AN ABSTRACT OF THE DISSERTATION OF

Gregory B. Stewart for the degree of Doctor of Philosophy in Geology presented on March 20, 2006.
Title: Patterns and Processes of Sediment Transport following Sediment-filled Dam Removal in Gravel Bed Rivers.

Abstract approved:___________________________________________________

Gordon E. Grant

Dam removal is increasingly viewed as a river restoration tool because dams affect so many aspects of river hydrology, geomorphology, and ecology; but removal also has impacts. When a dam is removed, sediment accumulated over a dam’s lifetime may be transported downstream; and the timing, fate and consequences of this sediment remain some of the greatest unknowns associated with dam removal. In this thesis, I develop a conceptual model for erosion and deposition following removal of sediment-filled dams in mountain streams, and use field studies to document actual change. The data show that reservoir erosion in mountain rivers is likely to occur by knickpoint migration, with 85% of stored sediment being released during a single storm event in two field studies, at shear stresses less than that required for mobilization of the median surface particle size. Coarse sediment is predicted to deposit close to the dam with channel aggradation decreasing exponentially with increasing distance downstream, although some channel features are shown to have a greater propensity for aggradation than others. Field studies show that turbidity associated with dam removal and reservoir erosion may decrease hyporheic exchange, but gravel deposition (e.g., 470 m$^3$ of gravel from Dinner Creek Dam) has the potential to more than offset that decrease, and increased hyporheic exchange is shown to reduce diurnal temperature change. Macroinvertebrate density and taxa richness did not respond to dam removal itself, but rather with time-lagged reservoir erosion. Following reservoir erosion, macroinvertebrate density recovered quickly, although longterm taxa community composition appears to be altered. On the Sandy River, field measurements of shear stress and patterns of sediment deposition following cold lahars were used as an analog to predict the fate of fine sediment, which is likely to deposit far from the dam. Results show that the Sandy River has little capacity for fine sediment storage in pools above RK 6.4 (~ 42 kilometers below Marmot Dam) at discharges associated with reservoir sediment releases. Taken as a whole, this paper illustrates a complex suite of process that may accompany removal of sediment-filled dams in mountain rivers.
PATTERNS AND PROCESSES OF SEDIMENT TRANSPORT FOLLOWING SEDIMENT-FILLED DAM REMOVAL IN GRAVEL BED RIVERS

by

Gregory B. Stewart

A DISSERTATION submitted to Oregon State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Presented March 20, 2006
Commencement June 2006

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

________________________________________________________________________
Gregory B. Stewart, Author
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Dr. Gordon Grant contributed to the study design and report write-up for the Cougar Reservoir sediment intrusion study presented in Chapter 3, and provided edits for all the chapters.

Sara Lewis performed all the grain-size analysis for the Cougar Reservoir sediment intrusion study and contributed to the report write-up.

Bill Gerth and Shannon Claeson performed the majority of the benthic macroinvertebrate identification presented in Chapter 4, and both helped with benthic macroinvertebrate analysis including NMS.
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CHAPTER 1 – INTRODUCTION

Although dams are traditionally considered permanent landscape fixtures, the number of dams removed each year is beginning to exceed the number of new dams constructed in the United States (Figure 1). American Rivers (1999) identified more than 450 dams removed from U.S. rivers since 1912; most were small and no longer performed the functions they were created for, posed environmental or safety concerns, and/or were removed because costs of dam rehabilitation were greater than the dam’s perceived benefits.

Whereas the structural life of a dam may be a century or longer, planning and economic studies rarely exceed 50 years. As dams age, maintenance and rehabilitation costs increase, while the benefits that dams provide generally decrease (Born et al., 1998; Morris and Fan, 1998). A recent study of small flood control dams in 22 States found that: 1) more than 22% of the 10,000 dams included in the study were in need of rehabilitation, 2) at least 650 of those dams posed a threat to public health and safety, and 3) the cost of rebuilding and upgrading just those 650 was nearly $400 million (Natural Resources Conservation Service, 2000). Of the more than 77,000 dams listed in the

Figure 1: Dams built and removed per decade from 1900-2000 and per year from 1990-2000 (Source NID, 2000 and American Rivers, 1999).
U.S. National Inventory of Dams (NID) database (National Inventory of Dams, 2000), approximately 28% are beyond the average design life of 50 years; by the year 2020 that number will increase to more than 70% (Figure 2).

The call for dam removal is not only driven by the high maintenance costs but also by an increasing awareness of the environmental impacts of dams. Dams are known to have a wide range of effects on river ecosystems (Dynesius and Nilsson, 1994; Ward and Stanford, 1995; Power et al., 1996; Andersson et al., 2000, World Commission on Dams, 2000), channel morphology (Williams and Wolman, 1984; Ligon et al., 1995), and hydrology (Williams and Wolman, 1986; Graf, 1999). Given dams effects, it has been argued that dam removal should be viewed as a river restoration tool (American Rivers, 1999; Pejchar and Warner, 2001).

Dam removal is not without environmental impacts, however (Stanley and Doyle, 2003). Over time, rivers adjust to the presence of dams and dam removal represents a disturbance to the adjusted regime (Grant, 2001). Dams create quiescent pools of water that trap as much as 95% of river sediment, with size classes ranging from silt and clay to large boulders (10^{-6}-10^{-6} m), and the release of stored sediment remains one of the most fundamental and least understood impacts of dam removal (Heinze Center, 2002).
Sediment released by dam removal has the potential to significantly affect downstream geomorphic and ecological systems by reducing pool volume (Rathburn and Wohl, 2001) and altering water chemistry (Stanley and Doyle, 2002), streambed composition (Wohl and Cinderelli, 2000) and food web dynamics (Doeg and Koehn, 1994). Sediment can be removed prior to dam removal, but sediment extraction is expensive and does not address the desire, in many cases, to increase sediment availability downstream of the dam.

Dams are built in a variety of geomorphic settings and for many different uses, including water storage and hydroelectric power generation. Just as dam purposes vary, so do their impacts and the potential impact of their removal. Although much basic research in geomorphology and water resource engineering over the last century has focused on our ability to predict the fate of river sediments, it remains difficult to accurately predict when and where sediment will erode and/or deposit over a wide range of spatial and temporal scales. In the case of dam removal, the problem is especially difficult with disturbance propagating both upstream and downstream through erosional and depositional processes that are coupled in time and space (Grant, 2001). It has been argued that our ability to forecast the effects of dam removal requires semi-quantitative documentation of dam removal processes over a wide variety of conditions, dam heights, with multidisciplinary effort (Pizzuto, 2002). In this way, an empirical set of case lore can be built with which to test more rigorous dam removal models.

Much has been written on dam removal, yet the majority of scientific literature published to date is based on anecdotal evidence or has focused on broad contextual issues surrounding large dams. Detailed dam removal studies are few, and those that do exist have been limited to low gradient rivers with a limited range of bed material sizes. Few, if any, studies have examined the effects of dam removal in steep gravel-bed rivers. In this thesis I use data from the removal of two small dams in Oregon and data collected below a large dam scheduled for removal, to test several hypotheses regarding reservoir erosion mechanisms, methods for estimating reservoir erosion volumes, patterns of downstream deposition, and potential downstream ecological impacts. The hypotheses presented below are keyed to chapters where each is addressed.

**Hypotheses and Findings**

**Null hypothesis 1:** Diffusion-type sediment transport equations can be used to model reservoir erosion.

Most of the reservoir erosion modeling done to date assumes that shear stress on
surface grains will drive erosion. If so, a reservoir deposit will evolve as a rotating knickpoint and steady-state diffusion equations can be used to predict sediment yield as a function of time.

**Finding:** In Chapter 2, I show that mountain reservoirs with a mixture of grain sizes are likely to erode by stepped knickpoint migration, and in these systems diffusion equations will significantly underestimate the rate at which reservoir sediment erodes.

**Null hypothesis 2:** Calculations of the volume of sediment that will erode from a reservoir following dam removal must consider upstream width-adjustments that will occur before a stable channel is established.

No formula has been developed to predict the volume of sediment that will erode from a dam, yet predictions of downstream impacts require such estimates. Published conceptual models of reservoir erosion suggest that the width of the incising channel will change through time and affect the volume of sediment released.

**Finding:** Data presented in Chapter 2 suggests that simple geometric relationships can be used to constrain the volume of sediment that can be released from a reservoir in the first season after removal, assuming that reservoir erosion proceeds by stepped knickpoint migration, although downstream deposition and the presence of buried obstructions may significantly reduce the actual volume released. Because erosion in mountain streams is episodic and width adjustments may occur many years after initial reservoir erosion, I cannot reject the null hypothesis.

**Null hypothesis 3:** Increased turbidity during dam removal will reduce downstream hyporheic exchange.

Hyporheic exchange, where stream water flows through the riverbed and returns to the stream, is an important but poorly understood process in alluvial channels. Fine sediment released into river can be advected into the riverbed where it fills interstitial spaces and reduces hydraulic conductivity and hyporheic exchange.

**Finding:** In Chapter 3, I present evidence to show that fine sediment released from a reservoir can indeed become stored in the channel bed. The degree to which fine sediment affects hyporheic exchange could not be established, but the data generally support the proposition that fine sediment releases reduce hyporheic exchange and show that coarse sediment deposition can significantly increase hyporheic exchange.
Null hypothesis 4: Removal of sediment filled dams, where reservoir erosion proceeds by knickpoint migration, will result in relatively short-term changes to the downstream benthic macroinvertebrate community.

Downstream sedimentation associated with dam removal can change water quality, chemistry, temperature, and substrate composition. Benthic macroinvertebrate communities are especially susceptible to reservoir sediment releases because they live on and within the streambed. However, because they are able to rapidly recolonize the lotic environment following disturbance, changes in macroinvertebrate communities should occur on the same timescales as the disturbance.

Finding: In Chapter 4 we show that changes in water chemistry and quality during dam removal had little effect on downstream macroinvertebrate abundance or community composition. Coarse sediment releases that aggraded the channel and changed channel morphology did caused short-term changes in macroinvertebrate abundance, but long-term changes in community composition (primarily through loss of rare taxa).

Null hypothesis 5: Sediment released from a dam will move downstream as a wave that both disperses and translates.

Sediment releases are commonly modeled as dispersing or translating downstream and whether sediment disperses, translates, or does both determines the magnitude and extent of downstream aggradation.

Finding: In Chapters 2, I find that coarse sediment released from a dam removal on a steep mountain river dam is likely to show a dispersive pattern of downstream deposition. Data presented in Chapter 5, suggests that fine sediment released in mountain rivers can translate over significant distance depending on the flow regime, because transient storage that enhances sediment dispersion may be limited.

Null hypothesis 6: At the channel unit scale, sediment eroded from behind a dam will deposit preferentially in pools.

Several studies have suggested that increased sediment loads in rivers may result in preferential sediment deposition in pools. If so, this could negatively impact fish species by reducing thermal and velocity refugia.

Finding: In Chapter 5 we use data from the Sandy River in Oregon to show shear stress in pools can limit sediment deposition at flows associated with reservoir erosion.
Taken together these results indicate reservoir erosion following dam removal in mountain rivers will occur by stepped knickpoint migration. Stepped knickpoints will create incised channels whose dimensions can be predicted \textit{a priori}. Sediment will be released episodically. The release of fine sediment will reduce downstream hyporheic exchange while coarse sediment releases will increase it. Coarse sediment will deposit in a dispersional wave with the greatest deposition near the dam, while fine sediment may translate far downstream with fine sediment deposition in pools limited to periods of low discharge. Coarse sediment deposition may cause changes in channel form and function that alters downstream biological communities.
CHAPTER 2 - EROSION AND DEPOSITION FOLLOWING DAM REMOVAL IN SEDIMENT-FILLED MOUNTAIN RESERVOIRS

Abstract

In this paper I develop a conceptual model for primary erosion and sediment release from small sediment-filled reservoirs and model predictions are tested against patterns and processes of erosion and deposition associated with the removal of two small dams in Oregon. In each case, reservoir erosion was driven by a series of upstream migrating knickpoints that eroded more than 85% of reservoir sediment in a single event, at shear stresses less than that required for mobilization of the median surface particle size. Knickpoint migration was rapid with rates of up to 10 m/hr. Downstream deposition was greatest near the dams and decreased exponentially with increasing distance downstream, but was non-uniform with runs and riffles aggrading more than plunge pools or steps. Where plainbed morphology existed, channel deposition was greatest along the channel thalweg and outside of bends resulting in less sinuosity and the creation of pool-riffle morphology. The volume of sediment that would be released by dam removal was significantly over-estimated in each case, though simple geometric prism models appear to provide reasonable estimates of maximum yield.

Introduction and background

The release of stored reservoir sediment remains one of the most fundamental, yet poorly understood processes associated with dam removal (Heinz Center, 2002). Reservoir sediment releases have the potential to significantly affect downstream geomorphic and ecological systems by reducing pool volume (Rathburn and Wohl, 2001), altering water chemistry (Stanley and Doyle, 2002), streambed composition (Wohl and Cinderelli, 2000), and food web dynamics (Doeg and Koehn, 1994). Just as the effect of dams on rivers vary, so too will the effects of dam removal: some will have little or no affect while others will stimulate dramatic affects on river and ecosystem processes (Grant, 2001). It has therefore been argued that our ability to forecast the effects of dam removal requires semi-quantitative documentation of dam removal processes over a wide variety of conditions, dam heights, and with multidisciplinary effort (Pizzuto, 2002).

Sediment-filled dams in mountain rivers represent an important subset of dams under consideration for removal. Sediment-filled dams are less able to perform value-added
functions, including water storage and flood control, while the large quantity of sediment stored in their reservoirs greatly complicates removal efforts. When a sediment-filled dam is removed, a knickpoint remains. A knickpoint, derived from the German word Knickpunkt or ‘bend point’, is a sharp slope break in the longitudinal profile of a river, generally characterized by a zone of erosion that migrates upstream within the channel (Brush and Wolman, 1960; Schumm et al., 1984). Knickpoints have been studied in the context of landscape evolution (Holland and Pickup, 1976; Gardner, 1983; Seidl et al., 1994) and soil erosion (Seginer, 1966; Brian, 1990; Bennett, 1999) for many years. An understanding of knickpoint behavior is critical to predicting the dynamics of reservoir erosion. As knickpoints migrate upstream they evolve into either: 1) rotating knickpoints, where the knickpoint face lengthens as the knickpoint moves upstream, or 2) stepped knickpoints, where a vertical knickpoint face is maintained (Figure 1). The mode of knickpoint evolution is determined by relative erosion rates at the top and bottom of the knickpoint face (Holland and Pickup, 1976; Stein and Julian, 1993). If the top of the knickpoint face erodes faster than the base of the knickpoint, the slope of the knickpoint face decreases through time, as the knickpoint rotates into the reservoir around a point at the dam base. Preferential erosion at the base of the knickpoint results in erosion by mass failure and a near vertical face is maintained even as the knickpoint migrates upstream.

