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Geomorphic Responses to Dam Removal in the United States – a Two-Decade Perspective

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13.1 Introduction

In the past few decades there has been increasing popular and political momentum in the United States to remove dams. What began with removal of small dams impounding modest sediment volumes has progressed to removal of large dams impounding millions of cubic meters of sediment. The reasons for removal are varied, but commonly relate to diminished function, costly maintenance, concerns over safety, and to acknowledgment that dams impair fish passage and other ecosystem functions and services (e.g., Babbitt 2002; Poff and Hart 2002; O'Connor, Major, and Grant 2008; Service 2011; Lovett 2014). However, decisions to remove dams are clouded by uncertainties over potential environmental benefits and detriments of removal. Concerns and uncertainties surround sediment release especially (e.g., Downs *et al.* 2009). Although a number of small (<10 m tall) and a few tall (≥10 m) dams had been removed by the early 2000s (e.g., Bednarek 2001; Hart *et al.* 2002; Poff and Hart 2002; Pohl 2002, 2003; Bellmore *et al.* 2015, 2016), there were few detailed studies of geomorphic responses to those removals from which to draw conclusive insights. As a result, hypotheses regarding potential geomorphic responses of river systems to dam removal in the 1990s and early 2000s were drawn largely from analogies and concepts of fluvial geomorphology (Doyle, Stanley, and Harbor 2002; Pizzuto 2002). Since then, newer physical and numerical models that simulate channel evolution in reservoirs and downstream distributions of eroded sediment have sharpened insights on possible river responses (e.g., Cantelli *et al.* 2007; Cui and Wilcox 2008; Grant *et al.* 2008; Downs *et al.* 2009; Greimann 2013; Podolak and Wilcock 2013; Ferrer-Boix, Martín-Vide, and Parker 2014; Gartner, Magilligan, and Renshaw 2015). Furthermore, a number of detailed field studies have now examined responses to dam removal (Bellmore *et al.* 2015; Table 13.1). As a result of these more recent modeling and field studies, we are positioned to test the veracity of posited hypotheses regarding geomorphic responses to dam removals. And as the number of post-removal field studies has grown, we can assess whether common responses have emerged. Understanding outcomes of dam removals has a broader context than simply helping dam owners and stakeholders make decisions. Better knowledge of how river systems respond to sediment pulses introduced by dam removals informs assessments of hazards from natural dam failures; sediment injections from natural processes such as landslides (Hoffman and Gabet 2007), wildfires (Shakesby and Doerr 2006), and volcanic eruptions

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Table 13.1 Dam removals and failures studied in detail between 1990 and 2015.

Dam (State)	River	Height (m)	Reservoir sediment volume (m^3)	Sediment composition*	Removal strategy†	Sources
Brownsville (OR)	Calapooia	2–3	10 000–15 000	Gravel	Sudden	Walter and Tullos (2010); Kibler, Tullos, and Kondolf (2011); Tullos, Finn, and Walter (2014)
La Valle (WI)	Baraboo	~2	140 000	45% sand, 40% silt, 15% clay	Sudden	Doyle, Stanley, and Harbor (2003); Greene, Krause, and Knox (2013)
St. John (OH)	Sandusky	2.2	200 000	Gravel, sand	Sudden	Cheng and Granata (2007)
Brewster (IL)	Brewster Creek	2.4	18 000	70%–99% silt and clay	Phased	Straub (2007)
Secor (OH)	Ottawa	2.5	5000–9000	Sand	Sudden	Harris (2008); Harris and Evans (2014)
Manatawny (PA)	Manatawny Creek	2.5	Uncertain; mostly dredged	Sand, gravel	Phased	Bushaw-Newton *et al.* (2002); Skalak *et al.* (2011)
Simkins (MD)	Patapsco	3	67 000	Sand, fine gravel	Sudden	MJ Collins (unpublished data)
Rockdale (WI)	Koshkonong	3.3	287 000	35% sand, 45% silt, 20% clay	Sudden	Doyle, Stanley, and Harbor (2003)
Anaconda (CT)	Naugatuck	3.3	11 900	Sand, gravel	Sudden	Wildman and MacBroom (2005)
Stronach (MI)	Pine	3.6–5	800 000	70% sand, 30% gravel	Phased	Burroughs *et al.* (2009)
Munroe Falls (OH)	Cuyahoga	3.7	Uncertain	70% sand, 20% mud, 10% gravel	Phased	Rumschlag and Peck (2007); Peck and Kasper (2013)
Homestead (NH)	Ashuelot	4	Uncertain	Sand	Sudden	Gartner, Magilligan, and Renshaw (2015)
Merrimack Village (NH)	Souhegan	4	62 000	95% sand	Sudden	Pearson, Snyder, and Collins (2011); Santaniello, Snyder, and Gontz (2013)
IVEX (OH)	Chagrin	7.4	236 000	Mud	Sudden	Evans *et al.* (2000); Evans (2007)
Savage Rapids (OR)	Rogue	12	150 000	70% sand, 30% gravel	Sudden	Bountry, Lai, and Randle (2013)
Milltown (MT)	Clark Fork	12.8	5.5 million‡	Sand	Sudden§	Evans and Wilcox (2014)
Marmot (OR)	Sandy	15	750 000	~50% gravel, 50% sand	Sudden	Major *et al.* (2012)
Elwha (WA)	Elwha	32	4.9 million	47% mud, 53% sand and gravel	Phased	Randle *et al.* (2015); Warrick *et al.* (2015)
Condit (WA)	White Salmon	38	1.8 million	60% sand, 35% mud, 5% gravel	Sudden	Wilcox, O'Connor, and Major (2014); Colaiacomo (2014)
Barlin (Taiwan)	Dahan	38	10.5 million	Gravel, sand	Sudden	Tullos and Wang (2014)
Glines Canyon (WA)	Elwha	64	16.1 million	44% mud, 56% sand and gravel	Phased	Randle *et al.* (2015); Warrick *et al.* (2015

* Mud is combined silt and clay (< 0.063 mm).

† Full base-level fall was achieved within minutes to days in sudden removals, and weeks to years in phased removals.

‡ Approximately 40% of this sediment was excavated before breaching as part of Superfund remediation efforts.

§ Part of the infrastructure was removed in phases while contaminated sediment was excavated. However, sediment release owed to sudden breaching of the remaining remnants of the dam.

(Pierson and Major 2014); behavior of legacy sediment (James 2013; Merritts *et al.* 2013); and restoration activities such as gravel augmentation (Sklar *et al.* 2009).

More than 87 000 dams taller than 1.8 m have been catalogued in the United States (Figure 13.1; US Army Corps of Engineers 2013), and more than 1100 have been removed intentionally – most since 2000 (American Rivers 2014). Since the early 2000s, intentional dam removals and some unintentional failures have released varying magnitudes of diversely composed sediment to river systems. Removed dams have been as tall as 64 m (Figure 13.2a) and have impounded sediment volumes ranging from a few thousands to several millions of cubic meters (Figure 13.2b). Stored sediment compositions have ranged from predominantly mud (≤0.063 mm) to predominantly gravel (Table 13.1). During some removals, stored sediment was released abruptly when the full barrier height of a dam was breached suddenly; in others, sediment was released more slowly as base-level changed gradually during phased removal of a dam.

Generally, effects of dam removals have been site specific, but an analysis of about 20 well-studied removals (Table 13.1) reveals common patterns and controls on geomorphic response. The removals examined, however, are geographically limited. They are distributed unevenly, mostly in the northern and eastern United States, and all but one large-dam removals are in the Pacific Northwest (Figure 13.1). They are mainly run-of-river structures that passed water freely over their crests (Csiki and Rhoads 2010) or impounded small to moderate reservoir pools (≤30 million m^3; Randle *et al.* 2015). Absent are removals of dams that stored very large volumes of water, that markedly altered flow, or that impounded large volumes of mostly mud. Here, we discuss patterns of and controls on geomorphic response within a contextual framework of volume and composition of stored reservoir sediment, style and rate of dam removal, processes eroding sediment from the reservoir upon dam breaching, and river hydrology during and after dam removal. Our analysis encompasses sandy alluvial and bedrock river systems in addition to those that are gravel-bedded. We conclude by summarizing common findings that have emerged from these studies.

13.2 Reservoir and Downstream Channel Responses to Dam Removal

Variations among physical settings, dam characteristics, and removal strategies have led to widely varying channel responses after removals. Common to most removals, however, is a coupled-system response of reservoir erosion and downstream sediment transport and deposition. But the rates and processes by which this coupled system operates vary among settings.

13.2.1 Reservoir Erosion

Trajectories of reservoir erosion and channel development following dam removal have been posited to follow conceptual channel-evolution models describing response to base-level fall. Doyle, Stanley, and Harbor (2002) proposed a multistage model that describes a spatial and temporal evolutionary sequence in which channel initiation begins at the dam site and migrates upstream through the reservoir. Initially, a narrow channel starts incising after reservoir water has drained. Channel-incision owing to headcut (a near-vertical step change in channel profile), knickpoint (a width-limited abrupt inflection in channel profile), or knickzone (a nearly channel-spanning abrupt inflection in channel profile) migration proceeds upstream. Channel widening owing to mass-wasting of channel banks follows incision. An aggradational stage of development follows this degradational stage as upstream erosion delivers and deposits abundant sediment to the downstream reach of reservoir. The aggradational stage promotes continued channel widening, but at a diminishing rate. As rates of sediment

