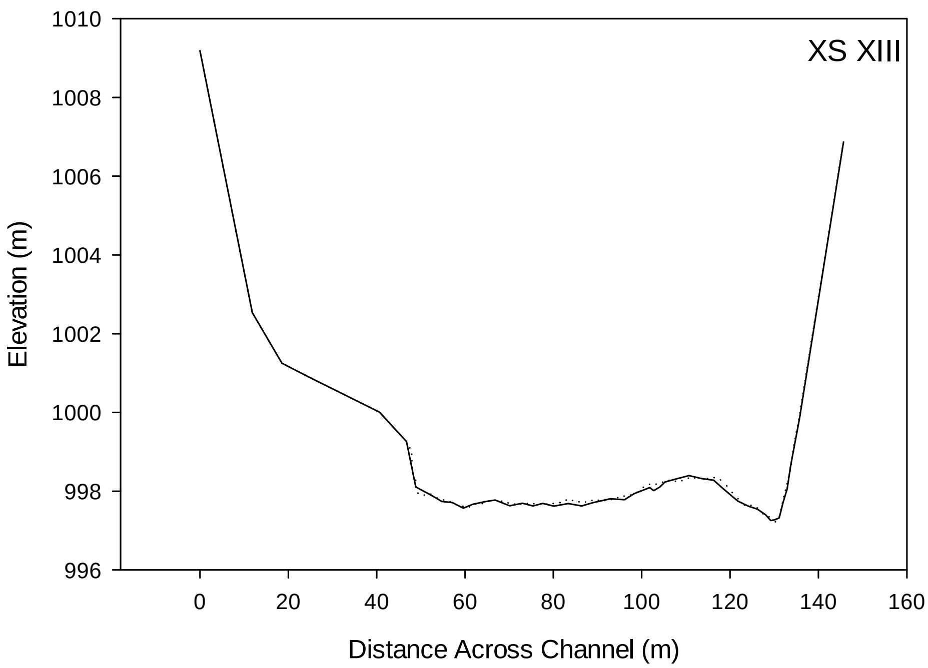
140
160


XS VIII
Elevation (m)
Distance Across Channel (m)
1006
1004
1002
1000
998
996
994
992
0
20
40
60
80
100
120


XS IX
Elevation (m)
Distance Across Channel (m)
Spring 2008
Fall 2008
1006
1004
1002
1000
998
996
994
992
0
20
40
60
80
100
120


XS X
Elevation (m)
Distance Across Channel (m)
1004
1002
1000
998
996
994
992
0
20
40
60
80
100
120


XS XII
Elevation (m)
1008
1006
1004
1002
1000
998
996
994
0
20
40
60
80
100
120
Distance Across Channel (m)
Spring 2008
Fall 2008


XS XIII
Elevation (m)
1010
1008
1006
1004
1002
1000
998
996
0
20
40
60
80
100
120
140
160
Distance Across Channel (m)

APPENDIX II: GPS DATA

Cross Section Endpoints

XS	LEFT, RIGHT BANK	NORTHING (m)	EASTING (m)	ELEVATION (m)
I	LB	5195178.190	280412.059	996.528
	RB	5195089.003	280428.991	993.973
II	LB	5195220.775	280739.838	997.488
	RB	5195134.691	280745.823	993.728
III	LB	5195212.319	280809.260	993.038
	RB	5195132.641	280817.565	994.004
IV	LB	5195239.652	280998.052	998.257
	RB	5195149.244	281018.633	994.240
V	LB	5195241.480	281016.129	996.419
	RB	5195155.819	281046.419	992.313
VI	LB	5195437.388	281406.577	997.563
	RB	5195374.575	281451.592	992.636
VII	LB	5195415.850	282378.782	1000.150
	RB	5195330.015	282504.381	997.364
VIII	LB	5195609.324	282473.540	1001.366
	RB	5195575.822	282570.991	996.487
IX	LB	5195657.152	282498.946	1001.888
	RB	5195615.008	282590.356	996.058
X	LB	5196008.978	282755.632	998.610
	RB	5195911.458	282789.424	1001.142
XII	LB	5196381.472	283202.879	1004.966
	RB	5196270.827	283193.439	998.336
XIII	LB	5196379.322	283232.525	1001.861
	RB	5196271.265	283224.812	1001.244
XIV	LB	5196565.467	283526.208	1004.525
	RB	5196517.933	283663.921	1006.835

All data are in UTM 12 North, North American Datum 1983, using the GEOID Model 2003.

Sediment Sampling Locations

XS	NORTHING (m)	EASTING (m)	ELEVATION (m)	NOTES
XIII	5196535.959	283560.075	996.052	pc
XII	5196308.905	283227.209	994.195	pc
XI	5196289.973	283178.348	994.703	pc
X	5195940.170	282774.567	994.076	pc
IX	5195652.475	282564.543	992.465	pc
XIII	5195588.640	282540.567	992.068	pc
XII	5195316.176	282437.679	991.540	pc
XI	5195393.505	281384.146		pc
V.A	5195207.180	281067.338	999.360	pc
V.B	5195196.594	281081.780	999.378	pc
V	5195207.481	281032.549		sc
IV	5195198.906	281006.162		sc
III	5195193.115	280808.284	986.894	sc10
II	5195170.450	280744.040	986.712	sc7
II	5195181.237	280743.167	986.643	sc8
II	5195199.788	280743.287	987.041	sc9
I	5195161.152	280415.343	986.434	sc1
I	5195160.886	280414.741	986.561	sc2
I	5195161.078	280413.844	986.569	sc3

All data are in UTM 12 North, North American Datum 1983, using the GEOID Model 2003. SC = soil core, PC = pebble count.

Appendix III: Exponential Decay Derivation

Q_s flux of sediment out of the reservoir reach, m^3 /day
V_o initial volume of sediment, m^3
α decay constant, dimensionless
t, time, days

$$\frac{\partial V}{\partial t} = -\alpha V \qquad (3)$$

Rearranging equation 3:

$$\frac{\partial V}{V} = -\alpha \partial t \qquad (4)$$

And taking the natural logarithm of V we show that

$$\ln V = -\alpha t + c \qquad (5)$$

$$V(t) = e^{-\alpha t} e^{c} \qquad (6)$$

At time zero,

$$V = V_o = e^{c} \qquad (7)$$

Therefore,

$$Q_s = \frac{\partial V}{\partial t} = -\alpha V = -\alpha V_o e^{-\alpha t} \qquad (8)$$