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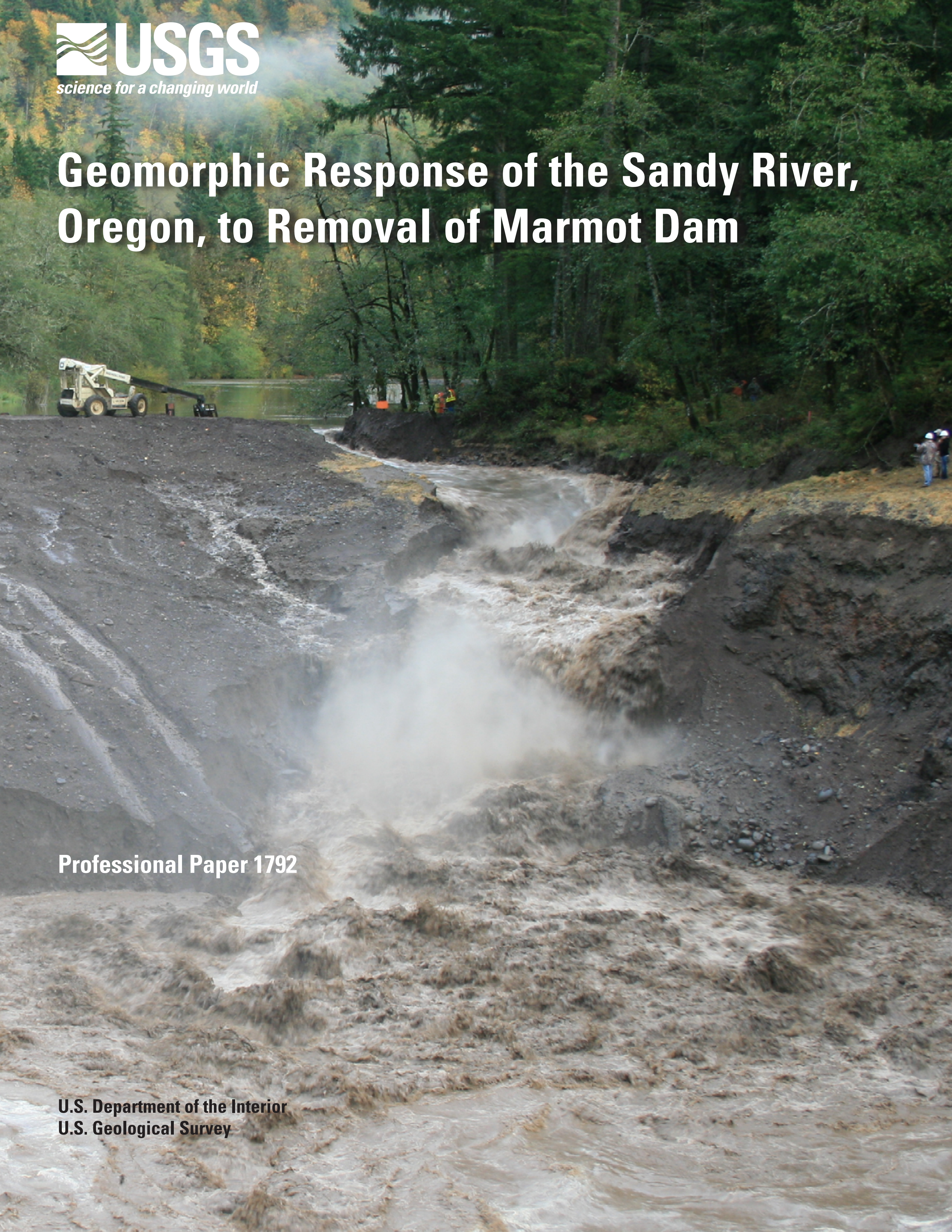
Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam



Professional Paper 1792

U.S. Department of the Interior
U.S. Geological Survey

COVER:
Breaching of the temporary cofferdam standing in place of Marmot Dam on October 19, 2007. View is from the headgate house along the canal that diverted water around the dam as part of the Portland General Electric Bull Run Hydropower Project.

Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam

By Jon J. Major, Jim E. O'Connor, Charles J. Podolak, Mackenzie K. Keith, Gordon E. Grant, Kurt R. Spicer, Smokey Pittman, Heather M. Bragg, J. Rose Wallick, Dwight Q. Tanner, Abagail Rhode, and Peter R. Wilcock

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic decimeter (dm^3)	61.02	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per minute (m/min)	3.281	foot per minute (ft/min)
meter per hour (m/hr)	3.281	foot per hour (ft/hr)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year ft/yr)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Mass	
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound, avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)

Multiply	By	To obtain
	Mass	
metric ton per day (t/d)	1.102	ton per day (ton/d)
megagram per day (Mg/d)	1.102	ton per day (ton/d)
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)
metric ton per year (t/yr)	1.102	ton per year (ton/yr)
	Hydraulic gradient	
meter per meter (m/m)	3.281	foot per foot (ft/ft)
	Concentration	
milligrams per liter (mg/L)	0.0001335	ounce per gallon (oz/gal)
	Mass transport rate	
kilograms per second (kg/s)	2.205	pounds per second (lb/s)
kilograms per second (kg/s)	86,400	kilograms per day (kg/d)
kilograms per second (kg/s)	190512	pounds per day (lb/d)

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of suspended sediment in water are given in milligrams per liter (mg/L).

Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam

By Jon J. Major[1], Jim E. O'Connor[1], Charles J. Podolak[2], Mackenzie K. Keith[1], Gordon E. Grant[3], Kurt R. Spicer[1], Smokey Pittman[4], Heather M. Bragg[1], J. Rose Wallick[1], Dwight Q. Tanner[1], Abagail Rhode[5], and Peter R. Wilcock[2]

Abstract

The October 2007 breaching of a temporary cofferdam constructed during removal of the 15-meter (m)-tall Marmot Dam on the Sandy River, Oregon, triggered a rapid sequence of fluvial responses as ~730,000 cubic meters (m^3) of sand and gravel filling the former reservoir became available to a high-gradient river. Using direct measurements of sediment transport, photogrammetry, airborne light detection and ranging (lidar) surveys, and, between transport events, repeat ground surveys of the reservoir reach and channel downstream, we monitored the erosion, transport, and deposition of this sediment in the hours, days, and months following breaching of the cofferdam.

Rapid erosion of reservoir sediment led to exceptional suspended-sediment and bedload-sediment transport rates near the dam site, as well as to elevated transport rates at downstream measurement sites in the weeks and months after breaching. Measurements of sediment transport 0.4 kilometers (km) downstream of the dam site during and following breaching show a spike in the transport of fine suspended sediment within minutes after breaching, followed by high rates of suspended-load and bedload transport of sand. Significant transport of gravel bedload past the measurement site did not begin until 18 to 20 hours after breaching. For at least 7 months after breaching, bedload transport rates just below the dam site during high flows remained as much as 10 times above rates measured upstream of the dam site and farther downstream.

The elevated sediment load was derived from eroded reservoir sediment, which began eroding when a meters-tall knickpoint migrated about 200 m upstream in the first hour after breaching. Rapid knickpoint migration triggered vertical incision and bank collapse in unconsolidated sand and gravel, leading to rapid channel widening. Over the following days and months, the knickpoint migrated upstream more slowly, simultaneously decreasing in height and becoming less distinct. Within 7 months, the knickpoint had migrated 2 km upstream from the dam site and became a riffle-like feature approximately 1 m high and a few tens of meters long. Knickpoint migration, vertical incision, and lateral erosion evacuated about 15 percent of the initial reservoir volume (125,000 m^3) within 60 hours following breaching, and by the end of the high flows in May 2008, about 50 percent of the volume had been evacuated. Large stormflows in November 2008 and January 2009 eroded another 6 percent of the original volume of impounded sediment. Little additional sediment eroded during the remainder of the second year following breaching.

The rapid erosion of sediment by the modest flow that accompanied dam breaching was driven mainly by the steep hydraulic gradient associated with the abrupt change of base level and knickpoint formation and was aided by the unconsolidated and cohesionless character of the reservoir sediment. In the ensuing months, transport competence diminished as channel geometry evolved and the river gradient through the reservoir reach diminished. Changes in profile gradient in conjunction with channel coarsening and widening led to a rapid slowing of the rate of reservoir erosion.

Sediment transport and deposition were strongly controlled by channel-gradient discontinuities and valley morphology downstream of the dam site. Those influences led to a strong divergence of sand and gravel transport and to deposition of a sediment wedge, as much as 4 m thick, that tapered to the preremoval channel bed 1.3 km downstream of the dam site. After 2 years, that deposit contained about 25 percent of the total volume of sediment eroded from the reservoir. The balance was distributed among pools within the Sandy River gorge, a narrow bedrock canyon extending 2 to 9 km downstream of the dam site, and along the channel

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farther downstream. A two-fraction sediment budget for the first year following breaching indicates that most of the gravel eroded from the reservoir reach was deposited within the sediment wedge and within the gorge, whereas eroded sand largely passed through the gorge and was broadly dispersed farther downstream.

The sequence of transporting flows affected the specific trajectory of reservoir erosion and downstream sediment transport during the 2 years following breaching. However, because the overall erosion was largely a consequence of knickpoint retreat and channel widening, which in the 2 years after removal had affected most of the reservoir reach, it is unlikely that the specific sequence of flows significantly affected the overall outcome. Because the knickpoint had largely passed through the reservoir within 2 years, and the remaining reservoir sediment is mostly isolated high above armored or bedrock banks, it is unlikely that substantial additional sediment from the reservoir site will enter the system unless very large flows occur. Continued channel evolution downstream of the dam site is probable as deposits formed in the first 2 years are episodically mobilized. Below the Sandy River gorge, detection of effects related to release of reservoir sediment is challenging, especially in areas of sand deposition, because of the high background supply of sand in the river and substantial channel dynamism.

Introduction, Purpose, and Scope

Dams and reservoirs have been an inherent part of the national landscape since at least the 17th century (Graf, 2005; Walter and Merritts, 2008), and have provided a variety of societal benefits ranging from powering early mills to serving as vast water-storage facilities that now impound years of annual flow for some large river systems. Although most dams are small and provide little or no water storage, approximately 75,000 dams in the United States are more than 2 meters (m) tall (Graf, 1999, 2005; U.S. Army Corps of Engineers, 2009).

In recent decades, the effects of dams on fluvial systems have become increasingly apparent (Williams and Wolman, 1984; Hunt, 1988; Graf, 1999, 2005, 2006; Schmidt and Wilcock, 2008; Walter and Merritts, 2008). As many of the Nation's dams have aged and lost functionality since the peak of dam building in the mid-twentieth century, safety and economic pressures combined with changing perceptions and values about river systems have spurred removal of many small dams and plans to remove some large ones (Task Committee on Guidelines for Retirement of Dams, 1997; American Rivers, 1999; Graf, 1999; Randle and others, 2010). About 900 dams nationwide have been removed since 1912, with the pace accelerating to 20 to 64 removals a year between 2000 and 2010 (American Rivers, 2010). The removal of Marmot Dam on the Sandy River, Oregon, exemplifies how dam removal is becoming an important means of restoring rivers and their dependent ecological systems (Pohl, 2002; Doyle and others, 2003b,c; O'Connor and others, 2008).

Although many consequences of damming rivers are known, less understood is how rivers respond to dam removal. Previous research on fluvial processes and use of geomorphic concepts and analogies, such as channel incision and knickpoint development, effects of increased sediment supply, and equilibrium channel development, can help guide evaluation of the geomorphic effects of dam removal (Pizzuto, 2002; Doyle and others, 2002). In addition, numerical and physical modeling can help provide quantitative insights. Keener understanding, however, relies on studying responses to dam removals. Despite the number of dams being removed nationwide, few studies have systematically evaluated the effects of dam removal on rivers and their ecosystems. The few existing geomorphic studies of dam removals mainly report on removals of small dams and do not span a wide range of river types, sediment releases, or sediment compositions (Doyle and others, 2003a; Ahearn and Dahlgren, 2005; MacBroom, 2005; Cheng and Granata, 2007; Evans, 2007; Rumschlag and Peck, 2007; Straub, 2007; Walter and Tullos, 2010; Pearson and others, 2011; Sawaske and Freyberg, 2012).

An important management issue associated with dam removal is the fate of sediment accumulated in reservoir pools (Shuman, 1995; Heinz Center, 2002, p. 85; Randle and others, 2010). For large dams, sediment accumulations can exceed tens to hundreds of millions of cubic meters, in many cases representing many years or decades of a river's sediment load. Concerns over dam removal are sharpened where stored sediment may be contaminated by decades of upstream land-use actions, such as for the recently decommissioned Milltown Dam in western Montana (Wilcox and others, 2008). Consequently, a primary research focus associated with dam removal is the fate of sediment once it is subject to renewed mobilization and fluvial transport (Doyle and others, 2002, 2003a; Cui, 2007; Cheng and Granata, 2007; Cui and Wilcox, 2008; Chang, 2008; Downs and others, 2009). The 2007 removal of Marmot Dam on the Sandy River, Oregon, provided an extraordinary opportunity to study erosion, transport, and deposition of coarse-grained, noncohesive sediment associated with dam removal on a high-gradient river.

On October 19, 2007, a temporary cofferdam standing in place of the 15-m-tall, 50-m-wide Marmot Dam was breached, allowing the 80-kilometer (km)-long Sandy River to flow freely from Mount Hood to the Columbia River (fig. 1) for the first time in nearly 100 years. Marmot Dam is one of the largest dams (in terms of its height and stored sediment volume) to be removed intentionally in the United States (table 1, fig. 2; Shuman, 1995). At the time, its breaching represented one of the greatest documented releases of stored sediment from any U.S. dam removal. Breaching of the cofferdam exposed approximately 730,000 cubic meters (m^3) of impounded sand and gravel to erosion, downstream transport, and deposition. A substantial monitoring effort, involving Portland General Electric (PGE, the utility owning the dam), several government agencies, academic institutions, and private industry, provided qualitative and quantitative observations of the fluvial response to dam removal. Monitoring activities included (1) measurements of water and sediment (suspended load and bedload) discharges at multiple locations upstream and downstream of the dam site before, during, and after breaching; (2) repeat surveys of channel profiles, cross sections, and valley-bottom topography upstream and downstream of the dam site (including multiple acquisitions of lidar topography); (3) photogrammetric measurements of channel response during breaching; (4) measurements of knickpoint migration and evolution through the reservoir reach; and (5) measurements of bed-sediment texture within the reservoir reach and at several downstream locations.

In this report, we use these measurements to document (1) volumes, rates, and processes of sediment erosion from the reservoir reach, (2) the volume, spatial extent, and character of downstream deposition, and (3) sediment transport rates during breaching and in association with several high-water episodes during the wet season subsequent to breaching. These data support a sediment budget, separated into gravel and sand components, encompassing sediment inflow into the reservoir reach, erosion from the reservoir, and downstream transport and deposition. Additional measurements of sediment erosion and deposition were continued in subsequent years.

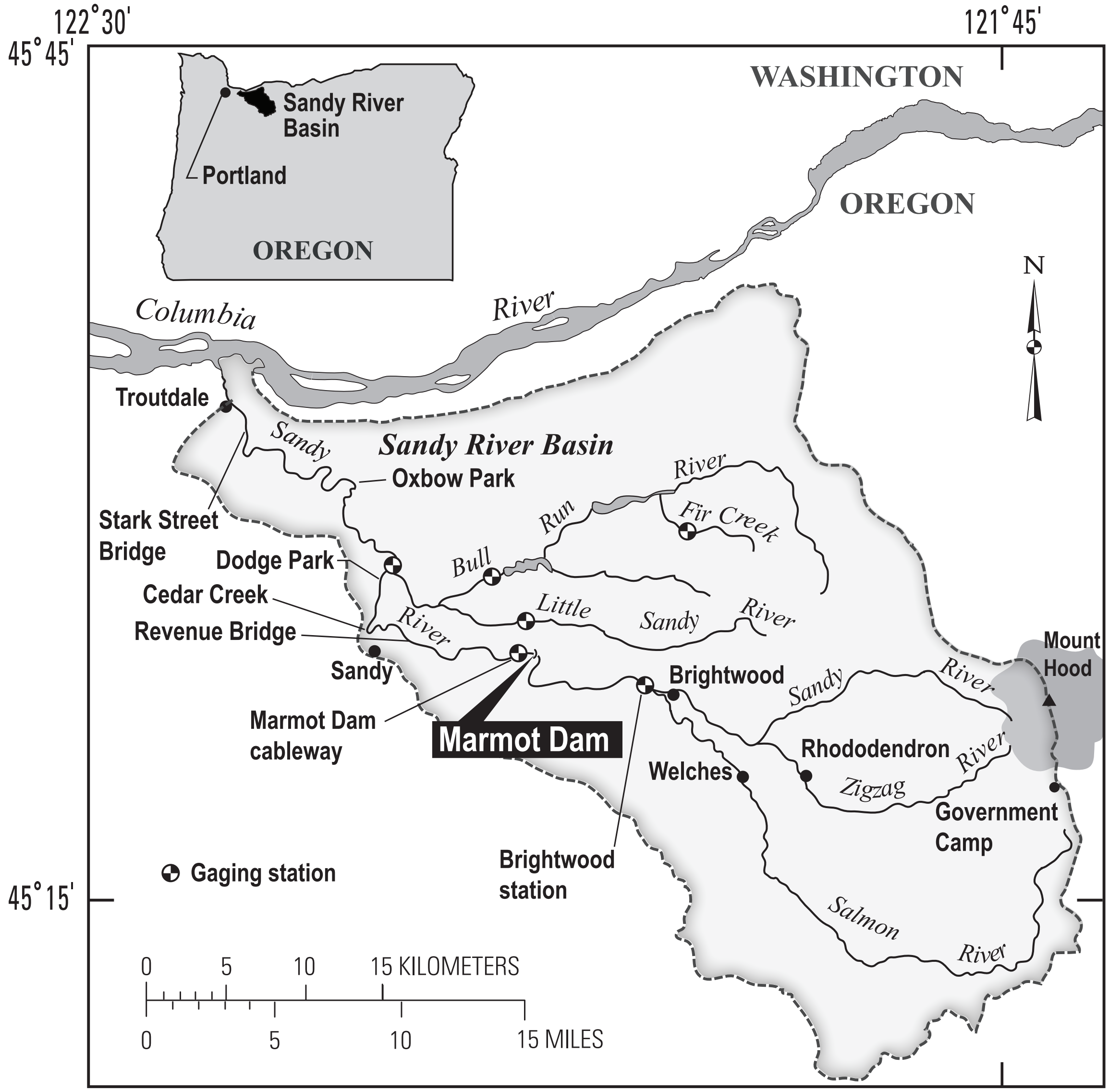


Figure 1. Location map of Sandy River Basin, Oregon, showing Marmot Dam and various sampling sites, gaging stations, and geographic locations discussed in text. The Portland Water Bureau Headworks precipitation gage is located near the gaging station on the Bull Run River.

The observations of the sediment response to the Marmot Dam removal allow for comparisons of predicted results from preremoval numerical and physical modeling efforts with actual outcomes, and they support general conclusions regarding sediment dynamics associated with dam removal.

Sandy River Basin—Physiography, Geology, and Hydrology

The Sandy River drains 1,300 square kilometers (km^2) of the rugged western Cascade Range in Oregon, including the western flank of Mount Hood volcano, before joining the Columbia River 20 km east of Portland (fig. 1). Basin altitude ranges from 3,428 m above sea level at the summit of Mount Hood to about 3 m above sea level at the river's confluence with the Columbia River. The basin is underlain by Miocene to Pleistocene volcanic and volcaniclastic bedrock (Trimble, 1963; Sherrod and Scott, 1995), and its headwaters contain abundant, coarse glacial and volcanic sediment (Crandell, 1980; Cameron and Pringle, 1986). Most of the sand and gravel transported through the system originates from late Pleistocene to Holocene glacial and volcaniclastic material from Mount Hood (Crandell, 1980; Cameron and Pringle, 1986; Pirot and others, 2008; Pierson and others, 2011) and from high bluffs cut into Pleistocene terraces flanking the river (Trimble, 1963).

The main-stem Sandy River runs 80 km from its source at Reid Glacier on the western flank of Mount Hood to its Columbia River confluence. Principal tributaries are the Zigzag River (drainage area 150 km^2), which joins the Sandy River at river kilometer (RK) 69 (defined above the Columbia River confluence), the Salmon River (280 km^2), which joins the Sandy River at RK 60, and Bull Run River (285 km^2), which joins the Sandy River at RK 30 (fig. 1). Over its course, the Sandy River evolves from a high-gradient boulder-cobble mountain stream to a low-gradient (0.0007 meter per meter, m/m) sand-bed channel near the Columbia River confluence (figs. 3, 4). The transition between a gravel and sand bed corresponds to the gradient decreasing below 0.001 m/m at about RK 10. The active channel and floodplain are variably flanked by bedrock (Tertiary volcanic, volcaniclastic, and sedimentary rocks), Pleistocene terrace gravels, and late Holocene lahar and volcanic sediment deposits from Mount Hood eruptions of the past 2,000 years. Along the lower 60 km of the Sandy River, active floodplain width averages 190 m, and the river's gradient generally decreases from about 0.007 to 0.0007 m/m. Between about RK 40 and 46, just downstream of the Marmot Dam site at RK 48.3, the river flows through a steeper (~0.01 m/m) and much narrower (average floodplain width is 34 m) section known as the Sandy River gorge before broadening abruptly downstream where the active floodplain is mostly between 100 and 500 m wide and the average gradient declines to about 0.006 m/m (fig. 3).

Flow in the Sandy River reflects the cool, wet winters and warm, dry summers of the region (fig. 5). Mean annual precipitation exceeds 2,000 millimeters (mm) for much of the Sandy River's drainage basin, most of which falls from October through May (Western Regional Climate Center, 2009) (fig. 5). Snowpack accumulates seasonally above 1,000-m altitude, and above 1,200-m altitude it can persist into July (Natural Resources Conservation Service, 2009; fig. 5). Altitudes between 200 m and 1,000 m are within the transient snow zone (fig. 5) and are subject to rain-on-snow events that can

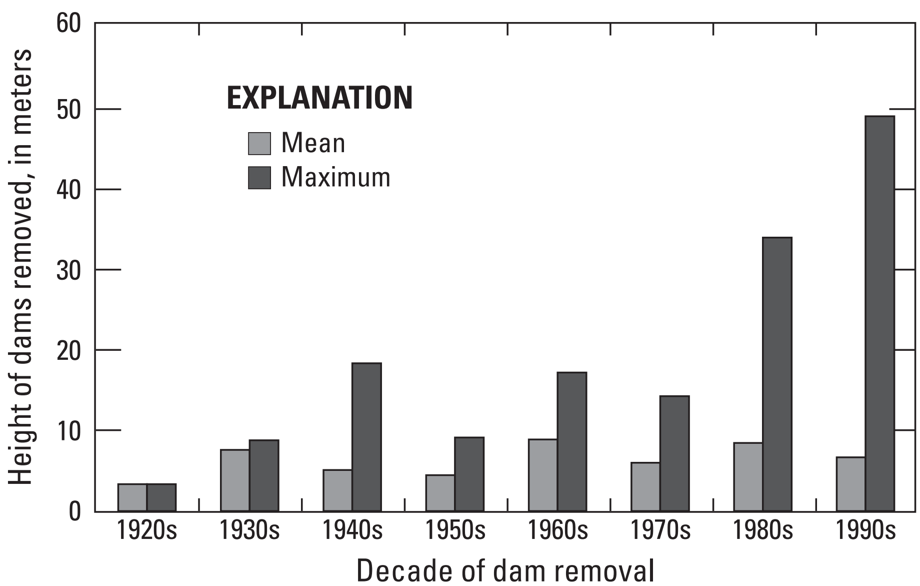


Figure 2. Mean and maximum heights of dams removed in the United States per decade from the 1920s through 1990s (after Pohl, 2003).

Table 1. Removals of dams in the United States 13 meters or taller (from American Rivers, 1999).

[trib., tributary; –, no data; m, meters; m^3, cubic meters]

State	River	Project name	Year removed	Height (m)	Stored sediment volume (m^3) [1]
Wash.	Elwha	Glines Canyon Dam	2011–2013	64	16 million
Tenn.	Duck Creek	Occidental Chem Pond Dam D	1995	49	–
Tenn.	Rocky Branch	Monsanto Dam No. 12	1990	38	–
Wash.	White Salmon	Condit Dam	2011	38	1.8 million
Tenn.	Duck Creek	Occidental Chem Pond Dam A	1995	37	–
Wash.	Elwha	Elwha Dam	2011–2013	32	3 million
Ill.	Mississippi River	Mississippi River Lock and Dam No. 26	1990	30	–
Utah	–	Atlas Mineral Dam	1994	28	–
N. Mex.	Santa Fe	Two Mile Dam	1994	26	–
Tenn.	Duck River	Monsanto Dam No. 7	1990	24	–
Kans.	–	Lake Bluestem Dam	–	21	–
N. Mex.	Pecos River	McMillan Dam	1989	20	–
Wash.	Hunters Creek	Hunters Dam	late 1990s	20	–
Tenn.	Quality Creek	Rhone Poulenc Dam No. 19	1995	18	–
Wis.	Prairie River	Prairie Dells Dam	1991	18	–
Wis.	Willow River	Willow Falls Dam	1992	18	–
Wis.	Willow River	Mounds Dam	1998	18	–
Mo.	–	Indan Rock Lake Dam	1986	17	–
Calif.	McDonald Creek (trib.)	C-Line Dam No. 1	1993	17	–
Colo.	Ouzel Creek	Bluebird Dam	1980	17	–
Idaho	Clearwater River	Grangeville Dam	1963	17	–
Mont.	Lone Tree Creek	Vaux No. 2 Dam	1995	17	–
Calif.	Mad River	Sweasey Dam	1970	17	–
Tenn.	Greenlick Creek	Monsanto Dam No. 4	1990	16	–
Tenn.	Rutherford Creek (trib.)	Occidental Chem Dam No. 6	1991	16	–
Mo.	Goose Creek	Goose Creek Lake Dam	1987	16	–
Tenn.	Greenlick Creek	Monsanto Dam No. 5A	1990	16	–
Utah	Box Elder Creek	Box Elder Creem Dam	1995	15	–
Oreg.	Sandy River	Marmot Dam	2007	15	750,000
Utah	Muddy Creek	Brush Dam	1983	15	–
N. Dak.	Stony Creek	Epping Dam	1979	14	–
Vt.	Youngs Brook	Youngs Brook Dam	1995	14	–
Ark.	Crow Creek	Lake St. Francis Dam	1989	14	–
Idaho	Clearwater River	Lewiston Dam	1973	14	–
Mont.	Peet Creek	Peet Creek Dam	1994	13	–
Tenn.	Tipton Branch	Laurel Lake Dam	1990	13	–
Ohio	Hamley Run (trib.)	Poston Fresh Water Pond Dam	1988	13	–
S.C.	Burgess Creek	Gallagher Pond Dam	1989	13	–
Mont.	Clark Fork River	Milltown Dam	2008	13	5 million[2]

[1]Data sources: Bountry and others (2010), Wilcox (2010), Inter-fluve, Inc., and others (2011).