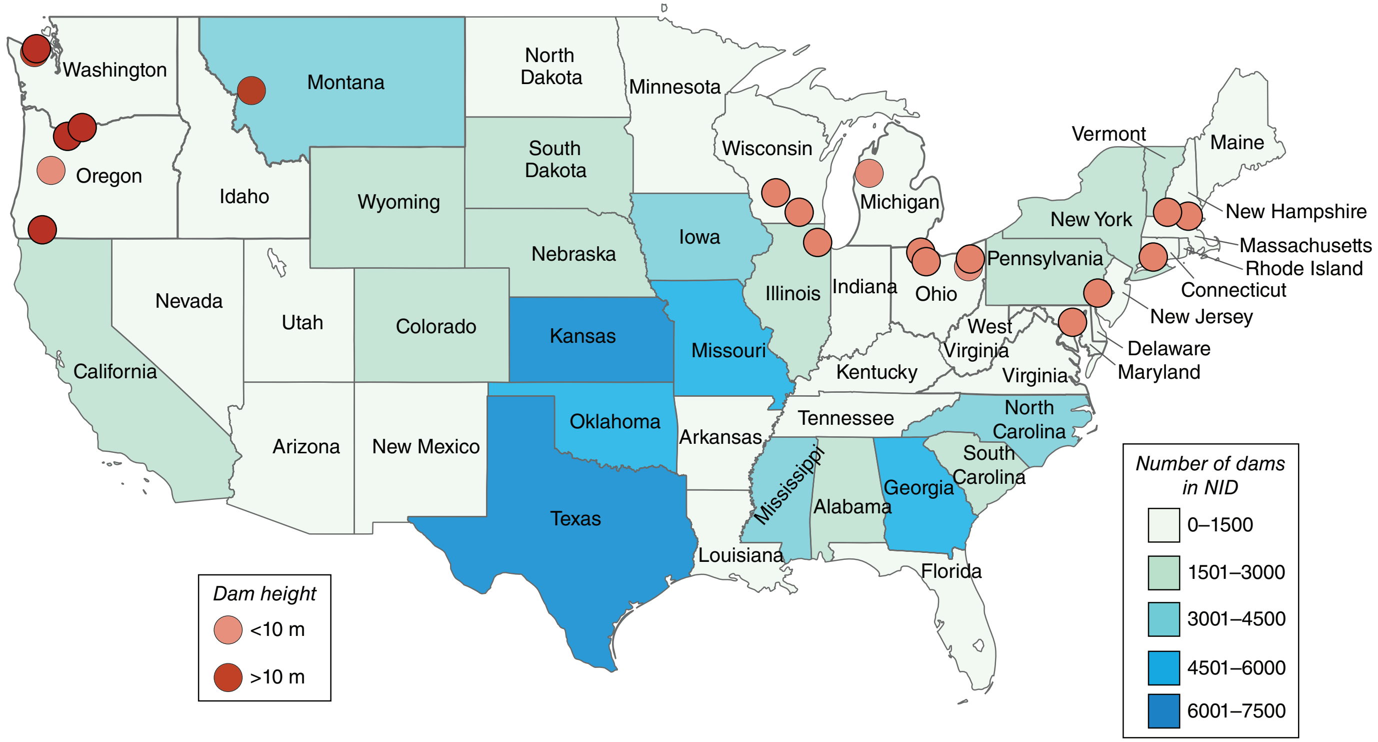

Figure 13.1 Map of United States showing the number of dams in each state catalogued by the US Army Corps of Engineers (2013) National Inventory of Dams (NID). Circles (color coded by threshold of dam height) show the geographic distribution of dam removals that inform this chapter (see Table 13.1).

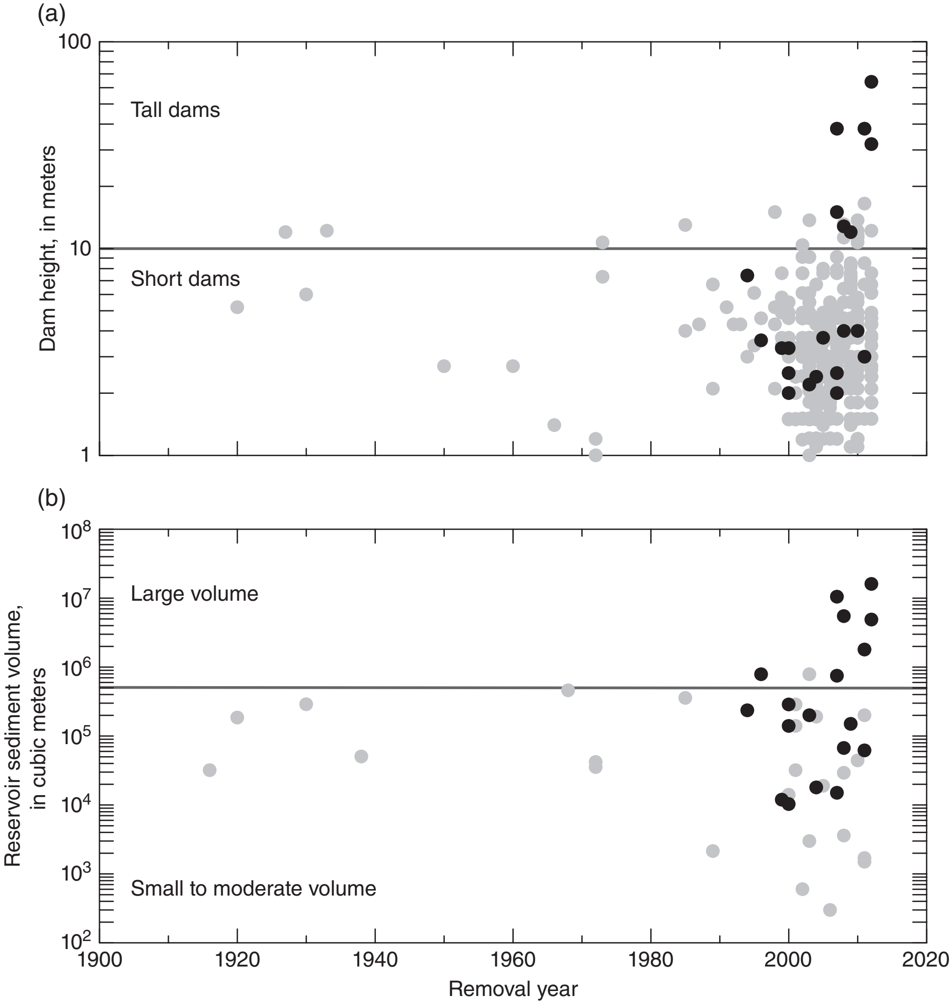

Figure 13.2 Dam height and impounded sediment volumes of documented dam removals (American Rivers 2014; Bellmore *et al.* 2015). Black circles show dam removals that inform this chapter (see Table 13.1).

delivery and aggradation decline, vegetation colonizes a newly developed floodplain, the channel stabilizes, and a new equilibrium condition establishes.

The proposed channel-evolution model generally describes conditions observed in reservoirs filled with sediment following sudden removal of a dam. In many instances, particularly when reservoir sediment was coarse grained (sand and gravel), erosion trajectories and channel development after dam removal progressed through several of the proposed stages very rapidly, especially when full base-level fall from reservoir elevation to downstream channel was sudden (e.g., Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Collins *et al.* 2014; Wilcox, O'Connor, and Major 2014). Channel widening may involve mass wasting, but in coarse, cohesionless fill nearly continuous raveling rather than discrete mass wasting may also feed bank sediment directly to the channel. Erosion of filled reservoirs composed of abundant fine sediment (sand and mud) can proceed through the proposed stages rapidly, or it can proceed slowly owing to tempered headcut or knickpoint migration, which limits the rate of stage progression. Incision through fine sediment commonly leads to mass wasting (e.g., Evans *et al.* 2000; Doyle, Stanley, and Harbor 2003; Wilcox, O'Connor, and Major 2014). In some instances, aggradation of the lower reservoir reach owing to input of sediment from upstream may have contributed to channel widening (e.g., Bushaw-Newton *et al.* 2002; Doyle, Stanley, and Harbor 2003; Cheng and Granata, 2007), but mostly it did not.

Erosion and channel development in partly filled reservoirs can proceed as proposed if there is little longitudinal variation in sediment transport. Otherwise, sediment eroded from the upstream part of the reservoir can be mostly redeposited in the downstream part without advancing past the dam site (e.g., Cheng and Granata 2007; Randle *et al.* 2015). Redistribution of sediment can occur when a reservoir contains little sediment or is influenced by grade control (e.g., Bushaw-Newton *et al.* 2002; Cheng and Granata 2007; Skalak *et al.* 2011; Greene, Krause, and Knox 2013; Gartner, Magilligan, and Renshaw 2015), or when a dam is removed in phases and retains a gradually dwindling pool. For example, phased removals of Elwha and Glines Canyon dams, Washington, triggered upstream erosion and delta progradation across reservoir widths before pool water was fully released (Randle *et al.*, 2015). Delta progradation led to wide, braided reaches within the reservoirs. Only after bedload sediment began passing the vestige of Glines Canyon Dam did the channel through its reservoir become narrowly incised and begin delivering substantial amounts of sediment downstream (Magirl *et al.* 2015; Randle *et al.* 2015).

Trajectories of reservoir-channel evolution can be modified by unexpected changes in boundary conditions. New boundary conditions after dam removal can result from sediment coarsening with depth, especially in gravel-rich reservoirs, or from exhumed bedrock, wood, or man-made structures. These roughness elements can limit bed erosion and affect channel development. Coarsening of the reservoir channel bed following breaching of Marmot Dam (Oregon) – from bed winnowing and exposure of coarser gravel at depth – rapidly slowed the rate of incision (Major *et al.* 2012). After breaching of Condit Dam (Washington), erosion exhumed a 4.5-m-tall timber-crib cofferdam that halted local channel incision until it was removed manually several months later (Wilcox, O'Connor, and Major 2014). Similarly, a timber-crib structure exhumed behind Brownsville Dam (Oregon) limited the rate and extent of channel incision (Zunka, Tullos, and Lancaster 2015). Reservoir erosion behind Secor Dam (Ohio) exposed a buried beaver dam that temporarily stalled knickzone migration (Harris and Evans 2014). Large wood as well as bedrock exhumed behind Merrimack Village Dam (New Hampshire) affected reservoir erosion and channel evolution (Pearson, Snyder, and Collins 2011). And an erosion-resistant reach of boulders exhumed behind Homestead Dam (New Hampshire) acted as a grade control that prohibited knickpoint migration, and thus limited channel incision (Gartner, Magilligan, and Renshaw 2015). There, altered boundary conditions also largely decoupled bed incision and bank erosion during evacuation of reservoir sediment.

Reservoir geometry can affect rates and magnitudes of sediment evacuation. In several reservoirs having small aspect ratios (width/length) or in those where lateral erosion could swing unobstructed, erosion rapidly evacuated large percentages (≥40%) of impounded sediment after full base-level fall was achieved (Figure 13.3) (e.g., Wildman and MacBroom 2005; Epstein 2009; Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Sawaske and Freyberg 2012; Bountry, Lai, and Randle 2013; Wilcox, O'Connor, and Major 2014; Collins *et al.* 2014; Warrick *et al.* 2015). By contrast, for reservoirs in which lateral erosion and landslides were limited, transport capacity diminished longitudinally, or the rate of base-level fall was strongly moderated, the rate and quantity of sediment evacuation were also limited (e.g., Evans *et al.* 2000; Doyle, Stanley, and Harbor 2003; Cheng and Granata 2007; Straub 2007; Burroughs *et al.* 2009).

