7 The Remains of the Dam: What Have We Learned from 15 Years of US Dam Removals?

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Abstract
Important goals for studying dam removal are to learn how rivers respond to large and rapid introductions of sediment, and to develop predictive models to guide future dam removals. Achieving these goals requires organizing case histories systematically so that underlying physical mechanisms determining rates and styles of sediment erosion, transport, and deposition are revealed. We examine a range of dam removals predominantly in the western US over the last decade, and extract useful lessons and trends that can be used to predict the response of rivers to future removals.

Keywords
Dam removal • Sediment • Transport • Erosion • Deposition • Reservoir

7.1 Introduction

Over the past 15 years, dam removal has evolved from a radical idea to an established approach for restoring geomorphic and ecologic function of rivers. In the United States in particular, dam removal has become a widespread technique for removing obstructions to fish migration and sediment transport, restoring normative flow and temperature regimes, and reconnecting upstream and downstream river reaches. Almost 1,000 dams have been removed in the U.S. in the past 100 years, with over half of these removals occurring in the last 10 years (Service 2011). Most dams removed are generally less than 15 m high, although recently some larger dams up to 70 m high have been removed (Doyle et al. 2003b; Sawaske and Freyburg 2012).

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Our scientific knowledge of how rivers respond to dam removal is expanding rapidly. Most scientific studies have focused on the sediment-related effects of individual dam removals, including detailed case studies in Oregon (Stewart and Grant 2006; Major et al. 2012; Walter and Tullos 2010), and across the Midwest and Northeast (Sawaske and Freyberg 2012). While findings from individual dam removals have been synthesized into broader and more generalized trends, most syntheses have described sediment evacuation from upstream reservoirs, with less attention given to how the rivers processed the sediment released downstream.

7.2 A Coupled Upstream/Downstream System

Dam removal intrigues river engineers and fluvial geomorphologists because it represents a coupled upstream/downstream problem of erosion, transport, and depositional fate of sediment. Removing a dam lowers the base level of the river upstream of the dam, increasing the hydraulic gradient through the former reservoir and subjecting sediments stored in the reservoir to fluvial erosion and entrainment. The style of resulting erosion depends in part on the style and rate of removal. Small dams whose reservoirs are full of sediment

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are often removed rapidly, instantly creating a knickpoint at the former dam crest. This knickpoint subsequently incises upstream through the stored sediments, typically downcutting and widening its channel as it proceeds upstream (Doyle et al. 2003a; Stewart and Grant 2006; Downs et al. 2009; Major et al. 2012). If the dam is removed in stages, typically because the dam is large or the reservoir is only partially filled with sediment, the removal of each stage or horizontal level of the dam lowers base level a corresponding increment. With reservoirs partially filled with sediment this lowered base level initiates reservoir drawdown and reactivation of the upstream sediment delta that typically forms where the upstream river enters the reservoir (Bromley et al. 2011). As the reservoir level continues to lower, delta progradation proceeds downstream, transporting and redepositing sediment along the reservoir length until the ever-diminishing dam crest is reached. This progradation also results in grain sorting of the stored and re-entrained sediment, with fine sediment released into the water column as suspended load, which is exported before the coarser bedload fraction reaches the crest of the lowered dam.

In case of either knickpoint retreat or delta progradation, the volumetric flux and grain size of sediment exported from the reservoir, determines the downstream response below the former dam site. Key upstream questions are how much sediment of what grain size will be eroded, what processes are responsible, and how fast will it be exported. Key downstream questions include how far the different grain sizes of exported sediment will be transported under what hydrologic conditions, where will it be deposited, and what effect will it have on channel morphology. While numerical and physical models have shown very encouraging results in addressing these complex questions (e.g., Grant et al. 2008; Cui and Wilcox 2008; Downs et al. 2009), most removals will not have access to these sophisticated approaches. Here we present empirical results useful in anticipating the consequences of dam removals.

The volume of sediment released due to dam removal is a first order control on the downstream response. Up until 2006, most of the dams removed were small and the sediment available for release during any dam removal was less than 10^5 m^3 (Fig. 7.1). Recently, sediment available for release following dam removal has exceeded that by two orders of magnitude, with the largest release to date associated with removal of Glines Canyon and Elwha Dams on the Elwha River in Washington State. Prior to this, virtually all removals involved either pre-removal excavation of stored sediment, or rapid removal of the structures, releasing sediment that had entirely or mostly filled the reservoirs. The Elwha removals involve staged, progressive dam lowering, and reservoirs partially filled with sediment.