Erosion and sediment transport rates are typically calculated with equations of the form

\[ q_s = k(\tau_0 - \tau_c)^p \]  

(1)

where \( q_s \) is the sediment transport rate, \( k \) is a dimensional constant, \( \tau_0 - \tau_c \) is shear stress.

Figure 1: Knickpoint morphology with two knickpoint evolution modes: rotating and stepped knickpoints as a function of shear stress (\( \tau_0 \)) and critical shear (\( \tau_c \)).
(\(\tau_o\)) above some critical value (\(\tau_c\)), and \(p\) is an exponent (Gessler, 1971). Shear stress is calculated as

\[
\tau_o = \gamma R_h S
\]  

(2)

where \(\gamma\) is the specific weight of the fluid, \(R_h\) is hydraulic radius, and \(S\) is the energy slope. In turbulent flow, critical shear stress is linearly proportional to sediment size. Thus, for a given sediment size, sediment transport rates are the greatest at the knickpoint lip where the energy slope is the steepest and preferential erosion results in a rotating knickpoint. Rotating knickpoints can be successfully modeled using diffusion type sediment transport equations, where sediment transport is proportional either to rate of change in the bed profile (Begin et al., 1981) or energy slope (Doyle and Harbor, 2003).

Assuming steady discharge and uniform grain size, the rate of change in the energy slope (\(dy/dx\)) decreases exponentially as the knickpoint rotates from near vertical to near horizontal, resulting in a sediment yield that declines exponentially through time (Doyle and Harbor, 2003).

Stepped knickpoints develop in stratified bed materials where resistant surface sediment overlies non-resistant sediment layers that become exposed at the knickpoint face (Gardner, 1983) and in homogeneous cohesive sediment under high Froude numbers where the drop height (\(D_h\)) is much greater than the upstream flow depth (\(h_n\)) (Stein and Julian, 1993) (Figure 2). When rivers carrying a wide range of grain sizes enter a reservoir, coarse sediment settles near the head of the reservoir, while finer sediment with lower settling velocities is carried deeper into the reservoir. As the reservoir gradually fills with sediment, sorting by fall velocity results in the layering of coarse sediment

![Figure 2: Headcut migration criteria from Stein and Julian (1993).](image-url)
over relatively finer sediment. Because critical shear is proportional to sediment size turbulent flows, fine sediment is easier to erode than coarse sediment of the same shape and density. Shear stress generated by the force of falling water impinging on the pool at the base of the knickpoint can expose and erode fine-grained sediment at the base of the deposit and undermine the knickpoint, at shear stresses less than those required to mobilize the coarse surface layer (Robinson and Hanson, 1994). Models of stepped knickpoint migration require knowledge of the spatial distribution of the various stratigraphic units, their internal shear strength, unit weight, erodibility and critical shear stress. These models generally assume that the material deposited downstream of the knickpoint does not affect the scour hole development (Hanson et al., 2001). When resistant material does fill the scour hole, knickpoint migration is slowed until the material can be dislodged or bypassed by the channel (Holland and Pickup, 1976). Assuming that reservoir sediment can be modeled as a tapered wedge with constant slopes and rate of knickpoint face migration, stepped knickpoints result in sediment yields that decline almost linearly though time (Figure 3).

Downstream of a dam, reservoir sediment deposition may induce channel bed elevation changes that appear to evolve as either a dispersive or translating wave (Pizzuto, 2002). The concept of sediment waves dates back to the work of Gilbert (1917), who recognized that sediment input from hydraulic mining caused a ‘wave’ of

![Figure 3: Erosion volume by headcut migration at a constant rate using pre-erosion channel dimensions from Dinner Creek, OR.](image-url)
sedimentation to propagate downstream from mining sites analogous to a water wave. Dispersive waves have been defined as those where the apex and trailing edge do not migrate downstream; whereas in translational waves all features, including leading and trailing edges, wave apex and centre of mass, advance downstream (Lisle et al., 2001) (Figure 4). Subsequent research has supported the theory that large sediment slugs may take the form of dispersive and/or translational waves (Pickup et al., 1983; Madej and Ozaki, 1996; Benda and Dunne, 1997; Lisle et al., 1997). In one study, it was found that the Froude number might determine whether sediment in gravel-bed rivers will disperse or translate downstream. Lisle and others (2001) found that bed material waves in coarse-bedded flumes translated downstream at low Froude numbers (< 0.35); but as the Froude number approached one, translation was eliminated and dispersion dominated.

Conceptual model and scope

Based on these two end-member processes of reservoir erosion and downstream deposition, I propose that there are at least four basic forms of reservoir erosion and downstream deposition following dam removal, and the form taken is largely determined by the grain-size distribution and Froude number (Figure 5). Case studies by Doyle and others (2003) in which dams were removed from low gradient rivers in southern Wisconsin, describe reservoir erosion in the form of stepped and rotating knickpoints with translation. On the Baraboo River, reservoir sediments composed of relatively unconsolidated sand and silt eroded as a rotating knickpoint over the course of several weeks; sand from the reservoir temporarily deposited downstream, but depth and cross-
sectional area returned to near pre-removal magnitude within three months (Fig 5-B). On the Koshkonong River, reservoir sediment with highly consolidated fine material (36% sand, 45% silt, 19% clay) overlying unconsolidated fine gravel \((d_{50} > 3 \text{ mm})\) eroded as a stepped knickpoint that migrated gradually upstream with no significant downstream deposition at shear stresses less than the threshold for either the consolidated surface fines or the subsurface gravel (Fig. 5-D). Rotating knickpoint with dispersion (Fig 5-A) has been modeled following removal of Marmot Dam on the Sandy River (Stillwater Sciences, 2000) and has been documented in flume studies (Cantelli et al., 2004), though field studies documenting this style of erosion and deposition are currently lacking.

Most of the reservoir erosion modeling done to date assumes that shear stress on surface grains will drive erosion. If so, a reservoir deposit may evolve as a rotating knickpoint and steady state diffusion equations can be used to predict sediment yield as a function of time (Doyle and Harbor, 2003). In this paper, I present evidence to suggest that sediment filled dams in mountain rivers are likely to erode by stepped knickpoint migration with dispersion (Fig 5-C). Mountain rivers carry a wide range of grain-sizes and, as outlined in the previous section, differential reservoir settling and selective entrainment is likely to result in resistant armor layers overlying more erodable sediment. Given this configuration, stepped knickpoint migration is likely. Because mountain rivers move sediment less frequently and bed movement typically occurs during storm events when the Froude number is close to one (Grant, 1997), dispersion is likely to dominate over translation downstream of the dam. Stepped knickpoint migration creates relatively simple reservoir channel geometries that may aid efforts to estimate sediment yields.

![Figure 5: Conceptual model showing four modes of reservoir erosion and downstream sediment deposition.](image-url)
associated with dam removal, though difficulties associated mapping buried obstructions
and the need to quantify deposition at the base of the dam are likely to limit actual
sediment yields.

Site Locations

**Dinner Creek**

Dinner Creek dam was a 3.2 m high dam located on Forest Service land at
43.7155°N, 122.7153°W (NAD83) in the Layng Creek watershed upstream of the city
of Cottage Grove, Oregon (Figure 6). The dam was constructed around 1925 to provide
water for the residents of Cottage Grove. By the mid-1970's, the reservoir behind the
dam had completely filled with approximately 3000 m³ of sediment (Hanek, 1999).
Surface sediments were composed of sand, gravel, cobbles and boulders with a surface
d_{50} (diameter for which 50% of sediment is finer) of 66 mm (small cobble). Subsurface
sediment was composed primarily of silty-sand. Drainage area above the dam is 21.3
km², average channel slope through the site is approximately 2.4%, and average channel
width is 8 m. Channel morphology is primarily plane bed with some forced pool/riffle
morphology. The Dinner Creek basin has a temperate climate with 65% of
the precipitation falling between November and March. Average monthly
precipitation ranges from 1.27 – 25.5 cm with an
average annual precipitation of 155 cm. Local geology is
associated with the Western Cascades province and has
a mixture of sedimentary rocks and basaltic lava
flows (Walker et al., 2003). Dinner Creek discharges into

![Figure 6: Site map showing locations of Dinner Creek and Maple Gulch Dams, OR](image)
Layng Creek, a tributary of the Middle Fork Willamette River, approximately 200 meters below Dinner Creek Dam.

**Maple Gulch**

Maple Gulch dam was a 3.4 m high concrete dam located at 42.5787°N, 123.0377°W (NAD83) in the Evans Creek watershed near Medford, Oregon (Figure 6). The dam was built in the early 1900’s to provide water for a local schoolhouse and was at some point raised and reinforced. During the last half-century, the reservoir gradually filled with approximately 600 m$^3$ of sand and silt overlain by gravel, and was eventually abandoned. Drainage area above the dam was 3.6 km$^2$, channel width is approximately 2.2 m, channel slope is 7%, morphology is constrained step-pool morphology, and surface d$_{50}$ is approximately 22 mm. Maple Gulch has a Mediterranean climate with cool, wet winters followed by dry, hot summers. Precipitation is greatest between late fall and early spring, with average monthly precipitation ranging from 1.1 – 11 cm with an average annual precipitation of 66 cm. Flow in Maple Gulch is intermittent and occurs only during winter months. Local geology is primarily partially weathered Paleozoic metamorphic rock and is part of the Klamath Geomorphic Province (Walker *et al.*, 2003).

**Methods**

Before and after the removal of Dinner Creek and Maple Gulch dams, reservoirs were surveyed with a Leica total station and photographed from monumented photo points. Repeat measurement of monuments were taken to establish a survey precision of ~1 cm. Surveys were collected along breaklines (as opposed to a uniform grid) to capture breaks in slope and were repeated after major storm events. Survey data were linearly interpolated within ArcInfo to create triangular irregular networks (TIN’s) and digital elevation model (DEM) lattices of the reservoirs with grid spacing of 0.2 m. Net erosion between surveys was calculated with the ArcInfo CutFill routine as the difference in DEM topography (Figure 7). Photographs were used to constrain the timing of reservoir erosion between topographic surveys.

To quantify downstream deposition, channel bed elevations were surveyed along regularly spaced cross-sections downstream of the dams before and after dam removal. Cross-sections at Dinner Creek and Maple Gulch dams were spaced at roughly two times the channel width (15 m and 6 m respectively). Three cross-sections were surveyed in Layng Creek below the confluence with Dinner Creek (60 m interval). Below the dams, deposition volume was calculated as the area of aggradation in each cross-section.
multiplied by the distance between cross-sections. Longitudinal profiles for each stream were created from TIN’s based on a compilation of cross-section data and supplemental topographic survey points.

At Dinner Creek, water discharge was estimated using a stage discharge relationship developed for an Omega Water Level Logger with Automatic Atmospheric Pressure Compensation located 125 m above the dam between 5 August 2003 and 12 December
2003. After December 13, when the water level logger was left stranded above the new incised channel, discharge was estimated by correlating gaged discharge measured 2 km downstream of Dinner Creek dam at a site on Layng Creek. Layng Creek has greater drainage area and higher base flow than Dinner Creek, but gage analysis showed that peak discharges at the Dinner Creek and Layng Creek gages occurred within one to two hours of each other over the period of record. Turbidity at Dinner Creek was measured with factory-calibrated Seapoint Sensors backscatter turbidity probe located 125 m below the dam. The probe was set to record turbidity from 0-250 FTU.

At Maple Gulch, peak discharge was calculated using a peak stage recorder from August 2002 until late January 2003. In January, the peak stage recorder was replaced with a TruTrak water stage recorder. Both instruments were located 150 m above the dam in a bedrock reach for which a stage discharge relationship was constructed. Discharge prior to January 2003 was estimated by correlating mean daily and peak discharge in Maple Gulch to mean daily discharge at the Morine Gage, located 26 km northeast of Maple Gulch in a basin of similar size and elevation and for which there was a longer period of record.

Results

Dinner Creek Chronology

When the reservoir behind Dinner Creek dam eventually filled with sediment, the channel upstream of the dam migrated outside the confines of the bedrock canyon through which it flowed, and in which Dinner Creek was built. At the time of dam removal, Dinner Creek flowed across the now buried canyon wall and approached the dam at nearly a 45-degree angle (Figure 8). When Dinner Creek dam was removed, fine sediment eroded from the knickpoint face leaving an armor layer of cobble and boulders (Fig. 8-B). From July 5th when dam removal was completed to November 15th, only 50 m³ of sediment eroded from the knickpoint face. Exposed bedrock and the presence of a coarse armor layer on the knickpoint face limited erosion. On November 17th, a 0.9 cms storm eroded an additional 40 m³, completely exposing the former bedrock canyon wall (Figure 8C).

On 13 December 2003, the largest storm event of the winter hit Dinner Creek with a peak discharge of 1.3 cms (Figure 9). The December 13th storm had a large enough discharge for the channel to erode through an alder terrace and around the bedrock canyon wall. Turbidity downstream began to rise early on the morning of the 13th and
Figure 8: Photo series from a single location showing erosion progression at Dinner Creek.

Figure 9: Discharge and cumulative erosion through time at Dinner Creek. Dashed line represents cumulative erosion timing constrained by observations and other data.
reached 50 NTU by 05:30. By 13:30 the turbidity probe had reached its upper detection limit, and by 14:50 the probe was recording null values suggesting it had become buried in gravel. Water surface at the gaging station located 125 m upstream of the dam had been climbing steadily all day (7.8 mm/hr, \(r^2=0.98\)) when at 16:15 it began to drop rapidly. Between 16:15 and 17:45, water surface elevation at the gage site dropped 18 cm (-48 mm/hr), then rose slightly and began a gradual decline (-6 mm/hr). During a site visit on the 15\(^{th}\), we found a rectangular channel with near vertical banks incised into the former reservoir with the extent of erosion reaching just beyond the gaging site. Surveys in January revealed a 45 cm drop in the average elevation of the gage cross-section. Based on the timing of the turbidity probe burial, the near instantaneous drop in water surface elevation at our gage site, and channel morphology as found on the 15\(^{th}\); we deduced that one or more stepped-knickpoints had migrated through the former reservoir. If knickpoint migration started at 05:30 and moved through the gage site 125 meters upstream at 17:45, it would suggest that the initial knickpoint moved at an average rate of over 10 m/hr. Erosion associated with the December 13\(^{th}\) storm was calculated to have released 1134 m\(^3\) of sediment or 86% of total reservoir erosion.