In nearly all removals, erosion increased channel gradient through the impoundment reach. Gradually that gradient approximated the pre-dam gradient (e.g., Burroughs *et al.* 2009; Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Wilcox, O'Connor, and Major 2014). In the absence of lateral

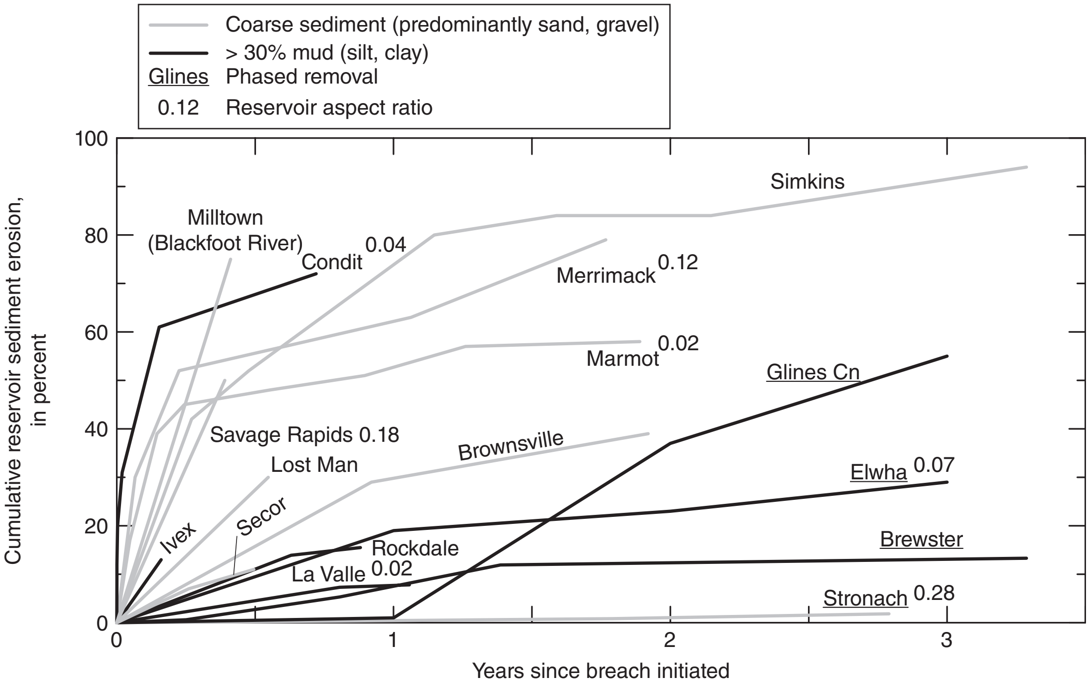

Figure 13.3 Percentage of reservoir sediment eroded with time since dam removal. Numbers near dam names indicate reservoir aspect ratio (width-to-length). The great increase in erosion at Glines Canyon Dam during the second year after removal began largely reflects final loss of pool water and release of bedload past the remnant structure. Through the first year after removal began, eroded sediment was mostly redeposited in a delta that prograded across the partly filled reservoir. (Original plot by Sawaske and Freyburg (2012); this version adapted from Grant and Lewis (2015).)

erosion, landslides, or large floods that can access remnant sediment, approximation of the pre-dam gradient limits the amount of reservoir sediment that can be evacuated. In cases where a reservoir reach contains little sediment, where dam removal is incomplete or has been replaced with grade-control, where negative transport gradients exist, or where conditions cause sediment redistribution rather than evacuation, reservoir profile change may be limited and renewed deposition may be induced (e.g., Cheng and Granata 2007; Skalak *et al.* 2011; Greene, Krause, and Knox 2013; Gartner, Magilligan, and Renshaw 2015).

13.2.2 Downstream Deposition

Abrupt increases in sediment delivery, even during phased removals, produce downstream effects of varying spatial and temporal extent. Downstream effects typically include channel aggradation; changes in channel gradient, width, and bed texture; filling of pools; and formation or modification of channel bars; some of these channel modifications are persistent, others are transient. In many cases, the greatest sediment impacts were close to dam sites, but varying channel morphology, volume and caliber of released sediment, and sediment delivery processes can extend or suppress sediment effects in the downstream direction.

13.2.2.1 Spatial Extents of Sediment Impacts

Spatial gradients in transport capacity owing to variations in channel slope, size and size-distribution of released sediment, and river hydrology affect sediment deposition and thus the spatial extent of sediment impact (e.g., Cui and Wilcox 2008; Gartner, Magilligan, and Renshaw 2015). Commonly, sand and finer sediment travel farther downstream than does gravel (Figure 13.4). In general, the greater and coarser the gravel content of released sediment, the more limited the initial spatial extent of downstream impact. In some cases downstream sediment sinks, such as deep pools (Bountry, Lai, and Randle 2013), other reservoirs (Evans *et al.* 2000; Peck and Kasper 2013; Collins *et al.* 2014), confluences with larger rivers (Pearson, Snyder, and Collins 2011; Wilcox, O'Connor, and Major 2014), or coastal zones (Warrick *et al.* 2015), have limited the spatial extent of sediment impact regardless of transport capacity. Where downstream transport was not interrupted, sediment released from removals of tall (≥ 10 m) dams has generally traveled farther than sediment released from removals of short (< 10 m) dams (Bellmore *et al.* 2015; Grant and Lewis 2015). Principal impacts of released sediment containing more than 20% gravel typically have extended no more than about 5 km downstream – a reach over which most gravel accumulated (e.g., Cheng and Granata 2007; Burroughs *et al.* 2009; Kibler, Tullos, and Kondolf 2011; Major *et al.* 2012; Bountry, Lai, and Randle 2013; Tullos and Wang 2014). Although released sand has traveled farther downstream than gravel, it has sometimes spread so thinly along channels that accumulations are difficult to detect (e.g., Major *et al.* 2012; Collins *et al.* 2014). By contrast, large-volume pulses of gravel, sand, and mud released by removals of Milltown Dam (Montana) and Glines Canyon Dam (Washington) traveled at least 15–20 km downstream (Evans and Wilcox 2014; East *et al.* 2015; Warrick *et al.* 2015).

13.2.2.2 Changes in Channel Gradient

Sediment erosion and downstream delivery after dam removal can alter channel gradient. The trajectory of change in channel gradient through the reservoir reach and downstream is toward a smooth profile. This new profile is mostly similar to the pre-dam profile, but not always. Exhumed bedrock, man-made structures, and coarse alluvium may inhibit channel incision in the reservoir reach and prevent development of a smooth profile. Downstream, valley shape and morphology influence flow and stress distributions, which can alter sediment accumulation and affect channel gradient.

Large releases of sand or sand and gravel generally aggraded river channels within a few kilometers downstream of dam sites and increased channel gradient (e.g., Burroughs *et al.* 2009; Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Wilcox, O'Connor, and Major 2014). By contrast, sand and mud, whether released abruptly or during phased removals, have had relatively little effect on channel gradient (e.g., Evans *et al.* 2000; Doyle, Stanley, and Harbor 2003; Rumschlag and Peck 2007; Skalak *et al.* 2011).

Downstream changes in channel gradient are not always correlated positively with the volume and caliber of released sediment. Despite release of a large amount of sand and gravel following catastrophic failure of Barlin Dam, Taiwan, which induced as much as 7 to 10 m of aggradation, channel gradient within 1 km of the dam site remained relatively uniform owing to the narrow valley configuration. However, sediment accumulation in a wider reach farther downstream decreased channel gradient (Tullos and Wang 2014). Release of muddy sand and gravel to the Elwha River caused little change in downstream channel gradient, except in the lowermost 1.5 km of channel affected by tidal variation, because most of the released sediment passed through (East *et al.* 2015; Warrick *et al.* 2015). Similarly, release of tens of thousands of cubic meters of sand and gravel by removal of Savage Rapids Dam (Oregon) caused little gradient change downstream because it mostly filled deep pools (Bountry, Lai, and Randle 2013; Tullos, Finn, and Walter 2014).

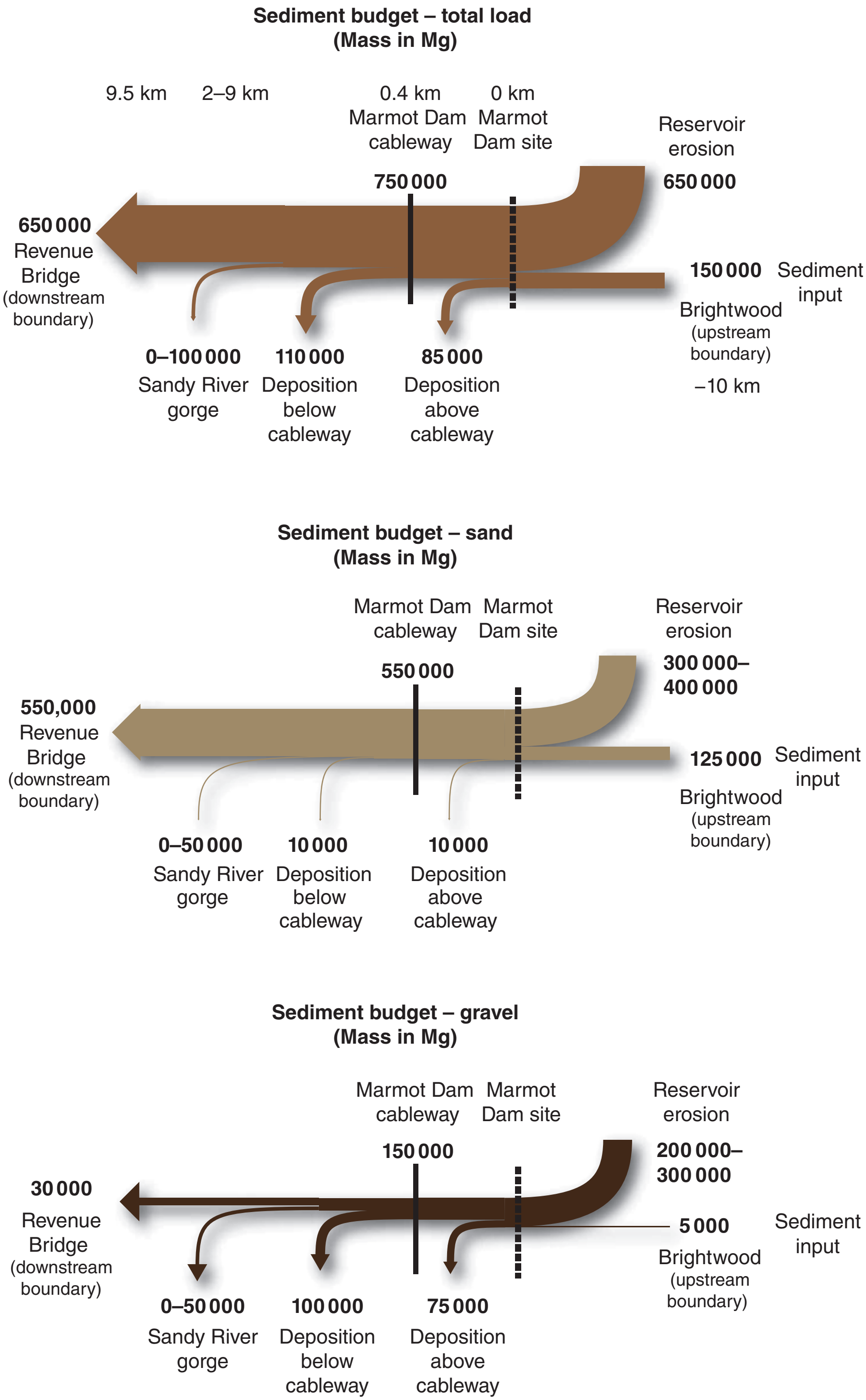

Figure 13.4 First-year compositional budgets for sediment released by removal of Marmot Dam (Oregon). Figure shows estimated upstream input to reservoir, erosion from reservoir, loss to depositional storage, and output at the exit of Sandy River gorge, ~10 km downstream of the dam site. (From Major *et al*. 2012.)