[2]About 2.2 million cubic meters was removed manually before dam breaching.

trigger major flooding (Harr, 1981; Marks and others, 1998). The annual hydrograph of the river (fig. 5) is driven largely by prolonged, low-intensity autumn and winter rainfall augmented by spring melt of high-altitude snowpack; the greatest discharges result from heavy tropical-style rainfalls (Neiman and others, 2011) and warm rainfall on snowpack. Mean annual flow of the Sandy River at Marmot Dam (fig. 1) is about 38 cubic meters per second (m^3/s), and the mean annual flood is about 460 m^3/s (table 2), but late summer flows typically are less than 20 m^3/s. The 0.5 annual-exceedance-probability discharge (the 2-year return-interval flow) is 415 m^3/s, and the 0.01 annual-exceedance-probability discharge (the 100-year return-interval flow) is 1,425 m^3/s (table 2). Although the Bull Run River (fig. 1) contributes substantial flow to the Sandy River (table 2), it contributes little sediment because most is retained by reservoirs and lakes in the upper Bull Run watershed.

The unconsolidated volcanic and glacial debris in the Sandy River headwaters and in exposed banks and bluffs along the channel provide abundant sediment to the river. For example, between 2000 and 2006 multiple debris flows having volumes of a few tens of thousands to a few hundreds of thousands of cubic meters entered the Sandy River headwaters (T. Deroo, U.S. Forest Service, written commun., 2009). On the basis of regional river data indicating an average annual suspended-sediment yield of 100–200 megagrams (Mg; equivalent to a metric ton, t) per square kilometer (Mg/km^2) (Major and others, 2000), and further assuming an average suspended-load-to-bedload transport ratio of 3:1 and an average transport bulk density of 1.7 Mg/m^3, we estimate that the average annual volume of sediment transported in the Marmot Dam reach of the Sandy River is about 100,000–200,000 m^3. This estimate is consistent with the approximately 100,000 m^3 of sediment that passed a measurement station at Brightwood, Oregon, 10 km upstream of Marmot Dam (fig. 1), in water year (WY) 2008 (a water year runs from October 1 through September 30).

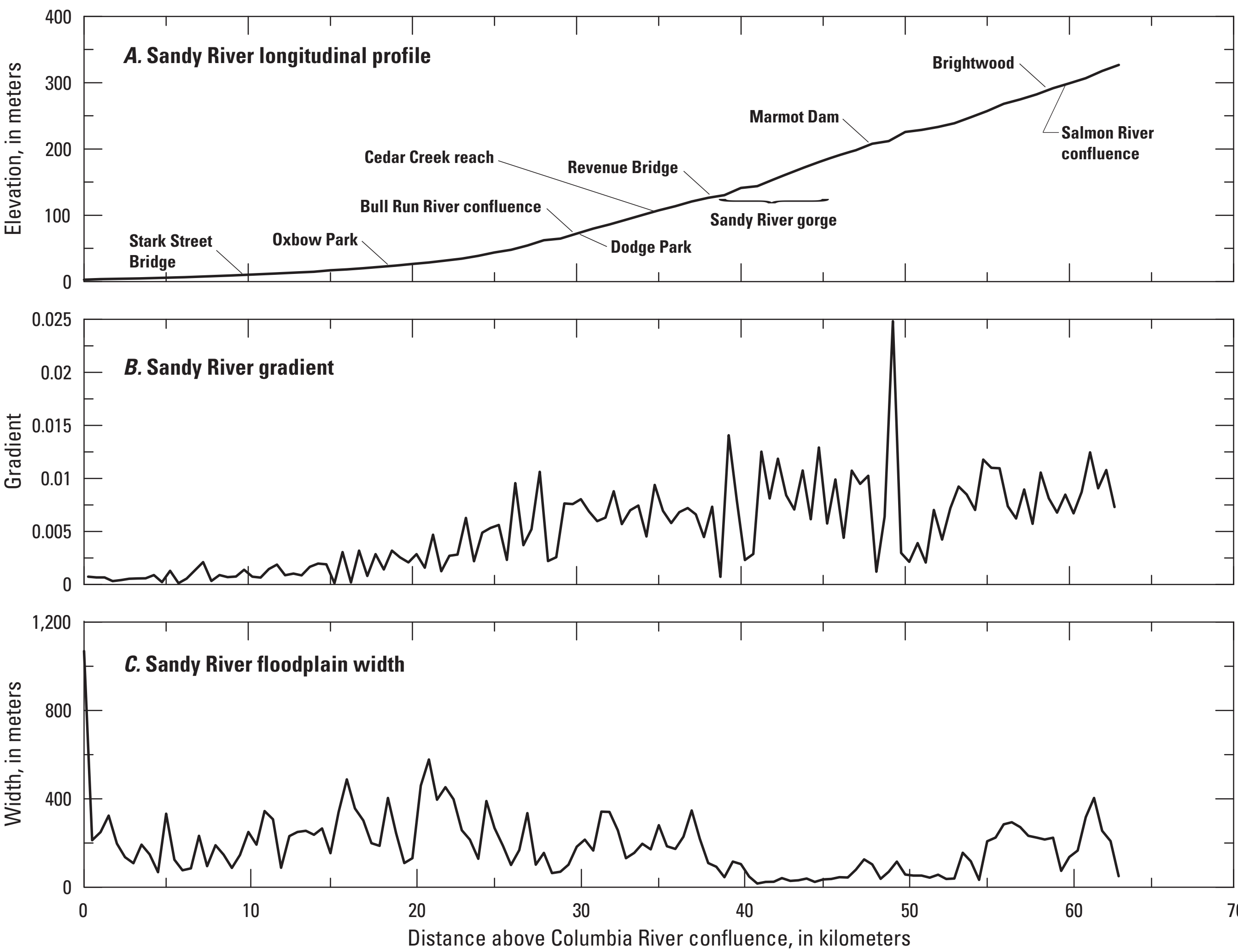


Figure 3. Characteristic longitudinal profile, channel gradient, and floodplain width of the Sandy River. Profile and width data were extracted from a preremoval digital elevation model.

Figure 4. Photographs of reaches of Sandy River discussed in text (see figure 1). *A*, Brightwood looking upstream; wetted channel width approximately 25 meters (m). *B*, At Marmot Dam looking downstream; wetted channel width approximately 25 m. *C*, Near Revenue Bridge looking upstream; wetted channel width about 40 m, note person (in circle) for scale. *D*, Dodge Park looking downstream; wetted channel width about 30 m, note people for scale. *E*, Stark Street Bridge looking upstream; wetted channel width about 45 m. *F*, Troutdale looking upstream; wetted channel width about 50 m, note people for scale.

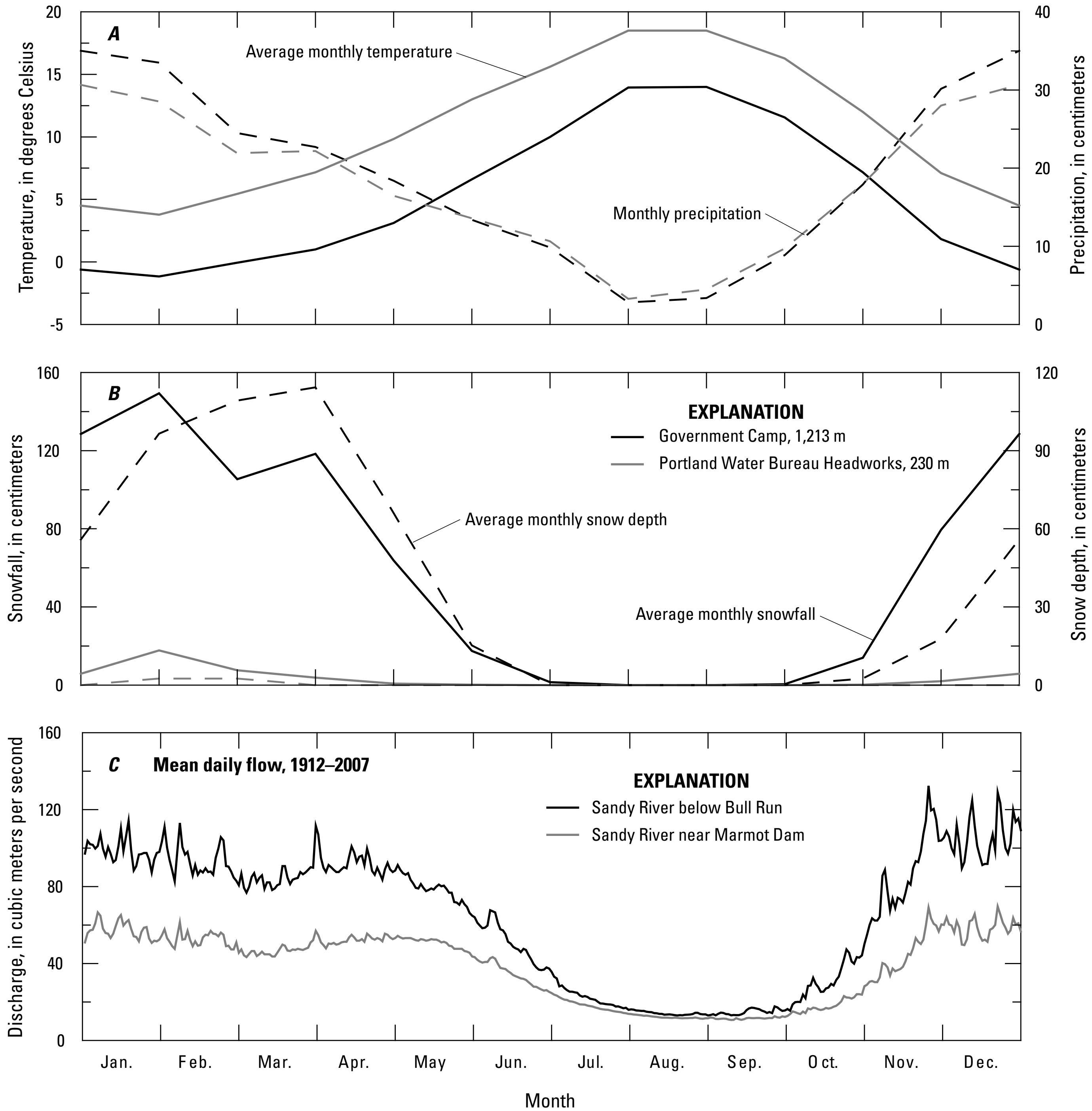


Figure 5. Regional climate and hydrology for the Sandy River Basin. *A*, Average monthly temperature and precipitation at Government Camp (elevation 1,213 meters (m); 1951–2005) and the Portland Water Bureau Headworks in the Bull Run River Basin (elevation 230 m; 1904–2008) (fig. 1). See figure 5*B* for explanation of line colors. *B*, Average monthly snowfall and snow depth. *C*, Seasonal distribution of mean daily streamflow on the Sandy River near Marmot Dam and below Bull Run (1912–2007).

Table 2. Hydrological characteristics of the Sandy River.

[Q, water discharge; km^2, square kilometers, m^3/s, cubic meters per second]

Station	Station ID	Basin area (km^2)	Gage date (years of record)	Mean annual flow (m^3/s)	Mean annual flood (m^3/s)	Q_{2yr} (m^3/s) [1]	Q_{5yr} (m^3/s)	Q_{10yr} (m^3/s)	Q_{25yr} (m^3/s)	Q_{50yr} (m^3/s)	Q_{100yr} (m^3/s)
Sandy near Marmot Dam	14137000	684	1912–2007 (93)	37.9±1.1	464±261	414	632	799	1,028	1,221	1,425
Bull Run near Bull Run [2]	14140000	277	1908–2008 (101)	18.6±5.1	308±124	286	405	480	570	634	696
Sandy below Bull Run	14142500	1,129	1911–2008 (64)	64.2±13.5	798±389	719	1,065	1,322	1,679	1,968	2,278
Little Sandy near Bull Run	14141500	57.7	1920–2008 (89)	4.1±0.8	65±30	61	87	105	130	150	170

[1]Flow frequency statistics for Sandy River near Marmot Dam and Little Sandy River from Cooper (2005); statistics for Bull Run and Sandy below Bull Run from G. Hess (USGS, written commun., 2011). Q_{2yr} is the 2-year-recurrence-interval discharge.

[2]This is a regulated river; hence, all flow values are regulation affected.

Marmot Dam Setting and Removal

The setting and removal strategy for Marmot Dam significantly influenced the resulting fluvial response. The removal process was guided, in part, by several studies done before decommissioning. Those studies provide a valuable basis on which to compare predicted consequences of dam removal with actual consequences.

Context

Marmot Dam was the only dam on the main-stem Sandy River and was located near the middle of the basin at RK 48.3 (fig. 1). The dam was downstream of the Salmon River confluence but upstream of the Bull Run River confluence and 2 km upstream of the entrance to the Sandy River gorge. The original dam, a rock-and-timber crib structure completed in 1913 by the Mount Hood Railway and Power Company (Taylor, 1998), was modified in 1989 resulting in a 15-m-high, 50-m-wide concrete dam (fig. 6). Behind the dam, a narrow, sediment-filled reservoir extended about 3 km upstream. PGE owned and operated the dam, which diverted water from the Sandy River as part of the company’s 22 megawatt Bull Run Hydropower Project, an elaborate infrastructure that delivered water from the Sandy River to a powerhouse 9 km distant using a system of canals, flumes, tunnels, and off-channel storage (Esler, 2009). In 1999, facing a 2004 expiration of its Federal Energy Regulatory Commission operating license and high anticipated costs (relative to revenue) for future maintenance and upgrading of fish passage around the dam, PGE announced it would surrender its license and decommission the hydropower project (Esler, 2009). That decommissioning culminated in the removal of Marmot Dam and associated facilities in

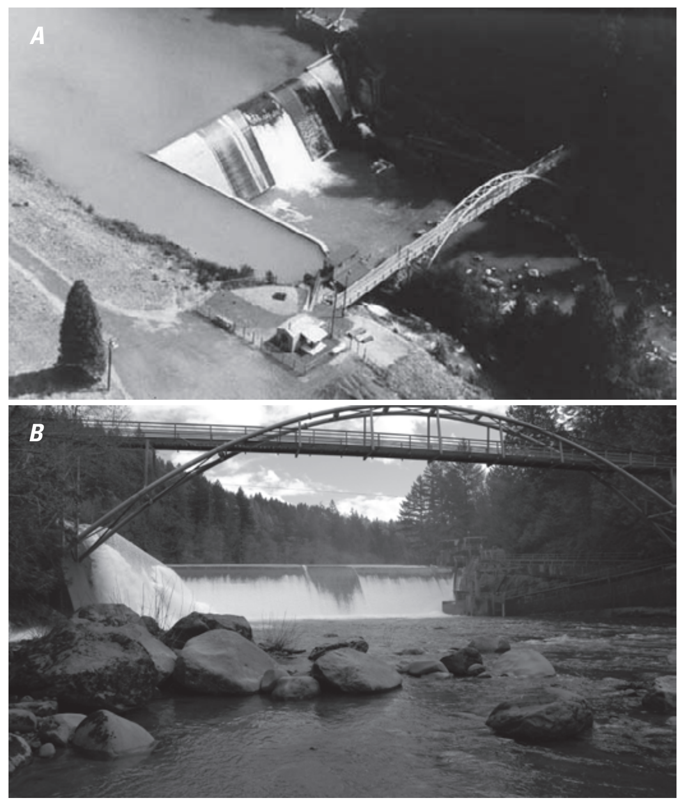


Figure 6. Views of Marmot Dam before breaching. *A*, Aerial view to the southeast of Marmot Dam and its water-diversion canal. The canal diverted water from the Sandy River to the powerhouse on the Bull Run River. The camera used to obtain the imagery shown in figure 7 was mounted to the headgate house on the diversion canal on the upstream side of the pedestrian bridge. Photo courtesy of Portland General Electric. *B*, Ground-level view of Marmot Dam looking upstream. Note the boulders and texture of the river channel immediately downstream of the dam before removal.

2007, as well as the removal of a smaller structure on the Little Sandy River in 2008.

Of the many issues surrounding the decision to remove the dam, one of the most difficult concerned handling of the sediment that had accumulated in the reservoir reach (Esler, 2009). At the time of decommissioning, the 3-km-long reservoir behind the dam was filled with nearly 750,000 m^3 sand and gravel (Squier and Associates, 2000), a volume equivalent to about 5 to 10 years of average annual sediment load. Most sediment transported by the river had been passing the dam for decades. Ultimately, PGE opted, with consensus from several local stakeholder groups and various Federal, State, and local agencies, to remove the dam as quickly as possible with minimal manual removal of stored sediment (Esler, 2009), a scenario informally termed the "blow-and-go" option. The attractive elements of this approach were its low cost and minimal in-channel disturbance during demolition. The primary drawbacks of this plan were (1) the uncertain consequences (and possible adverse effects to downstream aquatic habitat) of providing an energetic, high-gradient mountain river unfettered access to a large volume of unconsolidated, coarse-grained sediment and (2) the possibility that incomplete incision of reservoir sediment might produce a barrier to fish passage.

Preremoval Studies

In planning for removal, PGE commissioned physical and numerical studies to characterize the preremoval reservoir and downstream channel conditions and to predict the effects of a variety of removal scenarios (Squier and Associates, 2000; Stillwater Sciences 2000a,b; Stewart and Grant, 2005; Marr and others, 2007; Cui and Wilcox, 2008). The reservoir characterization studies estimated the total volume of stored sediment and discerned that it was composed approximately of equal proportions of uncontaminated, homogenously mixed sand and gravel (Squier and Associates, 2000). The studies predicting removal consequences indicated that under the preferred removal scenario: (1) headward knickpoint migration, partly guided by pre-dam valley-bottom topography, would drive rapid reservoir erosion (Marr and others, 2007); (2) the river slope profile through the reservoir reach would at first rapidly and then gradually decline and approach upstream and downstream values within 5 to 10 years (Stillwater Sciences, 2000a; Cui and Wilcox, 2008); and (3) a substantial volume of coarse sediment would accumulate between the dam site and the entrance to the Sandy River gorge 2 km downstream in the first year following removal (Stillwater Sciences, 2000a; Cui and Wilcox, 2008). Numerical models also predicted that in the first year following removal there would be lesser, but locally significant, gravel accumulation between the Sandy River gorge exit and the Bull Run confluence and local sand accumulation of as much as 0.4-m thickness in the lower 10 km of the river valley (Stillwater Sciences, 2000a,b; Cui and Wilcox, 2008).

Dam Removal

PGE removed Marmot Dam between July 1 and September 30, 2007 (Esler, 2009). Removal entailed building an earthen cofferdam across the top of the impounded sediment 70 m upstream of the concrete structure, diverting the Sandy River around both the coffer and concrete dams, installing wells and pumps to dewater and stabilize the cofferdam and underlying sediment, removing about 20,000 m^3 of sediment (less than 3 percent of the total impounded) between the coffer and concrete dams, and then demolishing and removing the concrete structure.

Breaching of the cofferdam was scheduled for late 2007, between seasonal fish runs, to minimize adverse impacts to resident and migratory fish. An additional objective of the schedule was to have sufficient flow at breaching to reduce the risk of blocking fish passage owing to incomplete incision through reservoir sediment. A controlled breach, however, was constrained by the 60 m^3/s capacity of the diversion channel. At the time of breaching, the reservoir was completely filled with sediment except for a shallow pool of water about 1.5 m deep. Experiments using a scaled physical model of Marmot Dam and its impounded reservoir suggested that initial breaching of the south end of the cofferdam (river left) would most effectively maximize sediment removal (Marr and others, 2007).

Heavy rainfall, a rising river, and a discharge forecast for 68 m^3/s prompted PGE to begin the breaching process at about 1000 Pacific Daylight Time (PDT) on October 19, 2007. Pumps dewatering the cofferdam and underlying sediment were removed beginning around 1200 PDT. At about 1330 PDT, water began seeping through the earthen dam and triggering small but growing mass failures on its downstream face. At about 1700 PDT, with flow approaching 50 m^3/s, the cofferdam crest was notched and water began spilling (fig. 7; Major and others, 2010). An initial channel about 2 to 3 m wide and 1 m deep developed at the dam crest and on the dam face (figs. 7, 8; Grant and others, 2008). By 1720 PDT, the notch was 3 to 4 m wide and about 1 to 2 m deep and the channel on the dam face had developed multiple 2- to 3-m-high steps. The steps on the dam face migrated upstream at a rate of meters per minute (Grant and others, 2008), but the notch at the dam crest did not incise significantly until 1745 PDT, when the steps on the dam face coalesced, intercepted the dam crest, and formed a knickpoint about 2 m tall that then migrated rapidly upstream. At that time, flow vigorously enlarged the breach and the small volume of impounded water was rapidly released (figs. 7, 8). By 1800 PDT, the river had incised nearly 8 m through the earthen dam (fig. 9) and began eroding laterally; by 2330 PDT most of the cofferdam and underlying sediment had been removed, leaving only the well casings that housed the dewatering pumps to mark the location of the former cofferdam (fig 7; Major and others, 2010).

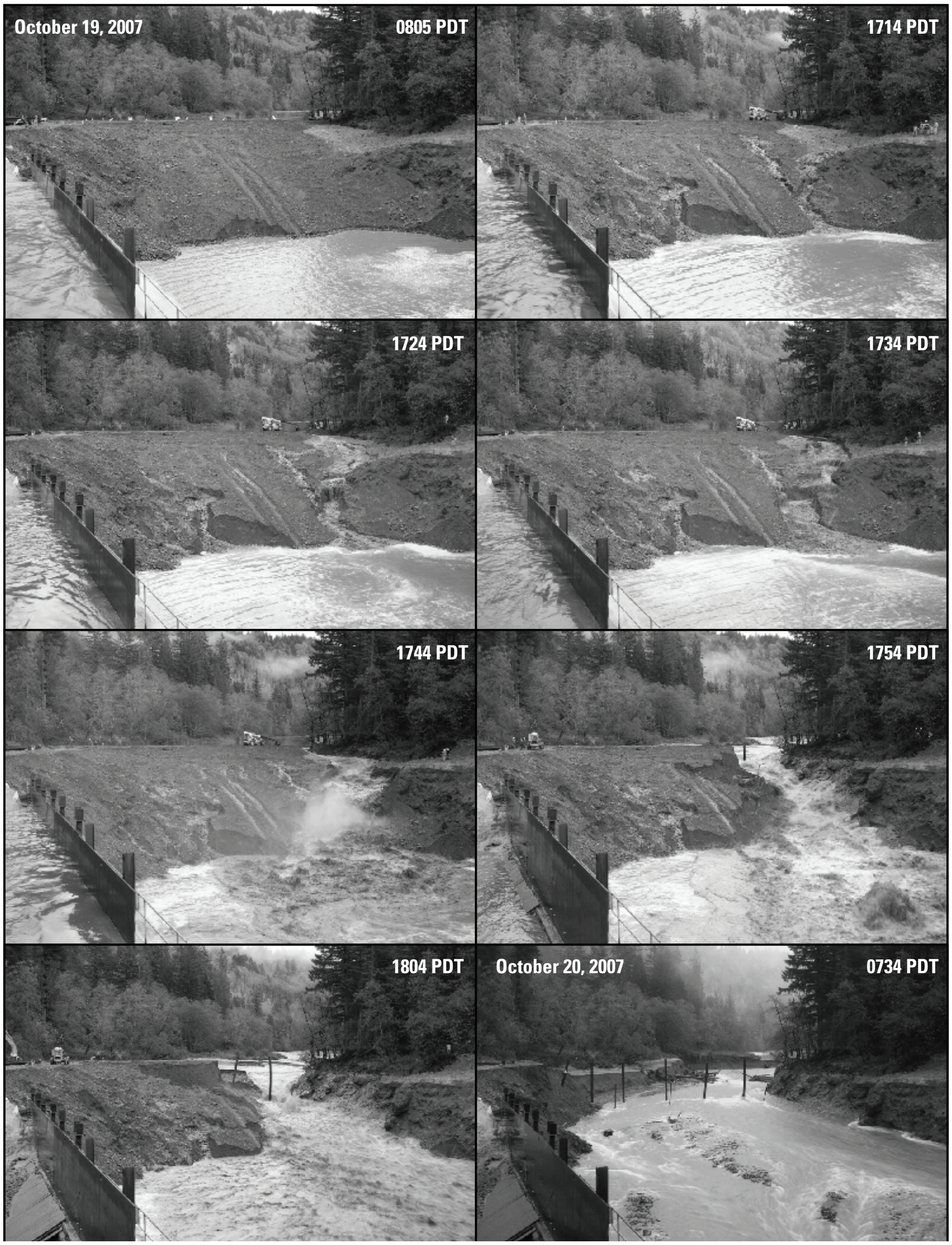


Figure 7. Time-lapse images of breaching of the temporary earthen cofferdam and underlying reservoir sediment after removal of the concrete Marmot Dam structure. The first image, at 0805 Pacific Daylight Time (PDT) on October 19, 2007, was taken before the pumps dewatering the earthen dam were removed. Shortly after the pumps were shut off, water began seeping through the sediment, gradually triggering small mass failures. Once all the pumps were removed, crews carved a small notch in the crest of the dam and released the impounded water (~1700 PDT). Note the seepage and mass failures on the face of the earthen dam evident at 1714 PDT and the channel and small knickpoints that developed as water overtopped the dam after it was notched. Once the multiple knickpoints migrating up the dam's face reached the crest and coalesced (~1740 PDT), the dam began to erode rapidly and a knickpoint raced up the reservoir reach (see also Major and others, 2010). By the following morning, the earthen dam and a substantial volume of reservoir sediment had been removed. Exposed well casings are about 10 meters tall and mark the former location of the cofferdam. Note people in some images for scale.