Reservoir erosion at Dinner Creek was threshold driven and did not scale with discharge as might be expected by surface shear stress or diffusion based models. Pebble counts taken before Dinner Creek dam removal show the median grain size was small cobble (\(d_{50}=66\) mm). Given the surface grain size, post-removal channel slope and configuration; we used the shields diagram and Chiew and Parker’s (1994) correction factor for incipient motion on non-horizontal slopes

\[
\frac{\tau_c}{\tau_o} = \cos(\phi) \left( 1 - \frac{\tan(\phi)}{\tan(\theta)} \right)
\]

where \(\phi\) is any streamwise bed slope and \(\theta\) is the angle of repose for the sediment size (38\(^\circ\)), to calculate critical shear stress required to move the surface armor layer (56 Pa). Discharge associated with incipient motion was estimated by the Manning equation

\[
V = \frac{1}{n} S^{1/2} R^{3/2}
\]

where \(V\) is velocity, \(n\) is Manning roughness, \(S\) is slope, and \(R\) is hydraulic radius. For a 7 m wide channel with a 2.43% slope (post-erosion channel slope, greater than reservoir channel slope) and Manning roughness of 0.04, critical discharge to move bed sediment was calculated at 2.6 cms (92 cfs). Peak discharge for the 13 December 2003 storm did
not exceed 1.4 cms (50 cfs) (Table 1). When back calculated to estimate critical slope for a 1.4 cms event, we get an equilibrium slope of approximately 9.8%. Thus, discharge was not great enough to move the median particle size anywhere except along the knickpoint face and knickpoint rotation would have only reduced the knickpoint face to a more stable slope (e.g., Figure 5B).

Of the 1312 m$^3$ of sediment eroded from behind Dinner Creek Dam, 470 m$^3$ (36%) of sediment deposited in the channel within 150 m of the dam (Table 1). Longitudinally, width-averaged deposition was greatest near the dam, and decreased exponentially with increasing downstream distance (Figure 10). Cross-sectional deposition was not uniform, however, except near the dam. The greatest deposition occurred primarily along the former channel thalweg, creating an alternate bar morphology, where a plane bed morphology has existed previously (Figure 11). Rapid deposition in the channel thalweg produced unusual convexities in the cross-section profile (Figure 12).

Cross-sections in Layng Creek below the confluence with Dinner Creek exhibited only minor deposition (< 10 cm), most of which occurred around roughness elements in the channel thalweg. Observations suggest that gravel and cobble deposition in Layng Creek was very localized with significant deposition limited to channel expansions zones
Figure 10: Width averaged deposition below Dinner Creek dam through time.

Figure 11: Deposition downstream of Dinner Creek dam showing areas of erosion along channel margins and deposition along the channel thalweg. DEM created from topographic surveys collected prior to dam removal and 1 year after dam removal.
Figure 12: Dinner Creek cross-section profiles showing aggradation and degradation associated with reservoir erosion. Dates for each survey shown in legend (top right).
with strong eddy currents. Pebble counts taken above and below the dam and confluence in Dinner and Layng Creeks respectively; show no significant change in surface grain size before and after dam removal (Figure 13).

**Maple Gulch Chronology**

As shown in Figure 7, Table 2, and Figure 14, stepped knickpoints released 143 m$^3$ of sediment (93% of reservoir erosion) in two events at Maple Gulch. Although a

Table 2: Maple Gulch erosion and deposition.

<table>
<thead>
<tr>
<th>Date</th>
<th>Erosion (m$^3$)</th>
<th>Deposition* (m$^3$)</th>
<th>Method</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-Aug-02</td>
<td>0</td>
<td></td>
<td>Survey</td>
<td>Pre-removal survey.</td>
</tr>
<tr>
<td>30-Aug-02</td>
<td>41</td>
<td>12</td>
<td>Survey</td>
<td>Reservoir sediment moved during dam demolition.</td>
</tr>
<tr>
<td>15-Nov-02</td>
<td>47</td>
<td>23</td>
<td>Survey</td>
<td>Nov. 10 storm washes fine sediment out of the reservoir leaving a V-shaped erosion wedge armored with gravel. Fine sand/silt sequentially filled pools to the elevation of the riffle crests before spilling into the next downstream pool.</td>
</tr>
<tr>
<td>17-Dec-02</td>
<td>71</td>
<td>66</td>
<td>Survey</td>
<td>Dec, 16 storm produces a 1.5 m high vertical headcut extending 8 m into the reservoir. Deposition greatest near the dam, decreasing downstream.</td>
</tr>
<tr>
<td>27-Dec-02</td>
<td></td>
<td></td>
<td>Photo</td>
<td>Headcut does not advance despite an increase in discharge on Dec. 21</td>
</tr>
<tr>
<td>28-Dec-02</td>
<td></td>
<td></td>
<td>Photo</td>
<td>Headcut migrates 14 m upstream onto a bedrock sill.</td>
</tr>
<tr>
<td>31-Dec-02</td>
<td>190</td>
<td>140</td>
<td>Survey</td>
<td>Photos suggest that all erosion between Dec. 17 and Dec. 31 is associated with the Dec. 28 storm event.</td>
</tr>
<tr>
<td>21-May-03</td>
<td>193</td>
<td>139</td>
<td>Survey</td>
<td>Surveys show almost no subsequent erosion.</td>
</tr>
<tr>
<td>1-Dec-03</td>
<td>195</td>
<td>145</td>
<td>Survey</td>
<td>Surveys show almost no subsequent erosion.</td>
</tr>
</tbody>
</table>

*Based on linear interpolation of deposition area (m$^2$) in 33 cross-sections equally spaced at 6 meter intervals below dam.
knickpoint was initiated by a November 16th storm, the vertical knickpoint remained in one location until December 28th despite a small storm event on December 21st. When discharge increased significantly on December 28th, the knickpoint eroded headward onto a bedrock terrace that ran parallel to and used to confine the pre-dam channel. Site visits in the summer of 2004 and 2005 revealed little subsequent erosion and continued erosion.

Of the 195 m$^3$ of sediment eroded from behind Maple Gulch dam, approximately 145 m$^3$ (74%) deposited within 200 meters of the dam. Deposition at Maple Gulch exhibited a downstream dispersion pattern with the greatest deposition occurring near the dam and decreasing downstream (Figure 15). Riffles were generally more likely to exhibit deposition compared with boulder steps and plunge pools, though uniform spacing of cross-sections resulted in a few cross-sections being placed in transitional areas or places where aggradation was unlikely (i.e., lip of a step).

Figure 14: Discharge and cumulative erosion through time at Maple Gulch. Dashed line represents cumulative erosion during periods when erosion timing is constrained by observations or other data.
Hanek (1999) used waterline surveys and refractive seismic tests to estimate pre-dam channel dimensions and suggested that approximately 3000 m$^3$ of sediment would ultimately be mobilized following Dinner Creek dam removal. Using simple geometric relationships for a trapezoidal channels sediment wedge:

$$ V = \frac{h}{4} \left( 2w \cdot \tan(\theta) + \frac{x}{\tan(\theta)} \right) $$

where $h$ is the dam height, $w$ is the downstream channel width, $x$ is the length of the deposit determined from the intersection of the downstream channel slope and the reservoir slope, $\theta$ is the slide slope angle; Stewart (2000) also estimated an erosional volume of 3000 m$^3$. As shown above, reservoir erosion in the first year was only half that. At Maple Gulch, equation 4 was used to estimate a sediment yield of 590 m$^3$. As shown above, sediment yield at Maple Gulch was less than 200 m$^3$ in the first two years.

**Discussion**

At both Dinner Creek and Maple Gulch, fine sediment eroded from the knickpoint face as water began to flow over it. Selective entrainment removed fine sediment from.
the knickpoint face leaving those particles whose size exceeded the river’s transport capacity, which served to inhibit further erosion. With each subsequent storm event, mobile sediment was entrained and the entrainment threshold for the remaining sediment increased. After a series of erosion and armoring events, discharges capable of removing the armor layer were large enough to maintain a scour hole at the base of the deposit and one or more stepped knickpoints propagated upstream. Once knickpoints developed, they moved rapidly upstream (~10m/hr) until one of the following conditions were met: 1) flows decreased and a scour hole could no longer be maintained (MG), 2) the knickpoint ran into an obstruction that prevented undermining of the channel (MG and DC), or 3) the knickpoint migrated so far upstream that grain size was no longer stratified (DC). Reservoir erosion at each of the sites was slowly progressive but punctuated by large events that did most of the geomorphic work.

Downstream of the Dinner Creek and Maple Gulch dams, sediment deposition was greatest near the dam and decreased exponentially with increasing downstream distance. This result is in general agreement with Lisle and others (2001) finding that at high Froude numbers, bed material waves tend not to translate, but rather disperse downstream. Reservoir erosion at Dinner Creek and Maple Gulch occurred during winter storm events when Froude numbers in these steep mountain creeks was close to 1. It should be noted, however, that only 36% and 74% of the sediment released at Dinner Creek and Maple Gulch, respectively, could be accounted for. Grain size analysis shows that the downstream deposits were of the same caliber as the surface layer in the reservoir. Hydraulic data suggest that the fine sediment which eroded from the base of the knickpoint migration is unlikely to have deposited immediately downstream of the dam at the discharges associated with reservoir erosion. While it is possible that fine sediment translated downstream as a coherent wave, discontinuous pockets of freshly deposited fine sediment were found in Layng Creek suggesting some longitudinal dispersion.

Cross-sectional deposition was generally not uniform except in confined reaches immediately downstream, where channel aggradation was the greatest. Prior to reservoir erosion, the downstream thalweg in Dinner Creek was mapped along the outside of channel along the bends. Deposition associated with the Dec. 13th storm was greatest along the channel thalweg creating stable lateral cobble bars on the outside bends and slightly eroding the inside of bends. Where the channel thalweg crossed from one outside bend to the next, deposition created a large transverse riffle. Channel morphology
changed from plane-bed to a pool-riffle. At Maple Gulch, where channel morphology was step-pool, channel aggradation varied depending on channel morphology. Cross-sections placed in riffles and channel expansions tended to aggrade while cross-sections placed across plunge or at the lip of steps showed little or no deposition.

Reservoir sediment yield in the first two years at both Dinner Creek and Maple Gulch was much less than the predicted sediment yield. The primary causes for the overestimate were: 1) the assumption that banks erode back to a “stable” side slopes of 1.5H:1V, 2) the assumption that full height of the dam could be used in the estimate of the reservoir volume, and 3) the inability to evaluate how channel migration after reservoir sedimentation might prevent the channel from returning to its pre-dam configuration. At Dinner Creek, deposition at the base of the dam effectively reduced the dam height by 30% and stepped knickpoint migration created near vertical banks. At both Dinner Creek and Maple Gulch, the dams were built within bedrock-confined valleys. As reservoir filled with sediment, the upstream channel was able to migrate outside the bounds of the bedrock valley. When the dam was removed, the channel eroded towards the oncoming flow and up onto the former bedrock valley wall. At Dinner Creek, discharge eventually exceeded the threshold required for the channel to migrate laterally off the bedrock wall. If discharge becomes large enough to inundate the valley floor, the same may occur at Maple Gulch. Photos taken during Spring 2006 at Dinner Creek show that additional erosion occurred during the 2005/2006 Winter suggesting that the predicted sediment yield may eventually be attained, though it is too early to determine that.

Conclusions

Both Dinner Creek and Maple Gulch exhibited patterns of erosion and deposition that stand in contrast with much of the previously published work on the geomorphic impacts of dam removal. Rather than eroding as rotating knickpoints where erosion is proportional to discharge, both reservoirs exhibited episodic stepped knickpoint migration where knickpoint movement was limited by intrinsic system thresholds and the presence of buried obstructions that maintained an elevated base level. Once initiated, knickpoints migrated upstream at rates approaching 10 m/hr. Coarse sediment deposition immediately downstream of the dam effectively reduced dam height creating a time variable base level that limited the volume of sediment eroded. Deposition of coarse
sediment was concentrated along the channel thalweg and decreased with increasing distance from the dam.

Differences in removal method, geomorphic setting, and discharge regime all contribute to differences in the geomorphic effects of dam removal. Just as dams are different, so too will be the effects of dam removal. Differences in geomorphic context and removal method not only affect the timing and magnitude of erosion, but also the downstream sediment trajectory and associated geomorphic and ecological impacts. In order to predicting the effects of any given removal, we must begin to construct a set of case lore based on field studies of actual dam removals.
CHAPTER 3 - CHANGES IN HYPORHEIC EXCHANGE AND WATER TEMPERATURE FOLLOWING RESERVOIR SEDIMENT RELEASES ASSOCIATED WITH DAM DRAWDOWN AND REMOVAL

Abstract

Sediment releases associated with dam removal have the potential to affect hyporheic exchange by altering channel morphology and/or streambed sediment composition. Reservoir drawdown can serve as an analog to dam removal when deltaic sediment are exposed to fluvial erosion. The drawdown of a large flood control reservoir in Oregon in 2002 resulted in erosion of deltaic sediments and a prolonged release of turbid water. Freeze core analysis of downstream salmon spawning gravels showed that fine sediment released from the reservoir had intruded into bed, but the impact on hydraulic conductivity and hyporheic exchange could not be assessed. In a second study we directly examined changes in hyporheic exchange and diurnal temperature flux associated with increased turbidity and sedimentation following the removal of a small dam in Oregon. Dam removal increased turbidity for short periods of time as fine sediment eroded from the reservoir, but the effect was to reduce hyporheic exchange by less than 30% and produced no discernable changes in diurnal temperature. Deposition of 470 m$^3$ of gravel and cobble from the upstream reservoir produced a more than 50x increase in hyporheic residence time and significantly reduced diurnal temperature fluctuations through the downstream reach.

Introduction

Dams are known to have a wide range of effects on river ecosystems (Dynesius and Nilsson, 1994; Ward and Stanford, 1995; Power et al., 1996; Andersson et al., 2000, World Commission on Dams, 2000), channel morphology (Williams and Wolman, 1984; Ligon et al., 1995; Grant et al., 2003), and hydrology (Williams and Wolman, 1986; Graf, 1999). Given these effects, it been argued that dam removal should be viewed as a river restoration tool (American Rivers, 1999; Pejchar and Warner, 2001). Dam removal, however, is not without environmental impacts (Stanley and Doyle, 2003). Over time, rivers adjust to the presence of dams and dam removal itself represents a disturbance to the adjusted regime (Grant, 2001). Dams create reservoirs that trap as much as 95% of river sediment, with size classes ranging from silt and clay to large boulders (10$^{-6}$-10$^{9}$ m), and the release of stored sediment following dam removal remains one of the
most fundamental and least understood impacts of dam removal (Heinz Center, 2002). Sediment released by dam removal has been shown to significantly affect downstream geomorphic and ecological systems by reducing pool volume (Rathburn and Wohl, 2001), altering water chemistry (Stanley and Doyle, 2002), grain size distribution (Wohl and Cinderelli, 2000) and food web dynamics (Doeg and Koehn, 1994). In this paper, we examine how dam removal might affect instream hyporheic exchange and temperature flux by changing streambed sediment composition.