Most documented gradient changes have been in low-gradient (≤ 0.0006) reaches, even in steep mountain rivers. At Marmot Dam, the channel gradient in the first kilometer below the dam site was exceptionally shallow (~0.0001) compared to that farther upstream and downstream, and in this reach a large amount of sediment accumulated initially. Likewise, below Stronach (Michigan) and Merrimack Village dams, sediment accumulated in low-gradient (0.0006) reaches. Downstream of several other dam removals (or following sediment flushing from extant dams), sediment commonly filled pools (Wohl and Cenderelli 2000; Bountry, Lai, and Randle 2013; Tullos, Finn, and Walter 2014; Wilcox, O'Connor, and Major 2014) or uniformly aggraded already steep channel reaches (Tullos and Wang 2014), and therefore caused little change in overall channel gradient. Thus, morphologic variations in valley width, depth, and locations of pools, and other downstream influences that can affect base level (such as larger rivers or reservoirs) can affect sediment accumulation and gradient changes.

13.2.2.3 Changes in Channel Width

After dam removal, some downstream channels widened considerably whereas others changed little. Channels subject to substantial aggradation commonly widened because reaches became braided and the river spread across its floodplain at nearly all flows (e.g., Pearson, Snyder, and Collins 2011; Major *et al.* 2012; East *et al.* 2015) (Figure 13.5). By contrast, widths of channels that accumulated little sediment or that were morphologically constrained changed little (e.g., Bushaw-Newton *et al.* 2002; Doyle, Stanley, and Harbor 2003; Cheng and Granata 2007; Straub 2007; Peck and Kasper 2013).

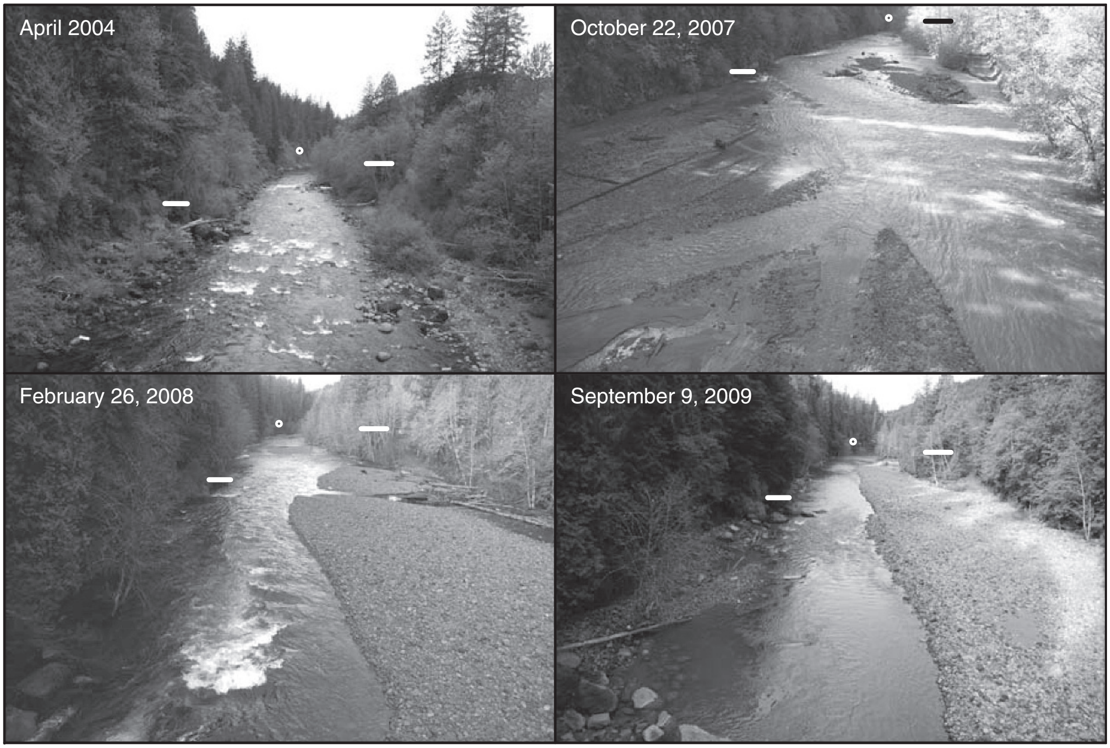

Figure 13.5 Photographs showing temporal channel changes immediately downstream of Marmot Dam. The dam was breached on October 19, 2007. Horizontal bars and dot indicate identical locations among photographs.

Sometimes, valley morphology affected active channel width more than did sediment deposition (e.g., Skalak, Pizzuto, and Hart 2009; Skalak *et al.* 2011; Tullos and Wang 2014; Wilcox, O'Connor, and Major 2014).

13.2.2.4 Changes in Channel Bed Texture

Sediment released by dam removal can shift grain-size distribution of the downstream channel bed toward that of the reservoir deposit, but that shift can vary spatially and temporally. Dam emplacement commonly induces coarsening (winnowing) of the downstream bed as sediment supply is restricted. As a result, dam removal commonly induces fining of the channel bed until upstream input declines and the river reworks deposited sediment. Though the bed may coarsen after initial sediment input is reworked, it may remain finer than the pre-removal bed under new equilibrium conditions. Typically, most fining is restricted to within a few kilometers of the dam site (e.g., Cheng and Granata 2007; Rumschlag and Peck 2007; Skalak *et al.* 2011; Major *et al.* 2012; Colaiacomo 2014; Harris and Evans 2014), but following some removals changes in bed texture have extended at least a few tens of kilometers downstream (Draut and Ritchie 2015; Evans and Wilcox 2014; East *et al.* 2015). Bed fining is not a universal response to dam removal, however. Along some gravel-bed rivers, released sediment coarsened the channel bed (Burroughs *et al.* 2009; Kibler, Tullos, and Kondolf 2011; Tullos and Wang 2014); in others, bed texture changed little. Muddy sand released by removals of low-head dams on rivers in the Midwestern United States had negligible impact on downstream channel texture (e.g., Doyle, Stanley, and Harbor 2003).

Even where downstream fining in a gravel-bed river is negligible, deposition of fine sediment may be ecologically significant. After removals of Elwha River and Milltown dams, fine sediment infiltrated and clogged interstitial pore spaces in gravel beds for months (Draut and Ritchie 2015; Evans and Wilcox 2014). Although these fine deposits were at most a few centimeters thick, they likely degraded habitat quality for benthic macroinvertebrates and fish redds (Wood and Armitage 1997; Jones *et al.* 2012). On Elwha River, habitat degradation occurred before arrival of the main sediment pulse (East *et al.* 2015).

13.2.2.5 Changes in Channel Patterns and Bedforms

Sediment release by dam removal can have other short-lived effects on channel morphology besides altering channel gradient, width, or bed texture. These effects include changes in channel pattern, filling of channel pools, and creation and modification of channel bars. Glide morphology can replace pool–riffle morphology when hydraulic controls are buried (Kibler, Tullos, and Kondolf 2011; East *et al.* 2015). Aggradation ≥ 1 m can change a channel from a single-thread to multithread pattern (Figure 13.5) (e.g., Major *et al.* 2012; Tullos and Wang 2014; Wilcox, O'Connor, and Major 2014), and new bar formation can increase channel sinuosity and braiding index (East *et al.* 2015). Multithread patterns commonly persist during high rates of bedload transport. After sediment-transport rates diminish and aggradation ceases, channels incise and revert to single-thread patterns. Reversion to a single-thread channel can happen swiftly, within days to months (e.g., Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Wilcox, O'Connor, and Major 2014). Even where gross channel patterns were not altered, channel pools commonly filled (e.g., Wohl and Cenderelli 2000; Bountry, Lai, and Randle 2013; Peck and Kasper 2013; Harris and Evans 2014; Wilcox, O'Connor, and Major 2014) and channel relief was modified (Zunka, Tullos, and Lancaster 2015).

Sediment release by dam removal may create new channel bars or modify existing bars. New bars may grow or existing bars may enlarge as released sediment moves downstream (Wohl and Cenderelli 2000; Doyle, Stanley, and Harbor 2003; Kibler, Tullos, and Kondolf 2011; Major *et al.* 2012; East *et al.* 2015; Zunka, Tullos, and Lancaster 2015). But even these geomorphic changes can be short-lived. Within weeks of breaching Marmot Dam, bars flanking the channel within 1 km of the dam site were finer grained and positioned in locations independent of bars that existed prior to breaching. Within 2 months, however, bar surfaces had coarsened, and within a year bar locations, forms, and compositions were similar to those before breaching (Major *et al.* 2012). After removing Brownsville Dam, downstream bar area and volume within 1 km of the dam site increased several fold and new riffles formed – changes that persisted for at least 2 years (Kibler, Tullos, and Kondolf 2011). But valley morphology and river dynamism may influence formation and modification of channel bars more than does sediment release by dam removal. After failure of Barlin Dam, forms and distributions of downstream bars remained unchanged even after passage of 10^7 m^3 of gravel and sand (Tullos and Wang 2014).

13.3 Factors Influencing Responses to Dam Removals

The varying responses to dam removal – both in the reservoir and downstream – are affected by several controlling factors. Studies so far suggest important controls include dam height, reservoir sediment volume and composition, removal strategy, and downstream channel and valley morphology. Hydrology and watershed setting appear to be subordinate influences on the initial geomorphic response downstream, but may have great influence on longer-term response. Sawaske and Freyburg (2012) noted similar influential factors in an analysis of responses to 12 small-dam removals. O'Connor, Duda, and Grant (2015) briefly summarize more recent findings.

13.3.1 Dam Height and Removal Strategy

Dam height influences geomorphic response to removal in two ways. First, it affects the amount of sediment and water in storage. Tall dams typically store large volumes (>500 000 m^3) of sediment and may impound large volumes of water. By contrast, short dams are typically run-of-river structures that store small to moderate volumes of sediment and limited water, and they typically have passed sediment for many years. Second, dam height controls the overall base-level fall induced by dam removal.