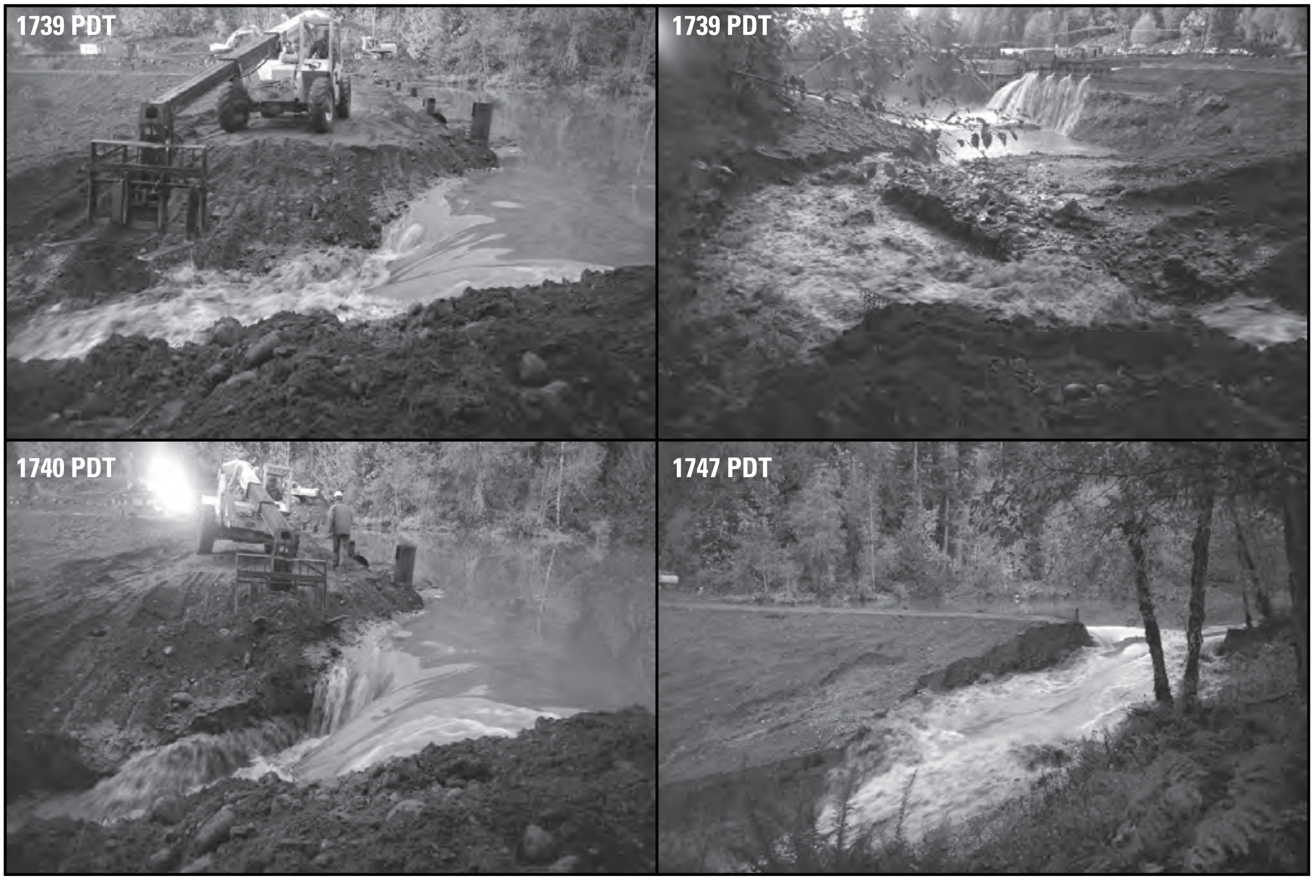


Figure 8. Erosion at crest of the earthen cofferdam during breaching of Marmot Dam on October 19, 2007.

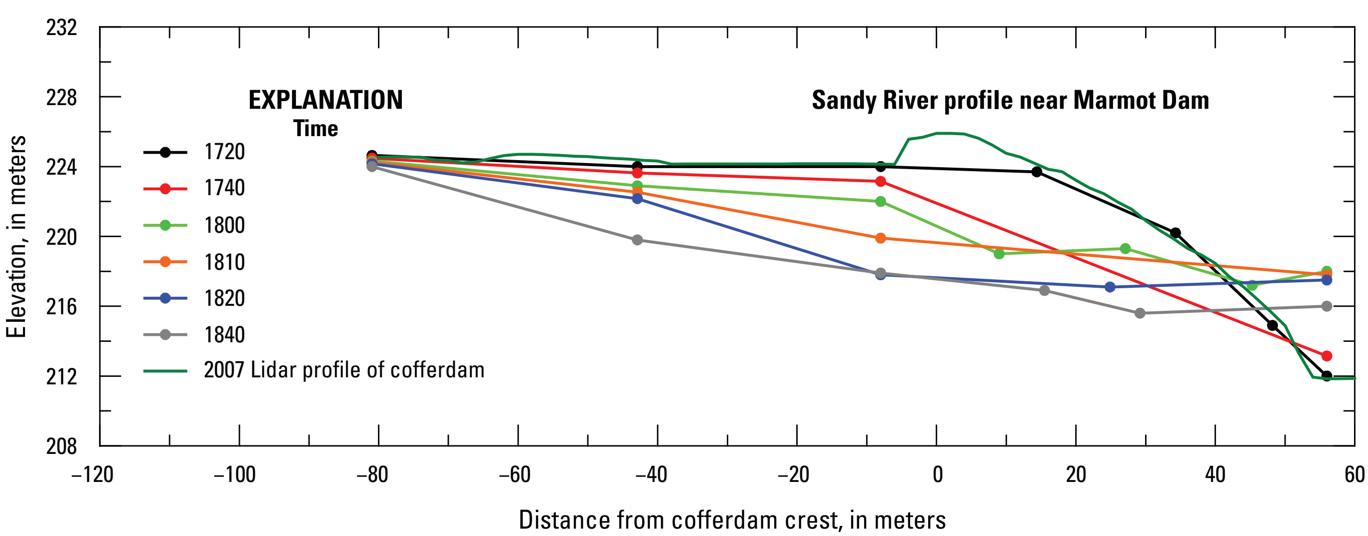


Figure 9. Longitudinal-profile development of the Sandy River within tens of minutes following breaching of the earthen cofferdam standing in place of Marmot Dam on October 19, 2007. The profiles are based on average water-surface elevation (NAVD88 datum) measured photogrammetrically from images obtained every 10 minutes during and after breaching by cameras placed around the lower reservoir reach (see Major and others, 2010). Times shown are Pacific Daylight Time (PDT). Positive distances are downstream.

Reservoir Erosion

One focus of our study was to document the rates and processes by which the stored sediment was eroded. In support of this effort, we (1) conducted channel profile and cross-section surveys multiple times after breaching; (2) analyzed high-resolution airborne lidar topography acquired twice before breaching (October 22, 2006, and September 29–October 7, 2007) as well as a year after breaching (September 29–October 1, 2008); (3) compared repeat cross-section surveys by David Evans and Associates (DE&A), a contractor for PGE; (4) made photogrammetric measurements using fixed cameras stationed around the lower 300-m reach of the impounded reservoir; (5) monitored knickpoint position and height by Global Positioning System (GPS) and channel surveys during and subsequent to breaching; and (6) made postremoval grain-size measurements (both surface pebble counts and subsurface bulk samples). We consider sediment evacuation from the reservoir on two time scales: (1) the period of rapid erosion during breaching and the ensuing ~60 hours and (2) the subsequent period of much slower erosion during the winters of 2007–08 and 2008–09. Methods for computing reservoir erosion, along with analysis of error, are provided in the appendix.

Knickpoint Migration and Initial Sediment Erosion

On breaching, reservoir erosion resulted mainly from interactions among knickpoint migration, channel incision, and lateral erosion. Headward erosion began after an approximately 2-m-high knickpoint developed at the dam crest during breaching (fig. 8). Once formed, the knickpoint split immediately into two arcuate knickpoints that advanced rapidly upstream at meters per minute for the first several minutes (fig. 10). The knickpoint on river right moved laterally toward the north shore of the reservoir, whereas the knickpoint on river left advanced more directly upstream. The lateral knickpoint stalled by 1802 PDT because the knickpoint advancing more directly upstream incised through the sediment more rapidly and diverted river flow from the lateral knickpoint (fig. 10). Rapid incision associated with knickpoint passage swiftly formed a narrow channel upstream of the cofferdam along river left, a channel that maintained a nearly constant width for several hours before it progressively widened (Major and others, 2010). The migrating knickpoint advanced 150 m upstream within 50 minutes of breaching of the cofferdam but then slowed substantially, requiring more than 15 hours to advance an additional 250 m (fig. 10). As the knickpoint advanced upstream, its height diminished from about 2 m to less than 1 m. After knickpoint passage and slowing of channel incision, channel widening began (Major and others, 2010).

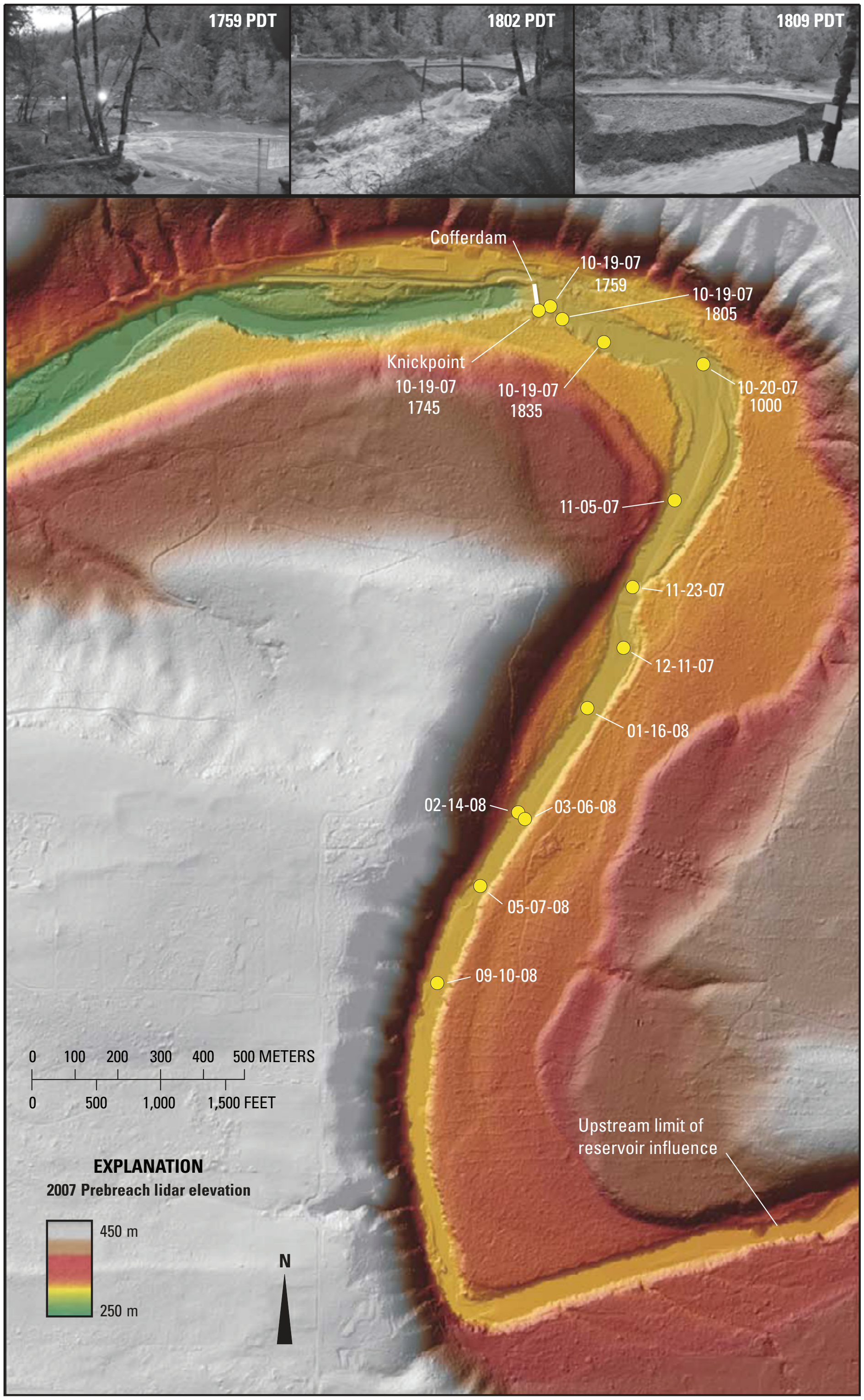
Within 90 minutes after breaching, the Sandy River had incised as much as 10 m vertically at the cofferdam site (fig. 9), and after several hours the river formed a channel as much as 40 m wide through much of the lower 300 m of the reservoir (fig. 7; Major and others, 2010). As a result, the abrupt gradient discontinuity owing to the presence of the dam diminished considerably (figs. 7, 9). An analysis of oblique photographs taken at 10-minute intervals indicates that the river incised the sediment at and near the cofferdam at rates as great as 12 m per hour (m/hr) in the first 2 hours after breaching (fig. 9). Rapid incision promoted nearly continuous collapse of meters-high vertical banks of unconsolidated fill (fig. 11; Major and others, 2010), leading to channel widening at rates as great as 10 m/hr (table 3), especially in the first 24 hours following breaching.

The breaching flow and ensuing 60 hours of high flow (fig. 12) eroded approximately 125,000 m^3 of sediment from the reservoir reach (table 3), mainly from the lower 500 m (figs. 13, 14). This large amount of erosion, about 17 percent of the volume of impounded sediment and approximately equal to the average annual sediment load of the Sandy River at this location, was associated with a peak flow of about 80 m^3/s (fig. 12)—a flow just twice the mean annual river flow and only 20 percent of the 2-year return-interval discharge at this position in the basin. River discharge reached that peak 32 hours after breaching, then subsequently waned to its mean annual value after 65 hours (fig. 12). On the basis of time-lapse photography (Major and others, 2010), we estimate that nearly all of the channel change documented by our first postbreach survey in early November 2007 occurred within 60 hours after breaching.

Longer Term Reservoir Erosion and Bed Coarsening

Continued erosion and changes in channel gradient in the reservoir reach were monitored through September 2009 using traditional survey methods. The extent of each survey varied depending on flow and access conditions, but all surveys extended at least 1 km upstream of the dam site (fig. 14). Each survey allowed estimation of the additional volume eroded since the previous survey. Our surveys were supplemented by DE&A cross-section surveys, a postbreach airborne lidar survey on September 29–October 1, 2008, and episodic mapping of the knickpoint position and height between surveys.

The sequence of surveys shows progressive incision and decreasing channel gradient in the reservoir reach (fig. 14) and the diminishing rates of knickpoint migration (fig. 10), volumetric sediment loss (fig. 15), and channel widening (table 3). After the first 60 hours, the knickpoint had evolved to a low-relief (<1 m tall) riffle several meters long. Subsequently, its rate of migration through the reservoir slowed considerably, from tens of meters per day in the first month following breaching to just a few meters per day during the 7- to 12-month period after breaching (table 3). By early November 2007, this discontinuity had migrated about 700 m



Base map modified from Oregon Department of Geology and Mineral Industries 2007 digital data, 1-meter resolution.
Lambert Conformal Conic projection.
Horizontal datum: North American Datum of 1983.

Figure 10. Knickpoint migration through the reservoir reach following breaching of Marmot Dam. Photographs taken on October 19, 2007, shortly after breaching was initiated show the remnant arcuate knickpoint that advanced toward the north side of the reservoir and the cap of fine sediment that overlies the sand and gravel that composes the bulk of the reservoir sediment. On the lidar image, dates (and times) of knickpoint position are shown. By October 20, 2007, the knickpoint had diminished to a low-relief riffle. Approximate positions of the knickpoint (riffle) in February and March 2008 were obtained using a handheld Global Positioning System (GPS) during visits between reservoir surveys. The topographic base was acquired using airborne lidar between September 29 and October 7, 2007. Date format is two-digit month, day, and year, and times for October 2007 dates are Pacific Daylight Time (PDT).

through the reservoir, and by mid-December 2007, following the year's peak discharge, it had migrated about 1 km. About a year after breaching, the riffle had migrated nearly 2 km (fig. 10). Following large storm flows in November 2008 and January 2009 (fig. 12), the riffle had migrated farther upstream, but had become less well defined, and its exact position was uncertain because our surveys in January and September 2009 did not reach far enough upstream. Annual surveys of channel cross sections in the reservoir reach (fig. 16) document local incision and widening, with magnitudes of both decreasing upstream.

Our surveys show that the magnitude and rate of reservoir erosion were initially large and rapid but then diminished substantially (fig. 15). Within 2 months, nearly 40 percent of the initial sediment volume was removed. By January 2008, the magnitude and rate of erosion had slowed substantially, and after 1 year approximately half of the initial sediment volume had eroded (fig. 15; table 3). The only subsequent episodes of substantial reservoir erosion occurred when a net volume of 43,000 m^3 was evacuated during the second year following breaching in conjunction with two large flows in November 2008 and January 2009 (fig. 12; table 3), the latter of which exceeded the 10-yr return-period discharge (table 2). Cross section surveys (fig. 16) indicate that much of this later erosion further widened and incised the channel, particularly between 620 m and 2,180 m upstream of the dam site. By September 2009, nearly 2 years after breaching, a total of 425,000 m^3 of sediment had been eroded—nearly 60 percent of the total reservoir volume. This volume of sediment is not an unusual load for the Sandy River, probably about double the average annual sediment load for this 2-year period. Although the estimated magnitude of erosion may have been affected by sediment input to the reservoir reach from upstream, the preponderance of evidence, including extensive lateral erosion and incision between surveys, suggests that sediment deposition within the reservoir reach did not significantly affect our erosion measurements.

Rates of channel widening within the reservoir reach similarly diminished with time (table 3). Lateral erosion initially widened the reservoir channel in the immediate vicinity of the cofferdam at rates exceeding 200 m per day (m/d). Farther upstream in the reservoir, the channel widened considerably more slowly at averaged rates as great as 30 m/d in the period between breaching and our first reservoir survey

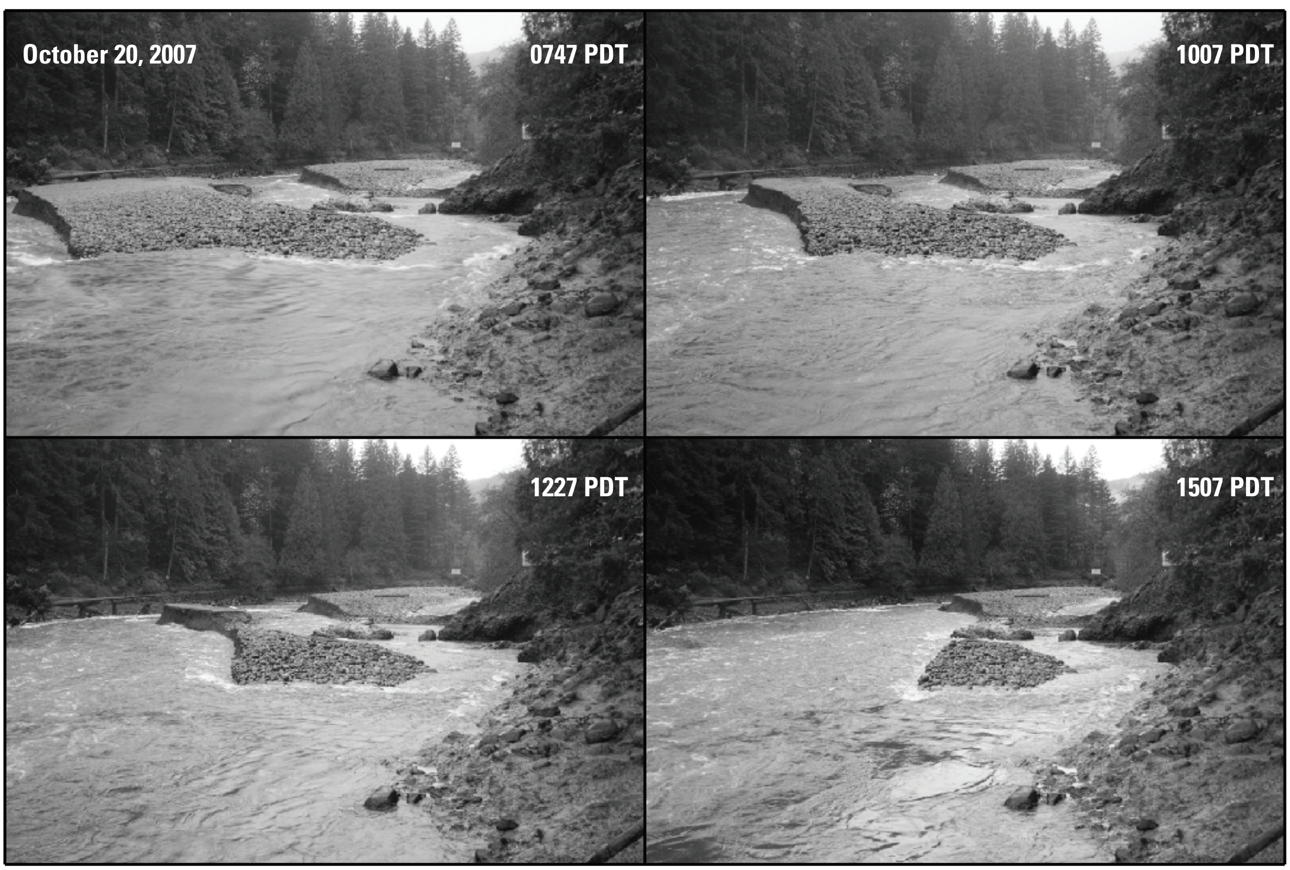


Figure 11. Time-lapse images of reservoir erosion following breaching of Marmot Dam. The first photograph is from the morning following breaching (see also Major and others, 2010). View is downstream from the north (right) side of the reservoir about 300 meters upstream of the dam site. Times shown are Pacific Daylight Time (PDT).

Table 3. Magnitudes and rates of sediment erosion, knickpoint retreat, and channel widening within the Marmot Dam reservoir reach and associated peak discharges.

[–, no data; m, meters; m/d, meters per day; m^3, cubic meters; m^3/d, cubic meters per day; m^3/s, cubic meters per second]

Survey date	Mean erosion volume (10^3 m^3)	Minimum erosion volume (10^3 m^3)	Maximum erosion volume (10^3 m^3)	Cumulative erosion volume (10^3 m^3) [1]	Percent of initial sediment volume eroded [1]	Reservoir erosion rate (10^3 m^3/d) [2]	Knickpoint position upstream from cofferdam (m)	Knickpoint migration rate (m/d)	Maximum channel widening rate within reservoir (m/d)	Respon-sible peak discharge (m^3/s) [3]	Peak discharge date
Oct. 19–21, 2007	–	–	–	–	–	–	150–400	480–4,800	260	80[5]	Oct. 20, 2007
Nov. 5, 2007	125	108	142	125	17	30–60[4]	725	20–100	30	80[5]	Oct. 20, 2007
Nov. 23, 2007	82	78	86	207	11	3–5	950	10–40	0.7	176	Nov. 17, 2007
Dec. 11, 2007	79	75	82	286	11	4–5	1,100	8–10	1.5	231	Dec. 3, 2007
Jan. 16, 2008	42	41	44	328	6	1–2	1,250	4–8	1.3	230 138	Dec. 23, 2007 Jan. 12, 2008
May 7, 2008	20	19	21	348	3	0.2–0.3	1,750	4–6	0.1	124	Mar. 18, 2008
Sep. 10, 2008	25	24	26	373	3	0.2–0.4	2,000	2–4	0.4	208	May 17, 2008
Jan. 21, 2009	43	43	43	416	6	0.2–0.3	–	–	0.2	572 850[6]	Nov. 13, 2008 Jan. 1, 2009
Sep. 8, 2009	6	6	6	422	1	0.03	–	–	0.2	cumulative	–

[1]Based on mean erosion volume.