Hyporheic exchange occurs when surface water flows through the stream bed, mixes with groundwater, and eventually returns to the stream (Figure 1). Hyporheic water differs from surface water in several aspects including dissolved oxygen and nutrients (Triska et al., 1993); but perhaps the greatest difference is related to temperature regime (Poole and Berman, 2001). Water temperature is a measure of heat energy in a stream, which is determined by external drivers including climate (i.e., solar radiation, air temperature, and wind speed), riparian vegetation, and water source (Sullivan and Adams, 1991). While these external drivers determine total heat; internal buffers, including the hyporheic zone, control the temporal and spatial distribution of heat energy within the stream. Buffers act to regulate temperature by removing heat from the channel when temperature is high and releasing heat to the channel when stream temperatures are low (Poole and Berman, 2001). The hyporheic zone acts as a slow mixing reservoir and upwelling water from the hyporheic zone is generally cooler in summer and warmer in winter than associated surface waters, thereby providing thermal refugia for stenothermic fish species including salmonids (Nielson et al., 1994).

Hyporheic exchange is enhanced by channel bedforms that generate subsurface head gradients (Harvey and Bencala, 1993) and coarse sediment with large hydraulic conductivities (Packman and Salehin, 2003). The introduction of fine sediment into an otherwise coarse bed can act to decrease hydraulic conductivity and hyporheic flow rates by as much as an order of magnitude (Koltermann and Gorelick, 1995; Wu,
2000; Packman and Mackay, 2003). When a dam is removed, sediment trapped in the upstream reservoir begins to erode. If a reservoir releases fine sediment that deposits within downstream channel bed interstices, the effect is to potentially decrease hydraulic conductivity and hyporheic exchange. Coarse sediment releases that create channel bedforms with large interstitial spaces act to increase hyporheic exchange. Whether coarse sediment is released before fine sediment and the degree to which fine sediment can be expected to deposit within the hyporheic zone are functions of the reservoir sediment composition, method of dam removal, discharge regime, downstream grain size distribution, and channel morphology.

During the spring of 2002, a large flood control reservoir operated by the U.S. Army Corps of Engineers (USACOE) on the South Fork McKenzie River, Oregon, was retrofitted with a temperature control structure requiring drawdown of Cougar Reservoir over several months. The drawdown caused incision of the reservoir delta resulting in a sustained release of turbid water from Cougar Reservoir. Given concerns over the impact of fine sediment on downstream spawning, we sampled salmon spawning gravels to determine how much fine sediment associated with the drawdown was retained in bed interstices. Using a space-for-time substitution, where sites above the dam (e.g., not impacted by the release) were used as proxies for pre-drawdown samples, freeze core and clay mineralogy analysis showed elevated levels of clay in the channel bed that were most likely associated with the sediment release. A lack of pre-drawdown data, however, prevented analysis that might have shown what effect the fine sediment intrusion had on hyporheic exchange or spawning success.

The removal of Dinner Creek dam in 2003 provided an opportunity to directly measure the effects of sediment releases on hyporheic exchange and water temperature using pre- and post-removal monitoring. Sediment releases associated with dam removal affected hyporheic exchange in predictable ways. Increased turbidity appeared to cause a reduction hyporheic exchange while the release of coarse gravel aggraded the downstream channel and significantly increased hyporheic exchange, which in turn, reduced instream diurnal temperature fluctuations.

**Site descriptions and drawdown / removal chronologies**

**Cougar Reservoir**

Cougar Reservoir was built in 1963 on the South Fork McKenzie River at 44.1285°N, 122.2410°W (WGS84/NAD83) in the Willamette National Forest, Oregon.
In April 2002, the U.S. Army Corps of Engineers (COE) lowered the water surface of Cougar Reservoir below minimum pool elevation. Reworking of exposed deltaic and lake bottom sediments by the South Fork McKenzie and other reservoir tributaries increased suspended sediment concentrations in the remaining reservoir. The result was a prolonged discharge of turbid water, containing high concentrations of silt and clay, from Cougar Reservoir. Although the COE had predicted in its Environmental Impact Statement (EIS) that turbidity would increase during the drawdown (predicted levels of 30 NTUs with spikes of 100 NTUs), the magnitude, timing, and duration of the turbidity release was underestimated. Between April 1st and May 25th of 2002, turbidity levels at the South Fork gauging station below the dam averaged 68 NTUs with spikes of 379 NTUs.

During the summer of 2002, nine field sites were chosen for freeze core bed sediment sampling to evaluate the degree to which fine sediment associated with the turbidity release had intruded into the channel bed. Sites were chosen based on the following criteria: 1) upstream of a riffle crest where downwelling could be expected; 2) lack of geomorphic or anthropomorphic disturbances immediately upstream that might have contributed fine sediment to the site (e.g., recent bank erosion or tree fall); and 3) presence of salmon spawning gravels as identified by the Oregon Department of Fish and Wildlife.

Because no pre-drawdown bed sediment samples were available below Cougar Reservoir, reference data were collected at sites located above Cougar Reservoir on the South Fork McKenzie (SFA1 & SFA2) and on the mainstem McKenzie above the confluence with the South Fork (MS1). Four ‘treatment’ sites were located below Cougar on the South Fork McKenzie (SFB1, SFB2, SFB3, and SFB4) and two treatment sites were located on the mainstem McKenzie below the South Fork confluence (MS2 and MS3) (Figure 2). At two sites, SFA1 and SFB2, replicate samples consisting of three cores were collected to evaluate within-site variance.

Sites above Cougar Reservoir had an average drainage area of 372 km², channel width of 20 m, and channel slope of 1.2%. Channel morphology is step-pool and pool-riffle, with a dominant substrate of cobble, boulder, and bedrock. Gavel patches are not common, but can be found behind boulders and in eddies. Below Cougar Reservoir, sites had drainage areas ranging from 495-511 km², average channel width of 25 m, and 0.5% channel slope. The South Fork McKenzie transitions from confined bedrock to anastamosing planform with secondary channels associated with large woody debris.
Channel morphology is pool-riffle and forced pool-riffle and the dominant substrate is cobble. Gravel patches are not common but are found in side channels and along channel margins. The mainstem McKenzie has a drainage area ranging from 510 km² at MS1 above the South Fork confluence to 1405 and 2321 for MS2 and MS 3, respectively. Channel width measured 45 m above the confluence and width and slope averaged 80 m and 0.1% below the South Fork Confluence, respectively. The mainstem McKenzie is moderately confined and meandering, with pool-riffle morphology and cobble and boulder substrate. Gravel patches are not common except near side-channels and in small pockets along channel margins.

**Dinner Creek Dam**

Dinner Creek Dam was a 3.2 m high dam located on Forest Service land at 43.7155°N, 122.7153°W (NAD83) in the Layng Creek watershed upstream of the city of Cottage Grove, Oregon (Figure 3). The dam was constructed around 1925 to provide
water for the residents of Cottage Grove. In August 2003, Dinner Creek Dam was removed because it was a fish passage barrier and no longer served any useful purpose.

At the time of dam removal, the reservoir behind Dinner Creek Dam was completely filled with sediment that had accumulated over the life of the reservoir. Surface sediments were composed of sand, gravel, cobble and boulder with a surface $d_{50}$ (diameter for which 50% of sediment is finer) of 66 mm (small cobble). Subsurface sediment was composed primarily of silty-sand. The dam had a drainage area of 21.3 km$^2$, 2.4 % channel slope, and 8 m average channel width. Channel morphology downstream of the dam was primarily plane bed with some forced pool-riffle morphology. Upstream of the dam the channel had an anastamosing planform and pool-riffle morphology.

During dam removal, turbidity downstream of the dam increased as fine sediment eroded from the exposed reservoir sediments. After dam removal was completed, turbidity downstream of the dam decreased to background levels except during storm events that resulted in reservoir erosion. Between August and December 2003, four storm events eroded a total of 1312 m$^3$ of reservoir sediment, 86% of which was associated with the migration of a knickpoint during a storm on December 13$^{th}$. Of the 1157 m$^3$ released during the December 13$^{th}$ storm, approximately 459 m$^3$ of sediment deposited within 150 m downstream of the dam (Stewart, this issue).
Methods

McKenzie River

Sediment sampling on the McKenzie River was conducted using freeze cores, which preserve fine sediments within river gravels by the removal of a frozen block of river substrate. To create a pool of quiescent water in the river, a trashcan with the bottom removed was placed over a section of spawning gravels at each coring location. Within the trashcan, three 2.5 cm diameter hollow metal rods (triangular configuration with 5 cm spacing between rods) were driven into the substrate to a depth of approximately 45 cm. Approximately 20 kg of liquid CO$_2$ was then simultaneously injected into the three rods over a period of 5 – 10 minutes to freeze the pore water in the gravel. Each core was extracted using a portable tripod crane and then melted using propane torches into bins of approximately equal lengths (11.5 cm). Bins were marked A - D with A representing gravels nearest the stream bed surface and D representing approximately 33.5 - 45 cm below the surface (Figure 4). Bins were lined with ziplock bags so samples contained both sediment and associated pore water.

In the lab, sediment from each bin was oven dried at 40° C and sieved by phi size. A hydrometer tube was used to analyze particle size for the <2 mm fraction. In the hydrometer, 40 g of fines were placed in 1 L of water and allowed to settle. Grain size was determined based on settling rates and measured water density over time. Because some clay and silt remained absorbed on the

Figure 4: Freeze core on the McKenzie River (left) that is melted into 11.5 cm bins lined with plastic.
larger grains following dry sieving, one bin in each core was sonified and washed to remove absorbed fine sediments. The washed gravels were then re-weighed to determine how much additional clay and silt was removed during sonic washing. The top three layers of SFB2-3 were also washed to see if there was any change in the abundance of absorbed clay and silt with depth.

Dinner Creek

Water quality changes and topographic surveys of reservoir erosion and downstream deposition were conducted using methodologies described by Stewart (this issue). Water temperature was recorded at 5 min intervals between 15 July 2003 and 8 August 2004 using Onset HOBO Water Temp Pro recorders wired into 15 cm long lead pipes placed into the channel thalweg 250 m above the dam, at the base of the dam, and 130 m below the dam.

Rhodamine WT (Bright Dyes, Miamisburg, OH) was used for a series of tracer tests to evaluate changes in hyporheic exchange following dam removal and reservoir erosion. The dye is considered conservative and mass of dye present in the stream channel after the time required for stream water to advect and disperse is assumed to have entered the hyporheic zone, where it traveled at a reduced velocity, before reentering the stream channel (Figure 5).

Tracer tests were conducted immediately prior to dam removal, two months after dam removal, and one year post dam removal. In each case, lab calibrated Turner

![Diagram of tracer test data](image-url)

**Figure 5:** Example of tracer test data in which dye concentration is measured through time. When compared against the advection/ dispersion model, it is clear that the dye solution is not just advected and dispersed down the channel, but enters some sort of transient storage zone (assumed to be hyporheic).
Designs 10-AU field fluometers running off 12-V deep cycle batteries were deployed at the dam and 130 m below the dam. Undiluted 2.5% Rhodamine dye was injected 130 meters above the dam at a constant rate for 3.5 hr. Fluometers were started at least 1.5 hours prior to injection to measure background fluorescence and instream dye concentration was recorded in 10 sec intervals for a minimum of 24 hours (in most cases, several days). Background concentration (mean of measurements over >1.5 hr period preceding injection) was subtracted from tracer data prior to analysis.

Two different methods were used to analyze the tracer test data for changes in hyporheic exchange. In the upstream reach, the relative size of the hyporheic zone was evaluated based on the rate of decay in tracer concentration. Faster decay rates in late time tracer concentration (>7 hours after the end of the tracer injection) were assumed to correlate with a smaller hyporheic zone. Because tracer concentration decayed as a power-law (Haggerty et al., 2002), data were log-transformed prior to regression analysis.

At the downstream site, the relative size of the hyporheic zone was determined by comparing time-synchronized concentration curves. For each tracer test, the mean water velocity between the two fluometers was calculated and times for the downstream flurometer were shifted so the curves plotted on top of each other. The relative change in residence time (i.e, hyporheic storage) was calculated over a 24-hour period as the integral of the positive difference between the downstream and upstream fluometers on the falling limb minus the dispersion effect calculated on the rising limb (Figure 6). Absolute differences were estimated by total tracer flux over the same 24-hour period. Because the downstream flurometer in the second tracer test stopped working at ~ 22.7 hours, regression analysis was used to estimate the endpoint concentration at 24 hours ($r^2=0.985, n=4396$).

**Results**

**McKenzie River**

Sediment from bins A and D (0 - 11.5 cm and 34.5 - 45 cm) were sometimes absent or contained a sample that was too small for analysis, so reported grain size represents bed sediment 11.5 - 34.5 cm below the surface. In addition, washing of gravels revealed that an average of 6.2 g (+/- 4.6 g) of additional silt and clay remained sorbed to the gravels after sieving (Figure 7). Grain size was based on sieve and hydrometer analysis and therefore underestimates the volume of silt and clay in each sample.
Figure 6: Overlaid concentrations from the third tracer test showing the dispersion effect and release of tracer from the hyporheic zone. The relative size of the hyporheic zone for the reach between the dam and downstream fluorometer is estimated as the difference in the area between the curves where downstream concentration exceeds the upstream concentration on the falling and rising limbs respectively.

Figure 7: Quantity of silt and clay in the bed including additional silt and clay estimated by washing.
All sites analyzed were dominated by moderately to poorly sorted, coarse to very coarse gravel. In addition to gravel, reference sites above Cougar Reservoir (SFA1 and SFA2) contained minor amounts of sand and little clay. Replicates taken at SFA2 revealed little within-site variability (Figure 7). Treatment sites on the South Fork McKenzie below Cougar Reservoir (SFB1, SFB2, SFB3 and SFB4) were relatively enriched in all >2 mm size fractions, especially clay. Replicate samples at SFB2 revealed considerable within-site variability, though all the downstream samples were enriched with silt and clay compared to upstream sites. Mainstem McKenzie sites, including the reference site, contained moderate amounts of sand, silt and clay. When plotted on a ternary diagram, sites broke out into three general groups representing South Fork above the dam, South Fork below the dam, and mainstem McKenzie (Figure 8). No clear trend in fine sediment abundance with distance from dam was established, but clay mineralogy

Figure 8: Ternary plot showing relative abundances of sand, silt, and clay for each site.
of samples collected in the reservoir and at downstream sites suggests that clay found in the South Fork below Cougar dam came from Cougar Reservoir as opposed to local sources (Stewart et al., 2002).

**Dinner Creek**

During dam removal, ISCO water samples taken from Dinner Creek had turbidities ranging from 43-200 NTU (87-1040 mg/L; n=5). Samples taken in the evenings after removal work had ceased show that instream turbidity declined rapidly, with after-work turbidities ranging from 2-18 NTU (0-89 mg/L, n=13). Following complete dam removal, turbidity in Dinner Creek remained near background levels except during storm events that eroded portions of the former reservoir.