Removal strategy affects the rate at which full base-level fall is achieved, which influences the rate of reservoir erosion and downstream sediment delivery. Full base-level fall is achieved rapidly during sudden removal of a dam, or gradually during phased removal. Sudden breaching of tall dams, including Savage Rapids Dam (12 m), Milltown Dam (12.8 m), Marmot Dam (15 m), Condit Dam (38 m), and failure of Barlin Dam (38 m) induced rapid and extensive erosion in the respective reservoirs (Figure 13.3). Sudden breaching led to rapid but varying degrees of channel incision, channel widening, knickpoint and knickzone advance, and, at Condit Dam, highly mobile landslides (Epstein 2009; Major *et al.* 2012; Bountry, Lai, and Randle 2013; Tullos and Wang 2014; Wilcox, O'Connor, and Major 2014). By contrast, phased removals of 64-m-tall Glines Canyon Dam and 32-m-tall Elwha Dam, neither of which impounded a reservoir filled with sediment, resulted in comparatively slower sediment release because rates of base-level fall were modulated and because deltas had to prograde through dwindling pools before bedload passed the dam sites (Randle *et al.* 2015). Although reservoir erosion was mostly by channel incision and fluvial lateral widening, many small-scale slumps and bank collapses (1–5 m tall) also contributed to sediment delivery (Randle *et al.* 2015). However, neither extensive landslides nor pronounced knickpoint migration occurred.

Erosional processes similar to those observed after breaching of tall dams have been observed after sudden and phased removals of smaller dams. In many instances, those processes have removed sediment more slowly from reservoirs behind small dams (Figure 13.3) (e.g., Doyle, Stanley, and Harbor 2003; Harris and Evans 2014). However, following removals of 4-m-tall Merrimack Village Dam (New Hampshire; Pearson, Snyder, and Collins 2011) and 3-m-tall Simkins Dam (Maryland;

Collins *et al.* 2014), rapid incision and channel widening in sandy reservoir sediment removed more than 40% of the stored volumes within months (Figure 13.3). By contrast, phased removals of small dams (e.g., Brewster Creek and Stronach dams; Table 13.1) strongly modulated erosion of reservoir sediment (Straub 2007; Burroughs *et al.* 2009; Figure 13.3). Although similar processes erode and evacuate sediment from reservoirs impounded by both small and tall dams, these examples show the rate and magnitude of base-level fall induced by dam-removal strategy has a strong influence on the rate and magnitude of reservoir-sediment erosion.

13.3.2 Relations Among Reservoir Sediment Volume, Rate of Sediment Release, and Background Sediment Flux

Two dimensionless ratios, both incorporating a river's background sediment flux, may provide predictive insights on the extent and duration of geomorphic impact upon dam removal. One ratio, V^*, provides a relation between the volume of stored reservoir sediment and volume of average annual sediment load at the dam site (e.g., Burroughs *et al.* 2009; Major *et al.* 2012; Tullos and Wang 2014; Wilcox, O'Connor, and Major 2014). The other ratio, E^*, provides a relation between the volume of sediment eroded in the first year after removal (or the first year after sediment began passing a dam site if removal was phased) and background sediment flux (Grant and Lewis 2015).

The ratio V^* provides a measure of the potential magnitude of perturbation to the downstream channel. It may also provide some insight on potential duration of the downstream response. For example, if V^* is relatively small (≤20), the overall downstream impact may be modest (though locally impressive) because the downstream channel receives a sediment input not substantially greater than that to which it is equilibrated. Also, the primary downstream response to sediment release may be of relatively short duration (months to years) because the river will likely redistribute released sediment swiftly and reequilibrate. By contrast, if V^* is large (several tens to hundreds), the river system may receive a sediment input much greater than that to which it is equilibrated and may take many years, and possibly decades, to effectively redistribute released sediment and reequilibrate.

Two removals highlight the potential utility of V^* as a gross predictor of order-of-magnitude duration of principal downstream geomorphic response. Marmot Dam stored about 750 000 m^3 of sediment. At its location, the average annual sediment flux of Sandy River is about 100 000 to 200 000 m^3. Hence, removal of Marmot Dam released an effectively small volume of sediment to Sandy River – probably less than a decade's worth ($V^* < 10$; Figure 13.6). Despite swift erosion of a large amount of stored sediment (>40% within 8 weeks; Figure 13.3; Major *et al.* 2012), suspended-sediment loads returned to background level within months of removal and pre-removal channel form and texture just downstream of the dam site – the reach most affected by released sediment – began to reestablish (Figure 13.5; Major *et al.* 2012). Within a year of removal, channel form and texture in that reach had largely reestablished though bed elevation and relief remained significantly changed from pre-removal conditions (Major *et al.* 2012; Zunka, Tullos, and Lancaster 2015). Within about 5 years after removal, morphology and longitudinal profile of the channel extending 2 km downstream of the dam site had mostly stabilized (J.J. Major unpublished data; Zunka, Tullos, and Lancaster 2015). By contrast, two dams on Elwha River stored much greater relative volumes of sediment (Figure 13.6). The Glines Canyon (~16 million m^3) and Elwha (~5 million m^3) dams impounded a combined ~21 million m^3 of sediment (Randle *et al.* 2015). The average annual sediment load of Elwha River entering Lake Mills behind Glines Canyon Dam is about 200 000–300 000 m^3 (Curran *et al.* 2009; Magirl *et al.* 2015). Thus, Glines Canyon Dam impounded about 50–80 years of average annual sediment load (V^* ~50–80), and Elwha Dam impounded about 15–25 years of (unregulated) average sediment load (V^* ~15–25). Over the first 2 years of phased removal of these dams, about 7 million m^3 of

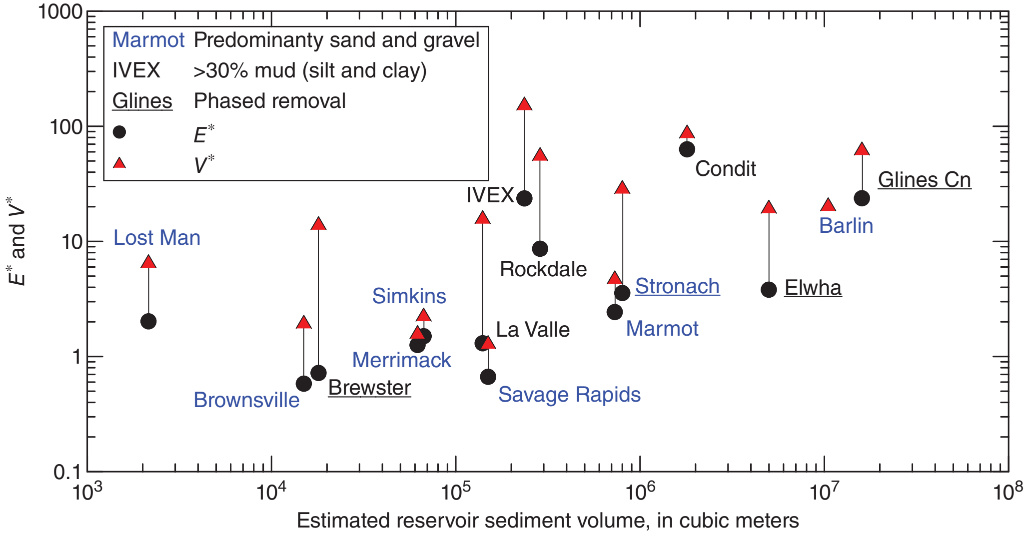

Figure 13.6 Volumes of stored sediment (V^*) (triangles) and volumes of sediment eroded during first year following dam removal (E^*) (black dots) relative to background sediment fluxes as a function of stored sediment volumes for recent dam removals. Vertical lines added for clarity to identify data points for given dams. Data for Glines Canyon Dam are for the second year following initiation of breaching because that is when most sediment, especially bedload sediment, began passing the dam site (see Figure 13.3 for additional information).

sediment was released (Randle *et al.* 2015), an amount equivalent to about 20–40 years of average annual load. Most of that released sediment passed through the 22-km-long channel corridor below Glines Canyon Dam and was delivered to a coastal zone (Warrick *et al.* 2015). However, the sediment deposited along the channel induced changes in elevation, pattern, and texture (East *et al.* 2015) to which the river is still responding some 4 years (at the time of this writing) after removals began. Sediment release from the former Lake Mills reservoir will continue over the coming years, especially during high-discharge events. The duration of major downstream response remains to be determined. These two examples show the relative magnitude of stored sediment to background sediment flux can influence the duration of downstream geomorphic response, especially if the river is able to access and erode large amounts of stored reservoir sediment.

Though the relative magnitude of the amount of sediment in storage broadly influences the nature and duration of downstream geomorphic response, the rate at which sediment is released is clearly an influential factor. Grant and Lewis (2015) approached the influence of rate of sediment release using the dimensionless ratio E^*. They examined the utility of using this ratio for predicting patterns of downstream sediment transport. For a limited number of removals in the US Pacific Northwest, they found that E^* did a better job of predicting the transport distance of coarse sediment (sand and gravel) than fine sediment (mud and fine sand). In general, fine sediment was transported downstream as suspended load and its transport distance correlated poorly with E^*. By contrast, coarse sediment is transported as bedload and its transport distance – when not interrupted by downstream sediment sinks such as other reservoirs or confluences with larger rivers – appears to correlate positively with E^*. That is, the greater the initial sediment delivery relative to background sediment flux, the farther downstream coarse sediment (mostly sand) is transported. If this simple empirical relation holds for other regions (especially for small dams on low-gradient rivers), it may prove a useful tool for quickly estimating possible spatial consequences of dam removals.

13.3.3 Reservoir-Sediment Grain Size

Sediment grain size (caliber) influences reservoir erosion processes and downstream effects of released sediment. In conjunction with the style of dam removal and degree to which sediment fills a reservoir, sediment grain size influences the nature and pace of reservoir erosion. It also affects consequent transport and storage of sediment downstream, and the distribution and residence time of the transported sediment.

Upon dam removal, reservoirs impounding coarse sediment commonly erode more completely and more rapidly than do those impounding fine sediment (Figure 13.3). The principal exception to this is Condit Dam, where highly mobile landslides swiftly evacuated a great amount of fine sediment. Differences in sediment characteristics, such as cohesion and consolidation of fine sediment, sediment stratification, and degree of saturation affect these granulometric differences in erosion rates. But the apparent differences may be biased by the limited number of removals and removal strategies examined to date, especially among large-dam removals. Few large dams impounding mostly fine sediment have been removed. And among those dams which we examined that impounded fine sediment, nearly half were removed incrementally, which modulated the rate of base-level fall (Figure 13.3). Nevertheless, differences among grain-size distributions of reservoir sediment appear to influence erosion rates upon dam removal.