[2]Maximum rate estimates are bounded by timing of the peak discharge likely responsible for most of the erosion, and minimum estimates are bounded by the dates of reservoir surveys.

[3]Discharges are rounded to the nearest 0.5 m^3/s.

[4]Estimated initial erosion rate. The computation assumes that the bulk of the initial 125,000 m^3 of sediment eroded occurred in the first 48 to 96 hours following breaching.

[5]The median discharge at the Marmot measurement station during the 60 hours following breaching of the dam was 52.3 m^3/s.

[6]Estimated peak discharge.

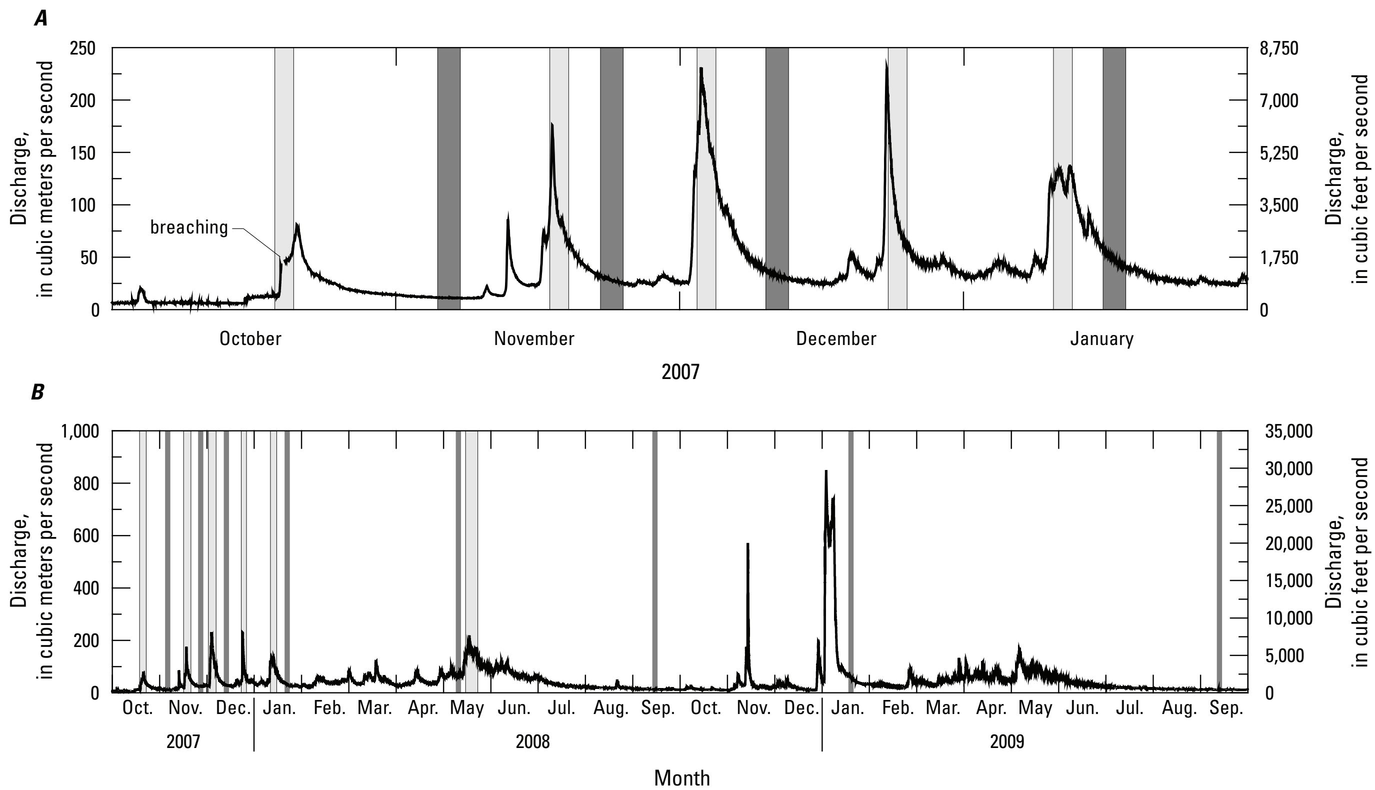


Figure 12. Hydrograph of Sandy River near Marmot Dam (see fig. 1; table 2) estimated for water years 2008 and 2009. Light gray vertical bars denote periods of high water when sediment and water discharge measurements were made at multiple measurement stations. Dark gray vertical bars denote times of surveys of reservoir reach and downstream channel. *A*, Detailed hydrograph of first few months after breaching, from October 2007 through January 2008. *B*, Hydrograph for the 2 years following breaching, from October 2007 through September 2009.

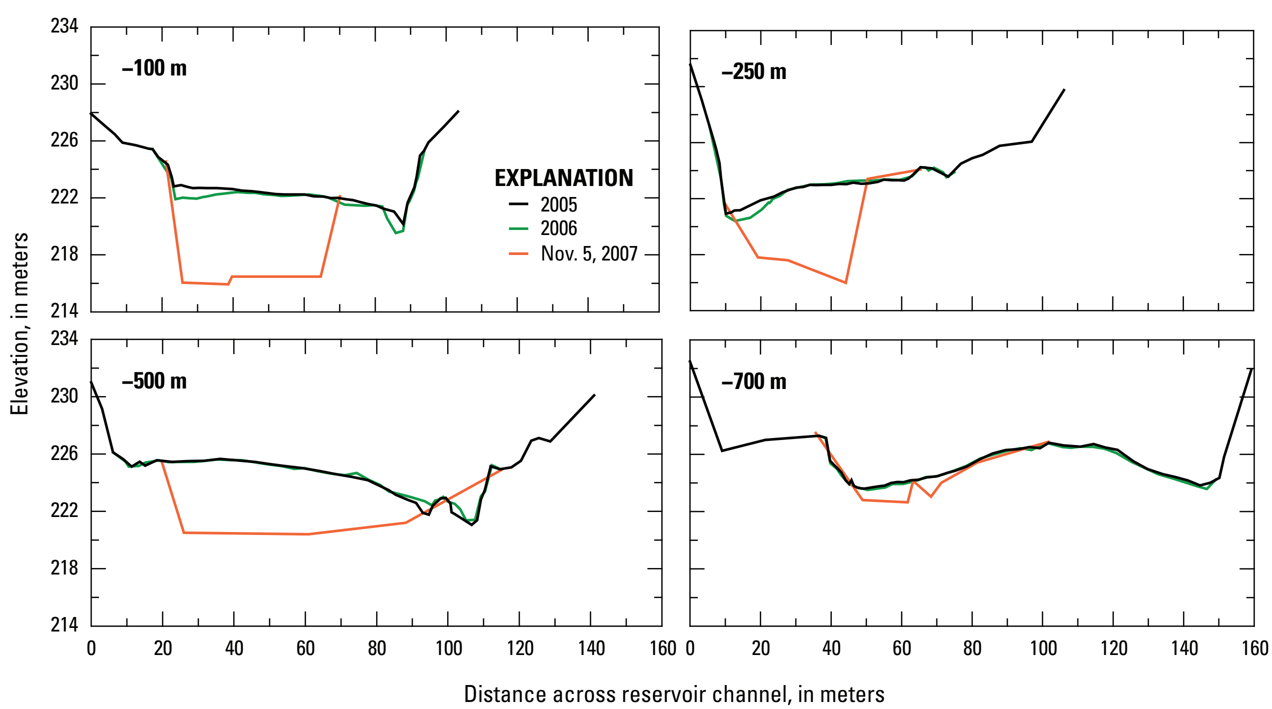


Figure 13. Channel cross sections in the reservoir reach behind Marmot Dam site (distances measured upstream of dam site) before and shortly after breaching showing sediment erosion by modest discharge during the first 60 hours following breaching. The 2005 and 2006 profile data are courtesy of Portland General Electric.

2 weeks later. By mid-November 2007 averaged widening rates in the reservoir reach had declined tenfold and by May 2008 had declined to well below one meter per day (table 3).

The decreased erosion rate resulted from both depletion of easily mobilized sediment and bed coarsening. Although we did not track channel-bed particle size systematically through the reservoir reach, we conducted modified-grid Wolman counts (Kondolf and others, 2003) of at least 100 particles on terrace treads abandoned by progressive incision 400–700 m upstream of the cofferdam location. Locations of each grid were acquired by hand-held GPS (horizontal position uncertainty of less than 6 m), and their vertical altitudes were determined by relating horizontal position to the September–October 2008 lidar survey. Grain size shows a strong inverse relationship with elevation above the local water surface of September 8, 2009 (fig. 17*A*). The grain sizes range from sand (median grain diameter, d_{50},<2 mm) near the original surface of reservoir sediment, 7 m above the September 2009 water surface, to cobbles (d_{50} between 130–160 mm) for three measurement sites within a meter of the September 2009 water surface.

The rate of bed-material coarsening on the abandoned terrace treads can be evaluated approximately by considering the rate of incision 400 m upstream of the cofferdam site. Here, more than half of the total incision measured by September 2009 occurred within days of breaching (figs. 17*B*–*D*). The eroded surfaces left in the wake of this incision are increasingly coarser grained, ranging from sand capping a remnant of undisturbed reservoir deposit ~7 m above the September 2009 water surface (terrace 1; fig. 17*A*, *C*–*F*) to cobble gravel (d_{50}=156 mm) on the terrace tread just 0.5 m above the September 2009 water surface (terrace 4; fig. 17*A*, *F*). The terrace tread 0.3 m above the elevation of the November 5, 2007, water surface (terrace 3, ~3 m higher than the September 2009 water surface; fig. 17*B*, *D*–*F*), which formed within days of breaching, also has a median grain diameter in the range of cobble gravel (d_{50}=135 mm; fig. 17*A*). The median grain diameter on that terrace tread, similar to the maximum median grain diameter measured on the lower terrace tread (terrace 4), shows that the channel coarsening proceeded very quickly. The 3 m of incision below the November 2007 terrace tread over the subsequent

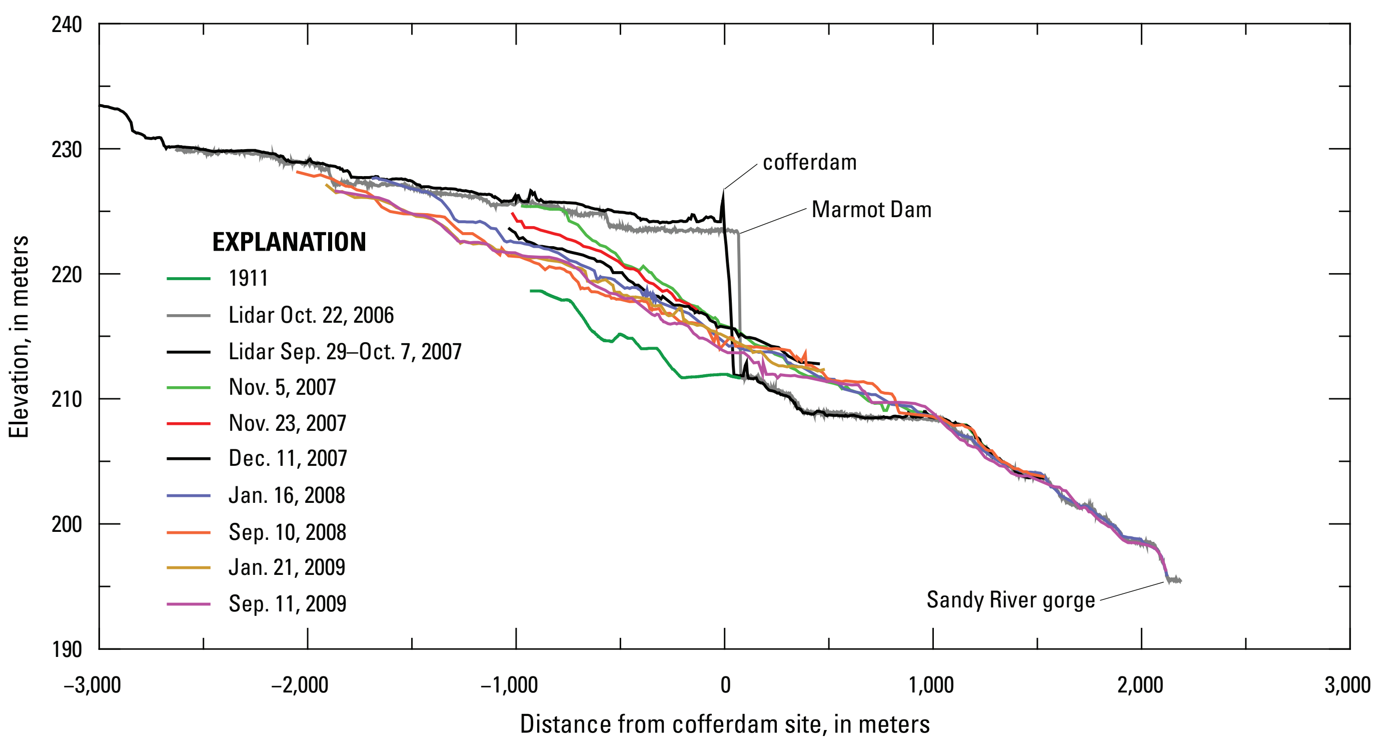


Figure 14. Longitudinal water-surface profiles of Sandy River before and after breaching of Marmot Dam. The water surfaces at times of surveys were generally within one meter of the channel thalweg. Surveyed profiles extend from about 2 kilometers (km) upstream of dam site to about 2 km downstream of dam site. The 2006 lidar profile shows the concrete structure in place; the 2007 profile is of the cofferdam and underlying sediment after the concrete dam was removed. The 1911 profile is a triangulated-irregular-network-generated reconstruction of topography digitized from a 1911 partial topographic map (Portland General Electric archives) and rectified to create a pre-dam topographic surface.

2 years (but mainly over the first year after breaching), a period that included the largest flows of 2008 and 2009, resulted in little further coarsening of the channel bed (fig. 17*B*). These observations indicate that most of the channel-bed coarsening within the reservoir reach occurred during or soon after knickpoint passage, and that this coarsening resulted in rapidly slowed rates of incision. Coarsening of the channel bed resulted from winnowing of sand and possibly from exposure of coarser gravel stored at depth (Squier and Associates, 2000) within the reservoir.

In general, the cumulative erosion of reservoir sediment scales with cumulative flow volume in a logarithmic manner (fig. 15*B*). This relation, indicative of a rapid decline in the rate of sediment erosion, is consistent with rapid incision and channel widening being the primary factors driving erosion. These rapidly evolving fluvial processes contrast with slower acting processes, such as gully network expansion or channel migration, which would be expected to result in a heavier tailed exponential-decay relation (Graf, 1977; Everitt, 1968) typically associated with sediment yield from disturbed landscapes (for example, Gran and others, 2011).

Sediment Deposition

A substantial amount of the eroded sediment accumulated in the 2-km-long channel reach below the dam site and above the Sandy River gorge; the remainder of sediment was deposited within the gorge and farther downstream. Deposit volumes were tracked by repeat channel surveys after each major storm following breaching and at the ends of WY 2008 and 2009 by comparison of prebreach and postbreach lidar topography (appendix), through repeat soundings at measurement sites 0.4,

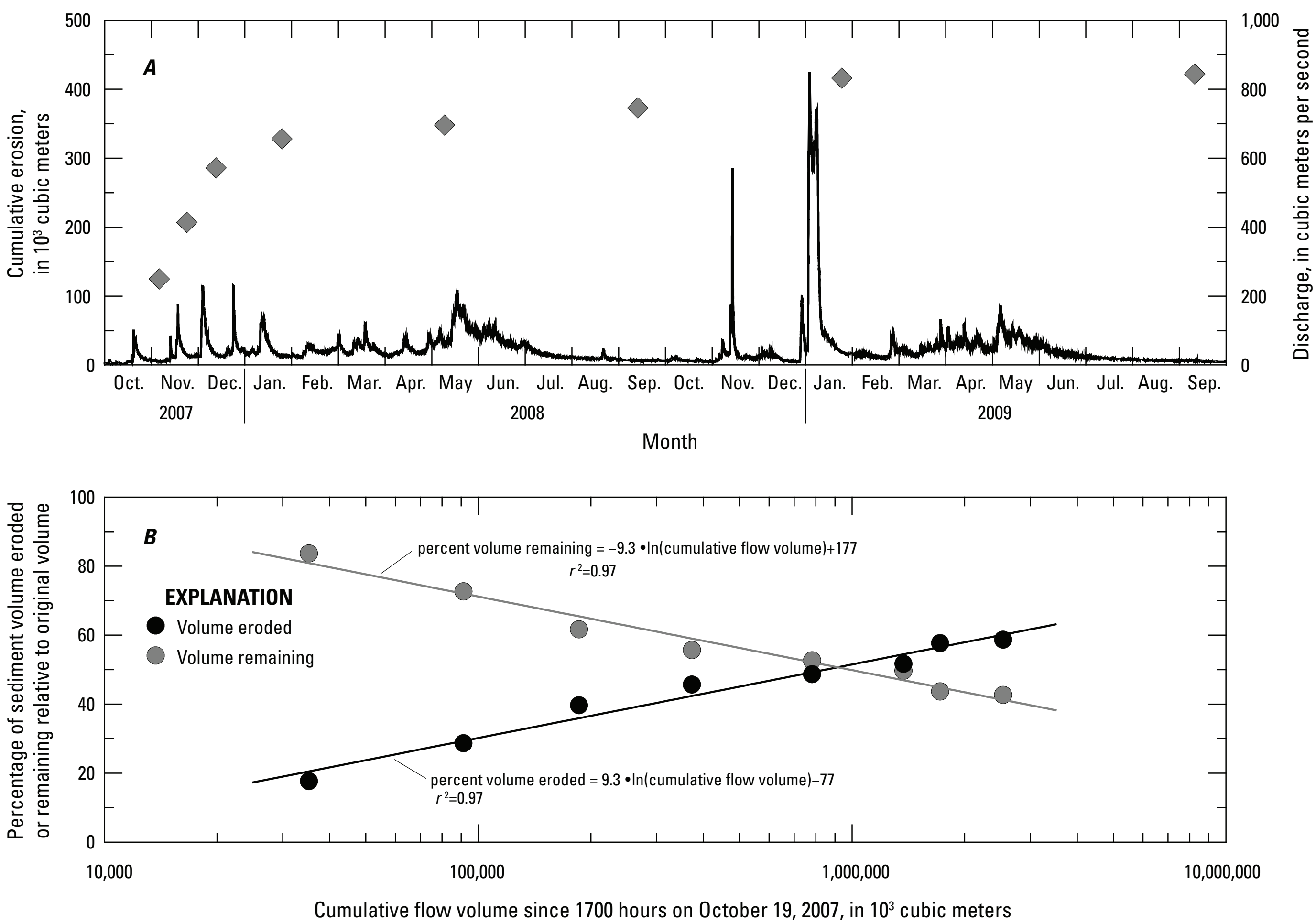


Figure 15. Erosion of reservoir-reach sediment impounded by Marmot Dam. *A*, Cumulative erosion of reservoir sediment (diamonds) as a function of time and hydrograph of Sandy River showing water discharge at Marmot Dam measurement station. Reservoir erosion was determined from ground surveys conducted during low flow following high-flow events. *B*, Percentage of sediment volume eroded from and remaining in the reservoir reach relative to the original volume stored as a function of cumulative flow volume since time of cofferdam breaching on October 19, 2007.

18, and 39 km downstream from the dam site, and by qualitative observations of sediment deposition in the largely inaccessible gorge. These measurements are supplemented by partial longitudinal-profile surveys conducted in September 2007 (before breaching) and June 2009 by the Bureau of Reclamation (Bauer, 2009) and by local site surveys of channel geometry, bed texture, and sediment facies by Podolak and Wilcock (2009) and Podolak and Pittman (2011). Similar to our consideration of reservoir erosion, we separate the discussion of sediment deposition into the initial 60 hours following breaching and subsequent annual changes.

Initial Sediment Deposition Following Breaching

After breaching, sediment eroded from the reservoir reach was deposited rapidly along the 2 km of channel and valley bottom between the dam site and the Sandy River gorge. There, deposition mainly in the days following breaching produced a 1.3-km-long sediment wedge tapering from approximately 4 m thick at the site of the cofferdam to the prebreach channel bed at its distal end (figs. 14, 18). This deposit largely maintained its form for the 2 years following breaching (figs. 14, 19). Sediment deposition at the Marmot Dam measurement station, 0.4 km downstream of the dam site, began within 3 hours of breaching, judging from channel soundings and a rise in water stage during steady discharge. Over the following 39 hours (through 1200 PDT on October 21), stage (and the channel bed) rose at an average rate of 0.063 m/hr. The bed aggraded 3.2 m within 3 days after breaching, and 4.2 m within a month (figs. 20, 21). Repeat soundings at this site show that as the valley bottom aggraded, active channel width increased (fig. 21). Bedload transport of sand accompanied channel aggradation during the first 18 hours after breaching, followed by transport and deposition of predominantly gravel bedload. Consequently, the channel immediately downstream of the dam site transformed rapidly from a single thread, boulder-cobble bed to a multithread

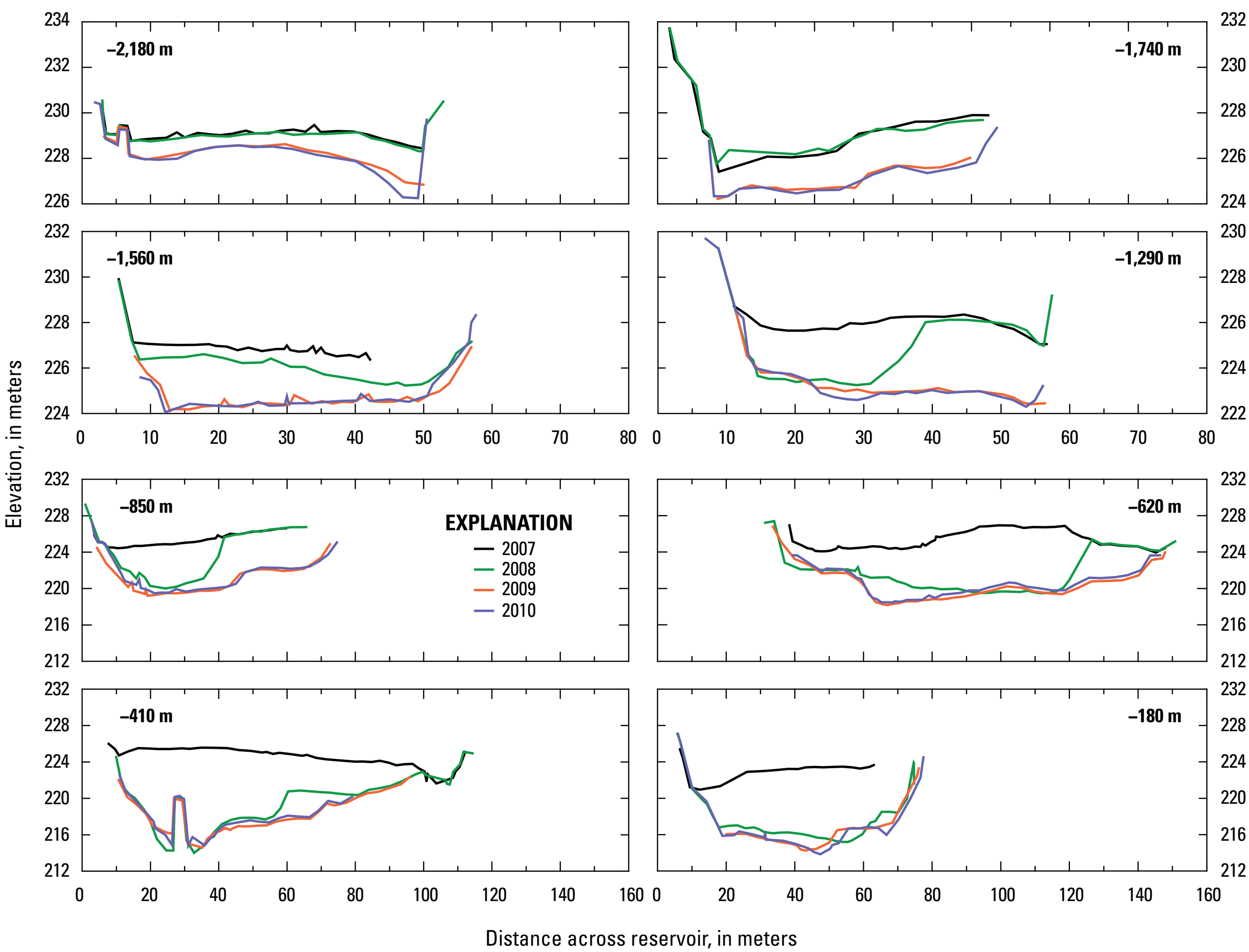


Figure 16. Channel cross sections at various locations in the reservoir reach (distances measured upstream of dam site) before breaching of Marmot Dam and approximately annually for the 3 years after breaching. Data courtesy of Portland General Electric.