Temperature data were analyzed over three different time periods corresponding to: pre-removal, removal to Dec. 13th (when 86% of reservoir erosion occurred), and post Dec. 13th. Figure 9 shows diurnal temperature change (Δ°C) measured as the difference between maximum and minimum temperature for a given calendar day in reaches upstream and downstream of the dam for each of the three time periods. In each case, diurnal temperature change for a 24 hr period at the top of the reach is plotted against diurnal temperature change at the downstream probe over the same 24 hour period. Prior to dam removal, diurnal temperature change increased 6% between the upstream temperature probe and the dam base (230 m, $r^2=0.99$) and 25% between the dam and downstream probe (130 m, $r^2=0.99$). After dam removal, temperature fluctuation decreased by 6% over the upstream reach ($r^2=0.99$) but continued to increase by approximately 25% in the downstream reach ($r^2=0.88$). After the December 13th storm that eroded a large portion of the reservoir and caused significant downstream channel aggradation, average diurnal temperature fluctuation increased only 0.6% and 0.7% in the upstream and downstream reaches, respectively ($r^2=0.99$ and 1.0 respectively).

Late time concentration (>7 hours after the end of tracer injection) for each of the six fluorometers decayed as a power-law as upstream hyporheic storage reservoirs became depleted. At the fluorometer stationed at the dam, the power-law decay rate was -1.035 ($r^2 = 0.98$) prior to dam removal (Figure 10). After dam removal, but before the reservoir had eroded the power-law decay rate was 49% slower (slope = -0.53, $r^2=0.96$). In the third test, which occurred after dam removal and reservoir erosion, the power-law decay rate was faster than in either of the two previous tests (slope = -1.12, $r^2 = 0.995$) with an 8% increase over pre-removal conditions.
Figure 9: Diurnal temperature change over a 24-hr calendar day (Max-Min °C) over two reaches (upstream to dam and dam to downstream) for three time periods.
Analysis of concentration curves at the downstream sites revealed that a significant portion of tracer never passed the downstream fluorometer (Figure 11). To estimate the amount of tracer lost to absorption, total tracer mass to pass each station was calculated for the first 24 hours. Approximately 5%, 19%, and 15% of the tracer was lost between the two fluorometers in the first, second, and third tracer tests, respectively. To adjust for non-conservative losses and differences between injected concentrations, the mass of Rhodamine WT to pass each fluorometer in the first 24-hour period was standardized (i.e., concentration proportionately adjusted so that the total mass of tracer passing each station in a 24-hour period was equal). Data were also standardized over 48- and 96-hour periods using late time regression analysis to determine endpoint concentrations. The relative size of the hyporheic zone (hyporheic + dispersion minus dispersion) for each of the standardizations is shown in Table 1. As predicted for downstream of the dam, hyporheic tracer decreased after dam removal but before the storm and then increased following course sediment deposition. Standardizing over a 48 hr period increased the differences between tests by 14-18% and extending the standardization out to 96 hours had little additional effect.
Figure 11: Concentration profiles for upstream and downstream fluorometers with the downstream fluorometer time offset to match upstream fluorometer (time refers to time since injection at upstream fluorometer) prior to standardization.
Table 1: Changes in downstream hyporheic exchange determined as the difference between standardized concentrations in the upstream and downstream fluorometers. Data show hyporheic releases become less important with increasing time with less than a 0.5% change between 48 and 96 hours. Percent flow through the hyporheic calculated over 96 hour period using power-law regression to determine endpoint concentration.

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<td>0%</td>
<td>14%</td>
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<td>% increase at 96 hr</td>
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<td>% flow through hyporheic</td>
<td>0.0010%</td>
<td>0.0007%</td>
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Discussion

Grain-size analysis of the South Fork and mainstem McKenzie river sediments suggest a relative enrichment in fines in the alluvial reaches below Cougar Reservoir following drawdown as compared with the reaches above the reservoir. Upstream reaches and mainstem McKenzie sites had clay fractions representing 2.5% of the < 2mm sample by weight as opposed to 9.5% in the South Fork below the dam. An increase in fines was not detectable below the confluence of the South Fork on the mainstem McKenzie River. Because no in-situ sampling of gravels was conducted prior to the reservoir release in the spring of 2002, it was not possible to discern whether the fines pre-dated the release, but reservoirs generally act as setting basins and it would be unusual to see significant quantities of fine sediment stored in channel beds below a dam. More importantly, however, it was not possible to determine the effect of fine sediment intrusion into the bed on hyporheic exchange or salmon spawning success.

Data from Dinner Creek show that increased turbidity was a transient phenomenon that only occurred during dam removal and post-removal storms. Exposure to high turbidity was not as prolonged as on the McKenzie, hyporheic exchange downstream of the dam did decrease slightly (<30%) following dam removal but prior to reservoir erosion. Despite a small decrease in hyporheic residence time, no change in diurnal temperature exchange was discerned.

Dam removal did increase residence time upstream of the dam. In the period following dam removal but prior to reservoir erosion, water was seen seeping from the knickpoint face just upstream of the dam temperature probe. Some of the seepage may have contained intercepted groundwater, though tracer test data show a large increase in late-time tracer concentration in the upstream reach suggesting that stream water was
being advected through reservoir sediment. Near the dam fact, dam removal would have significantly increased head differential and driven the movement of water through reservoir sediments. Thus at Dinner Creek, dam removal without reservoir erosion increased hyporheic exchange and decreased diurnal temperature flux upstream of the dam, but had little effect downstream.

During the largest storm of the season, sediment eroded from the reservoir and deposited in the downstream channel creating new channel bedforms. Tracer test data presented in Table 1 show a more than 50 fold increase in net hyporheic tracer downstream of the dam following the storm and a net decrease in diurnal temperature change. Prior to erosion, diurnal temperature flux increased 25% over the downstream reach length compared with only 0.7% after the storm. These data suggest that gravel deposition and the transition from plain-bed to pool-riffle morphology increased bed sediment hydraulic conductivities and local hydraulic gradients which served to increase hyporheic exchange and buffer stream temperatures.

Upstream of the dam, hyporheic exchange was decreased over both pre- and post-removal (but pre-erosion) conditions and diurnal temperature flux, which was increasing 6% prior to dam removal and decreasing 6% after dam removal but prior to erosion), was increasing 0.6% following the storm. The decrease in hyporheic exchange over post-removal pre-erosion conditions was probably driven largely by the loss of head gradients near the knickpoint face while the decrease between pre-removal and post-erosion can be explained by replacement of an anastomosing planform with pools and riffles (prior to dam removal) with an incised rectangular channel with few bedforms after removal. While decreases in hyporheic exchange may generally be associated with increases in diurnal temperature flux, continued groundwater interception in the upstream reach may have continued to work as a temperature buffer.

This raises a set of issues for managers interested in removing dams. How will the sequencing of flows, relative abundance of coarse and fine sediment, removal method, and geomorphic setting affect the impact of dam removal on hyporheic exchange. The plan to removal of Condit Dam on the White Salmon, for example, calls for blasting a hole in the bottom of the dam during a large storm. In that case, fine sediment at the base of the lake would be sucked out of the hole and the lake would drain at high discharges that might limit fine sediment deposition downstream. Erosion of coarse sediment from the upstream delta would be offset in time (possibly occurring the next storm or next winter). The result might be similar to Dinner Creek with a short-term decrease
in hyporheic exchange and steam temperature buffering followed by a large increase in hyporheic exchange associated with coarse sediment deposition. On the other hand, the removal plan for Glines Canyon Dam on the Elwha River involves cutting small sections out of the dam, slowly letting the lake drain and the delta erode. In this case, reworked delta sediments may be released, while fine silt and clay stored at the base are still protected by the bottom of the dam. Released gravel, which is expected to serve as spawning habitat, may become ‘clogged’ with fine silts and clays once dam removal is complete and fines trapped at the base of the reservoir begin to erode.

Conclusions

Rarely are scientists given warning of large sediment releases to rivers, but dam removal represents an unusual exception. Because the timing of Dinner Creek Dam removal was known and large sediment releases were predicted, it was possible to directly evaluate the effects of reservoir sediment erosion and deposition on channel morphology, macroinvertebrate communities (this issue), and hyporheic exchange. Differences in methodology, sediment release length and timing, and downstream channel morphology complicate efforts to make direct comparisons between Dinner Creek and Cougar Reservoir. However, taken together these studies show that sediment releases affect hyporheic exchange in predictable ways, which in turn can be used to predict secondary changes on processes that are influenced by hyporheic exchange, including stream temperature and water quality.

Cougar Reservoir studies showed that fine sediment released into a gravel bed river is likely to intrude into the bed. As shown at Dinner Creek, the effect may be to decrease hyporheic exchange. If coarse sediment is released in conjunction with or after the fines (Dinner Creek knickpoint erosion occurred at flows less that that required to break up and move the reservoir surface armor layer; Stewart this issue) then the result may be to increase hyporheic exchange, possibly by aggrading the bed with high hydraulic conductivity sediment and/or creating bedforms.

Just as dam building affects rivers, so does dam removal. Many of the effects from dam removal will be subtle and unintended. In this study we have documented primary and secondary effects of sediment releases on hyporheic exchange in a mountain river. Dam removal provides an excellent experiment on river processes because change of a known magnitude occurs at a prescribed time and place. If we are to evaluate how sediment releases will affect channel processes in other regions and under other
circumstances, it is time we began to build a set of dam removal case-lore based on interdisciplinary research.
CHAPTER 4 – CHANGES IN BENTHIC MACROINVERTEBRATE DENSITY AND COMPOSITION FOLLOWING DAM REMOVAL

Abstract

Dam removal has the potential to affect downstream macroinvertebrate communities through changes in water quality, physical habitat, and species interaction. In this paper, I document changes in macroinvertebrate community abundance and composition following the removal of a small dam in Oregon whose reservoir had filled with sediment. Changes in water quality associated with dam removal, including increased turbidity and pH, were transient and had little affect on downstream macroinvertebrate communities. Winter storms that eroded a large proportion of reservoir sediment did, however, affect macroinvertebrate communities primarily through the loss of rare taxa. Macroinvertebrate density returned rapidly to pre-event conditions while changes in community composition were still evident 2 years after dam removal and 1.5 years after reservoir erosion.

Introduction

Dams are known to have a wide range of effects on river ecosystems (Dynesius and Nilsson, 1994; Ward and Stanford, 1995; Power et al., 1996; Andersson et al., 2000, World Commission on Dams, 2000), channel morphology (Williams and Wolman, 1984; Ligon et al., 1995), and hydrology (Williams and Wolman, 1986; Graf, 1999). As dams age, maintenance and rehabilitation costs increase while the benefits that dams provide generally decrease (Born et al., 1998; Morris and Fan, 1998). In recent years, campaigns have begun to restore rivers by removing aged dams (American Rivers, 1999; Pejchar and Warner, 2001), but dam removal itself is not without environmental impacts (Stanley and Doyle, 2003). Although American Rivers (1999) has identified more than 450 dams removed from U.S. rivers since 1912, the ecological effects from dam removal remain poorly documented (Bednarek, 2001).

Dams are built for a wide-range of purpose and just as the purpose of dams vary, so do their effects. The same is true for dam removal. The removal of some dams will stimulate dramatic effects while others will have little impact. Dams whose reservoirs have filled with sediment (hereto referred to as sediment-filled dams) represent a unique subset of dams under consideration for removal. Sediment-filled dams tend to be older,
smaller, and less able to perform value added functions including water storage and flood control. Because sediment-filled dams have little ability to alter flow, temperature, or sediment transport regimes; the ecological impacts associated with dam removal are likely to be associated primarily with sediment releases from the decommissioned reservoir. Instream sediment releases have been shown to reduce invertebrate richness and abundance in experimental channels (Shaw and Richardson, 2001).

Sediment releases impact aquatic insects through both direct and indirect pathways. Direct effects on benthic macroinvertebrates include interference with food gathering, physical abrasion, and physical dislodgement (Culp et al., 1986; Waters, 1995). Increased turbidity limits the ability of insects to visually locate food resources, whereas suspended sediment interferes with feeding and respiratory mechanisms of larval insects (Gray and Ward, 1982). Suspended sediments may also damage exposed gills or other body parts and may increase the likelihood of physical dislodgment. Given their size, many benthic macroinvertebrates can escape direct effects of suspended sediment by moving into interstitial spaces within the streambed, but high proportions of fine sediment within the hyporheos can smother invertebrates and/or decrease habitat availability (Richards and Bacon, 1994).

Of indirect effects, a propensity towards drift is the most common behavior cited in response to increased suspended sediment load (Culp et al., 1986; Gray and Ward, 1982; Quinn et al., 1992; Doeg and Koehn, 1994, Shaw and Richardson, 2001). Drift is initiated when insects residing on the streambed propel themselves into the water column and drift downstream with the flowing water. Drift without recruitment can reduce invertebrate abundance and/or richness in the affected area. Suspended sediment may also reduce the quantity of light that reaches the streambed, which reduces primary production, periphyton biomass, and macroinvertebrate feeding efficiency (Quinn et al., 1992). Changes in substrate composition are also likely to affect macroinvertebrate community composition and abundance because macroinvertebrates are closely associated with a given range of particle sizes (Cummins and Lauff, 1969).

Given their high fecundity and mobility, stream macroinvertebrate populations may recover relatively quickly following disturbance by drifting in unaffected upstream areas. Following the removal of a small weir in Armstrong Creek, Australia, the releases of approximately 100 m$^3$ of sediment had significantly reduced insect abundance and diversity 14 days after removal. At 45 days, insect abundance and diversity had recovered to pre-removal levels. Macroinvertebrate abundance and diversity fluctuated
over the next five months as sediment continued to be flushed through the system, but approximately eight months after the release, insect fauna appeared to stabilize and had higher abundance and diversity levels than pre-removal, but community composition had changed (Doeg and Koehn, 1994).

How the ecological effects of dam removal will be manifest is dependent on a wide-range of factors, including the dam’s operational history and its geomorphic and ecological context. In this paper, I examine changes aquatic macroinvertebrate assemblage following the removal of a small mountain river dam in Western Oregon whose reservoir had filled with sediment. Dam removal and subsequent small reservoir erosion events were found to be largely transient and to have little impact macroinvertebrate abundance or taxa richness. However, when a single storm event eroded over 1100 m$^3$ of sediment (86% the first year’s reservoir erosion) in less than two days (Stewart, this volume, Chapter 2), both taxa richness and abundance declined below the reservoir. While macroinvertebrate abundance recovered within the timeframe of months, taxa richness remained reduced two years after dam removal. Long-term changes in taxa richness were largely associated with the loss of rare species and most likely were the result of long-term changes to aquatic conditions.