Grain size of released sediment affects downstream impacts and responses regardless of removal strategy. Released fine sediment commonly has less downstream impact than coarse sediment. Apart from small-volume fine-sediment deposition as interstitial fill, most fine sediment is transported downstream as suspended load that temporarily increases turbidity and suspended-solids concentration (Doyle, Stanley, and Harbor 2003; Granata, Cheng, and Nechvatal 2008; Major *et al.* 2012; Magirl *et al.* 2015). Following some removals, fine sediment accumulated thinly on floodplains or along channel margins when flows were either deep enough to spill overbank or had relatively little transport capacity relative to fine-sediment supply (e.g., Evans *et al.* 2000; Draut and Ritchie 2015). In instances where downstream reservoirs interrupted sediment transport, substantial amounts of fine sediment accumulated (Evans *et al.* 2000).

Even large-volume releases containing abundant fine sediment have had relatively little downstream impact. Although abundant fine sediment at Condit Dam promoted conditions for hyperconcentrated flow upon breaching, that flow selectively draped the downstream channel corridor with sand and largely passed mud through the system (Wilcox, O'Connor, and Major 2014). Most of the fine sediment released by the concurrent removals of the Elwha River dams passed through the 22-km-long downstream corridor (Warrick *et al.* 2015). Fine sediment retained along the channel corridor initially infiltrated the pre-removal gravel bed, formed small bars along the channel margin, or draped floodplain channels (Draut and Ritchie 2015; East *et al.* 2015), but its deposition prompted little geomorphic response.

Coarse sediment, by contrast, can prompt substantial downstream geomorphic response. Coarse sediment release can increase bedload transport many fold, aggrade channel beds, coarsen or fine downstream bed texture, and modify channel pattern and morphology. These effects commonly are pronounced when large amounts of coarse sediment are released rapidly, especially when the amount released overwhelms transport capacity.

Coarse-sediment released by removals of small dams, mostly sand, has had modest impact relative to that released by removals of tall dams. Although sediment released by some small-dam removals caused substantial (1–3 m) channel aggradation, most releases induced only minor changes in bed elevation within a few kilometers downstream of a dam site. Commonly, those releases had little to modest effect on channel pattern owing mainly to pool filling, modification of local channel relief, or minor modifications to channel bars and riffles. They have also had varying effects on channel-bed texture. Typically, the effects of coarse sediment released by small-dam removals have been short-lived (months to perhaps a few years). By contrast, downstream impacts of coarse sediment released by removals of tall dams have been more profound regardless of removal strategy. Voluminous releases that have delivered sediment pulses that rival substantial natural events in scale have aggraded channel beds by as much as 10 m (Tullos and Wang 2014) and substantially modified channel relief, channel patterns, and bed texture (Major *et al.* 2012; Colaiacomo 2014; Tullos and Wang 2014; Wilcox, O'Connor, and Major 2014; East *et al.* 2015; Zunka, Tullos, and Lancaster 2015).

The effects of releasing large volumes of coarse sediment appear to last longer if the sediment contains a substantial proportion of gravel. After breaching Marmot Dam, gravel that accumulated in the 2-km-long reach downstream of the dam site (Figure 13.4) has remained largely in storage for nearly a decade after removal (J.J. Major unpublished data). Released sand that moved much farther downstream had limited and apparently short-lived effects (Major *et al.* 2012). Sand and minor gravel released by removal of Condit Dam swiftly aggraded the channel bed several kilometers downstream of the dam site by as much as 1 m after passage of the initial hyperconcentrated flow, but within days of attaining maximum aggradation that fill was incised nearly to the pre-removal level of channel riffles (Wilcox, O'Connor, and Major 2014). Such rapid incision shortly after maximum aggradation was due, in part, to a lack of gravel capable of armoring the bed surface and to rapid reduction of sediment supply.

13.3.4 Breach and Post-Breach Hydrology

There is little correlation between the proportion of sediment evacuated from the reservoir and magnitude of river flow during and after dam breaching. Several dams have been breached during low to moderate flows – flows much smaller than the 2-year-return-interval flow. Yet, during breaching and in the ensuing days to months these moderate flows in many cases rapidly evacuated large fractions of impounded sediment (Figure 13.7; Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Bountry, Lai, and Randle 2013; Collins *et al.* 2014; Tullos and Wang 2014; Wilcox, O'Connor, and Major 2014; Magirl *et al.* 2015; Zunka, Tullos, and Lancaster 2015). Even during phased removals, such as those on Elwha River, moderate flows eroded large fractions of reservoir sediment if the rate of base-level fall induced sufficient change in slope to mobilize a broad range of sediment sizes (e.g., Magirl *et al.* 2015; Randle *et al.* 2015). By contrast, large flows have been most important for accessing and evacuating harder-to-reach remnant sediment that becomes isolated along reservoir margins or stranded on terraces, and in redistributing sediment deposited downstream (Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Harris and Evans 2014; Tullos and Wang 2014). In gravel-rich rivers, large flows become especially important for evacuating remnant reservoir sediment and redistributing it as the channel within the reservoir and downstream armors.

Breaches that released substantial water volumes generated brief peak flows equivalent to low-frequency, high-magnitude floods. But in two well-documented examples, those water releases did not erode large amounts of sediment from reservoirs. Evans *et al.* (2000) documented a release of about 38 000 m^3 of water within minutes during failure of IVEX Dam (Ohio), producing a 466 m^3/s peak flow (>100-year flood?), yet only about 25 000 m^3 (10%) of impounded sediment had eroded after 2 months. Breaching of Condit Dam released 1.6 million m^3 of water in a little more than an hour, generating a 420 m^3/s peak flow (>100-year flood). However, substantial evacuation of reservoir sediment did not occur until landslides became prevalent after the water had drained (Wilcox, O'Connor, and Major 2014).

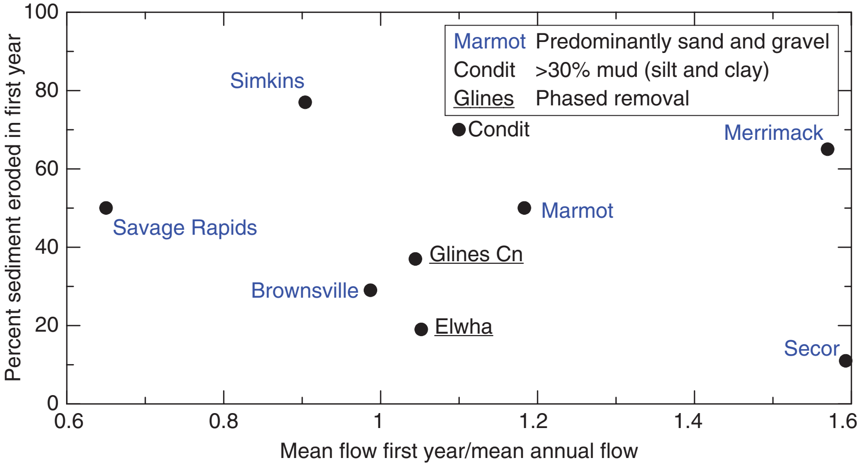

Figure 13.7 Fraction of reservoir sediment volume eroded as function of relative mean-flow magnitude during first year following dam removal. Data for Glines Canyon Dam are for the second year following initiation of breaching because that is when most sediment, especially bedload sediment, began passing the dam site (see Figure 13.3 for additional information). Data for Secor Dam represent fraction of sediment eroded within 6 months of breaching.

Lack of correlation between rate of sediment erosion and flow magnitude reflects the relative importance of process-based erosion versus event-based erosion, a conceptual model proposed by Pizzuto (2002) and extended by Pearson, Snyder, and Collins (2011). Process-based erosion, which is largely independent of flow magnitude, occurs when there is a great change in reservoir equilibrium upon dam removal (sudden channel initiation, rapid migration of headcuts and knickpoints, etc.). Event-based erosion follows when high flows are needed to access and exceed transport thresholds for remnant sediment (Pearson, Snyder, and Collins 2011). Removals to date highlight the general validity of this conceptual model.

Under disequilibrium conditions caused by reservoir-sediment release, modest flows can also transport abundant sediment downstream. For example, during the first year after removal of Marmot Dam, peak flows were no larger than 60% of the discharge of a 2-year flood and mean annual flow was only 18% greater than long-term mean flow. Under these conditions, unit-width bedload fluxes within 10 km downstream of the dam site approached some of the highest values measured for gravel-bed rivers (3–4 kg/s/m; Major *et al.* 2012). During the phased removals of the Elwha River dams, 2 years of muted flows having peak discharges about 70% of the discharge of a 2-year flood transported 90% of the released sediment (~9 million tonnes) to the river mouth (Magirl *et al.* 2015; Warrick *et al.* 2015). Release of a small volume of gravel (~15 000 m^3) by removal of Brownsville Dam and subsequent modest flows during the year after removal led to substrate coarsening, growth of channel bars, and an increase in habitat heterogeneity within a few hundred meters of the dam site, but little change farther downstream (Kibler, Tullos, and Kondolf 2011).

To date, there has yet to be an intentional dam removal contemporaneous with, or followed closely by, a large, naturally occurring flood. Thus, there is uncertainty regarding exactly how a river system might respond to such a scenario. Major *et al.* (2012) speculated that the sequencing of flow magnitudes at Marmot Dam influenced reservoir-sediment erosion at the time scale of individual events, but had little effect on total erosion 2 years after removal. They further speculated that had large-magnitude flows occurred at or shortly after breaching, a similar proportion of reservoir erosion would have been achieved after 2 years, but likely by a different erosion trajectory. Comparison of erosion trajectories at Merrimack Village Dam (MVD) and Simkins Dam (Figure 13.3) support this speculation. Both dams were of similar height and stored similar sediment volumes and compositions (Table 13.1), had similar upstream contributing areas, similar hydroclimate regimes, and were removed suddenly. No large flows (≥10-year event) occurred within 2 years of removal of MVD (Pearson, Snyder, and Collins 2011) whereas a 10-year event occurred within months of removal of Simkins Dam (Collins *et al.* 2014). Similar proportions of reservoir sediment eroded after 2 years from each dam site, but by slightly different trajectories.

13.3.5 Downstream Valley Morphology

Downstream valley morphology can affect overall river system response to sediment release from dam removal. Valley morphology can act as a filter that affects sediment storage and transport and influences the fate of differential sediment distribution. After removal of Marmot Dam, released gravel accumulated largely along a narrow, low-gradient reach immediately downstream of the dam site. By contrast, nearly all released sand passed much farther downstream (Figure 13.4; Major *et al.* 2012). Following failure of Barlin Dam, resistant valley walls and valley-forced meandering affected the locations, sizes, and geometries of channel bars, channel width, and lateral migration (Tullos and Wang 2014). Following breaching of Condit Dam, a narrow, bedrock-confined reach immediately below the dam passed much of the released sediment several kilometers downstream to a broader, lower-gradient reach where it accumulated thickly (Colaiacomo 2014; Wilcox, O'Connor, and Major 2014). In the weeks following breaching, bed elevation within the bedrock reach adjusted toward the pre-removal level of riffles but pools remained filled (Colaiacomo 2014). After removal of Savage Rapids Dam, the overall bed elevation in the 3-km reach downstream of the dam site changed little, but spatially progressive changes in residual pool depths reflected downstream advance of sediment for at least 2 years after removal (Tullos, Finn, and Walter 2014).