7.3 Upstream Reservoir Erosion

We explore controls on rate and style of upstream reservoir erosion, specifically what controls how much sediment is removed over what time period. We utilize a recent synthesis of data from 12 small dam removals across the US (Sawaske and Freyburg 2012), and supplement their Fig. 7.5b with data from 4 additional dam removals: Condit, Savage Rapids, Elwha, and Glines Canyon (Fig. 7.2). In the most general terms, the sediment flux rises rapidly to an asymptote that ranges from less than 10 % to greater than 70 % of the initial sediment stored in the reservoir.

If we group the data by the style of removal (staged versus instantaneous) and the predominant grain size of the stored material (cohesive sediments, saturated fines, sand, gravel), several patterns emerge. First, the slowest erosion rates accompany staged removals. This is consistent with downstream process of delta progradation that moves more slowly than knickpoint retreat. After 10 years, only 10 % of the sediment stored behind the former Stronach dam in Michigan has been eroded (Burroughs et al. 2009). Among the rapid dam removals, the least volumes of stored sediment were eroded when the material was predominantly cohesive fines and clays; eroded volumes represent only 10 % of the initial stored sediment even a year after removal. Reflecting the fastest erosion rates were saturated deposits of non-cohesive fine sediment at Condit Dam that failed catastrophically

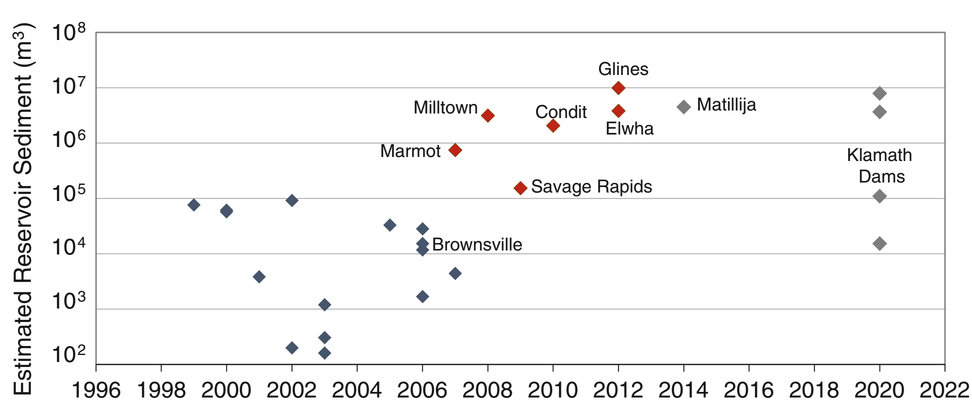


Fig. 7.1 Estimated reservoir sediment stored behind selected dams prior to removal. (Major et al. 2012; unpublished data)

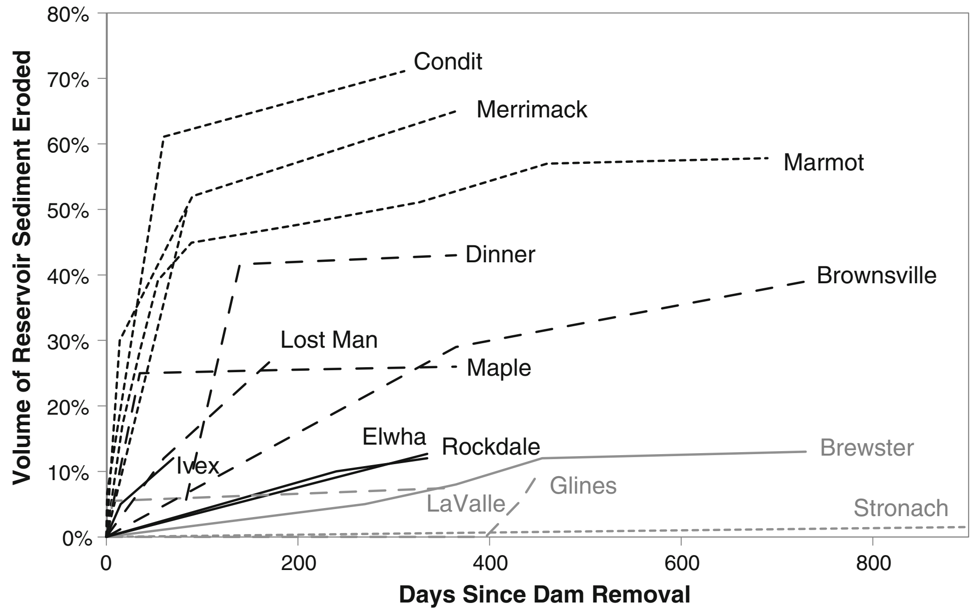


Fig. 7.2 Patterns of sediment evacuation after staged (*gray shading*) or rapid (*black lines*) dam removal. General sediment size and cohesiveness is indicated by *line* type as follows: *Solid* cohesive, fine sediments, *long dash* gravel, *short dash* >55 % sand. (O'Connor et al. 2001; Sawaske and Fryburg 2012; Stewart and Grant 2005; Walter and Tullos 2012)