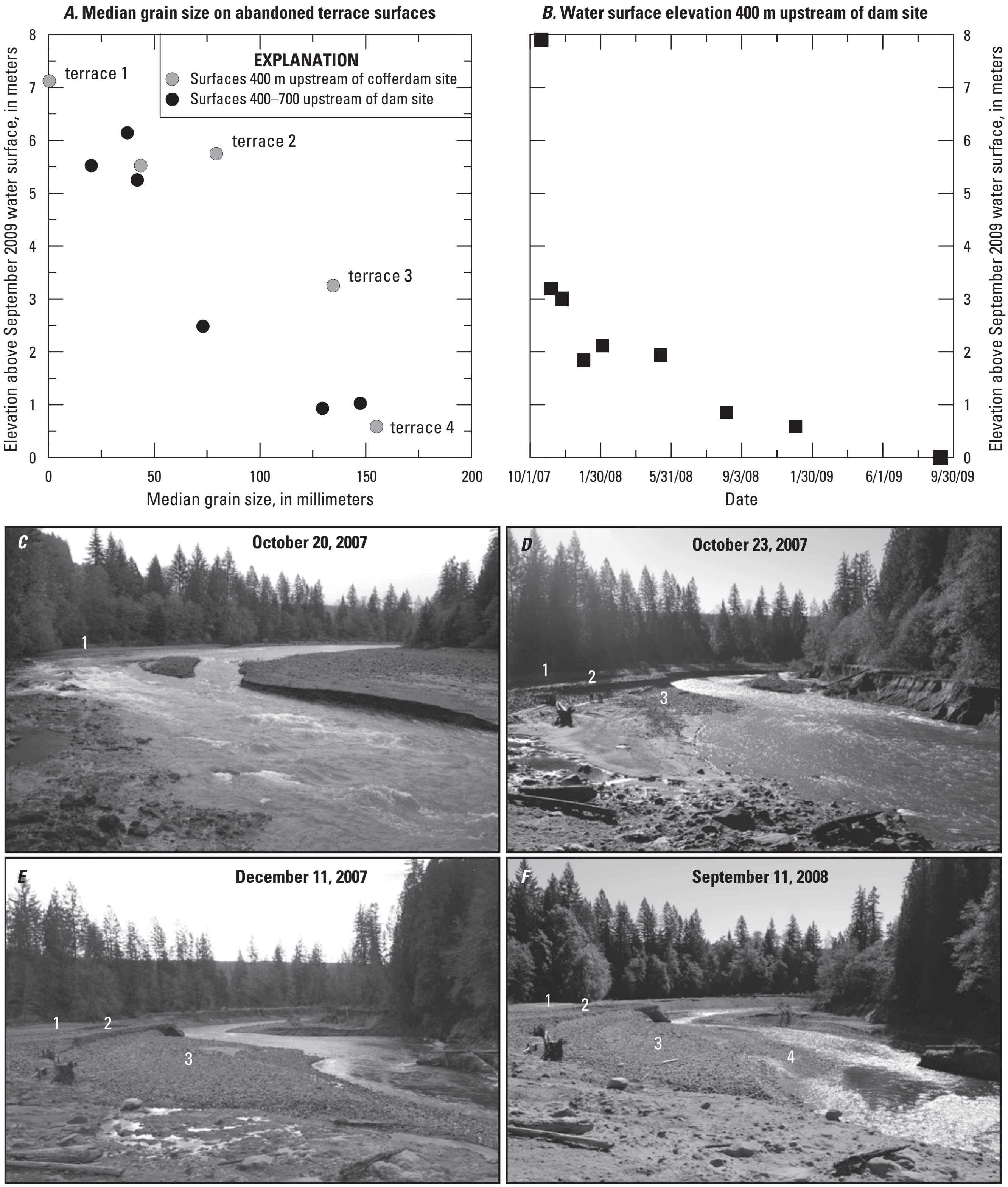


Figure 17. Relations among surface grain size, land-surface and water-surface elevation, and time for various terrace treads in the reservoir reach 400 to 700 meters (m) upstream of the Marmot Dam site. *A*, Median surface-grain diameter in relation to height above the September 8, 2009, water surface. *B,* Elevations of water surfaces at times of reservoir surveys relative to the September 8, 2009 water surface. *C–F,* Photographs (looking upstream) of terrace treads at various times after breaching of Marmot Dam. Numbered terraces on photographs correspond to numbered terraces in *A*.

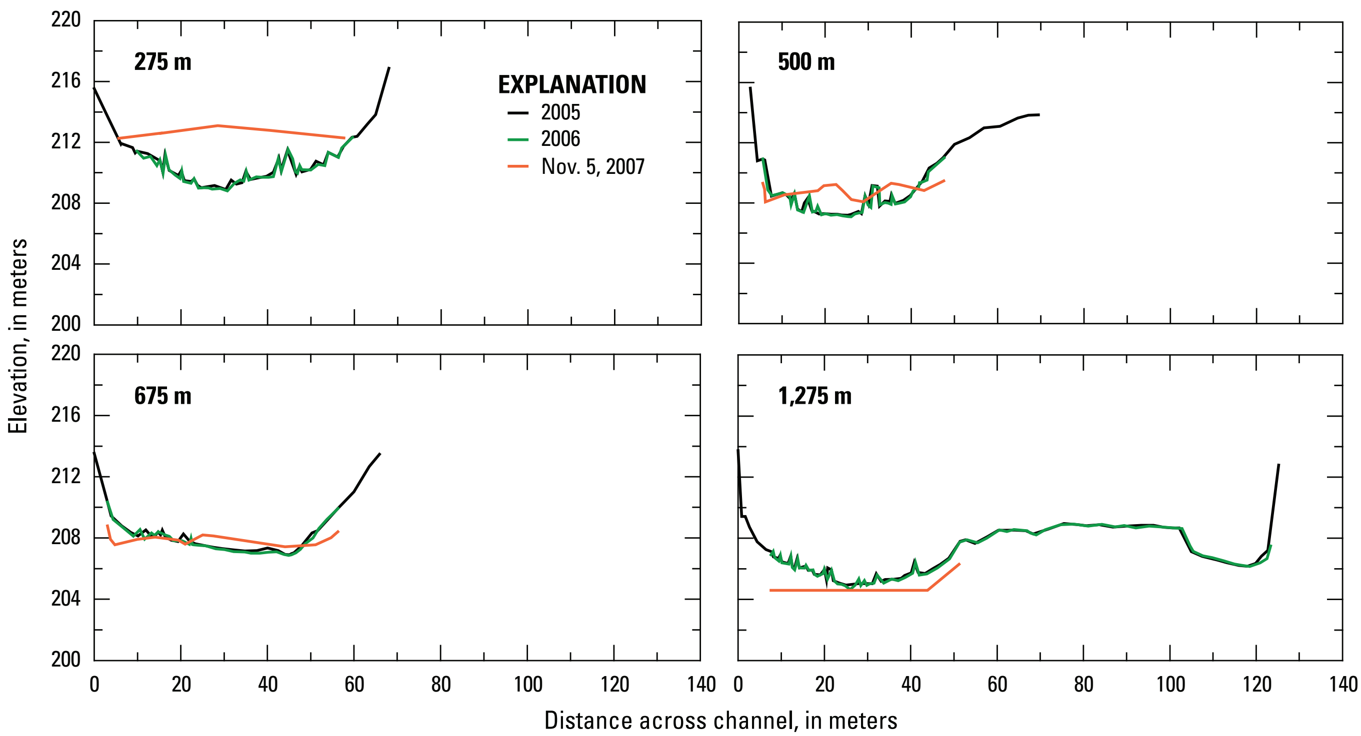


Figure 18. Channel cross sections showing deposition that occurred during the first 60 hours after cofferdam breaching on October 19, 2007, in the 1.3-kilometer-long channel reach below the Marmot Dam site (distances measured downstream of dam site). The 2005 and 2006 profile data are courtesy of Portland General Electric.

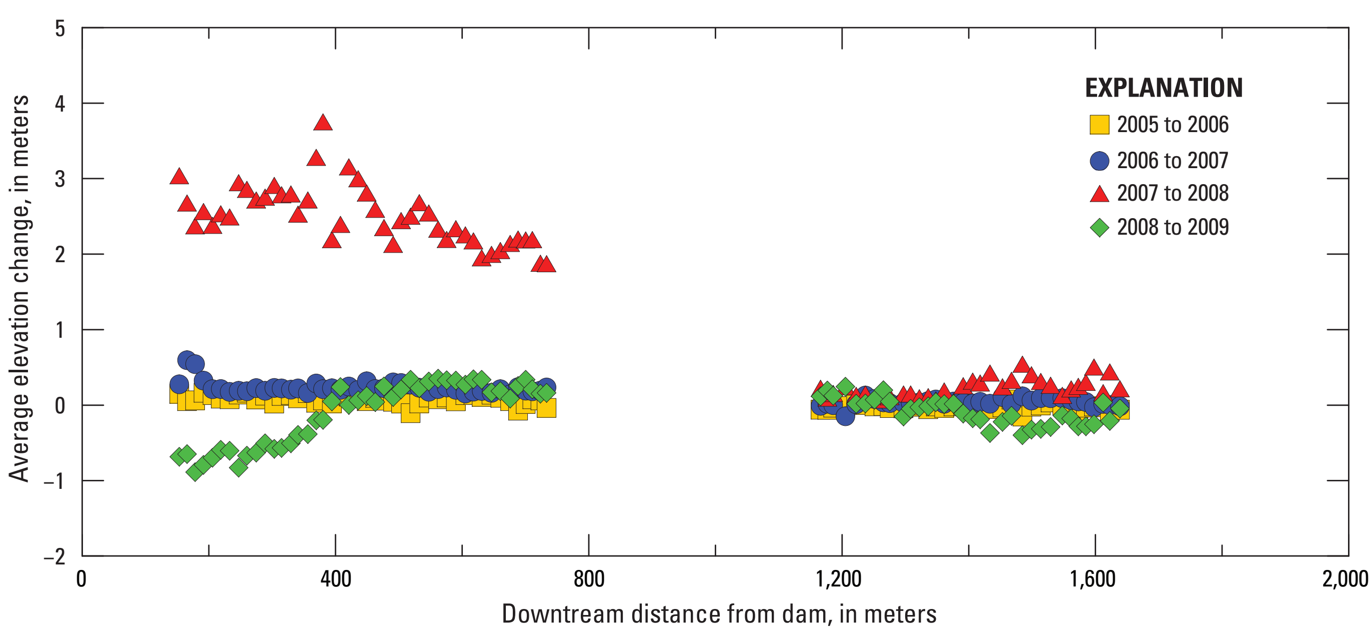


Figure 19. Annual changes in bed elevation at cross sections downstream of the site of Marmot Dam. The gap in cross-section surveys between 800 and 1,200 meters downstream represents an unsurveyed channel reach. Data courtesy of Portland General Electric.

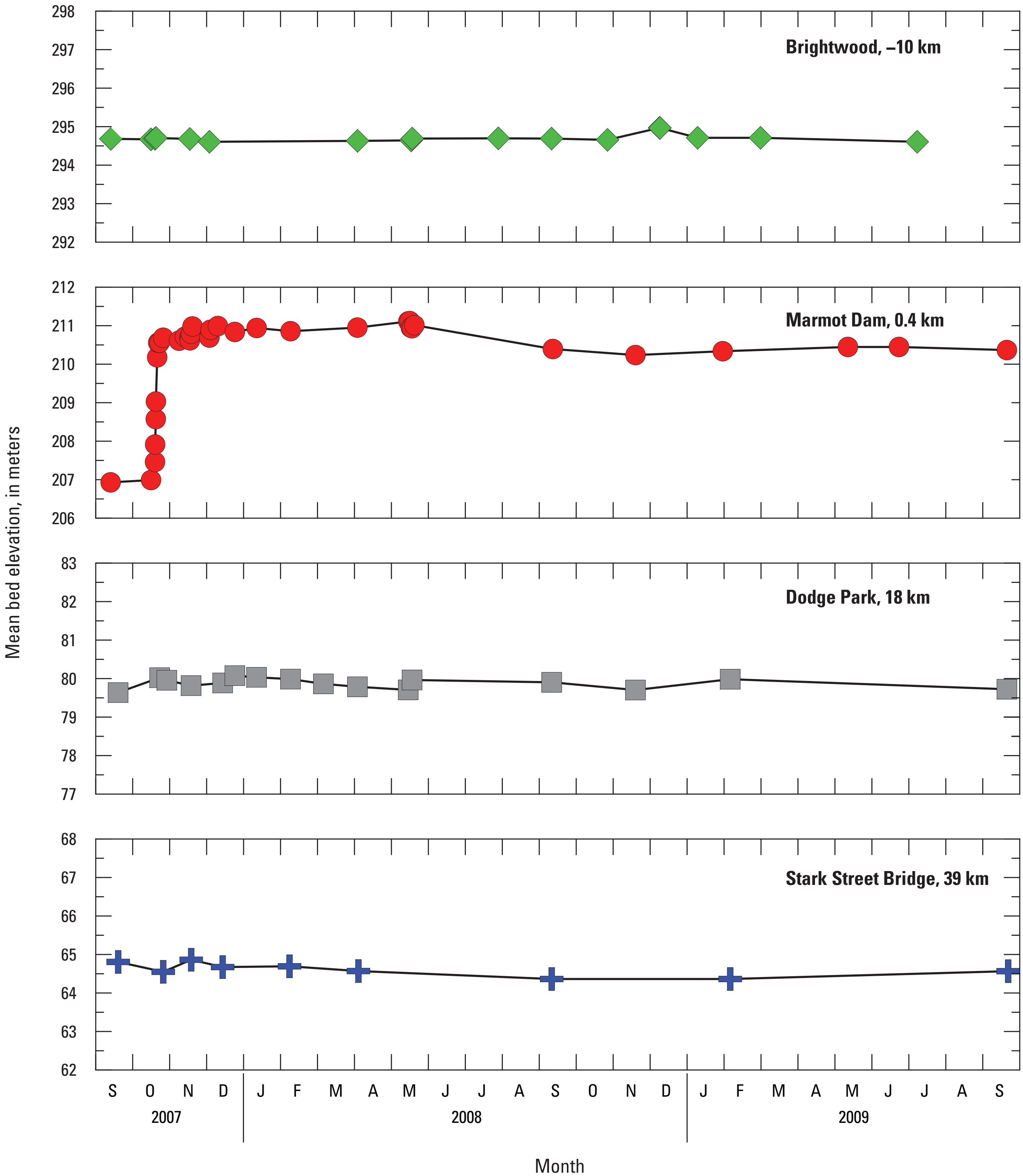


Figure 20. Time series of mean bed elevations at various measurement stations following breaching of Marmot Dam. See figure 1 for station locations. Distances shown are upstream (negative) and downstream (positive) of dam site.

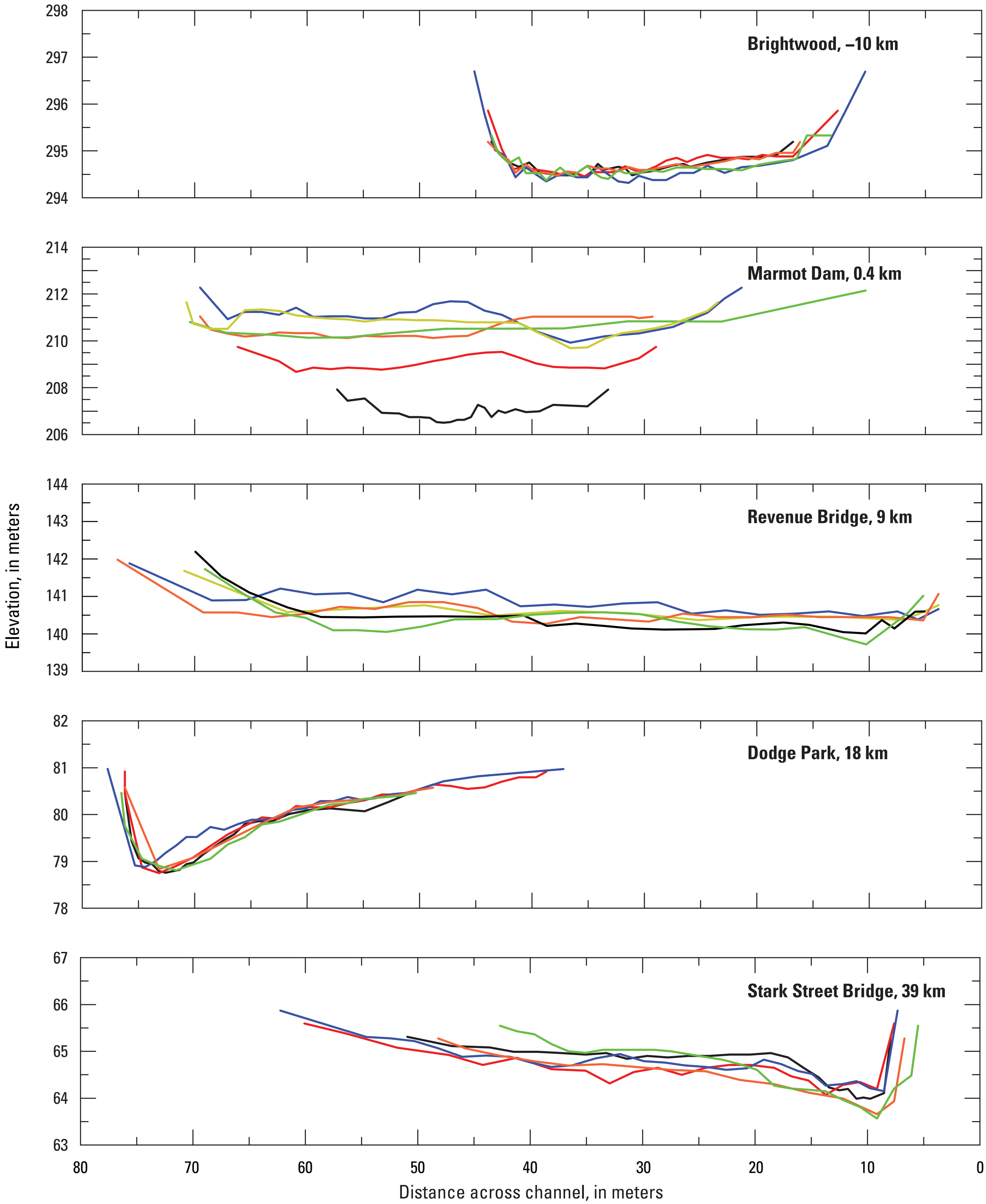


Figure 21. Time series of channel cross-section changes based on soundings at various measurement stations following breaching of Marmot Dam. See figure 1 for station locations.

channel with a sand-and-gravel substrate flanked by mobile sandy gravel bars (figs. 22, 23).

Our channel survey in early November 2007 showed about 65,000 m^3 of sediment—50 percent of the sediment eroded from the reservoir reach in the first 60 hours—deposited in the sediment wedge formed in the 2 km of channel below the cofferdam site immediately after breaching (table 4). Channel soundings at the Dodge Park measurement site 18 km downstream showed no net aggradation during the first 60 hours following breaching, and the Revenue Bridge site 9 km downstream showed only minor deposition within a month after breaching (fig. 21). A lack of increased bedload transport rates at these two measurement sites over the first 60 hours following breaching (discussed below) and longitudinal profiles surveyed by the Bureau of Reclamation (Bauer, 2009) in June 2009 suggest that the ~60,000 m^3 of eroded sediment not accounted for in the sediment wedge was probably deposited mainly within the Sandy River gorge, but some may have been dispersed and deposited farther downstream in locations where we have insufficient measurements to detect aggradation.

Longer Term Sediment Deposition near the Dam Site

Surveys and soundings conducted after the initial postbreach survey of November 2007 showed diminished rates of change during the ensuing 2 years as the valley bottom between the site of the cofferdam and the Sandy River gorge evolved from an accumulation zone to a zone primarily of transport (figs. 14, 19, 20, 21, 24). High-flow events between November 2007 and September 2008 (fig. 12) cumulatively eroded about 250,000 m^3 of sediment from the reservoir reach (table 3), but deposited only an additional 45,000 m^3 of sediment in the 2 km of channel above the Sandy River gorge (fig. 14; table 4). Thus, during the first year after breaching, about 30 percent of the approximately 375,000 m^3 of eroded sediment accumulated in the 2-km-long wedge below the dam site (table 4; figs. 14, 19, 24); the remainder passed farther downstream.

In the second year after breaching, as the rate of reservoir erosion declined markedly, the channel reach immediately below the dam site incised, resulting in net erosion of sediment from the depositional wedge (table 4). Erosion was mainly in the 0.5-km reach downstream of the cofferdam site where deposition had been greatest (figs. 14, 19, 24). This erosion was caused largely by stormflows in November 2008 and January 2009 (fig. 12). Differences between channel surveys in 2008 and 2009 showed as much as 1.5 meters of channel incision over a several-hundred-meter-long reach immediately downstream of the dam site (figs. 14, 19, 24), and channel soundings at the Marmot Dam measurement station showed a lowering of the mean bed elevation of as much as 0.6 m between December 2007 and September 2009 (figs. 20, 21).

Deposition Farther Downstream

Eighteen months after breaching, an April 2009 reconnaissance of the Sandy River gorge indicated that pools 2 to 3 m deep before breaching had largely filled with sand and gravel and that streamside sand and gravel bars had accumulated. The presence of 100-mm-diameter clasts of the concrete facing of Marmot Dam, introduced into the Sandy River during demolition, on a gravel bar at the exit of the Sandy River gorge (near RK 40) showed that gravel from the vicinity of the dam had moved at least 9 km downstream and through the gorge before the end of the second wet season after breaching.

Despite evidence that gravel-sized sediment from the vicinity of the dam had passed through the Sandy River gorge, and measurements of enhanced sediment transport beyond the gorge (described subsequently), there is little evidence of any substantive channel aggradation downstream of the gorge. Repeat topographic surveys near the exit of the gorge (Revenue Bridge site) showed bed fluctuations but minor net change from 2007 to 2009 (fig. 21), and surveys at sites of expected deposition another 4 and 21 km downstream (~13 km and 30 km downstream of the dam site) in July in 2008

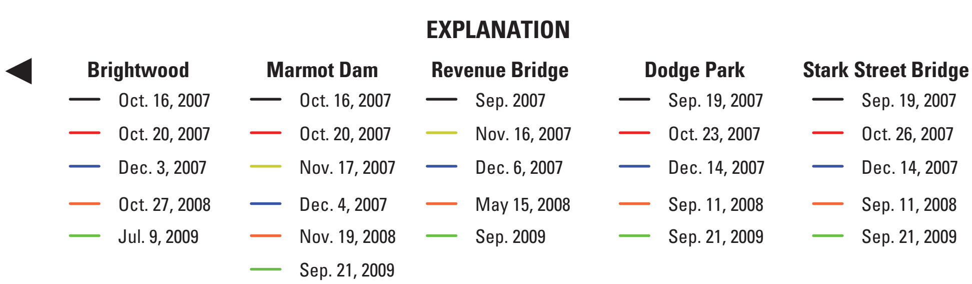


Figure 21.—Continued.

Figure 22. Time series of photographs of Sandy River from pedestrian bridge at Marmot Dam site. View is downstream; field of view is ~40 meters wide. Following the October 19, 2007, breaching, the channel rapidly aggraded and transitioned from the single-thread boulder-cobble channel shown in the April 2004 photograph to the multithread sand-and-gravel channel shown by the October 22 and November 5, 2007 photographs. By December 2007, the channel reverted to a single thread flanked by coarse gravel bars, although these bars show evidence of being remobilized by the higher flows that occurred during the second year after breaching, such as that in November 2008.

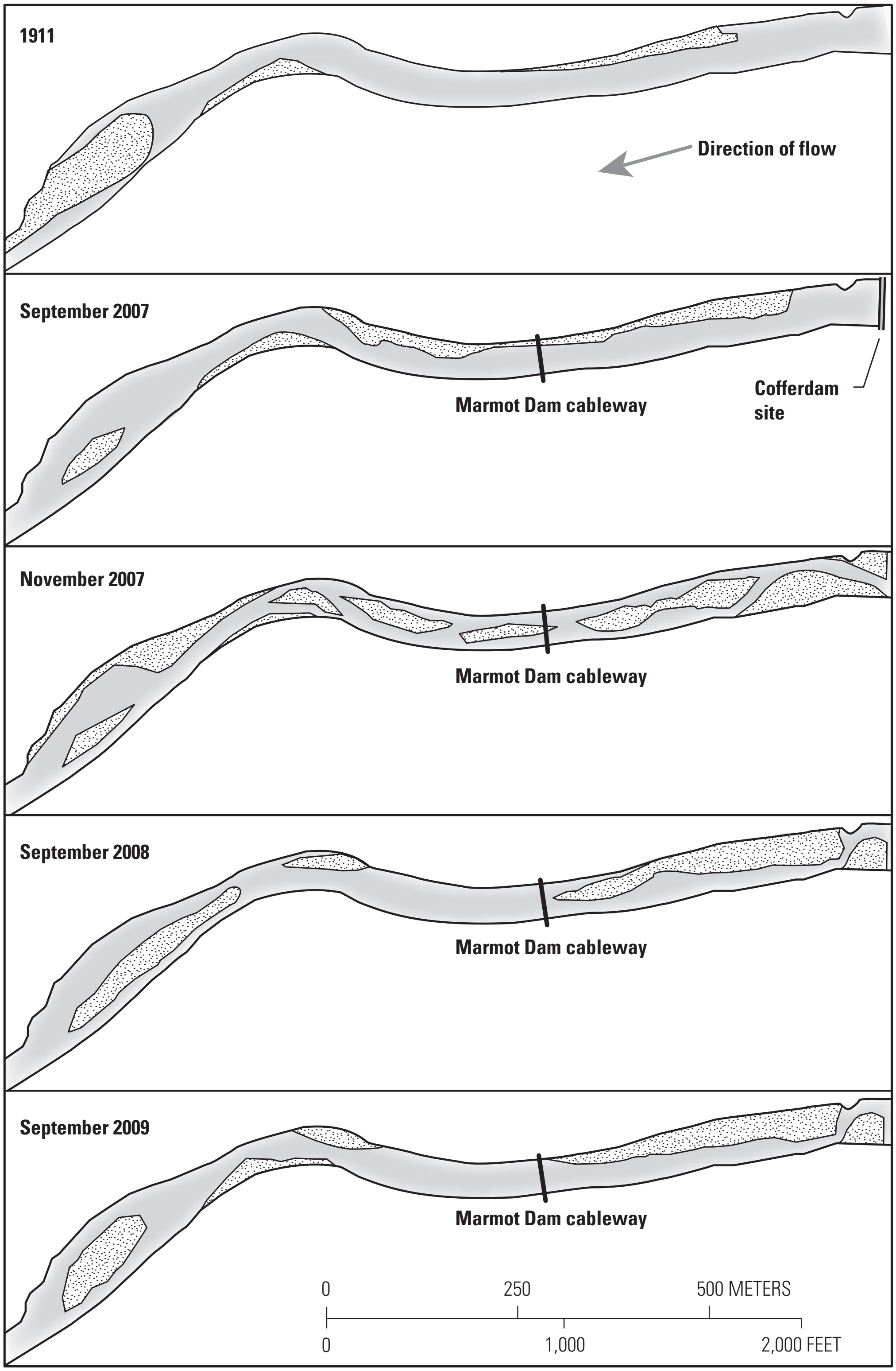


Figure 23. Bar planform evolution in the Sandy River near Marmot Dam obtained from surveyed edges of water surface and aerial photography at varying discharges (in cubic meters per second, m^3/s; from top to bottom: 27 m^3/s, 10 m^3/s, 42.5 m^3/s, 14 m^3/s, 16 m^3/s). Flow is from right to left. Locations of cofferdam and Marmot Dam measurement station are shown. Stippled pattern shows locations of gravel bars. The cofferdam was breached on October 19, 2007, after dam removal. The 1911 topographic map and 2008 aerial photographs provided courtesy of Portland General Electric.