Existing morphology can also affect bed relief, and thus channel complexity, that develops from deposition of released sediment. Sediment released to low-relief channels can increase local relief by building channel bars, but it can decrease relief in high-relief channels by filling pools, by replacing pool–riffle morphology with glides, and by forming short-lived mid-channel bars (Wohl and Cenderelli 2000; East *et al.* 2015; Zunka, Tullos, and Lancaster 2015). The style, timing, and duration of downstream sediment transport can also be affected by channel morphology. Channel bars and pools can serve as sites of temporary, or even long-lived, sediment accumulation (Wohl and Cenderelli 2000; Doyle, Stanley, and Harbor 2003; Kibler, Tullos, and Kondolf 2011; Harris and Evans, 2014), and floodplains can trap sediment even during low flows if channel aggradation is sufficient (e.g., Evans *et al.* 2000; Burroughs *et al.* 2009; East *et al.* 2015). These sediment-storage reservoirs can limit impact farther downstream by disrupting or buffering sediment transport and can extend the duration of impact of released sediment.

13.3.6 Watershed Geologic Setting and Geographic Context

Watershed geologic setting and geographic context can strongly affect response to dam removal. Where a dam sits in a watershed broadly influences the impact its removal has on the downstream channel. Its position influences the caliber and quantity of reservoir sediment, its hydrological regime, and the potential for the downstream channel to store or transmit sediment – all of which affect the spatial extent of downstream impact. Geographic context also includes the presence of dams upstream or downstream of the removed dam, which influences sediment supply and downstream transport and storage.

Though geologic and geographic context can affect short-term response to dam removal, they likely have greater influence on long-term response. Skalak, Pizzuto, and Hart (2009) argue that many rivers in the US Mid-Atlantic region are bedrock channels mantled with a thin gravel cover. This morphology is related to low rates of sediment supply, transport, and storage typical of the region. Thus, stability of exposed bedrock and boulders exerts a very strong control on overall channel morphology, which influenced long-term erosion, transport, and storage of sediment. Removals of small dams in this region typically release short-lived pulses of sediment commonly finer grained than the composition of the downstream bed. Although these pulses may briefly alter channel morphology and bed composition, sediment supplies eventually approach watershed delivery rates. Thus, long-term response to sediment delivery is more likely to be controlled by the configuration and stability of exposed bedrock and immobile boulders than by modest sediment release from dam removal. As a result, gross geomorphic characteristics of channels may remain relatively unaffected by small-dam removals (Skalak, Pizzuto, and Hart 2009; Skalak *et al.* 2011).

Responses to removals of tall dams in the US Pacific Northwest and to a dam failure in Taiwan also exemplify influences of geology and geography. Sandy River, Oregon, drains Mount Hood, an active volcano in the Cascade Range. Large volumes of volcanic sediment are stored along the length of Sandy River, and provide locally dynamic sediment sources. Upon removal of Marmot Dam, released sand passed far downstream. However, river dynamism and local sediment sources masked the distribution of that sand. The configuration of confined bedrock and wider alluvial reaches along White Salmon River affected the transport and storage of sediment released by breaching of Condit Dam (Colaiacomo 2014; Wilcox, O'Connor, and Major 2014). Similarly, valley-forced morphology as well as basin-wide variations in caliber and quantity of sediment transport owing to lithological influences affected rates and types of channel adjustments to the sediment pulse delivered by failure of Barlin Dam (Tullos and Wang 2014).

13.4 Time Scales of Channel Responses to Dam Removals

Channel perturbation involves a reaction time over which channel conditions diverge from a state of stability, and a relaxation time during which perturbed channel conditions converge toward a state of stability (e.g., Graf 1977; Pierson and Major 2014). In the context of dam removal, reaction times may be short or prolonged – hours to days following sudden removal, or months to years during phased removal. Relaxation times can be highly variable, and systems may converge toward an equilibrium state that differs from the pre-dam state. Following dam removal, reaction and relaxation timescales typically overlap. Although large amounts of reservoir sediment can be evacuated swiftly following initial breaching of a dam, erosion commonly continues to remove and deliver sediment downstream for protracted periods – months to years, perhaps decades. Thus, the channel downstream can simultaneously be responding to and relaxing from an initial perturbation while being perturbed further by additional sediment delivery. Nevertheless, relaxation times toward a state of relative stability following dam removals have been shorter than commonly anticipated – years, not decades. Pizzuto (2002) hypothesized that evolution of an equilibrium channel through reservoir sediment might take at least a decade depending on mass and grain size of the sediment. Yet in many cases more than a third, and sometimes two-thirds, of stored sediment has been evacuated within weeks to months of dam removal (e.g., Sawaske and Freyburg 2012; Figure 13.3), and relatively stable channels within reservoirs have established swiftly. Even during phased removals of Elwha River dams, approximately a third of the total sediment stored behind two dams was evacuated in the first 2 years of the removal project (Randle *et al.* 2015; Warrick *et al.* 2015), and about half evacuated after 3 years (C.S. Magirl unpublished data). But owing to continued erosion, reservoir-reach channels on Elwha River have yet to stabilize after 4 years.

Major downstream channel adjustments following dam removal commonly achieved apparent stability within months to years. In several instances, bed textures, channel patterns and gradients, bar morphologies, and sediment transport rates approached pre-removal or pre-dam conditions within a year or two, although pools commonly remained filled (Bushaw-Newton *et al.* 2002; Doyle, Stanley, and Harbor 2003; Pearson, Snyder, and Collins 2011; Major *et al.* 2012; Peck and Kasper 2013; Coloaiacomo 2014; Tullos, Finn, and Walter 2014; Tullos and Wang 2014; Kim, Toda, and Tsujimoto 2015; Zunka, Tullos, and Lancaster 2015). The principal exception is Elwha River owing to continued delivery of large amounts of sediment. But now that the dams have been removed completely and at least half the sediment has been evacuated, and mostly passed to the coastal zone, stability may be achieved within a few years. Although major channel adjustments commonly occur swiftly, minor adjustments, such as decimeter-scale fluctuations of bed elevation, migration of small secondary bars, and adjustments of particle sorting, may persist for several years (Skalak *et al.* 2011; Greene, Krause, and Knox 2013; Peck and Kasper 2013).

Although rivers appear to recover rapidly after perturbations induced by dam removals, long-term assessments of responses to removals are rare. As of 2015, the longest lasting responses to dam removals have resulted from accumulation of gravel, local aggradation and filling of deep pools with sand, or substantial deposition in downstream reservoirs that interrupted sediment transport (e.g., Evans *et al.* 2000; Evans 2007; Skalak *et al.* 2011; Major *et al.* 2012; Peck and Kasper 2013: Zunka, Tullos, and Lancaster 2015). Seven years after removal of Marmot Dam, the profile of Sandy River in the first kilometer below the dam site still reflects substantive gravel accumulation, and minor fluctuations of bed elevation and local redistribution of sediment among channel bars persist (J.J. Major unpublished data). Five years after removal of Munroe Falls Dam (Ohio) sand deposited on the channel bed 2–3 km downstream of the dam site continued to influence activation of meander-bend chutes at all but the lowest flow, particle sorting persisted, and sandy deltaic deposits remained at the head of a reservoir 5 km downstream (Peck and Kasper 2013). Four years after removal of the low-head Manatawny Dam (Pennsylvania), which impounded sand and gravel, modest channel adjustments continued both upstream and downstream of the dam site (Skalak *et al.* 2011). And 12 years after failure of IVEX Dam, sand released more slowly from a delta at the upper end of the reservoir-reach had delivered twice the volume to a downstream reservoir as did the initial flush of fine sediment released by failure (Evans 2007). The overall findings from recent dam removal studies of rapid relaxation of sediment perturbations present a contrast with the hypothesis of much longer-term adjustments to breaching of low-head, colonial-age mill dams in the US Mid-Atlantic region (Merritts *et al.* 2013). That hypothesis proposes that erosion of sediment impounded by these structures has persisted for decades to centuries after breaching, and largely accounts for most of the present-day, fine-grained load delivered downstream.

Construction or exposure of grade-control features after dam removal can affect long-term sediment accumulation and erosion in reservoirs and consequent downstream response. An analysis of geomorphic response 10 years after removal of La Valle Dam (Wisconsin) showed that a man-made riffle constructed at the dam site altered flow hydraulics and sediment transport (Greene, Krause, and Knox 2013). That riffle induced renewed sedimentation in the reservoir reach, which subsequent floods eroded and redistributed downstream. Similar hydraulic and sediment-transport conditions established behind Homestead Dam (New Hampshire) after resistant boulders were exposed just upstream of the dam site (Gartner, Magilligan, and Renshaw 2015).

Local and system-wide relaxation times also depend upon the manner in which a sediment pulse moves downstream. A pulse of sediment introduced to a channel may disperse in place and diffuse downstream, translate downstream as a discrete sediment wave, or exhibit hybrid behavior (Lisle *et al.* 2001; Lisle 2008; Sklar *et al.* 2009). The manner of transport affects the magnitude and duration of downstream impact – a sediment pulse that disperses downstream may induce lower-magnitude changes, but have longer-lasting impact than does a pulse translating as a discrete wave. Theoretical, experimental, and field studies indicate sediment pulses on gravel-bed rivers propagate by translation rather than dispersion when pulse volume is small relative to channel dimensions, grain size is finer than the downstream river bed, and Froude number is low (<0.4) (Lisle *et al.* 2001; Lisle 2008; Sklar *et al.* 2009; Madej *et al.* 2009; Pryor *et al.* 2011). By contrast, sediment dispersion is favored when sediment volume is large relative to channel dimensions, grain-size distribution is broad and contains particles coarser than the channel bed, and Froude number is high (>0.4). There are few studies of dam removals that specifically address the manner of downstream sediment propagation (e.g., Evans, Huxley, and Vincent 2007; Thomas *et al.* 2014), but some provide provocative, and sometimes contradictory, observations. Within a week of breaching Condit Dam, Wilcox, O'Connor, and Major (2014) documented a distinct rise and fall of the channel bed a few kilometers downstream of the dam site as large amounts of sand and some gravel passed. This rapid change of channel-bed elevation, even though sediment volume was large relative to channel dimensions and Froude number was high ($\sim$1), suggests passage of a translating sediment wave. Similar cycles of downstream aggradation and degradation were observed following release of gravelly sediment by failure of Barlin Dam (Tullos and Wang 2014). By contrast, East *et al.* (2015) suggest that progressive but sustained low-magnitude changes in bed elevation on Elwha River during phased dam removals reflect sediment-pulse dispersion – a result that owes largely to the great volume of sediment released. Subsequent to removal of Marmot Dam, proximally deposited gravel was redistributed, but by 7 years after removal there was no evidence that it had translated downstream as a discrete sediment wave (Major *et al.* 2012; J.J Major unpublished data).