**Study Site**

Dinner Creek dam was a 3.2 m high dam located on Forest Service land at 43.7155°N, 122.7153°W in the Layng Creek watershed upstream of the city of Cottage Grove, Oregon (Figure 1). The dam was constructed around 1925 to provide water for

![Figure 1: Location of Dinner Creek, OR showing upstream and downstream macroinvertebrate sampling areas above the and below the dam.](image)
the residents of Cottage Grove. During the first week of August 2003, Dinner Creek dam was demolished and removed with heavy equipment because it was a barrier to native trout and no longer served any useful purpose.

At the time of dam removal, the reservoir behind Dinner Creek dam was completely filled with sediment that had accumulated over the life of the reservoir. Surface sediments were composed of sand, gravel, cobbles and boulders with a surface d50 (diameter for which 50% of sediment is finer) of 64 mm (cobble). Subsurface sediment was composed primarily of silty-sand. Drainage area above the dam was 21.3 km², average channel slope through the site was approximately 2.4%, and average channel width is 8 m. Channel morphology was primarily plane bed with some forced pool/riffle morphology. The Dinner Creek basin has a temperate climate with 65% of the precipitation falling between November and March. Annual precipitation ranges from 134 to 180 cm. Local geology is associated with the Western Cascades province and has a mixture of sedimentary rocks and basaltic lava flows (Walker et al., 2003). Dinner Creek discharges into Layng Creek, a tributary of the MF Willamette River, approximately 200 meters below Dinner Creek Dam.

**Methods**

Before and after the removal of Dinner Creek dam, the reservoir was surveyed with a Leica total station and photographed from monumented photo points. Repeat measurements of monuments were taken to establish a survey precision of ~1 cm. Surveys were collected along breaklines (as opposed to a uniform grid) to capture breaks in slope and were repeated after major storm events. Survey data were linearly interpolated within ArcInfo to create triangular rectangular networks (TIN’s) and digital elevation model (DEM) lattices of the reservoirs with grid spacing of 0.2 m. Net erosion between surveys was calculated with the ArcInfo CutFill routine as the difference in DEM topography and photographs were used to constrain the timing of reservoir erosion between topographic surveys.

To quantify downstream deposition, channel bed elevations were surveyed before and after dam removal along cross-sections downstream spaced 15m apart. Three cross-sections were surveyed in Layng Creek below the confluence with Dinner Creek (60 m interval). Below the dam, deposition volume was calculated as the area of aggradation in each cross-section multiplied by the distance between cross-sections. Longitudinal
profiles for each stream were created from TIN’s based on a compilation of cross-section data and supplemental topographic survey points.

At Dinner Creek, water discharge between 5 August 2003 and 12 December 2003 was estimated using a stage discharge relationship developed for an Omega Water Level Logger with Automatic Atmospheric Pressure Compensation located 125 m above the dam. After December 13, when the water level logger was left stranded above the new incised channel, discharge was estimated by correlating gaged discharge measured 2 km downstream of Dinner Creek dam at a site on Layng Creek. Layng Creek has greater drainage area and higher base flow than Dinner Creek, but gage analysis showed that peak discharges at the Dinner Creek and Layng Creek gages occurred within one to two hours of each other over the period of record.

Turbidity at Dinner Creek was measured with factory-calibrated Seapoint Sensors backscatter turbidity probe located 125 m below the dam between 8/15/2003 and 1/21/04. The probe was set to record turbidity from 0-250 NTU. An ISCO automated sampler collected water samples at the same location as the turbidity probe. Samples were collected at 4-hour intervals during actual dam removal and at 12-hour until early January 2004. From these samples, a relationship between turbidity and suspended sediment concentration was determined in the lab. Water quality parameters including specific conductivity, dissolved oxygen (DO) and pH were measured in the field with a Hydrolab Hydroprobe at the same location. Four individual water samples were also collected at the same location during dam removal, and lab analyzed for soluble reactable phosphorous (SRP), nitrogen (NO3-N), and ammonia (NH3-N).

Benthic macroinvertebrates were collected with a 500 μm-net surber sampler (0.09 m² streambed area) randomly placed in 30 and 50 m reaches located approximately 230 m upstream of the dam and 80 m downstream of the dam respectively. Samples were collected in July, August, November, and December 2003, January and February 2004, and June 2005. Samples were sieved through 500 μm-mesh and stored in 70% ethyl alcohol. In the lab, each sample was sub-sampled for a minimum of 100 individuals, usually ¾ of the total sample. Aquatic insects were identified to the lowest practical taxonomic level, generally genus, except Chironomidae, which were identified to subfamily or tribe (Merritt and Cummins, 1996). All macroinvertebrates were counted for density (number/m²) estimates. Sub-sample densities were divided by the fraction sampled to obtain full-sample estimates.
To evaluate significance of invertebrate responses between the two reaches, macroinvertebrate density and taxa richness from the six surber samples were analyzed as pseudoreplicates using two-tailed t-tests assuming unequal variances with ten degrees of freedom (Hurlbert, 1984). Ordination analyses were used to contrast benthic macroinvertebrate community compositions between the sites above and below Dinner Creek dam. Ordination was performed on log-transformed density data for a single sample period and site (2 sites x 7 months). Eight rare taxa (defined as those found in only one of the 14 samples) were eliminated to reduce noise and aid in the analyses of community relationships, leaving 88 taxa for community analysis. Nonmetric Multidimensional Scaling (NMS) with PC-ORD software was used to find the monotonic relationship with the lowest stress and instability from a random starting configuration using a maximum of 400 iterations in 40 runs (Kruskal, 1964; Mather, 1976; McCune and Mefford, 1999).

Results

During dam removal, fine sediment eroded from the knickpoint face increasing turbidity downstream of the dam. ISCO water samples show that turbidity in Dinner Creek ranged from 43-200 NTU (87-1040 mg/L; n = 5) between 8am and 5pm during days of active dam removal. After dam removal work ceased each day, instream turbidity declined rapidly with non-work hour turbidities ranging from 2-18 NTU (0-89 mg/L, n = 13). Specific conductivity, pH, soluble reactable phosphorous (SRP), and ammonium also increased over background levels during dam removal, with pH hovering above 9 during work activity (Figure 2).

From August 5th, when dam removal was completed, to November 15th, only 50 m³ of sediment eroded from the knickpoint face. Erosion of the knickpoint lip was inhibited, in part, by the fact that the creek upstream of the dam had migrated laterally, and now flowed across a bedrock sill. On November 17th, a single storm event eroded an additional 40m³, all of which deposited downstream of the dam but largely upstream of the invertebrate sampling site. On 13 December 2003, the largest storm event of the season hit Dinner Creek with a peak discharge of 1.3 cms. The December 13th storm allowed the channel to erode through an alder terrace and around the bedrock canyon wall, releasing 1134 m³ of sediment (86% of total reservoir erosion). Of the 1312 m³ of sediment eroded from behind Dinner Creek Dam, 470 m³ (36%) deposited in the channel within 150 m of the dam. Longitudinally, width-averaged deposition was greatest the
Figure 2: Water quality samples from Monday, 4 August 2003, the first full day of dam removal work (work began late on Friday and recommenced Monday) showing specific conductivity (SpCond), dissolved oxygen (DO), pH, soluble reactable phosphorus (SRP), nitrate and nitrite (NO$_3^-$-N, NO$_2^-$-N) ammonia, NH$_3$-N, and total suspended sediment concentration (SSC).
near the dam, and decreased exponentially with increasing downstream distance. Cross-sectional deposition was uniform only near the dam however. The greatest deposition occurred primarily along the axis of the former channel thalweg and created an alternate bar morphology where plain bed morphology had existed previously (Figure 3). Width-average channel aggradation over the invertebrate sampling reach was 22 cm. Sediment deposition did not change the surface size composition of the channel bed, but did increase hyporheic exchange in the downstream sample reach (Stewart, this volume, Chapter 3).

Macroinvertebrate density and taxa richness showed no significant changes in response to dam removal, with density and richness at the upstream and downstream sites tracking together through November 23rd (Figure 4). The first macroinvertebrate sample taken after the December 13th storm event, which released the bulk of reservoir sediment, was collected on the 18th, five days after the erosive event. The December 18th sample showed significant decreases in both macroinvertebrate density and taxa richness at the downstream site relative to upstream site (p=0.04 and p=0.03 respectively). Density remained lower at the downstream site in both January and February, though differences were no longer statistically significant (p=0.09 and p=0.32 respectively); while taxa richness remained significantly lower at the downstream site in both January and February (p<0.02). Because macroinvertebrate abundance and community composition were predicted to recover quickly after reservoir erosion, no samples were collected between 2/27/04 and 6/15/05. The June 2005 samples were collected to see if macroinvertebrate community composition and abundance had recovered to pre-removal conditions. These samples, collected two years after dam removal, show that macroinvertebrate density had returned to pre-removal levels, but taxa richness remained reduced at the downstream site (p = 0.06). Taxa that disappeared from the downstream site were proportionately rare, each representing less than 1.33% of total macroinvertebrate abundance.

Prior to dam removal, Chironomidae (midge larvae) were the dominant taxa in both the upstream and downstream sites. Between August 2003 and February 2004, Heptageniidae (Cingymula, Epeorus, Ironodes, Rhithrogena) were the dominant taxa in both upstream and downstream sites. For samples collected in June of 2005, Baetis dominated the upstream site while Oligochaeta worms dominated the downstream site. Shannon’s diversity indices (a measure of species heterogeneity) were similar between upstream and downstream sites through time, with values ranging from 1.1 – 1.45. The
Figure 3: Sediment deposition downstream of Dinner Creek dam. Photo taken looking upstream at
the invertebrate sampling area, the dam is just visible in the top photo.
Figure 4: Dinner Creek macroinvertebrate density and taxa richness for sites downstream of and impacted by dam removal and upstream of dam affects.
downstream site showed no difference in abundance for taxa designated by the Oregon Watershed Enhancement Board (OWEB) as tolerant or intolerant to sediment (OWEB, 1999).

NMS described a two dimensional (2D) model that had a very low final stress values of 4.38 and an instability measure of 0.00001 (Figure 5). This low stress is partially due to the small sample size. The two axes together represent 96% of the community variance expressed in this ordination. Axis 1 represents 89% of the variance ($r^2 = 0.89$) and axis 2 represents 7% of the variance ($r^2 = 0.07$). Macroinvertebrate communities at the upstream and downstream sites were very similar to each other prior to the 13th December 2003 storm (i.e., points close together on the plot). After the storm, communities were quite dissimilar. By June 2005 macroinvertebrate communities at the upstream and downstream sites were more closely arrayed with the pre-storm community compositions, but still exhibit some dissimilarity between above and below dam-sites. Seasonality was a large factor affecting community composition and overall density. Samples appear to be orientated along axis 1 according to their overall macroinvertebrate

![Figure 5: NMS analysis of site macroinvertebrate community data showing a strong seasonal dependence and a shift of increased dissimilarity following reservoir erosion that is still present 2 years after dam removal and 1.5 years after reservoir erosion. Hollow symbols represent sites above dam, filled represent sites below dam, circles indicate samples collected before reservoir erosion, triangles indicate samples collected within 3 month of reservoir erosion, and squares represent samples collected 1.5 years after erosion.](image-url)
density, which also corresponds to season; greater densities in summer, less in autumn, and least in winter.

Discussion

Dam removal represents a disturbance to a system that has adjusted to the presence of a dam. This is especially true for small dams whose reservoirs have filled with sediment because these dams may have little ability to significantly alter ecological systems, except as migration barriers. Disturbance associated with the removal of dams whose reservoirs have filled with sediment is likely to be associated with reservoir erosion, which may significantly lag dam removal. Dams are likely to be removed during times of low discharge, while reservoir erosion may be limited high discharge events.

Data from Dinner Creek dam show that dam removal significantly increased downstream turbidity, pH, and ammonia for close to 24 hours over a 3-day period, but those changes were not manifest in macroinvertebrate abundance or composition. Following dam removal, macroinvertebrate community abundance and composition at the upstream and downstream sites exhibited only seasonal changes despite storms that eroded small portions of the upstream reservoir. It was not until a storm eroded 1134 m$^3$ of reservoir sediment and aggraded the downstream channel, that the downstream macroinvertebrate community showed any direct impact associated with dam removal. The storm and associated geomorphic changes significantly reduced macroinvertebrate abundance and composition at the downstream site. Following the storm, several macroinvertebrate taxa were randomly present or absent from samples suggesting they had become less common (and therefore harder to sample) compared to upstream populations. Macroinvertebrate abundance recovered relatively quickly at the downstream site, while taxa richness and community similarity (as modeled by NMS) remained reduced 2 years after dam removal and 1.5 years after reservoir erosion.

Differences in macroinvertebrate community composition 1.5 years after reservoir erosion are unlikely to be associated with a lack of recolonizing species, but rather to some change in the physical habitat of the downstream reach. Tracer tests and temperature data suggest that sediment deposition and morphologic change increased hyporheic exchange and reduced diurnal temperature flux in the downstream reach. These changes or possibly other unidentified changes in physical habitat, or possibly increased fish migration through lower Dinner Creek, are likely responsible for the long-term changes in macroinvertebrate community composition.
Conclusions

This study shows that dam removal can stimulate changes that result in long-term ecological change, even in dams thought to have little ecological impact. Dam removal is not the reversal of dam impacts, but represents an impact to an adjusted ecological system. Dam removal initiates a cascade of processes that impact ecosystems through primary, secondary, and tertiary effects. In the case of Dinner Creek, changes in macroinvertebrate composition were not elicited by primary changes associated with dam removal, but rather through secondary and tertiary effects associated with reservoir erosion, which was offset in time.
CHAPTER 5 - WHERE WILL THE DAM SEDIMENT GO: FIELD STUDIES BELOW MARMOT DAM, OR.

Abstract

Little is known about the long-term fate of sediment stored behind dams following dam removal. When Marmot Dam on the Sandy River in Oregon is removed in 2007, approximately 750,000 m$^3$ of coarse gravel and sand currently stored in the upstream reservoir will begin to erode. How this sediment will be apportioned in the downstream channel is largely unknown. One-dimensional sediment transport models predict that coarse sediment will deposit close to the dam while fine sediment released from Marmot reservoir will transit rapidly into the lower 10 km of the Sandy River with no appreciable storage upstream. In this study, I combined field measurements of shear stress with patterns of deposition following a series of lahars in the upper Sandy to predict the fate of fine sediment released into the Sandy River. Field and model results show that the Sandy River has little capacity for fine sediment storage in pools above RK 6.4 at discharges between 50 cms and 300 cms. At flows less than 50 cms, fine sand is predicted to deposit in pools; though fine sediment is expected to occupy no more than 17% of pool volumes unless flows fall below 50 cms. Fine gravel deposits in pools at flows less than 100 cms and may form lateral deposits occupying as much as 25% of pool volume at flows associated with the dam breach. At flows above 300 cms, strong eddies begin to form and sediment can become stored in lateral eddy beaches, but beach stratigraphy suggests that Sandy River beaches may have little additional sediment storage capacity.