Table 4. Time-series of deposition in the 2-kilometer-long channel reach below Marmot Dam (see appendix for methodological details).

[m^3, cubic meters]

Date	Mean deposit volume (10^3 m^3)	Minimum deposit volume (10^3 m^3)	Maximum deposit volume (10^3 m^3)	Deposit volume as percentage of total reservoir sediment eroded
Nov. 5, 2007	65	60	70	50
Sep. 30, 2008	110	90	130	30
Sep. 30, 2009	100	80	120	25

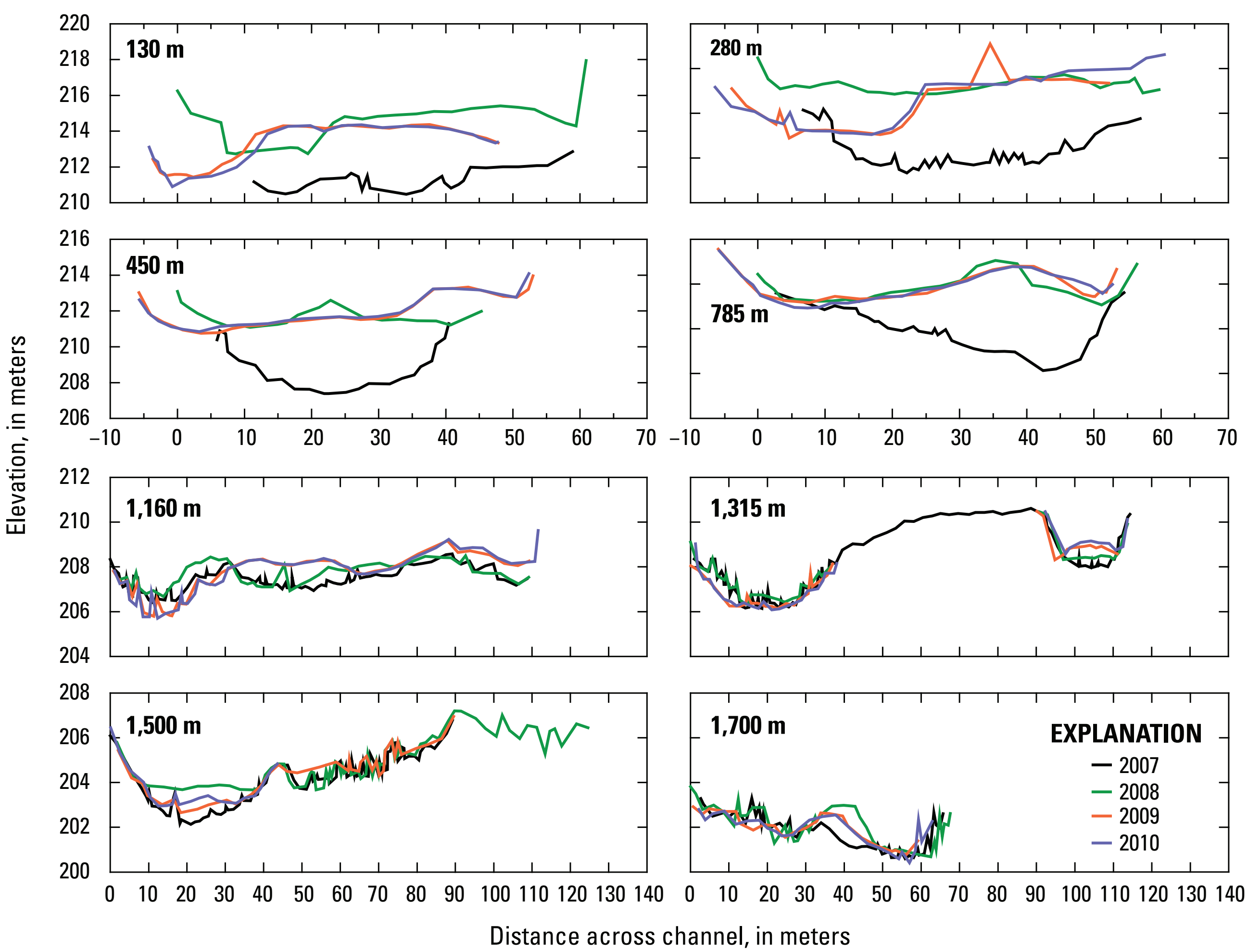


Figure 24. Channel cross sections at various locations below Marmot Dam site (distances measured downstream of dam site) before breaching in October 2007 and approximately annually for 3 years after breaching. Negative distances along the x axis represent lateral bank erosion beyond the monumented section marker placed during the first survey. Data courtesy of Portland General Electric.

and 2009 were unable to detect any bed-elevation change attributable to the released sediment (Podolak and Pittman, 2011). Repeat soundings at the Dodge Park and Stark Street bridges, 18 and 39 km downstream of the dam site (fig. 1), show mean-bed-elevation fluctuations of up to 0.5 m during the two years after breaching, but no systematic trends (figs. 20, 21). Longitudinal profile surveys by the Bureau of Reclamation (Bauer, 2009), although not continuous along the length of the river, also were unable to detect any substantial changes in bed elevation downstream of Revenue Bridge (RK 39) by June 2009.

Deposition and Channel Geometry

Although about 100,000 m^3 of sediment were deposited in the 2 km of channel downstream of the dam site within a year after breaching (table 4), channel morphology stabilized very quickly. In early November 2007, sandy gravel bars flanking the channel had a median surface grain size of 40 to 90 mm, and had locations generally independent of the bars that existed prior to breaching (figs. 22, 23). By December 2007, the channel adopted a single thread along the left side of the valley and bar surfaces had coarsened visibly (fig. 22). Within a year after breaching, a few attached bars having sizes and locations similar to those present prior to breaching had developed (fig. 23), and both the form and composition (surface d_{50} ~75–100 mm) of these bars, as well as bars farther downstream, were similar to those of preremoval bars (figs. 25, 26).

Between 1 and 2 km downstream of the dam site, where aggradation was less and the valley bottom was not completely buried, deposition was mainly on and appended to existing bars (figs. 19, 24, 26; Podolak and Wilcock, 2009). Nevertheless, significant remobilization of gravel bars during the high flows of November 2008 and January 2009 (fig. 22; Podolak and Wilcock, 2009) attests to persistent mobilization of sediment in this channel reach by these large flows.

Sediment Transport

Spatial and temporal variations of sediment transport rates during and subsequent to breaching were quantified by measuring water discharge, suspended-sediment load, and bedload at a single station upstream and at four stations downstream of the dam site (fig. 1; table 5). Measurements at Brightwood, 10 km upstream of Marmot Dam, and at three sites downstream—Marmot Dam measurement station (0.4 km downstream), Dodge Park (18 km downstream) and Stark Street Bridge (39 km downstream)—were obtained by the U.S. Geological Survey (USGS). Measurements near Revenue Bridge, about 9 km downstream of the dam site, were made by Graham Matthews and Associates (GMA) (Pittman and Matthews, 2008). We made measurements during six high flows in the year following breaching (fig. 12), but owing to personnel, safety, and equipment limitations, not all sites were measured during each high flow. Transport was measured at each site during at least two high flows, and at the Marmot Dam station sediment transport measurements were made during each of the targeted high flows including during breaching.

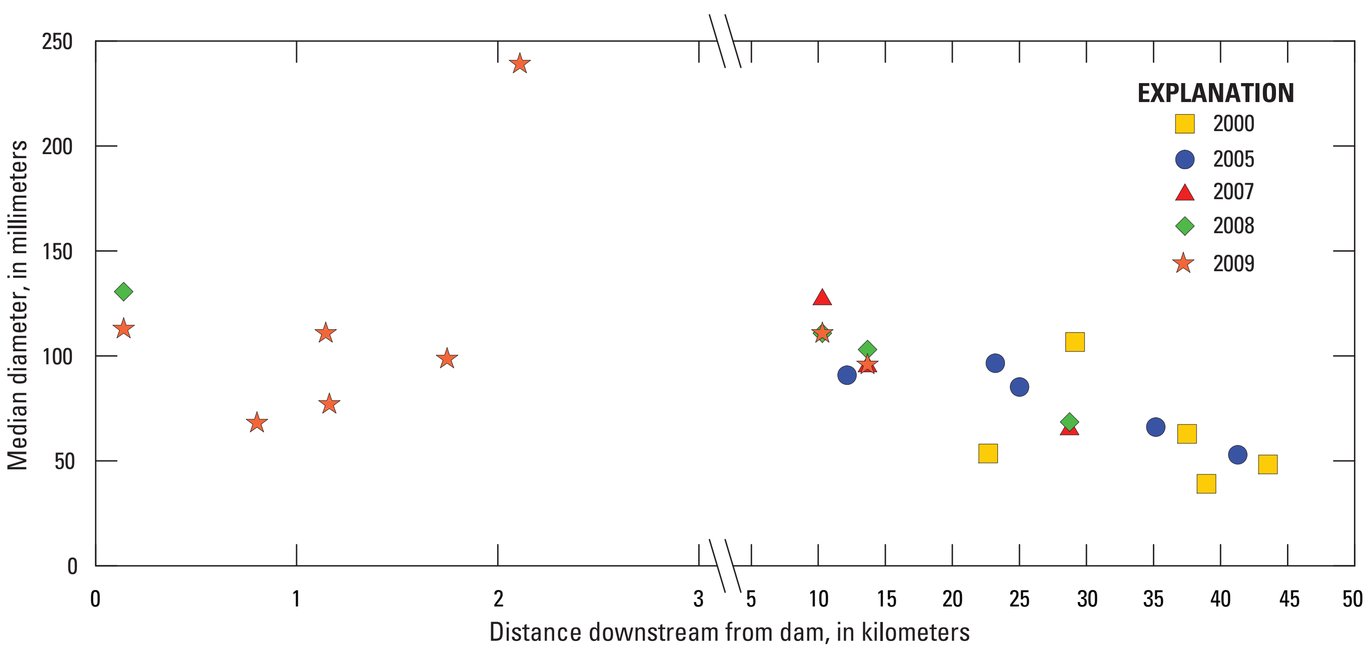


Figure 25. Median grain diameter of the gravel fraction on surfaces of gravel bars downstream of Marmot Dam as a function of time. Dam was breached in October 2007. Data for year 2000 from Stillwater Sciences (2000a); data for year 2005 from Stewart and Grant (2005).


A. July 13, 2007 16 m³/s
B. July 9, 2009 20 m³/s
C. July 15, 2007 7 m³/s
D. August 19, 2010 12 m³/s
E. July 9, 2007 15 m³/s
F. July 24, 2008 23 m³/s
G. July 25, 2007 15 m³/s
H. July 20, 2008 27 m³/s

Table 5. Measurement station locations and types of measurements made following breaching of Marmot Dam.

[–, no station number or no data]

Station name	Station number	Agency [1]	Location (river kilometer)	Principal period of measurement	Type of measurement [2]
Sandy River below Salmon River near Brightwood	14136500	USGS GMA	58.6	Sep. 2007–May 2008 Jan. 2009	w, c, bl, ss, t
Sandy River below Marmot Dam	14137002	USGS	47.9	Sep. 2007– May 2008	w, c, bl, ss, t
Sandy River near Revenue Bridge	–	GMA	39.3	Oct. 2007–Jul. 2008	w, c, bl, ss
Sandy River at Dodge Park	14138530	USGS	30.2	Sep. 2007–May 2008	w, c, bl, ss
Sandy River below Bull Run	14142500	USGS	29.8	Mar. 2006–Jul. 2008	w, t
Sandy River at Stark Street Bridge	453056122213701	USGS	9.5	Sep. 2007–Nov. 2007	w, c, bl, ss

[1]USGS, U.S. Geological Survey; GMA, Graham Matthews and Associates.

[2]Abreviations: w, water discharge; c, channel-geometry sounding; bl, bedload; ss, suspended-sediment load; t, turbidity.

Sediment-Transport and Water-Discharge Measurements

At all sites we measured bedload and suspended-sediment loads in conjunction with water discharge. Continuous stage measurements were recorded at Brightwood, near Revenue Bridge, and below Bull Run. Sediment- and water-discharge measurements at Brightwood, Dodge Park, and Stark Street Bridge were made from bridges, measurements near Marmot Dam were made from a cableway, and measurements near Revenue Bridge were made from a cataraft (Pittman and Matthews, 2008). Sediment-transport sampling followed established protocols (Edwards and Glysson, 1999; Diplas and others, 2008), but methods were adapted for time, safety, and local conditions. Standard methods were used to convert mean sediment concentration to suspended-sediment load (Gray and Simões, 2008), and a mean-section method (Edwards and Glysson, 1999) was used to compute bedload-transport rates unless all of the sampled bedload sediment from a measurement transect was collected in a single bag.

Suspended-sediment-discharge measurements require concurrent flow measurements, and calculations of annual sediment loads developed from sediment transport–water discharge relationships require annual hydrographs for the measurement sites. Flow discharges at the Brightwood and Revenue Bridge stations were determined from continuously recorded water stages in conjunction with site-specific rating curves for stage and discharge. At the Marmot Dam station, the existing relation between stage and discharge became invalid as the channel aggraded after breaching. At Dodge Park, a relation between stage and discharge was developed, but stage was not recorded continuously. Consequently, flows for WY 2008 and 2009 at the Marmot Dam station and Dodge Park were estimated using measurements from other locations (appendix).

Suspended-Sediment Transport

During WY 2008, we made 233 individual suspended-sediment measurements at the five measurement stations. Most of these measurements (227) were made

Figure 26. Comparative views of Sandy River at various locations downstream of the Marmot Dam site before and after breaching of the cofferdam in October 2007. *A, B*, Upstream views of Sandy River channel 1 kilometer (km) downstream of Marmot Dam, July 2007 and July 2009. Note the three boulders common on the right side of the July 2007 panorama and right center of the July 2009 panorama. *C, D,* Panoramic upstream to downstream view of Sandy River channel near Revenue Bridge, 9 km downstream of dam site, July 2007 and August 2010. Flow is from right to left. *E, F,* Panoramic upstream to downstream view of Sandy River channel near Cedar Creek, 13 km downstream of dam site, July 2007 and July 2008. Flow is from right to left. *G, H,* Panoramic upstream to downstream view of Sandy River channel at Oxbow Park reach, 30 km downstream of dam site, July 2007 and July 2008. Flow is from right to left. See figures 1 and 3 for locations.

at the Brightwood, Marmot Dam, Revenue Bridge, and Dodge Park stations, including 71 high-frequency pump samples collected at the Marmot Dam station during and after breaching on October 19–20, 2007. Six additional measurements were made farther downstream at Stark Street Bridge during WY 2008, and we returned to Brightwood during WY 2009 for 10 additional measurements (see appendix, tables A1, A2; note that tables A1–A3 are provided only as online electronic supplements at *http://pubs.usgs.gov/pp/1792/*) (Pittman and Matthews, 2008; Podolak and Pittman, 2011). Individual samples obtained during a cross-section transect were composited to obtain a mean concentration, and mean concentrations from multiple transects were averaged when computing relations between concentration and water discharge.

Depth-integrated suspended-sediment samples were obtained using a DH-59 or D-74 isokinetic sampler (Edwards and Glysson, 1999; Diplas and others, 2008; Pittman and Matthews, 2008). In addition to the depth-integrated samples, an automated pump sampler at the Marmot Dam station collected frequent (ranging from every 5 minutes to daily) suspended-sediment samples from the channel margin. Some of the channel-margin samples were compromised, however, by clogging of the sampler intake owing to bed aggradation; consequently, we present only a subset of those samples.

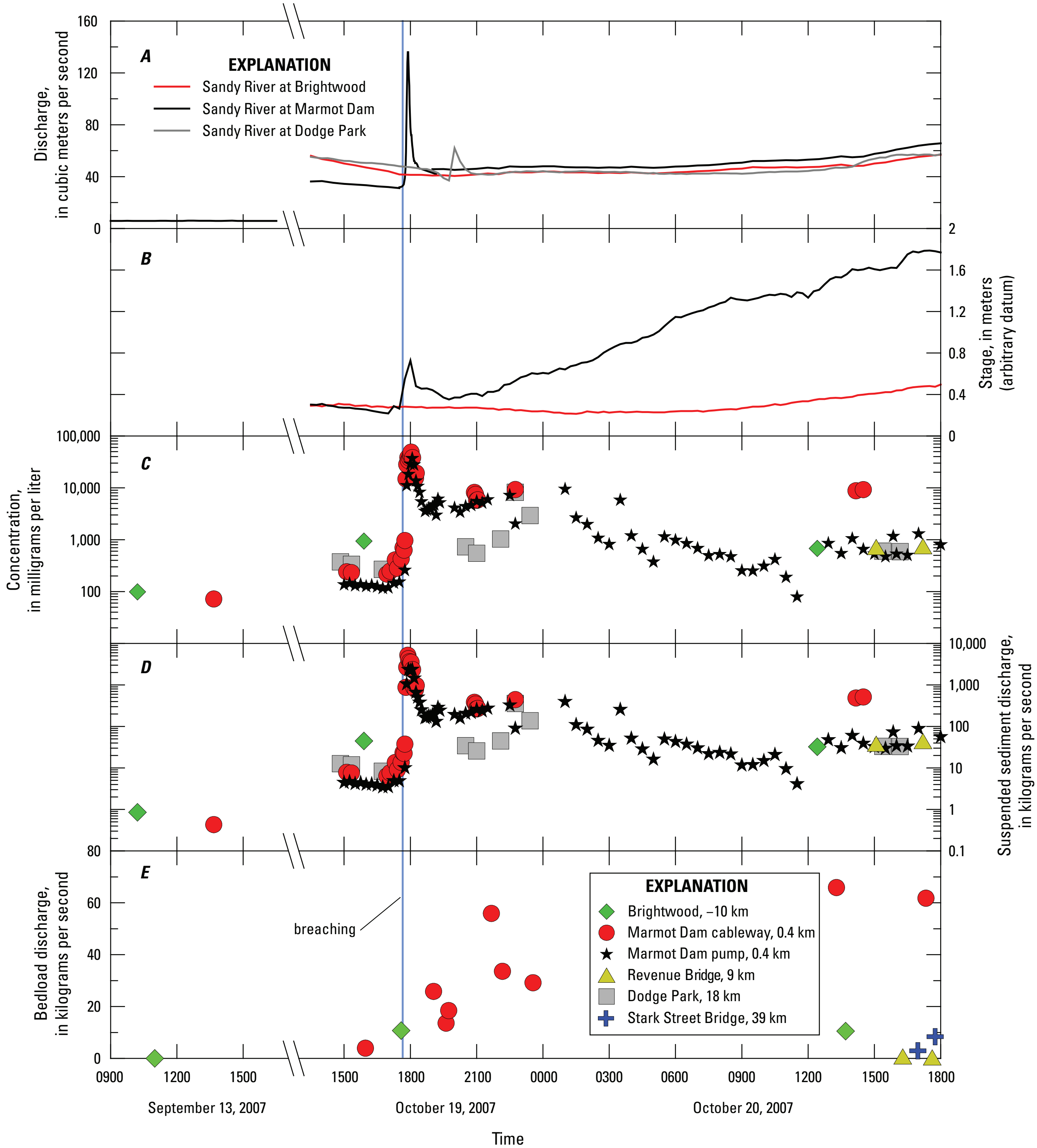
Suspended-sediment sampling protocols varied among sites and were adapted to local conditions. At Brightwood, Dodge Park, and Stark Street Bridge, measurement transects consisted of sampling suspended sediment from 5 to 10 vertical sections spaced evenly across the channel. When time and safety allowed, at least two complete transects were obtained for each sampling run. Near Revenue Bridge, depth-integrated suspended-sediment samples were obtained at 11 vertical sections spaced evenly across the channel. Multiple transects were obtained when time and safety allowed.

At the Marmot Dam station, sampling was complicated by rapidly changing conditions, especially during the 6 hours following breaching of the cofferdam. In the hours before breaching, suspended-sediment samples were collected from the cableway at five vertical sections across the channel, as well as at the channel margin using a pump sampler. During and after breaching, suspended-sediment samples were collected from a single vertical section in the middle of the channel in rapid succession, as well as every 5 minutes from the channel margin by the pump sampler, throughout the short-duration, high-discharge pulse of water that accompanied release of the small volume of stored water on breaching of the cofferdam. The sediment concentrations of those samples are similar and show that sediment was well mixed within the river, leading us to infer that the single vertical samples obtained mid-channel are representative of the mean sediment concentration immediately following breaching. By the following day, mid-channel samples had greater concentrations than did the channel-margin samples, suggesting that the sandy, suspended load was concentrated mid-channel.

Prebreach Transport

Prebreach measurements showed suspended-sediment concentrations upstream and downstream of the cofferdam ranged from about 100 to 1,000 milligrams per liter (mg/L (fig. 27 and table A1). Sediment concentrations at Brightwood, upstream of the dam site, were two to four times greater than those measured downstream of the dam site (fig. 27*C*; table A1), with the difference probably due to combined effects of deposition of some suspended sand in the reservoir slackwater and diversion of flow past the downstream measurement sites. The measured concentrations, when combined with streamflow discharge (fig. 27*A*), indicate prebreach suspended-sediment fluxes upstream and downstream of the dam of tenths to tens of kilograms per second (kg/s) (fig. 27*D*),

Figure 27. Time series of stage (water-surface elevation) and water and sediment fluxes above and below Marmot Dam site (see figure 1 for station locations). *A*, Water discharge. Before dam breaching some flow was diverted past the Marmot Dam measurement station, and hence the measured discharge below the dam site is less than that passing Brightwood upstream. After breaching, all flow passed the Marmot Dam measurement station. Owing to channel aggradation at the Marmot Dam gaging station, postbreach discharge immediately below the dam had to be estimated from regional gages. *B*, Stage. Sediment deposition led to a rising stage at the Marmot Dam measurement station beginning about 3 hours after breaching. *C*, Suspended-sediment concentration measured above and below the dam site. At the Marmot Dam measurement station samples were collected manually from a cableway and by an automated pump sampler at the channel margin. At all other stations, samples were collected manually from bridges or from a cataraft (see Pittman and Matthews, 2008). All samples were typically collected at equal width intervals across the channel. Immediately after breaching, samples collected from the Marmot Dam station cableway were obtained rapidly, but only at a single midchannel station. The similarity of concentrations between these single-station samples and pump samples from the channel margin show that suspended sediment was initially well mixed in the river. Cross-section samples were composited to compute a mean concentration. *D*, Suspended-sediment flux. *E*, Bedload flux. The mean flux was computed from samples collected at equal width intervals across the channel. Revenue Bridge data from Pittman and Matthews (2008). Distances identify station distance from Marmot Dam; positive values are downstream. Times shown are Pacific Daylight Time (PDT).


A
B
C
D
E
EXPLANATION
Sandy River at Brightwood
Sandy River at Marmot Dam
Sandy River at Dodge Park
Discharge,
in cubic meters per second
Stage, in meters
(arbitrary datum)
Concentration,
in milligrams per liter
Suspended sediment discharge,
in kilograms per second
Bedload discharge,
in kilograms per second
breaching
EXPLANATION
Brightwood, –10 km
Marmot Dam cableway, 0.4 km
Marmot Dam pump, 0.4 km
Revenue Bridge, 9 km
Dodge Park, 18 km
Stark Street Bridge, 39 km
0900
1200
1500
1500
1800
2100
0000
0300
0600
0900
1200
1500
1800
September 13, 2007
October 19, 2007
October 20, 2007
Time

values probably typical of the Sandy River at a discharge approximating the mean annual flow. For comparison, suspended-sediment fluxes at comparable discharge (30 to 40 m^3/s) on the White River near Tygh Valley, Oregon, which drains the southeast flank of Mount Hood, are typically less than about 5 kg/s (U.S. Geological Survey, 2011). At the Marmot Dam station, concentrations of prebreach samples collected at the channel margin were about half those of samples collected and composited from a channel transect, suggesting that before breaching, suspended sediment in the river immediately below the dam site was not well mixed (fig. 27*C*). Suspended sediment upstream at Brightwood consisted mainly of sand, whereas below the dam site it consisted mainly of silt and clay (particles smaller than 63 microns; fig. 28).