during the rapid drawdown of the lake following instantaneous removal (O'Connor et al. 2012). Extraordinarily high sediment flux transformed the river itself into a hyperconcentrated mudflow. Sediment erosion rates for non-saturated sands and gravels fall somewhere in the middle. Erosion rates were faster where sands comprised >55 % of the material compared to where the material was primarily gravel, suggesting that for non-cohesive, non-saturated sediment, the finer the material the faster the erosion rate.

There is evidence that erosion rates are not especially sensitive to flow magnitude and sequence, although the data are too sparse to answer this question definitively. Removal of Marmot Dam in Oregon was during relatively low flow conditions, yet approximately 20 % of the stored reservoir volume of sand and gravel was eroded in the first 48 h (Major et al. 2012). Winter flows in the first year after removal were less than half of the mean annual flood, yet eroded approximately 50 % of the reservoir sediment. Higher flows the following year increased cumulative total reservoir erosion to 63 %, indicating diminishing effectiveness despite increasing flow magnitudes. Had those higher flows happened earlier, Major et al. (2012) suggest that the same endpoint of total reservoir erosion would have been reached, only sooner.

7.4 Downstream Geomorphic Response

Sediment eroded from reservoirs is subsequently transported through river reaches downstream of the former dam site. The character, magnitude, and spatial distribution of downstream geomorphic response to the removal is determined by the style of transport and deposition of the reservoir sediment. At Marmot Dam, a detailed sediment budget was constructed to account for sediment released during removal (non-cohesive sand and gravel) and track its downstream progress (Major et al. 2012). One broadly applicable finding is that fine and coarse sediments have different fates. The fine sand fraction was transported many 10s of kilometers downstream and out of system without leaving a clear morphologic signal or response; most of the coarse fraction of gravel and cobbles was only transported several kilometers before being redeposited, resulting in bed aggradation of more than 3 m. The broad characteristics of these different behaviors are captured by current mixed-grain size transport models.

This critical question of how far downstream will the sediment be transported relates to both the volumetric flux out of the former reservoir (i.e., sediment supply) and the river's transport capacity; the grain size distribution is also a factor as noted above. To begin to tie these factors together, we developed a dimensionless ratio E*:

$$E^* = \frac{V_R F_A}{V_A}$$

where V_R is total sediment volume or mass stored in the reservoir (m^3 or tons), F_A is fraction of reservoir volume eroded in first year and V_A is background annual sediment flux (m^3 or tons). E* expresses the annual amount of sediment eroded from a former reservoir in relation to the background (pre-dam or pre-removal) annual sediment flux for the river where the dam was located (Fig. 7.3).

We explore the utility of E* as a means of predicting patterns of downstream sediment transport, using a subset of recent dam removals (Fig. 7.3). Examining downstream transport distances, defined by field evidence of either

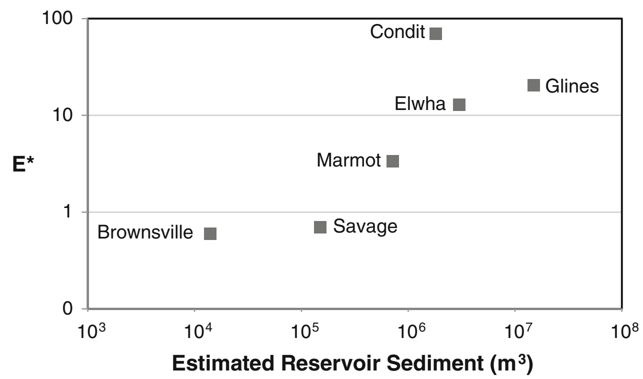


Fig. 7.3 Fraction of stored sediment eroded in the first year after dam removal relative to the background sediment flux (E*) for selected recent dam removals in the Pacific Northwest