Regardless of how sediment moves downstream, when its supply exceeds a river's transport capacity, deposition occurs and bed texture and morphology are modified. Experiments show introduced sediment pulses obliterate much of the downstream channel morphology at the reach scale and change both mean and spatial patterns of bed elevation and texture (Lisle *et al.* 2001; Cui *et al.* 2003; Sklar *et al.* 2009; Podolak and Wilcock 2013). Experiments also show bed topography and textural patterns adjust over different time scales (Podolak and Wilcock 2013). But even after channels have achieved largely stable topographic and textural patterns similar to those extant before passage of a sediment pulse, spatially variable secondary textural and topographic adjustments may persist, including changes in particle sorting, minor bed-elevation fluctuations, and migration of secondary bars much smaller in scale than major channel bars (Podolak and Wilcock 2013). Although these persistent secondary adjustments may induce only modest geomorphic changes to the downstream channel, they may have important ecological ramifications.

13.5 Common Findings from Analyses of Responses to Dam Removals

Despite the variety of dam heights, reservoir sediment volumes and compositions, and removal strategies, a number of common findings have emerged with regard to geomorphic responses following dam removals.

1) Rivers are resilient. After dam removals, rivers have largely achieved apparent stability – at least within their range of natural variability – within a few years rather than decades. Despite concerns about rapidly releasing possibly large volumes of sediment to river systems, most removals to date have shown adverse geomorphic impacts (such as complete bed-texture transformation, enhanced flood risk, or damage to fish habitat) are short-lived and have been neither as damaging nor as long-lasting as feared. Although locally minor steps in reservoir profiles sometimes developed owing to exposure of resistant bedrock, boulders, or buried structures, concerns about development of stepped profiles capable of impeding upstream fish passage have been unfounded thus far.
2) Modest streamflows can effectively evacuate large percentages of reservoir sediment and move it downstream. Rapid evacuation and transport is associated with two key factors: (i) sediment composition; and (ii) establishment of extraordinary river capacity and competence owing to abrupt change in base level during dam breaching. In general, reservoir sediment composed dominantly of sand and gravel erodes more swiftly and more completely than does reservoir sediment dominated by mud. The nature and pace of erosion can be strongly influenced, however, by exposure of natural and man-made features that can act as grade-controls and impose new boundary conditions.
3) Sediment volume and caliber exert a dominant control on downstream response to dam removal. Large amounts of released gravel have had more substantial and longer-lasting downstream effects than has released sand and mud. But even the most substantial channel changes caused by accumulation of coarse sediment (such as large changes in bed elevation, changes in bed texture, and loss of pre-removal channel pattern) have not had long-lasting adverse geomorphic effects.
4) Location of a dam within a watershed, existing valley morphology, and geologic and geographic settings can strongly influence channel response to dam removal. Locations and forms of channel bars may be governed largely by existing valley morphology. Rivers attain equilibrium more quickly within confined bedrock reaches than within wider, lower-gradient alluvial reaches. Regional lithology and bedrock exposure may exert a greater influence on channel morphology than either dam emplacement or sediment release by dam removal.
5) Predicting time to recovery from sediment release following dam removal remains challenging. Although a river will converge toward a state of equilibrium with the supplied sediment load, it may not return to its pre-dam state. Assessment of metrics such as V^* (ratio of impounded sediment volume to background sediment flux) or E^* (ratio of sediment volume eroded within 1 year of removal to background sediment flux) can provide qualitative insights regarding an order-of-magnitude time it may take for a river to converge to a state of stability. In general, rivers converged toward stability conditions within a few years when both V^* and E^* had values of ≤ 20.

These findings have been extracted from a limited number of field studies across geographically restricted regions of the United States and a single dam failure abroad. Hence, we have no information on geomorphic responses to dam removals from a vast region of the United States having great topographic, climatic, and ecological diversity. Detailed studies of responses to removals in underrepresented regions would bolster our ability to test the general applicability of these findings. Furthermore, there has yet to be clear integration of physical and biological responses to dam removals. Tighter integration of the nature and pace of geomorphic and ecological responses – and their interactions – is needed to develop more thorough assessment of the impacts of sediment release by dam removal.

Consistent and thorough documentation of physical and ecological responses to dam removals is needed to improve our understanding of environmental benefits and detriments of dam removal. We recognize that all studies are subject to logistical and financial constraints. Nevertheless, we encourage the community to document as thoroughly as possible the following conditions: (i) pre-removal, and if possible pre-emplacement, morphological and ecological conditions of a river system; (ii) reservoir-sediment volume, grain size, and spatial distribution of grain size; (iii) regional background sediment flux; (iv) rates and processes of reservoir-sediment erosion; (v) rates and magnitudes of downstream sediment transport; (vi) styles, rates, and magnitudes of post-removal channel changes downstream; and (vii) long-term geomorphic adjustments to sediment release. Such measurements will improve both our understanding of the factors that influence responses to removals and quantification of sediment budgets. Accurate sediment budgets would not only improve our understanding of the fate of released sediment, but could also improve our ability to evaluate potential physical and ecological impacts below dam sites. They would also provide critical data for evaluating numerical models that predict physical responses to dam removals.

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Discussion

Discussion by Timothy J. Randle and Jennifer A. Bountry

This is a good comprehensive review and analysis. A comparison of numerical and physical model predictions with the results from actual dam removal would be helpful in identifying where models can provide useful and accurate results and the areas where models need to be improved.

Dam height is likely just a surrogate for reservoir sediment volume, especially if the reservoirs are full of sediment when the dams are removed. A V^* ratio of about 10 may be a more appropriate index for conditions when the overall downstream impact may be modest and not imply too much precision.

From a practical prospective, E^* may not be a "useful tool for quickly estimating possible spatial consequences of dam removals" because it is difficult to predict ahead of time, except for relatively small sediment volumes. V^* may be the more useful predictive index.

The mud portion of reservoir sediment and the width of the reservoir relative to the alluvial river width may be useful indices for predicting the percentage of reservoir sediment that erodes.

Discussion by Kimberly Hill

In the presentation of dam removal monitoring, the topic of size dependence of stored and transported sediment was discussed along with the geomorphic response of the river to the dam removal. There is both recent and historic evidence that the addition of fine particles to a gravel bed can affect the mobility of the bed and therefore might influence the geomorphic response. It would be interesting to know how and with what frequency: the smaller particles in transport and storage were monitored and geomorphic response was determined. Do you see any short-term or long-term evidence of ecological effects such as fines fouling or sand capping?

Discussion by Mike Miles

The authors indicate that the downstream response to dam removal is strongly influenced by the volume and caliber of the stored sediment. However, the volume of stored organic material is also potentially important.

Cleveland Dam is located on Coquitlam River near Vancouver (British Columbia) on the west (wet) coast of Canada. The dam was constructed in 1954 and the Coquitlam reservoir was drained in 1992 to facilitate seismic up-grading. Channel incision through the reservoir 'sediments' exposed substantial quantities of buried large wood, smaller wood pieces, and particulate organic matter as in the following figure; in places these materials comprised > 50% of the total thickness of reservoir deposits (which generally exceeded 2 m).

This observation has implications for how we estimate the volume of "sediment" deposited in a reservoir, as comparative surveys over time will overestimate the mineral constituent. The deposited organic material will affect biological oxygen demand (BOD) as it is flushed downstream and residual organic materials can create water quality issues. The organic materials also have the potential to adversely affect downstream engineering works, such as water infiltration plants (e.g., following dam removal on Elwha River in Washington State, USA; Tim Randle and Brian Cluer, pers. comm. 2015).

These observations prompt three specific questions:

1) Do the authors have any data on regional variations in the organic content of reservoir deposits?
2) Can you suggest how to determine the volume, caliber, and distribution of deposited organic material?
3) Do you have examples of how the erosion of deposited organic materials following dam removal has influenced downstream physical and biological processes?

Sediment, wood, and other organic material deposited in the reservoir behind Cleveland Dam on Coquitlam River near Vancouver (British Columbia).

Reply by the Authors

Randle and Bountry comment on four points: (i) Models: not all dam removals need to be modeled, and relatively few removals have been modeled, but we agree that comparisons of physical- and numerical-model predictions with outcomes from dam removals are needed for removals having the potential to advance scientific knowledge. Such comparisons have been done for some removals (e.g., Marmot Dam). The few model comparisons that have been published show promise for predicting the nature and pace of reservoir erosion and distribution of downstream sediment. Space limitation prevented us from delving into this topic. (ii) Dam height: there are two ways dam height influences geomorphic responses – it affects the amount of water and sediment in storage and it controls overall base-level fall. Sediment volume, however, does not necessarily correlate directly with dam height. Variations in upstream sediment delivery, poor trapping efficiency, diverse valley geometries, and episodic scour of reservoir sediment can complicate relations between dam height and sediment volume. (iii) V^* and E^*: given the small data set, an order-of-magnitude V^* threshold is perhaps more appropriate; E^* may be a useful predictor *if* first-year erosion *could* be roughly estimated, and *if* relations between E^* and sediment travel distance are robust beyond the small data set for which the metric was developed. More data are needed. (iv) Reservoir sediment composition and aspect ratio: Figure 13.3 shows relations among reservoir sediment composition, aspect ratio, and erosion. More data are needed before specific indices can be developed with confidence.

Regarding Hill's comments, several studies monitored post-removal transport of fine suspended sediment by directly measuring concentrations or by monitoring turbidity. However, such monitoring efforts typically last for relatively short time periods (a few months to a few years). As we noted (section 13.2.2.4) fine sand and mud can infiltrate gravels after dam removal and adversely affect ecological conditions despite negligible geomorphic impacts. Gravel mobility is enhanced when finer sediment, especially sand, is released by dam removal.

Miles points to a significant issue that needs study – the role of organics in dam removal. There are two types of organics of concern: large woody debris, which can affect reservoir erosion and downstream geomorphic response, and particulate organic matter, even small amounts of which can affect water quality. In section 13.2.1 we note that exhumed large woody debris can hinder reservoir erosion; it can also control the location of new bar formation downstream from a former dam site (e.g., East *et al.* 2015). We are unaware of any data that highlight regional variations of organic content in reservoir deposits. Without extensive coring or geophysical data from reservoir deposits, we do not know of any efficient way to estimate the volume, caliber, and distribution of organic material, and dam owners may not wish to invest in such surveys. However, this represents an important area of research.