Transport at the Time of Breaching

Breaching of the cofferdam released a pulse of turbid water having an instantaneous suspended-sediment flux as great as 5,200 kg/s as it passed the Marmot Dam station (fig. 27*D*). The peak concentration in that pulse (49,000 mg/L) lagged the peak sediment flux (having a concentration of 38,000 mg/L) by about 10 minutes (figs. 27*C*, *D*). The initial sediment pulse passing the station was mainly silt and clay—presumably derived from material imported to construct the cofferdam and from thin, fine-grained beds that capped the impounded sediment at the downstream end of the reservoir (see the photographs in fig. 10). The suspended load coarsened rapidly, from less than 30 percent sand to nearly 80 percent sand, within an hour after breaching as the Sandy River incised into the stored sand and gravel (fig. 28). Following the initial peak, a flux of sand-rich suspended sediment ranged from several tens (as calculated from the pump samples) to hundreds (mid-channel and transverse samples) of kg/s for at least 24 hours. In contrast, the upstream (Brightwood) and downstream (Revenue Bridge, Dodge Park) suspended-sediment fluxes ranged from 30 to 50 kg/s (fig. 27*D*).

Transport by Subsequent High Flows

Suspended-sediment fluxes declined rapidly during the high flows that followed dam removal (fig. 29). By December 2007, suspended-sediment concentrations, fluxes, compositions and turbidities measured at the Marmot Dam station were similar to those measured farther downstream (figs. 29, 30, 31). Also by this time, streamflow at the dam site was clear between high-flow events, and during subsequent high flows it appeared to be less turbid than it had been immediately after breaching. On the basis of those observations, we infer that by December 2007, about 2 months after breaching, the suspended-sediment concentrations, fluxes, and compositions upstream of the dam site were probably similar to those measured downstream of the dam site. By May 2008, measured suspended-sediment concentrations, fluxes, and compositions were similar among all sites upstream and downstream of the dam site (figs. 29, 30).

Annual Sediment Fluxes

We used relations between suspended-sediment concentrations and water discharges in conjunction with annual flow records and bootstrap Monte Carlo simulations (appendix; table A3) to estimate mean suspended-sediment fluxes and their uncertainties at the four principal measurement sites for WY 2008. Additional measurements at Brightwood during WY 2009 (Podolak and Pittman, 2011) helped determine concentration-discharge relations for that site. Grain-size analyses of the sampled sediment (fig. 30;

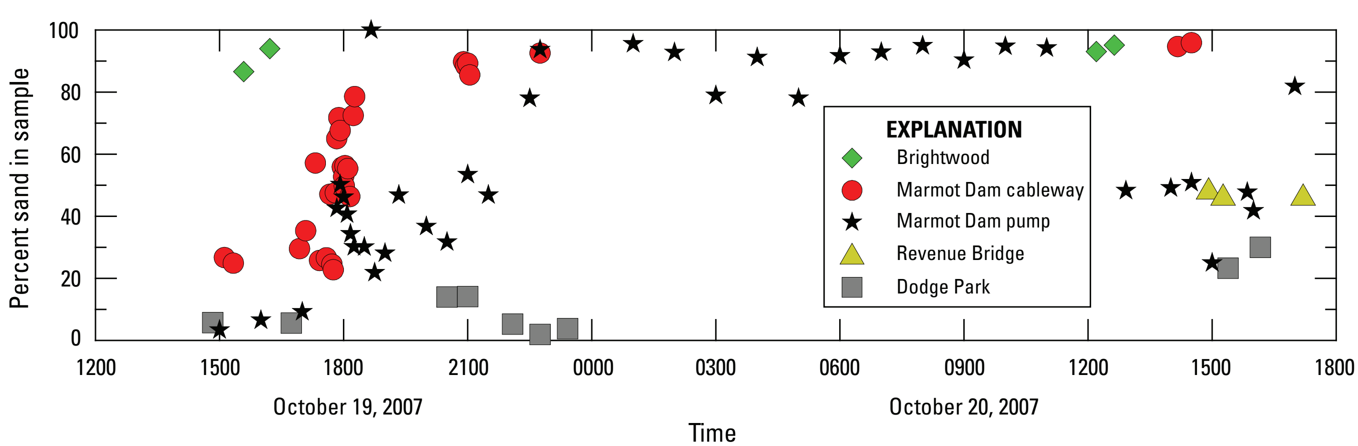


Figure 28. Percent sand in suspended-sediment samples collected during the first 24 hours after the breaching of Marmot Dam on October 19, 2007. Revenue Bridge data are from Pittman and Matthews (2008). See figure 1 for station locations. Times shown are Pacific Daylight Time (PDT).

tables A1, A2) permitted separate estimates of the fluxes of sand and fines (silt and clay particles finer than 63 microns) in addition to total suspended-sediment loads.

During WY 2008 the relations between suspended-sediment concentration and water discharge varied widely among sites and with time at individual measurement stations. At the Marmot Dam station, the overall relation between discharge and suspended-sediment concentration showed little correlation, but coherent relations emerged from consideration of separate time periods (fig. 32). Time-dependent consideration of relations between concentration and discharge also improved correlations for the Revenue Bridge and Dodge Park measurement stations (fig. 32). Analysis of the Dodge Park measurements excludes the initial postbreach pulse of fine sediment (measured on October 19, 2007) that passed the site because those concentration values are outliers to the overall trend and are presumably atypical of transport at this site.

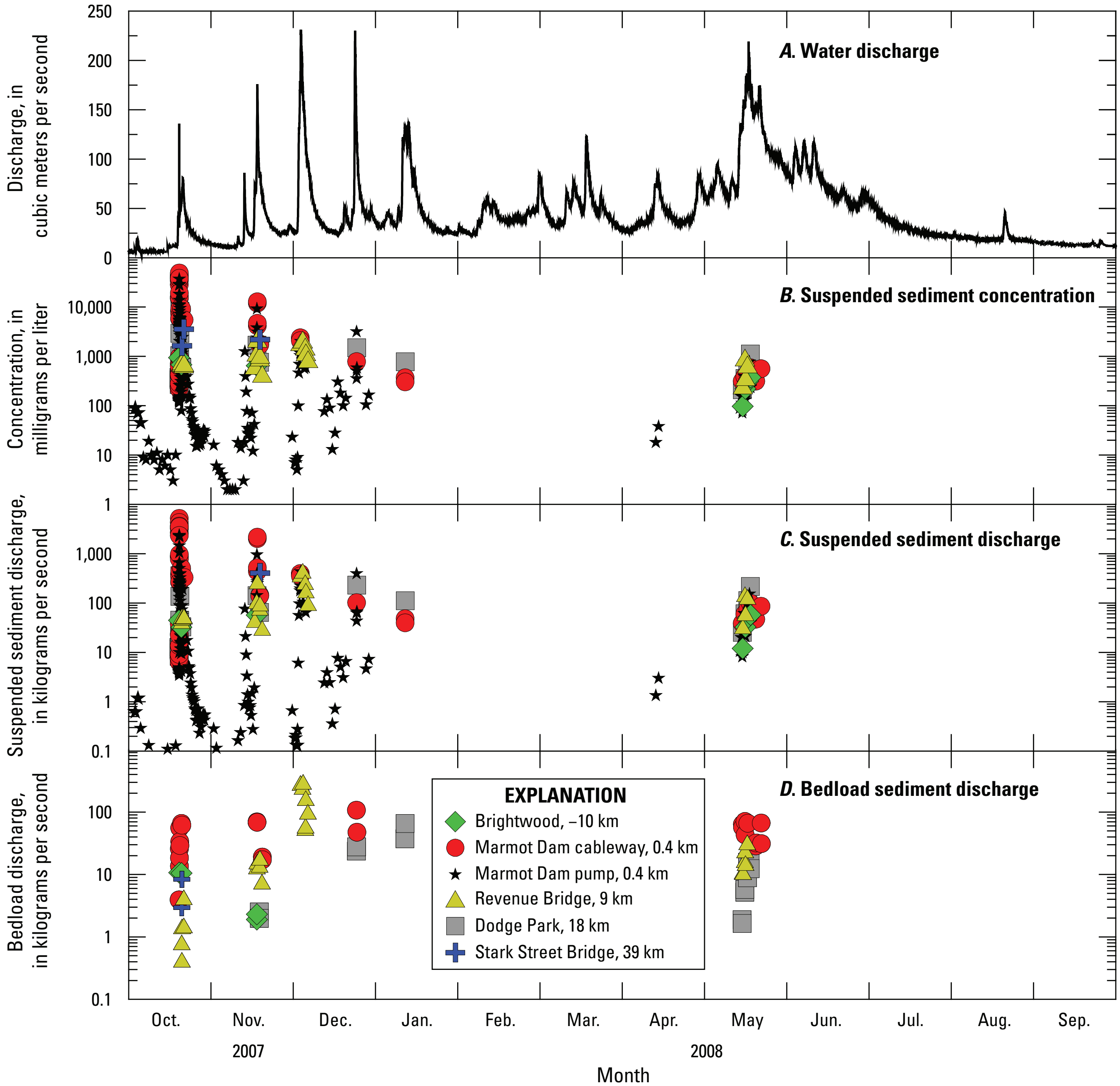


Figure 29. Time series of water discharge and sediment fluxes measured during high-flow events in the months following the breaching of Marmot Dam in October 2007. Revenue Bridge data are from Pittman and Matthews (2008). See figure 1 for station locations. Distances are station distance from Marmot Dam; positive values are downstream.

We applied the time-specific correlations between concentration and discharge to corresponding parts of the annual hydrographs (table A3) to estimate annual mass fluxes of sand, fines, and total suspended-sediment loads that passed each of the measurement sites. These estimates and their uncertainties were determined by bootstrap Monte Carlo simulations using the measurements composing each of the time-specific correlations and summed for WY 2008 (table 6). Details of the analysis methods and underlying data are provided in the appendix and tables A2 and A3.

Annual suspended-sediment fluxes estimated from the Monte Carlo simulations showed broad error bands (5th and 95th percentile values) owing to the scatter of our limited data. In some instances, we could not obtain a reasonable 95th percentile estimate. In the following discussion, and in the data summarized in tables 6 and 7, we present our best estimate of the mean transport past each measurement site in WY 2008, with error bands generally guided by the relationship between the 5th percentile and median values. These error bands, typically about ±30–50 percent, represent a balance between the small-sample Monte Carlo results and our confidence in the median value estimates.

Reservoir erosion markedly increased suspended-sediment transport below the dam site after breaching, but the magnitude of the transported load diminished within 18 km downstream at the Dodge Park measurement site. Upstream of the dam site, about 120,000 Mg of suspended sediment, composed of about 90 percent sand, passed the Brightwood measurement station (table 6). At the Marmot Dam station, the annual suspended-sediment load was about four times larger (about 465,000 Mg) and composed of about 80 percent sand. A similar load of suspended sediment (about 480,000 Mg) passed Revenue Bridge, 9 km farther downstream, and it was also composed of about 80 percent sand. Another 9 km downstream, however, the suspended-sediment load at Dodge Park had declined about 30 percent to about 340,000 Mg, yet remained about 80 percent sand.

Grain-size analyses of the sampled suspended sediment show compositional trends following breaching, mainly in the percentage of the load consisting of sand. At the Marmot Dam station before breaching, suspended sediment consisted of less than 30 percent sand, but it coarsened within an hour after breaching to about 80 percent sand (fig. 28) and exceeded 80 percent sand for the remainder of WY 2008 (fig. 30). At Revenue Bridge, suspended sediment measured within 24 hours of breaching consisted of approximately equal amounts of sand and fines (fig. 28), but by November 2007 suspended sediment had coarsened to 75 to 95 percent sand (fig. 30). At Dodge Park, the quantity of sand in the suspended load rose more slowly and did not exceed 80 percent until December 2007, 2 months after breaching (figs. 28, 30).

The rise of sand concentrations below the dam site represents interactions among the river, its discharge magnitude, and sediment sources along the channel. The rapid

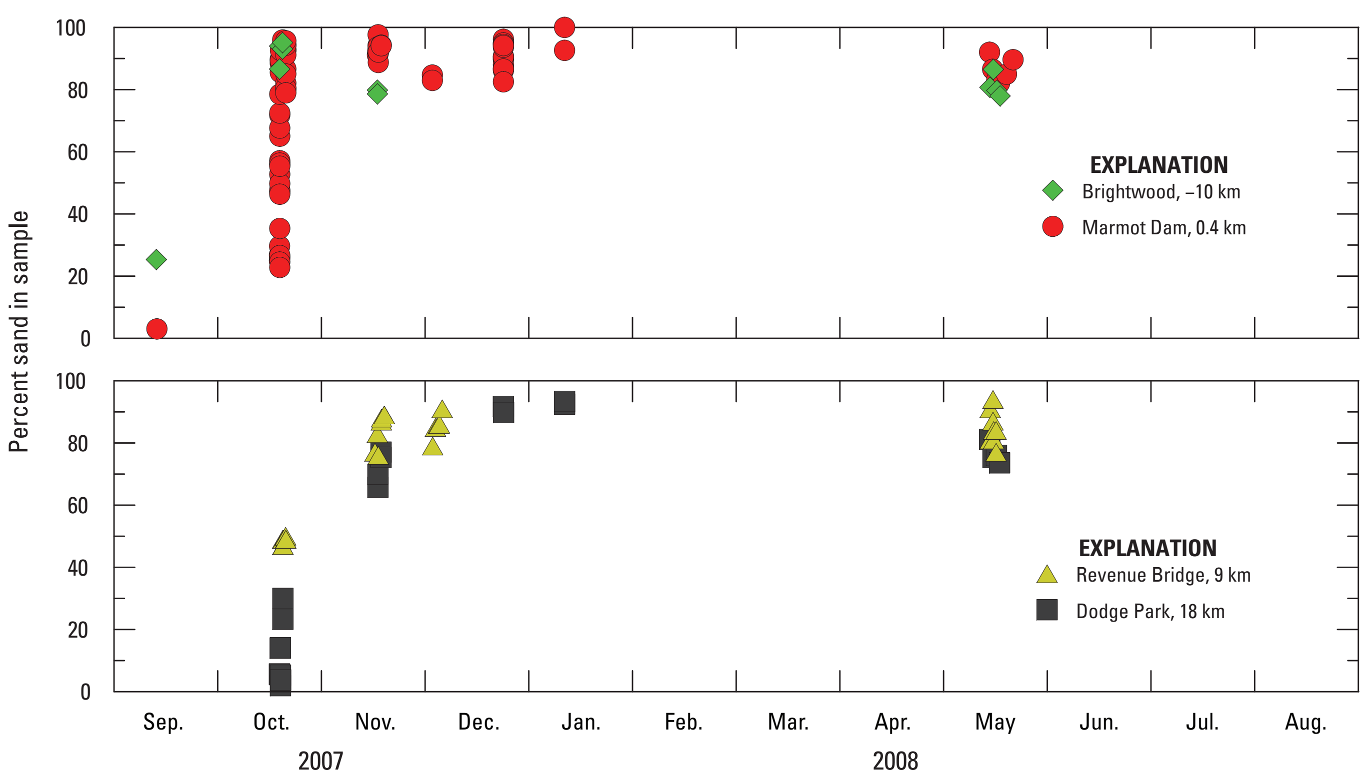


Figure 30. Percent sand in suspended-sediment samples collected in the months following breaching of Marmot Dam in October 2007. See figure 1 for station locations. Distances are station distance from Marmot Dam site; positive values are downstream.

rise in sand concentration at the Marmot Dam station clearly resulted from breaching of the cofferdam and erosion of sand from the reservoir. Farther downstream, interpretation of increasing sand concentration is more complicated because the higher postbreach flows would be expected to transport more sand in suspension even in the absence of erosion of reservoir sediment. The constant, high percentage of sand for all downstream sites for the remainder of WY 2008 after breaching, however, suggests that sand transport past both Revenue Bridge and Dodge Park was probably augmented by sediment supplied from the eroding reservoir. A lack of significant sediment source other than the reservoir between the dam site and Revenue Bridge bolsters this interpretation for that site. At Dodge Park, however, such an interpretation is more tenuous because the sand concentration at Brightwood (upstream of the eroding reservoir reach) also remained high and relatively constant throughout WY 2008 (fig. 30) and because there are substantial sources of sand exposed in banks and bluffs between Revenue Bridge and Dodge Park (for example, see Bauer, 2009).

Bedload Sediment Transport

We made bedload measurements before and during breaching of the cofferdam and during all subsequent high flows in WY 2008. Most of our measurements were at the Marmot Dam station, where we made 24 separate bedload measurements during WY 2008, and near Revenue Bridge, where we made 23 measurements. Farther downstream at Dodge Park we made 14 measurements during WY 2008. Upstream at Brightwood we made 6 measurements during WY 2008 and an additional 5 measurements in WY 2009 to better define the relation between bedload transport and water discharge (table A2).

All measurements were made by placing pressure-difference samplers on the bed for intervals ranging from 10 to 120 seconds, depending on transport rates. Most samples were collected over durations of 30 to 60 seconds. At the Marmot Dam station and near Revenue Bridge, we sampled bedload using a TR-2 bedload sampler (Diplas and others, 2008) having a 15×30-cm opening and a bag having 0.5-mm mesh size. During WY 2008, bedload passing Brightwood, Dodge Park, and Stark Street Bridge was sampled with a 2/3-scale modified TR-2 bedload sampler having a 10×20-cm opening. In January 2009, samples at Brightwood were collected with a full-sized TR-2 sampler (Podolak and Pittman, 2011).

Bedload-measurement transects generally consisted of measurements at 7 to 14 stations across the channel. At the Marmot Dam site, however, six bedload-transport measurements made during the first 6 hours after breaching consisted of measurements at only 1 to 6 stations across the channel. Some bedload samples collected at the Marmot Dam site consisted solely of sediment obtained at a single

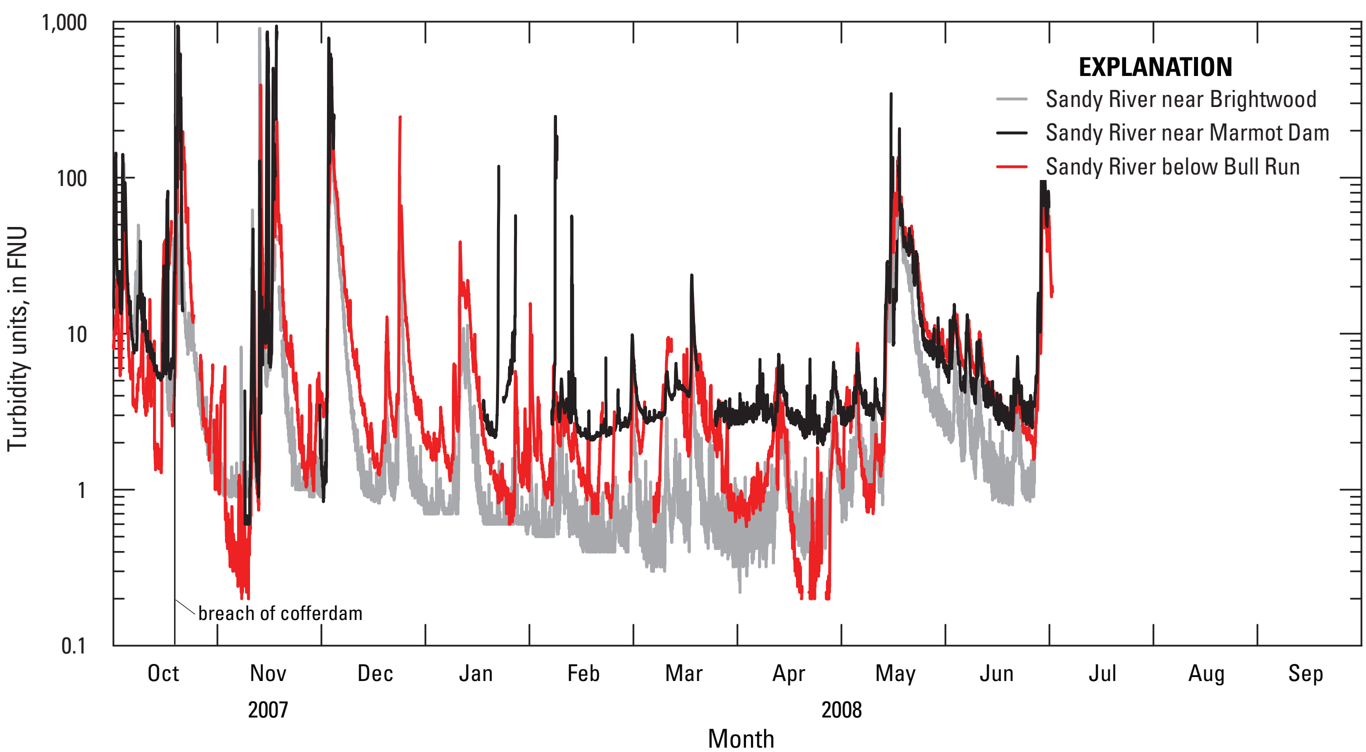


Figure 31. Turbidity measured during water year 2008 at the Brightwood, Marmot Dam, and Sandy River below Bull Run gaging stations. Units are given in Formazin Nephelometric Units (FNU).

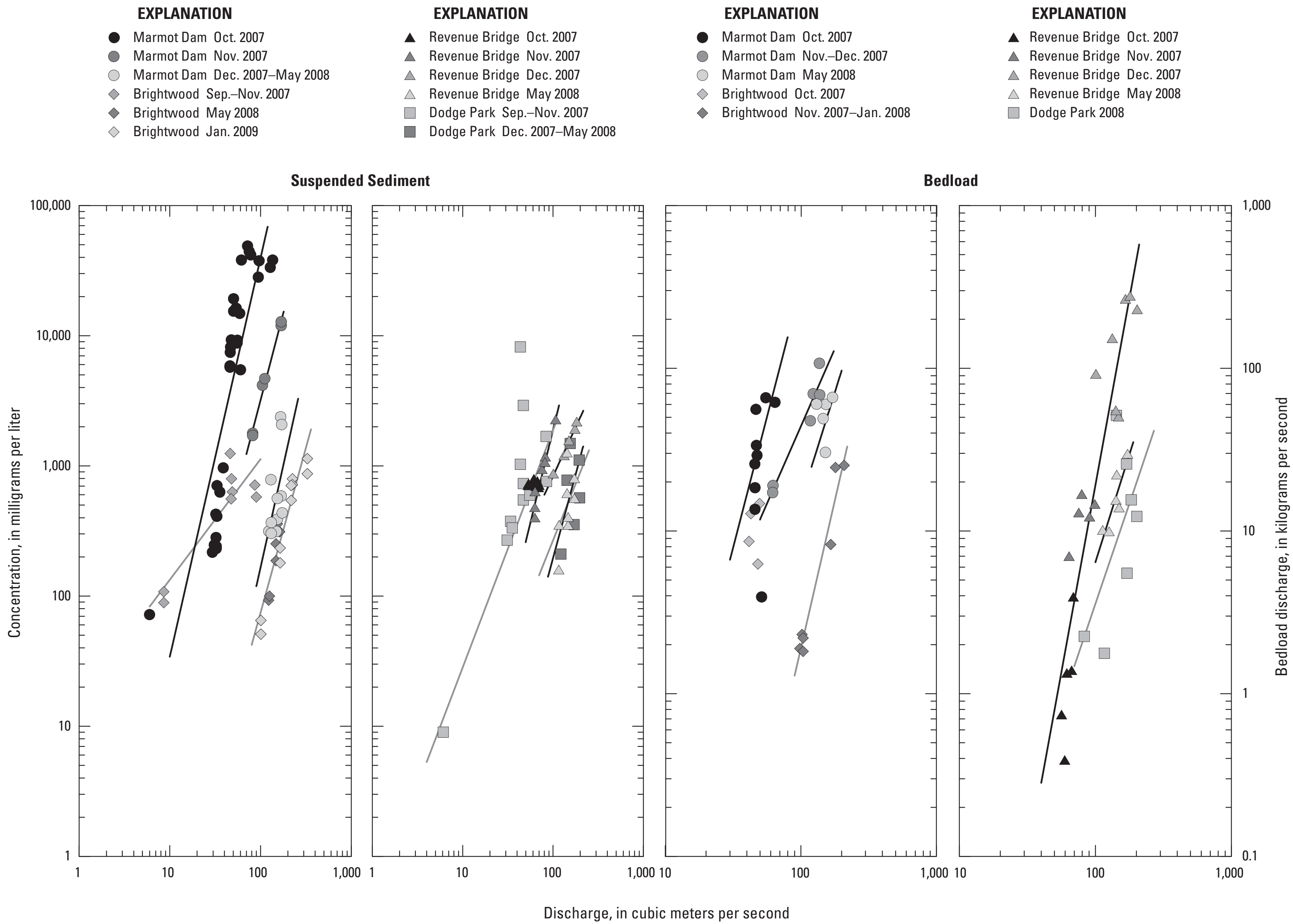


Figure 32. Relations among suspended-sediment concentration, bedload discharge, and water discharge at various measurement stations following breaching of Marmot Dam in October 2007. Power-law regression models show general data trends. Seasonal trends and outliers not used to define general trends are discussed in text. See figure 1 for station locations.

Table 6. Monte Carlo simulation estimates of annual sediment fluxes for water year 2008 following removal of Marmot Dam.