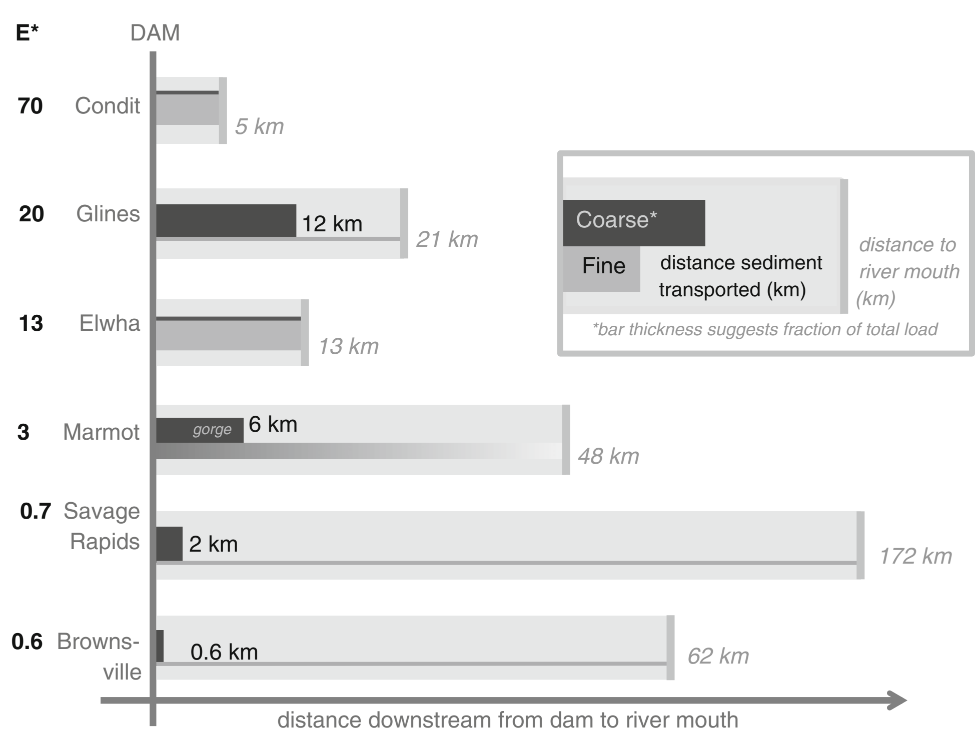
deposition (coarse) or transport (fine) for coarse and fine fractions of eroded sediment for sites arrayed by first-year E* values reveals several interesting patterns (Fig. 7.4). First, E* does a better job of predicting the distance that coarse sediment travelled than fine sediment. Fine sediment was transported far downstream of the dam removal site as suspended load. Second, transport distance for coarse fractions in the first year proceeds more or less linearly with E*. Condit appears an outlier to this trend because the downstream reach of river is only 5 km long before it enters the much larger Columbia River, where the sediment signal no longer traceable. Transport distances for coarse sediment will likely increase in subsequent years.

7.5 Lessons Learned

In the past 15 years, the science of predicting geomorphic response of rivers to dam removal has improved significantly. While this paper has only touched on some of the more salient lessons, several points stand out that may be useful to guide future removals. The case lore has given us a dramatically improved understanding of controls on the tempo and style of both upstream reservoir erosion and downstream fate of sediment. These can be viewed in terms of hierarchies of control on key geomorphic processes. For upstream reaches, key controls in order of decreasing influence on the rate and volume of sediment eroded are: (1) how the dam is removed (quickly or slowly); (2) whether the stored material is cohesive or non-cohesive; and (3) the overall grain size of the deposit (coarse or fine). The sequence of flows after dam removal may be important in determining the rate and timing of sediment efflux but is unlikely to control the total volume of reservoir sediment eroded.

For downstream reaches, the key controls on the fate of eroded and transported sediment are: (1) the grain size of the sediment (coarse or fine); and (2) the volume of sediment delivered from upstream relative to the river's capacity to transport sediment (E^*). An additional control not captured by E^* is the longitudinal profile and morphology of the downstream channel in terms of variations in opportunity to transport or store sediment. Overall, we've learned that the volume and grain size of the eroded sediment strongly

Fig. 7.4 Approximate transport distances for sediment released following dam removal for both fine and coarse fractions. Sites are organized from *top* to *bottom* by decreasing first-year calculated E^*. *Bar* thickness represents relative fraction of each grain size class in the initial reservoir deposit. (O'Connor et al. 2001; Sawaske and Fryburg 2012; Stewart and Grant 2005; Walter and Tullos 2012; unpublished data)



dictate the downstream channel response. The volume, in turn, is closely related to how the dam is removed.

Dam removals represent a full-scale, real-time experiment on how rivers respond to changes in sediment supply and base level. These case studies of dam removals provide a growing empirical database where the range of fluvial responses can be observed, hypotheses proposed and tested, and numerical and physical models validated. All of these complimentary approaches—empirical, numerical, and physical—are creating a predictive framework that can guide future dam removals, and help river managers predict the consequences on river resources.

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