Introduction

The release of stored reservoir sediment remains one of the most fundamental, yet poorly understood processes associated with dam removal (Heinz Center, 2002). Reservoir sediment releases have the potential to significantly affect downstream geomorphic and ecological systems by reducing pool volume (Rathburn and Wohl, 2001), altering water chemistry (Stanley and Doyle, 2002), streambed composition (Wohl and Cinderelli, 2000), and food web dynamics (Doeg and Koehn, 1994). The current inability to predict the fate of reservoir sediment has been the greatest impediment to removing large dams with significant reservoir sediment storage including Glines Canyon Dam on the Elwha River in WA and Matiaja Dam on the Ventura River in CA.
Marmot Dam is a 13 m high hydroelectric diversion dam owned and operated by Portland General Electric (PGE) on the Sandy River in Northwest Oregon. The Sandy River originates high on the slopes of Mount Hood and flows approximately 90 km through unstable volcanic ash and rock deposits to the Columbia River. The Sandy River has naturally high sediment loads that are periodically augmented by lahars originating from Mt. Hood. Marmot Dam was built and operated as a water diversion structure and its reservoir quickly filled with approximately 750,000 m³ of fine and coarse sediment. The removal of Marmot dam in 2007 will likely initiate the largest man-made sediment release associated with dam removal in US history.

In preparing the Environmental Impact Statement (EIS) for the Bull Run Hydroelectric project, of which Marmot Dam is a part, PGE hired Stillwater Sciences (2000) to develop a one-dimensional numerical sediment transport model for the Sandy River. The plan, as modeled, involves building a temporary cofferdam upstream of Marmot dam during the Summer of 2007. The river will be river diverted through existing flumes and the current roller concrete dam removed and older timber dam will be removed with excavators and controlled blasting. The cofferdam will be built to withstand flows up to 71 cubic meters per second (cms) (~ 2,500 cfs). When flows exceed this discharge, the cofferdam will fail and much of the 750,000 m³ of coarse sand and gravel stored in the reservoir will begin to erode. Based on historical flow frequencies, the cofferdam breach should occur in October. The Stillwater model incorporated the latest techniques for routing a sand/gravel mixture through a river channel. The modeling results suggest that much of the coarse sediment (gravel and larger) will deposit in two expansion reaches below the dam, while fine sediment (sand and finer) is predicted to transit rapidly into the lower 10 km of the Sandy River with no appreciable storage upstream (Stillwater, 2000).

Although one-dimensional sediment transport models are excellent tools for predicting deposition over large spatial and temporal scales, they cannot be used to predict how sediment will be distributed within a modeled reach. Although not represented by the model, an individual reach generally contains a wide range of geomorphic and hydraulic features, each created through differential erosion and deposition (i.e., pools, riffles, runs). For most ecologists, knowing how sediment will be distributed among these features (which also function as habitats) over time and space can be more important than knowing reach-average channel change.

For example, preferential pool filling is a common response to sediment increase along pool-riffle channels, and has been used to assess channel response to various land-
use activities (Lisle, 1982; Madej and Ozaki, 1996; Lisle and Hilton, 1991; Montgomery and Buffington, 1997). In a recent study, sediment released from a reservoir on North Fork Poudre River in Colorado translated and dispersed downstream as a wave, filling pools and leaving behind large eddy deposits that acted as sediment sources after the initial sediment wave had passed (Wohl and Cinderelli, 2000). Were a similar situation to occur on the Sandy River, the transient deposition of sediment in pools could significantly alter habitat availability for threatened anadromous salmonid species, even where reach-average deposition was negligible. Fine sediment may also deposit in eddies and pool margins (Doyle et al., 2003) where it is protected from scouring flows thus resulting in relatively long residence times (Rathburn and Wohl, 2003) and prolonging the time required to move the sediment downstream.

Because the Sandy represents the first time that such a large release of sediment will accompany a ‘blow and go’ dam removal, and with the Sandy providing critical habitat for threatened salmonids, I undertook an effort to evaluate the Sandy River’s potential for transient storage of fine sediment. The fate of coarse sediment was not evaluated because coarse sediment moves episodically at high discharges when field measurements are difficult to collect, and because other studies were better able to address patterns and processes of gravel erosion and transport following mountain dam removal (see Stewart, this volume, Chapter 2). To predict the fate of fine sediment, pool hydraulics and fine sediment storage in pools were measured along the Sandy River following a series of lahars that released more than 400,000 m$^3$ of coarse and fine sediment into the upper reaches of the Sandy River (Stillwater Sciences, 2001; Tom Deroo pers. comm., 2002). The lahars occurred in October 2000 and based on channel change at Marmot gage, it was suggested that it took about one year for the river bottom returned to its pre-debris flow geometry.

While the location, timing, and grain size distribution of the lahars were different from that of Marmot dam removal; the lahars were presumed to be relatively analogous to dam removal in terms of fine sediment routing and deposition patterns in the lower Sandy. In 2002, I measured the fraction of total pool volume occupied by fine sediment ($V^*$) in the Sandy River as an index of the supply of mobile sediment. In addition, to measuring the amount of fine sediment in the bottom of pools, I used an acoustic Doppler current profiler (ADP) to determine how pool hydraulics along the Sandy changed as a function of longitudinal position and discharge. From these data, I was able to calculate the maximum mobile particle size and the maximum percentage of pool volume subject
to further sediment deposition, as a function of discharge and longitudinal position. ADP
data could not be collected at peak winter discharges, when sand can be redistributed into
beaches that are protected from erosion as flows diminish (Schmidt, 1990). To evaluate
the degree to which high water beaches on the Sandy were acting as fine sediment
reservoirs, tracers were implanted into two beaches and the annual sediment flux was
calculated for each site.

Field and model results show that the Sandy River has little capacity for fine
sediment storage in pools above river kilometer (RK) 6.4 at discharges between 50 cms
(1800 cfs) and 300 cms (10,600 cfs). At flows less than 50 cms, fine sand is predicted to
deposit in pools; though fine sediment is expected to occupy no more than 17% of pool
volumes unless flows fall below 50 cms. Fine gravel deposit in pools at flows less than
100 cms (3500 cfs) and may form lateral deposits occupying as much as 25% of pool
volume at flows associated with the dam breach (~2500 cfs). At flows above 300 cms,
strong eddies begin to form and sediment can become stored in lateral eddy beaches,
but beach stratigraphy suggests that Sandy River beaches may not have little additional
sediment storage capacity.

Site Description

The Sandy River originates high on the slopes of Mount Hood in Oregon and flows
northwest for approximately 90 km to its confluence with the Columbia River (Figure 1).
The climate of the Sandy River basin is typical of western Oregon with mild summers
and wet winters. Annual precipitation varies from 70 cm near the mouth of the Sandy
River to more than 225 cm near its headwaters with heaviest precipitation typically
occurs between November and January (ODFW, 2002). Sandy River hydrology is
rainfall dominated giving the Sandy low summer and high winter discharges, the latter
generated by rainfall and rain-on-snow events, followed by moderate flows during spring
snowmelt.

Sandy Basin geology reflects a history of Tertiary and Quaternary volcanic events
and Pleistocene glaciations. Recent periods of volcanic activity from Mount Hood
include the Timberline and Old Maid periods (1,500 and 200 years ago respectively)
when numerous pyroclastic flows and lahars buried the lower Sandy River valley floor
(Scott et al., 1997). Glaciers in the headwaters of the Sandy River significantly affect
discharge and sediment loading. During the summer snowmelt period, the Sandy is often
turbid with glacial silt. Cold lahars triggered by rainstorms and snowmelt and originating
on Mount Hood periodically deliver sediment to the river. In early October 2000, a large rainstorm produced a series of lahars on Mt. Hood that released more than 400,000 m$^3$ of coarse and fine sediment into the upper reaches of the Sandy River (Stillwater Sciences, 2001; Tom Deroo pers. comm., 2002).

Marmot Dam is located at river kilometer (RK) 48 near the upstream end of the Sandy River Gorge at a drainage area of approximately 670 km$^2$. The original wood crib dam was built 1913 and was replaced in 1989 by a 14-m high, 104-m wide roller-concrete dam. Marmot Dam impounds a small 40 m x 3 km long reservoir that is filled with approximately 750,000 m$^3$ of coarse and fine sediment, of which 490,000 m$^3$ is primarily gravel/pebble and 260,000 m$^3$ is primarily sand (Squier Associates, 2000).

Stillwater Sciences (2000) delineated five different reaches below the dam. Coarse sediment released from Marmot Dam is predicted to deposit as a diffusive wave with
coarse sediment aggrading Reach 1 just below the dam, and the upper end of Reach 3 (Stillwater, 2000). Reach 2 encompasses the Sandy River gorge, which is too steep and confined for significant channel aggradation to occur. Fine sediment is predicted to transit rapidly into the lower 10 km of the Sandy River (Reach 5) with no significant aggradation upstream (Stillwater, 2000).

Field observations of coarse sediment deposition following the removal of Dinner Creek dam, a small mountain river in Oregon, were congruent with patterns of coarse sediment deposition predicted below Marmot dam (Stewart, this volume, Chapter 2; Stewart, 2005). Sites for this study were located in Reaches 3-5 between RK 38 and RK 6, which is marked by Fall Chinook spawning sites and where fine sediment was predicted by the Stillwater modeling to transit with little deposition. The majority of the sites were located in Reach 4, which is characterized by pool-riffle morphology, moderate confinement between mostly alluvial terraces, and numerous gravel/cobble bars. At summer discharges, channel width ranges from 50-80 meters. The two beaches that were surveyed to estimate lateral exchange were located at RK 26 and RK 21. Beach 1 is a 5400 m$^3$ perennial lateral eddy deposit that exchanges sand during high water events, while Beach 2 is a >3000 m$^3$ backwater eddy deposit.

**Methods**

*Residual pool volumes*

During the summer of 2002, I calculated the fraction of scoured pool volume occupied by fine sediment for individual pools on the Sandy River. Pool surveys were collected at low discharge during late summer, when water surface elevations in pools were controlled by the elevation of the downstream riffle crest. An acoustic Doppler current profiler (ADP) was used to measure cross-section depth for individual pools. Cross-sections within individual pools were spaced approximately one channel-width apart. ADP data were transmitted to a laptop in the field for real-time display and quality control. Cross-section quality was evaluated by calculated discharge, Signal to Noise Ratio (SNR), and distance-made-good. Multiple passes were linearly interpolated at 1-m intervals to create cross-section profiles reflecting residual area (cross-section area not occupied by sediment) (Figure 2). The area occupied by fine sediment was calculated by measuring the refusal depth to which an avalanche probe could be hand-driven into pool bottom sediments. Refusal depth was measured at approximately 5-meter intervals. Fine sediment volume and residual volume were calculated by multiplying measured sediment
and residual areas by the distance between cross-sections and summing along the entire pool length. The fraction of scoured pool volume occupied by fine sediment was then calculated as

$$V^* = \frac{V_f}{(V_f + V_r)}$$

(1)

where $V_f$ = fine-sediment volume and $V_r$ = residual pool volume, and $(V_f + V_r)$ is the scoured pool volume or volume of a pool if the fine sediment were removed (Lisle and Hilton, 1992).

**Maximum mobile particle size**

The following winter, six pools were selected for additional ADP data collection over a range of discharges to determine how changing hydraulic patterns associated with discharge fluctuations were likely to affect erosion and deposition. Incipient motion occurs when dimensionless shear stress ($\tau_*$) reaches some critical value ($\tau_{*c}$), which is largely a function of the particle Reynolds number ($Re_p$) (Shields, 1936). Dimensionless
shear stress \( (\tau_s) \), also known as the Shields parameter, is calculated as

\[
\tau_s = \frac{u_s^2}{(s-1) g d_s}
\]  

(2)

where \( u_s \) is shear velocity, \( s \) is specific gravity of sediment (assumed to be 2.65), \( g \) is gravitational acceleration, and \( d_s \) is sediment diameter. Shear velocity is most accurately determined using the depth-integrated form of the logarithmic profile, which describes the variation in velocity with height above the bed

\[
\frac{U}{u_*} = \frac{1}{k} \ln \left( \frac{h}{e z_0} \right)
\]  

(3)

where \( U \) is the depth integrated velocity, \( k \) is the von Karmen constant (assumed to be 0.4), \( h \) is the flow depth, \( e \) is the base of the natural logarithms, and \( z_0 \) is the bed roughness length (Wilcock, 1996). For turbulent flow over a rough boundary (gravel and cobble streams), \( z_0 = k_s / 30 \) where \( k_s \) is the roughness height (Julian, 1995). In this case, equation 2 takes the same form as the modified Keulegan relation used by Stillwater (2000) for their sediment transport modeling. Roughness height \( (k_s) \) was estimated using the formula \( k_s = 3d_{s4} \), where \( d_{s4} \) is the grain size for which 84% of bed material is finer.

Roughness height \( (k_s) \) was calculated using Wolman pebble count data collected in 2002 between Revenue Bridge (RK 38) and just above I-84 (RK 6). Data suggest that \( d_{s4} \) decreases exponentially from 136 mm at Revenue Bridge to 62 mm near RM 6; thus roughness height \( (k_s) \) decreases from 0.4 m to 0.19 m (Figure 3). These data were in general agreement with Stillwater modeling where roughness was assumed to decrease from 0.4 m at Marmot Dam to 0.25 m at the Columbia River (Stillwater, 2000).

Critical shear stress was estimated using an empirical equation by (Guo, 2002) based on the Shields diagram

\[
\tau_{rc} = \frac{0.11}{Re_*} + 0.054 \left[ 1 - \exp \left( - \frac{4 Re_*^{0.52}}{25} \right) \right]
\]  

(4)

where \( Re^* \) is the particle Reynolds number. Particle Reynolds number in equation 4, is

\[
Re_* = \frac{u_s d_s}{\nu}
\]  

(5)

where \( \nu \) is kinematic viscosity.

ADP data collected during the 2002/2003 winter were transmitted to a laptop in the field for real-time display and quality control and multiple passes were linearly
interpolated at 1-m intervals to create cross-section profiles (Figure 4). Shear stress was estimated using depth and velocity information provided by the ADP and equations 2 and 3. Grain-size associated with incipient motion was calculated by setting $\tau_s = \tau_{sc}$ and solving for particle size.

Additional fine sediment deposition

The additional volume that fine sediment could occupy based on current channel morphology ($V^{*}\text{add}$) was calculated as the pool area for which shear stress was less than critical for a given particle size, times the distance between cross-sections interpolated, summed over the length of the pool. The method was similar to that used to calculate $V^{*}$, except that it used incipient motion criteria to predict how much additional sediment might fit within the cross-section. Estimates of $V^{*}\text{add}$ represent a maximum because sediment deposition would reduce cross-sectional area, thereby increasing velocities needed to convey the same amount of water, which would act as a negative feedback on deposition. Three particle sizes were chosen to represent the median ($d_{50}$) grain size of the lower (fine grained) portion of reservoir deposit, as well as particles one standard deviation above and below the geometric mean ($d_{84}$ and $d_{16}$, respectively) as described by Stillwater (2000).
Beach stratigraphy

To evaluate fine sediment exchange during high discharge events, when field data collection was made difficult by highly transient flow conditions, I emplaced pea gravel in two beaches and measured beach exchange. Surface topography of two high water beaches were surveyed with a Leica total station during the summers of 2004 and 2005. Painted pea gravel (4 mm) was poured into 1.2 m by 10 cm diameter cylindrical holes augured into the level of the beach top to act as a stratigraphic marker and an indicator of the maximum depth of scour. The following summer, beaches were re-surveyed and longitudinal trenches were dug perpendicular to the main river axis for detailed stratigraphic analysis.

Results

Residual pool volumes

Pools on the Sandy River have two different morphologies: forced scour pools, where bedrock or large boulders impinge on downstream flow creating areas of high velocity and turbulence, and regularly spaced plunge pools that do not appear to be associated with a particular forcing mechanism, but are more likely a means of regulating flow energy dissipation. ADP data collected during the summer of 2002 show that the
maximum depth of surveyed plunge pools averaged 1.5 m (n = 7, stdev = 0.27 m) with pool depth never exceeding 2 m. Scour holes, on the other hand, were significantly deeper than plunge pools (p<0.01) with maximum depths averaging 2.4 m (n = 6, stdev = 0.32 m).

Figure 5 shows average measured fine sediment thickness and \( V^* \) plotted on top of Stillwater’s sensitivity test showing channel aggradation with a 10 fold increase in the rate at which fine sediment leaves Marmot reservoir (Stillwater, 2000, Figure 29a). This model run was chosen because it fit most closely with the measured data, because a lahar releases sediment rapidly as opposed to the slow rate exhibited by Stillwater modeling, and because Stewart and Grant (2005) concluded, based on research at Dinner Creek, that Marmot Dam would most likely erode faster than predicted by Stillwater’s basic model runs. Figure 5 shows that scour pools had higher measured \( V^* \) than plunge pools between RK 25 and RK 10, and scour pool fine sediment thickness was greater than predicted by Stillwater’s sensitivity tests. Below RK 10, measured \( V^* \) in plunge pools begins to exceed 15% and average fine sediment thickness is similar to thicknesses

![Figure 5: Stillwater Sciences (2000) figure 29a showing predicted channel aggradation (colored lines) plotted with measured pool-average fine sediment thickness and \( V^* \).](image)
predicted by Stillwater modeling. Below RK 6, field surveys revealed that the channel
bottom transitions from gravel to sand-bedded complicating efforts to measure V* . The
highest V* value (45% of pool volume occupied by fines) was measured a scour pool just
upstream of RK 14 where the channel widens into a broad valley.

**Maximum mobile particle size**

When calculating the maximum mobile particle for each pool at a given discharge,
it was found that mobile particle size varied linearly with discharge (Figure 6). When
the rate of change in mobile particle size with discharge is plotted against distance from
Marmot dam (\( \Delta d / \Delta Q = \text{regression slope in Figure 6} \)), it appeared that the maximum
mobile particle size decreased exponentially with increasing downstream distance.
Plunge pools higher in the system are predicted to move larger sediment sizes at lower
discharges than plunge pools lower in the system, and the rate of change in mobile
particle size with discharge for scour pools appears less than that for nearby plunge pools
(Figure 7).

![Figure 6: Change in maximum mobile sediment size as a function of discharge for 6 sites on the Sandy
River.](image.png)
Additional fine sediment deposition

As shown in Figure 8, the proportion of pool volume subject to further deposition (V*add) is largely a function of discharge unlike measured V* and mobile particle size which varied longitudinally. No difference in V*add was apparent between plunge and scour pools, and sites higher in the system (Rev, Dog) were no less prone to further deposition than those lower in the system, where significant quantities of fine sediment were already present (Stark, RSP). To calculate the relative residence time of additional fine sediment deposition in pools between RK 27 and RK 6, discharge in Figure 8 was replaced with flow recurrence interval (Figure 9). Flow recurrence interval in Figure 9 represents the average time that additional fine sediment could pool volume before discharges exceeded the threshold for entrainment. As shown by Figure 9, 90% of additional sediment deposition would have a mean residence time of less than 4 days.

Based on Figures 8 and 9, additional fine/medium sand (d_{16}) deposition is predicted to affect only 5% of pool volume above 60 cms (2100 cfs). The percentage of pool volume able to mobilize fine/medium sand decreases below this discharge, but even at base flow conditions of 12 cms (400 cfs), V*add is less than 50% and the residence time for 90% of the pool volume is less than 3 days. Coarse sand with a diameter of 0.5 mm
Figure 8: Proportion of current pool volume susceptible to additional deposition ($V^{*}_{\text{add}}$) for three sediment sizes representing the $d_{16}$, $d_{50}$, and $d_{84}$ of the lower fine-grained portion of Marmot reservoir.
(median grain size of the lower reservoir deposit) is less mobile than fine sand, but at 60 cms less than 10% of pool volume could be classified as depositional for most sites. At summer base flow conditions (12 cms) less than 60% of pool volume could be classified as depositional and the mean residence time for 90% of the pool volume is less than 4 days. Fine gravel with a diameter of 4 mm (d_{84} of lower reservoir unit) can occupy no more than about 10% of pool volume at flows exceeding 140 cms (5000 cfs). Below 140 cms, however, fine gravel can deposit in appreciable amounts, approaching 100% of pool volume at flows of 12 cms. At 12 cms, however, 4 mm fine gravel would only be mobile above RK 24.

**Beach stratigraphy**

Total station surveys and stratigraphic analysis show that Beach 1 gained 380 m³ and lost 290 m³ of sand over the 2003/2004 winter, which was a low water year with slightly above-average peak discharges. Erosion and deposition at Beach 1 most likely associated with a single 740 cms (26,000 cfs) storm event in January. On the falling limb of the hydrograph, turbidity in the Sandy River spiked between flows of 300-380 cms. The presence of high quantities of silt in unit J, and the lack of subsequent storm events with flows over 300 cms, suggest that changing hydraulic conditions during the January storm...
eroded part of K before depositing J (Figure 10). Trenching of Beach 2 showed that the introduced tracer was only 6 mm below the current beach surface, and surveys revealed showed no significant change in beach volume. Six different stratigraphic sequences with sharp contacts were noted, but were well below the level of the tracer surface.

Discussion

When Marmot Dam is removed, approximately 750,000 m$^3$ of sediment will be released into the Sandy River. Stillwater Sciences (2000) used a one-dimensional sediment transport model to predict that fine sediment released from the dam will translate into the lower 10 km of the Sandy River, with little deposition upstream (Stillwater Sciences, 2000). Field data from the Sandy River generally support these

Figure 10: Cross-section stratigraphy of Beach 1 showing where unit K eroded into the 2003 beach and deposited sediment that was later truncated by deposition of unit J.
findings, though data show that scour pools between RK 26 and RK 6 already contain large quantities of fine sediment. Sand less than 0.5 mm is predicted to deposit temporarily along pool margins, but fine sediment is unlikely to occupy more than 17% of current pool volume above RK 6 unless flows drop below 50 cms (1800 cfs).

Field surveys of fine sediment in pool bottoms, 1.5 years after a series of lahars released approximately 400,000 m$^3$ of sediment into the Sandy River, revealed that fine sediment occupied only a very small portion of pool volume above RK 23. Between RK 23 and RK 6, fine sediment occupied less than 10% of pool volume for plunge pools but 10-45% of pool volume in scour pools. One explanation for the difference between pool types, is that scour pools are ‘over deepened’. Using equations 2 and 3, we see that shear stress is proportional to the velocity over the natural logarithm of the flow depth

$$\tau_* \sim \left( \frac{U}{\ln(h)} \right)^2$$

(6)

where U is depth averaged velocity and h is flow depth. By continuity, as depth increases the velocity in a pool must decrease which results in decreasing shear stress. Scour pools on the Sandy River are significantly deeper than plunge pools. During periods of high discharge it was observed the bedrock or other obstructions impinging on the flow created significant turbulence. Turbulent exchange can produce very high shear and lift forces over small spatial and temporal scales. I propose that increased turbulence at very high discharges has allowed scour pools to erode deeper pool than they could by shear forces alone. High-suspended sediment concentrations can dampen turbulent exchange allowing fine sediment to deposit until the pool again becomes shear stress limited.

In this study, $V^{*\text{add}}$ was based on post-lahar channel geometry and estimated the potential aggradation laterally and longitudinally within a given pool. $V^{*\text{add}}$ is a static measurement and does not account for changes in pool hydraulics associated with a loss of cross-sectional area, nor does it account for uniform vertical aggradation (which is why it is considered a maximum estimate). Interestingly, while measured $V^*$ and mobile particle size demonstrated strong longitudinal gradients and morphological differences, $V^{*\text{add}}$ did not. Within a given pool, the percentage of pool planform area subject to additional deposition was similar among all pools, reaching a maximum of 18% of pool volume for coarse sand at flows above 50 cms. I expected that pools lower in the system would be subject to greater additional sediment deposition than pools higher in the system. The lack of a longitudinal gradient in $V^{*\text{add}}$ may suggest that accommodation space for fine sediment was already occupied when the surveys were taken (as suggested
by measured $V^*$). The Sandy River carries a naturally heavy sediment load and accommodation space within the valley bottom is limited.

**Conclusions**

In this paper, I present a technique for estimating likely depositional volumes based on simple shear stress criteria. Because data were collected over relatively short time periods relative to the time-variable nature of discharge and sediment transport on the Sandy, it remains difficult to know whether conditions captured in this study were transient or represented a relatively stable state. Unfortunately, given the large spatial domains of interest, establishing baseline conditions requires long-term monitoring not afforded by this study. Of the generalizations that can be made, the strongest may be that dam removal in an energetic river with high native sediment loads may not result in abnormally high sedimentation downstream because much of the accommodation space may already be filled.
As time progresses and dams continue to age, managers and policy makers are increasingly forced to re-evaluate costs and benefits associated with dam infrastructure. Thanks to State and National Environmental Policy Acts (SEPA & NEPA), cost/benefit analyses now include environmental analyses of all proposed actions, whether they involve continued operation, maintenance, or removal. While much is known about the environmental impacts of dams, our knowledge of dam removal affects is generally insufficient to predict impacts associated with any given dam removal. Just as the impacts associated with dam operation vary by region, type of operation, and geomorphic and ecological contexts; so too will the impacts associated with dam removal. Mountain river dams whose reservoirs have filled with sediment represent just one subset of dam types and settings.

Based on previously published research, I developed a conceptual framework for predicting patterns and processes of reservoir erosion and downstream deposition following dam removal. Using this framework, I tested a number of hypotheses relating to the removal of mountain river dams whose reservoirs have filled with sediment. As predicted by the conceptual model, Dinner Creek and Maple Gulch reservoirs eroded by knickpoint migration following dam removal. Sediment yields did not scale with time since removal or discharge, but instead appeared to be threshold driven making the use of diffusion type sediment transport models inappropriate. Coarse sediment (gravel) deposited as a diffusional wave, though riffles were more likely to aggrade than pools. At Dinner Creek, gravel deposition was greatest along the channel thalweg and changed channel morphology from plane-bed to pool-riffle. Alternate bars on the outside of the bed acted to straighten the channel as predicted by minimization of stream power theory, though there is no evidence that stream power minimization was the cause.

Dam removal initiates a cascade of processes that develop complex responses with primary, secondary and tertiary effects. Primary effects exhibited in this study include changes in channel morphology caused by sediment erosion and deposition. Secondary impacts included changes to hyporheic exchange and stream temperature. As predicted by our conceptual model of hyporheic exchange, fine sediment intrusion into the bed acted to reduce hyporheic exchange, while the creation of bedforms and deposition of coarse gravel increased hyporheic exchange. Increased hyporheic exchange simultaneously decreased diurnal temperature fluctuations as predicted, because
hyporheic zones act as stream temperature buffers. How long these changes persisted was not determined, nor was it possible to test assumptions regarding causal mechanisms. These remain interesting avenues for future research.

Changes to macroinvertebrate community composition were documented in association with reservoir sediment deposition, a tertiary effect. The removal of a small, sediment-filled dam in a mountain river had little impact on aquatic ecology because the dam had little ability to alter stream temperature, flow, or sediment transport regimes. Changes in water quality associated with dam deconstruction, including an increase of pH, had no detectable affect on macroinvertebrate populations. As predicted, sediment deposition from winter storms significantly decreased macroinvertebrate density, which recovered relatively quickly. Long-term changes in macroinvertebrate taxa richness were not predicted, and were most likely the result of altered stream conditions, including changes to the hyporheic zone and stream temperatures. The reduced taxa richness found downstream of the dam two years after removal is not likely due to a lack of recolonizing species, but rather a change in the physical habitat.

Dam removal research is aided by the fact that it is a management activity whose potential consequences can be evaluated and planned for. Reference data can be collected prior to activity, and in many cases early enough to establish base-line conditions. For example, the planned removal of Marmot Dam in 2007 on the Sandy River enabled me to establish baseline surveys and to make predictions regarding the fate of fine sediment following dam removal. Given the lack of a ‘reference’ condition against which field data could be compared, I used 1D modeling by Stillwater Sciences as my reference condition and found that the longitudinal changes fine sediment depth for plunge pools following the series of lahars fit modeling predictions for fine sediment aggradation following dam removal. Shear stress measurements and beach surveys suggested that the Sandy River had little additional space for fine sediment. Until Marmot Dam is removed in 2007, we will not know whether reservoir sediment erodes as a rotating knickpoint, as modeled by Stillwater Sciences, or conforms to the conceptual model for mountain river dams. Additional research on pool volumes in the Sandy prior to dam removal would provide a better set of baseline conditions against which dam removal effects could be evaluated, but the data collected on the Sandy will serve as a useful reference regardless.

This dissertation does not represent an attempt by me to census mountain river sediment-filled dam removal effects. For example, important issues relating to impacts on fish, riparian condition/function, and nutrient dynamics are not addressed here and
would benefit from studies specific to those issues. Dam removal affects rivers through a cascade of processes that are generally beyond the capacity for one person to resolve. Rather, dam removal studies would benefit from multidisciplinary efforts. It is time to expand our conceptual understanding of river and ecological processes and differences by developing dam removal case-lore over a range of dam sizes, operational regimes, and geomorphic and ecological settings.

Dams are built as for a variety of reasons including flood control, power generation, water diversion, and recreation to name a few. While of tangible benefits that dams provide decrease through time, their symbolic and historical generally do not. Dams are symbolic structures and for this reason, if no other, the decision to remove a given dam will generally be driven by policy as much as science. Our roll as scientists is to make sure that managers and policy makers have the best and most complete information available on the impacts associated with each of their management options.
BIBLIOGRAPHY