[–, data insufficient to obtain 95th percentile value; percentile values are 5th, 50th, 95th; NA, negligible amount of fractional transport; km, kilometers; Mg, megagrams]

Station	Distance (km) [1]	Composition [2]	Suspended load (Mg)			Bedload (Mg)			Total load (Mg)		
			5th	50th	95th	5th	50th	95th	5th	50th	95th
Brightwood	-10	Gravel	NA	NA	NA	2,500	3,500	5,000	2,500	3,500	5,000
		Sand	85,000	110,000	125,000	10,000	13,000	15,000	95,000	125,000	140,000
		Fines [3]	10,000	10,000	50,000	NA	NA	NA	10,000	10,000	50,000
		Total	95,000	120,000	175,000	15,000	17,000	19,000	110,000	140,000	195,000
Marmot	0.40	Gravel [3]	NA	NA	NA	90,000	120,000	–	90,000	120,000	–
		Sand	300,000	385,000	785,000	110,000	160,000	460,000	410,000	545,000	1,245,000
		Fines	50,000	75,000	120,000	NA	NA	NA	50,000	75,000	120,000
		Total	370,000	465,000	780,000	200,000	280,000	–	570,000	745,000	–
Revenue Bridge	9	Gravel	NA	NA	NA	20,000	30,000	60,000	20,000	30,000	60,000
		Sand	340,000	400,000	750,000	110,000	160,000	290,000	450,000	560,000	1,050,000
		Fines	60,000	80,000	600,000	NA	NA	NA	60,000	80,000	600,000
		Total	400,000	480,000	–	130,000	190,000	350,000	530,000	670,000	–
Dodge Park	18	Gravel	NA	NA	NA	1,000	5,000	–	1,000	4,000	–
		Sand [3]	160,000	270,000	–	14,000	30,000	–	175,000	300,000	–
		Fines	60,000	70,000	90,000	NA	NA	NA	60,000	70,000	90,000
		Total	220,000	340,000	–	15,000	35,000	–	235,000	375,000	–

[1]Distance above (negative) and below (positive) former dam site.

[2]Gravel refers to particles larger than 2 mm, sand refers to particles 0.063 to 2 mm, and fines refer to particles smaller than 0.063 mm.

[3]Residual calculation.

measurement station, whereas others represented stations composited during a transect measurement. Although all station measurements were compiled to compute a transect-averaged transport rate, bedload samples not composited during collection were processed individually for grain size. A similar sampling strategy was used at the Revenue Bridge site (Pittman and Matthews, 2008). All station measurements from a single transect were composited at Brightwood, Dodge Park, and Stark Street Bridge.

Transport at the Time of Breaching

Bedload transport rates at the Marmot Dam station increased rapidly after breaching. Immediately prior to breaching, bedload fluxes at Brightwood and at the Marmot Dam station were less than about 10 kg/s (fig. 27*E*). Within 3 hours after breaching, bedload flux at the Marmot Dam station increased from about 1 kg/s to as much as 30 kg/s, and within 20 hours after breaching attained rates of 60 kg/s. This rapid increase in bedload flux immediately below the dam site contrasts with the steady flux of less than 10 kg/s of sandy bedload that passed Brightwood and Revenue Bridge (fig. 27*E*). Bedload transport at the Marmot Dam station continued at high rates for much of the next 60 hours. In contrast, simultaneous measurements 9 km downstream near Revenue Bridge recorded bedload flux of less than 5 kg/s emerging from the Sandy River gorge (Pittman and Matthews, 2008).

The composition of bedload below the dam site gradually changed after breaching. Before breaching, bedload passing the Marmot Dam station was greater than 90 percent sand (fig. 33). During the first 4 hours after breaching, bedload remained mainly sand even as transport rates increased rapidly (fig. 33). Moderate amounts of gravel (particles larger than 2 mm, and as much as about 30 percent of measured load) began passing the site within 4 hours, but significant gravel transport (greater than or equal to 40 percent of measured load) was not detected until 18–20 hours after breaching, in conjunction with very high rates of bedload transport, rapid bed aggradation, and growth of mid-channel gravel bars (figs. 20, 21, 22, 27*E*).

Transport by Subsequent High Flows

Bedload transport past the Marmot Dam station remained elevated during subsequent high flows in WY 2008 compared to transport measured upstream and farther downstream. For example, measurements during the November 17–18, 2007, high flow—the first high flow following breaching—showed transport rates of less than 3 kg/s at Brightwood, nearly 70 kg/s at the Marmot Dam station, 12–17 kg/s near Revenue Bridge, and less than 3 kg/s at Dodge Park (fig. 29; table A2). This pattern continued through the winter and spring; during the May 2008 snowmelt peak, bedload transport rates at the Marmot Dam station continued to attain values of nearly 70 kg/s, while transport rates at Revenue Bridge remained mostly in the range of 10–20 kg/s and those at Dodge Park had increased to as much as 17 kg/s (fig. 29; table A2).

The greatest bedload transport rates during the wet season following breaching were measured during a high flow in early December 2007, which peaked at 231 m^3/s at the Marmot Dam station on December 3. Three bedload measurements made during December 3–4, 2007, near Revenue Bridge were between 230 and 280 kg/s at flows between 160 and 200 m^3/s (fig. 29; table A2; Pittman and Matthews, 2008). Equipment problems prevented reliable measurement of bedload transport at the Marmot Dam station, and thus we cannot directly compare the fluxes. However, if the relation between flux measurements observed at those two sites during other high flows held, the bedload flux past the Marmot Dam station at that time was probably several hundred kg/s.

The bedload fluxes measured on the Sandy River after breaching of Marmot Dam approach some of the highest measured values for gravel-bed rivers on a unit-channel-width basis. At Revenue Bridge, the December 3–4, 2007, measurements were as great as 3.9 kg/s/m for the 72.3-m-wide channel, and at the Marmot Dam station unit-width bedload transport rates were probably greater. Despite flows of less than 60 m^3/s at the time of breaching of the cofferdam, unit-width bedload transport rates on October 19 and 20 across the 20-m-wide channel at the Marmot Dam station exceeded 3 kg/s/m. These unit-width bedload transport rates exceed maximum unit-width bedload transport rates, as much as 2.1 kg/s/m, measured on other rivers in the western United States for discharges as great as the 2-yr return-interval flow (Pitlick and others, 2009; Wallick and others, 2010). The maximum measured unit-width bedload rates associated with the Marmot Dam removal, 3.9 kg/s/m, are matched only by measurements on the North Fork Toutle River, Washington (Pitlick, 1992), downstream of the voluminous debris-avalanche deposit associated with the 1980 eruption of Mount St. Helens. Hence, abrupt exposure of coarse-grained sediment to the high-gradient Sandy River induced extraordinary, transient bedload-transport rates.

During the year following breaching, bedload passing the Marmot Dam station was composed of substantially coarser sediment than was bedload passing other measurement sites. At that station, bedload composition ranged between 30 and 80 percent gravel, compared to the 5 to 35 percent gravel in samples collected near Revenue Bridge and the 2 to 16 percent gravel in samples from Dodge Park (fig. 34). At

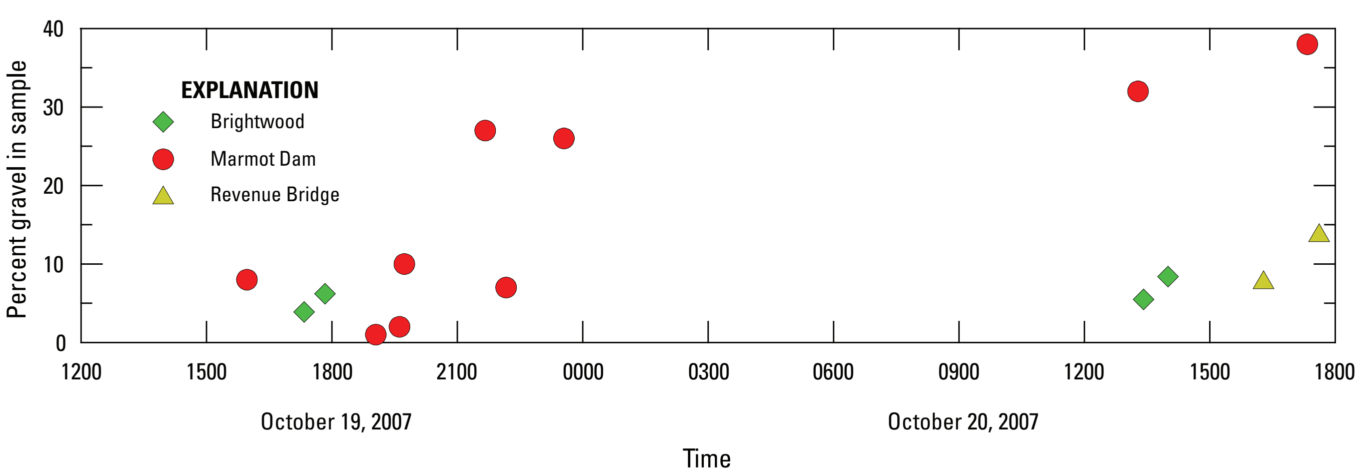


Figure 33. Percent gravel in bedload sediment measured during the first 24 hours following breaching of Marmot Dam on October 19, 2007. Revenue Bridge data are from Pittman and Matthews (2008). See figure 1 for station locations. Times shown are Pacific Daylight Time (PDT).

Brightwood, gravel composed 4 to 8 percent of the measured bedload in WY 2008 (fig. 34) but as much as 40 percent of the load measured in January 2009 (table A2). The greater gravel transport at the Marmot Dam station reflects both the abundant supply of gravel resulting from reservoir erosion and the overall greater transport rates immediately below the dam site.

Annual Sediment Fluxes

Similar to the analysis for suspended sediment, relations between bedload discharge and water discharge in conjunction with the flow records for WY 2008 and bootstrap Monte Carlo simulations (appendix) support estimates of annual bedload fluxes and their uncertainties. The sediment transport–water discharge relations for bedload at the Marmot Dam and Revenue Bridge stations are scattered and as a consequence were separated into periods defining distinct relations (fig. 32). Especially for the Marmot Dam station, transport rates relative to water discharge declined throughout WY 2008. That decline resulted in the definition of three sediment-transport rating relations: (1) a rating for measurements made October 19–20, 2007; (2) a rating for measurements made from November 17 through December 24, 2007; and (3) a rating for measurements made May 15–22, 2008 (fig. 32). Likewise, we developed two sediment-transport rating relations for the Revenue Bridge station: (1) a rating for measurements made from October through December 2007 and (2) a rating for measurements made in May 2008 (fig. 32). We judged the measurements at Brightwood and Dodge Park to be adequately represented by single rating relations for the entire water year, although the four October 2007 measurements of anomalously high sand transport at Brightwood were not considered in developing its sediment-transport rating relation (fig. 32). Those anomalous fluxes of fine sand are consistent with high fluxes of fine sand typically measured in suspended-sediment load during the first high flows of autumn in other Cascade Range rivers (K.R. Spicer, unpublished data), and they are likely related to flushing of dry ravel that accumulated along channel banks during summer low flows. However, because we lack sufficient data to adequately define a separate autumn transport relation at Brightwood, we excluded those outlier data from our annual-flux analysis.

The time-dependent relations between sediment flux and water discharge were applied to corresponding parts of the annual hydrographs (table A3) to estimate annual bedload transport amounts. Estimates of mean bedload fluxes and their uncertainties were made by bootstrap sampling of the data underlying the rating relations and Monte Carlo simulations. These analyses were conducted for the total bedload fluxes as well as for the fluxes of sand and gravel. For

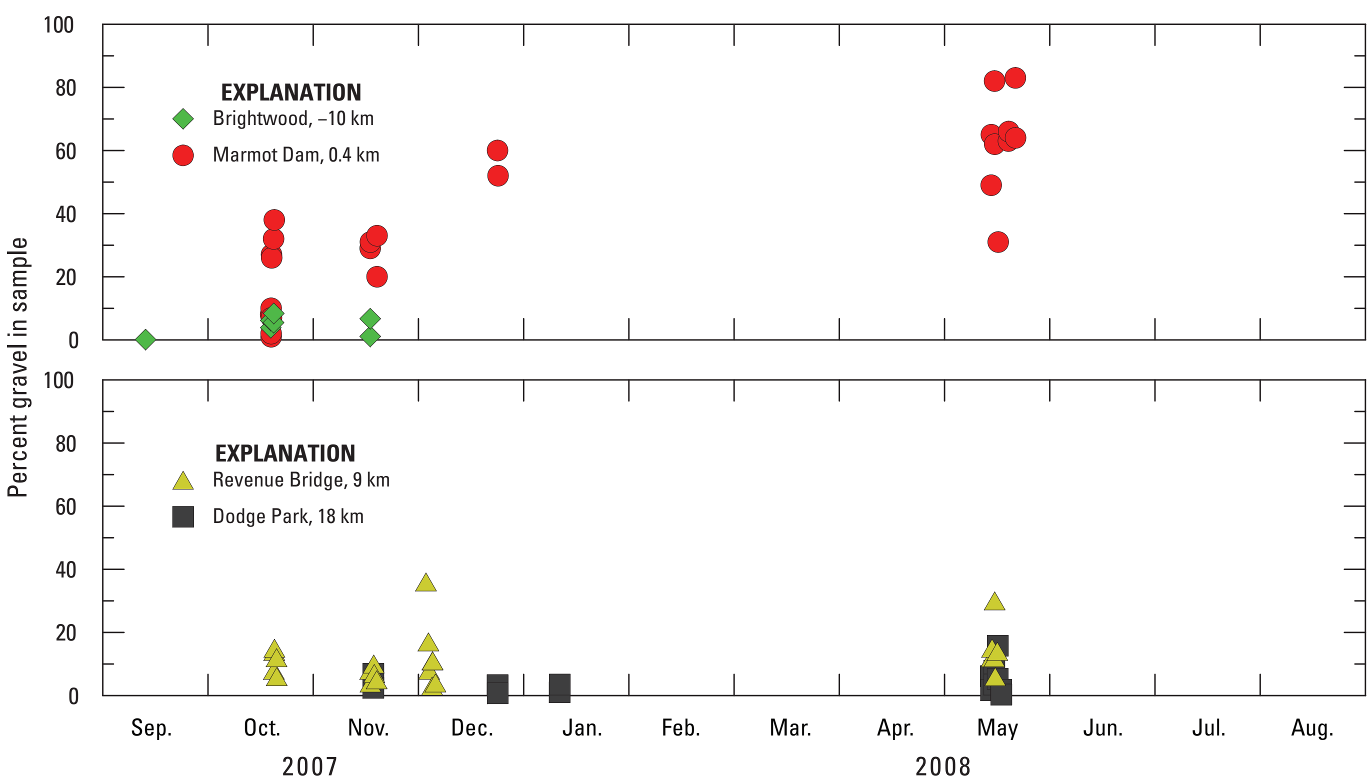


Figure 34. Percent gravel in bedload sediment measured in the months following breaching of Marmot Dam in October 2007. See figure 1 for station locations. Distances are station distance from Marmot Dam site; positive values are downstream.

some calculations, however, small sample sizes required us to estimate either the sand or gravel flux as a difference from more satisfactory estimates of total annual flux (table 6).

Erosion of reservoir sediment sharply increased bedload flux below the dam site, but that increased flux diminished as the sediment migrated downstream. Our estimates of annual bedload flux indicate that about 280,000 Mg of bedload passed the Marmot Dam station during WY 2008. That flux, composed of about 55 percent (160,000 Mg) sand and 45 percent (120,000 Mg) gravel, greatly exceeded the estimated bedload entering the reservoir (170,000 Mg past Brightwood). Nine kilometers downstream, the bedload flux at Revenue Bridge had declined by about one-third (to 190,000 Mg), and consisted of about 85 percent (160,000 Mg) sand and 15 percent (30,000 Mg) gravel. The difference in fluxes above and below the Sandy River gorge appears to be mainly the result of gravel deposition, although gravel attrition owing to abrasion may have been a contributing factor. Nine kilometers farther downstream, about 35,000 Mg of bedload, which consisted of 85 percent (30,000 Mg) sand and 15 percent (5,000 Mg) gravel, passed Dodge Park (table 6). The marked loss of bedload between the exit of the Sandy River gorge and Dodge Park was likely the result of deposition owing to the reduction in river gradient along this reach (fig. 3). Some of that loss, however, may also be the result of gravel attrition. If the loss was due solely to deposition, and if the sediment was dispersed uniformly across the reach, the resulting deposit would average 0.05 m thick over the average floodplain width of 200 m (fig. 3*C*).

The declining amounts of bedload transport with respect to water discharge at the Marmot Dam station in WY 2008 coincided with temporally increasing gravel content of the bedload (fig. 34). Multiple factors possibly contributed to these trends, including (1) coarsening of the reservoir channel bed in conjunction with incision of the reservoir sediment (fig. 17), which reduced overall sediment supply, transport rates, and sand content of bed material; (2) an overall sand content that may have been greatest in the downstream part of the reservoir (Squier and Associates, Inc., 2000), which was the source of much of the sediment initially evacuated from the reservoir reach; and (3) coarsening of the channel bed below the dam site as sand from the channel bed and bars was winnowed (fig. 21), which increased channel roughness.

Estimated Sediment Budget

Measurements of reservoir erosion, channel deposition, and sediment flux above and below the dam site and below the Sandy River gorge permit development of a sediment budget for the first year following breaching of Marmot Dam. The sediment budget provides a holistic view of the fate of the stored sediment following dam breaching. Grain-size analyses of the stored and deposited sediment, as well as of the sediment in transport, allowed estimates of separate budgets for the sand (less than 2 mm) and gravel (greater than 2 mm) fractions of the sediment.

The sediment budget encompasses the 20-km length of the Sandy River from Brightwood to the exit of the Sandy River gorge near Revenue Bridge. It is based on sediment input, output, and changes in storage along this reach (table 7; fig. 35). Input was computed from the estimated sediment flux at Brightwood. Reconnaissance observations indicate that sediment contributions from landslides and bank erosion between Brightwood and the reservoir reach were negligible. Although small tributaries contributed flow in this reach, they were likewise judged to contribute little sediment load. Output was computed from the estimated flux that emerged from the Sandy River gorge. Changes in storage were assessed by channel surveys from the reservoir reach to the gorge entrance, which were supplemented by an estimate of sediment flux that passed the Marmot Dam station. Flux measurements at Dodge Park, although not contributing directly to the sediment budget, provided additional information.

Our measurements of sediment erosion, transport, and deposition in the context of a sediment budget (table 7; fig. 35) demonstrate three key elements of the short-term geomorphic response to abrupt sediment loading of the Sandy River channel near the site of Marmot Dam. First, the sediment flux immediately downstream of the dam site following dam removal increased substantially owing to entrainment of impounded reservoir sediment. As a consequence of nearby deposition, however, that increase did not translate downstream in its entirety. Second, the valley bottom immediately below the dam site accommodated significant sediment storage. Approximately 200,000 Mg (120,000 m^3) were stored in the 2-km-long reach between the site of the cofferdam and the entrance to the Sandy River gorge. This deposition was about evenly split between the 0.4-km-long reach between the site of the cofferdam and the Marmot Dam measurement station and the 1.6-km-long reach between the Marmot Dam station and the entrance to the gorge. Storage within the 7-km-long Sandy River gorge may account for as little as a few thousand to as much as several tens of thousands of cubic meters of sediment (as much as 100,000 Mg) released from the reservoir (fig. 35; table 7). Third, the 9-km-long channel reach between the exit of the gorge and Dodge Park may have stored about 250,000 Mg (~150,000 m^3) of sand and (minor) gravel (table 7). Deposition along this reach, however, had not been detected by the sparse and discontinuous measurements of channel-bed elevation made in the two years following breaching (Bauer, 2009; Podolak and Pittman, 2011).

Balancing the sediment budget for this segment of the Sandy River was challenging owing to uncertainties in annual sediment transport, the precise composition of the reservoir sediment, and because of the logistical difficulties of making measurements within the Sandy River gorge, a tight bedrock canyon of little access. Through the gorge, the river flows steeply over bedrock and boulder steps and through long, deep pools that encompass about 50,000 m^2

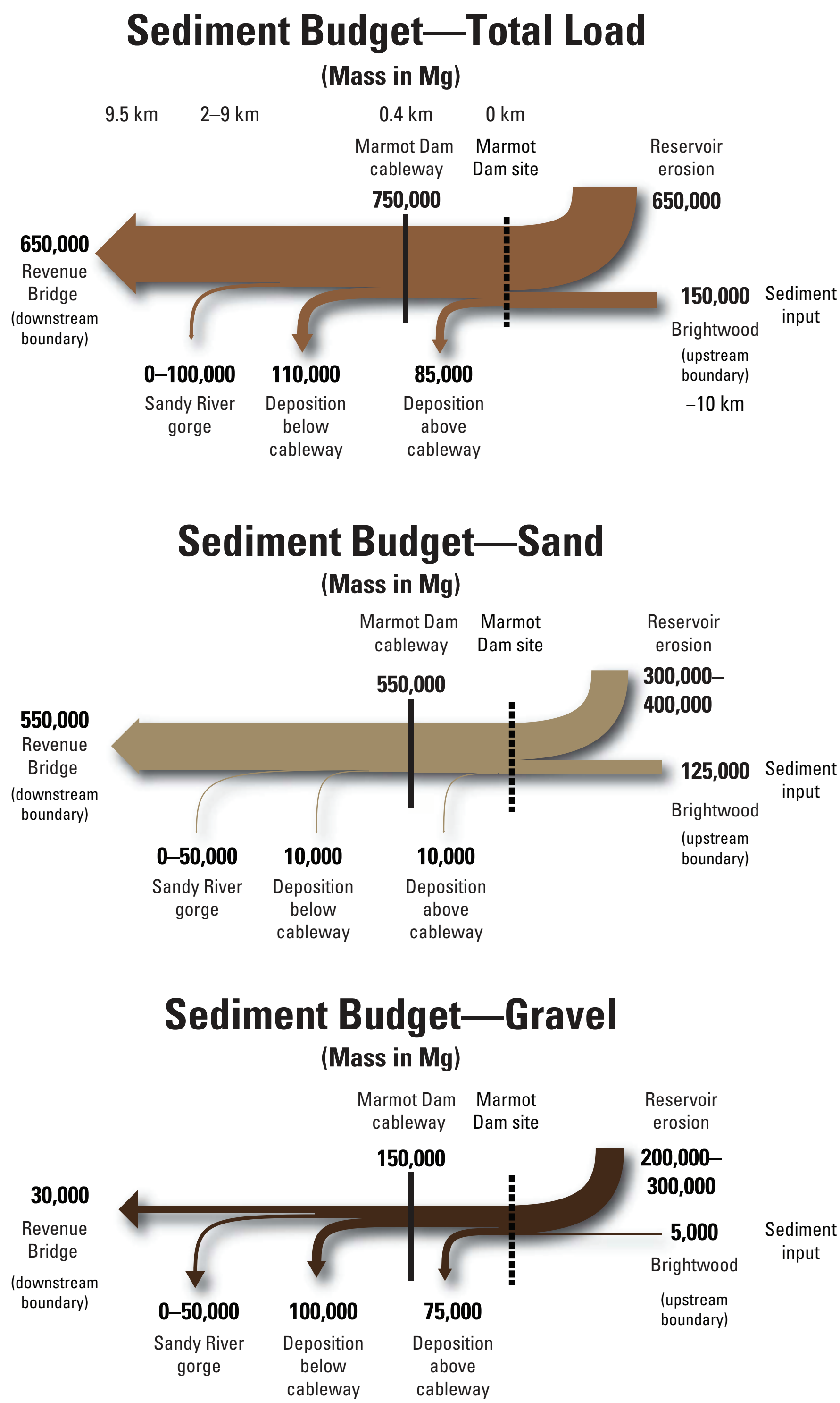


Figure 35. Schematic representations of estimated sediment budgets for total sediment, sand, and gravel eroded, transported, and deposited by the Sandy River in the vicinity of Marmot Dam during the first year following breaching of the dam in October 2007. Figure shows estimated upstream input to reservoir reach, erosion from reservoir reach, loss to depositional storage, and output at the exit of the Sandy River gorge in megagrams (Mg). Our measurements of reservoir erosion and channel deposition were converted from volume to mass assuming a bulk sediment density of 1.7 megagrams per cubic meter (Mg/m^3). See tables 6 and 7 for error estimates associated with various budget components.

Table 7. Estimated mass sediment budget for Sandy River near Marmot Dam for water year 2008 (see also table 6).
[–, no data; Mg, megagrams]

Location	Total mass [1] (Mg)	Gravel mass [1] (Mg)	Sand mass [1] (Mg)	Fines mass [1] (Mg)
Flux at Brightwood—input to reservoir reach	150,000±50,000	5,000±2,000	150,000±50,000	10,000±10,000
Reservoir erosion [2]	640,000±40,000	320,000±40,000	330,000±40,000	5,000±5,000
Deposition—cofferdam to Marmot Dam station	85,000 ±5,000	70,000±5,000	12,500±2,500	–
Flux at Marmot Dam station	750,000±250,000	150,000±50,000	550,000±200,000	50,000±25,000
Deposition below Marmot Dam station and above gorge	110,000±30,000	90,000±25,000	15,000±5,000	–
Storage in Sandy River gorge	[0–100,000]	[0–50,000]	[0–50,000]	[0–40,000]
Flux at Revenue Bridge	650,000±200,000	50,000±25,000	550,000±200,000	50,000±25,000
Flux at Dodge Park	400,000±150,000	5,000±2,000	300,000±150,000	50,000±25,000

[1]Mass flux values are estimated from bootstrap Monte Carlo simulations applied to annual hydrographs, and rounded to the nearest 50,000 Mg (see table 6). Estimated errors are guided by the relation between the 5th and 50th percentile values and are roughly ±30–50 percent. Erosional and depositional masses are computed from field and lidar surveys and converted using a mean bulk density of 1.7 megagrams per cubic meter (Mg/m^3). Error estimates for erosion and deposition are discussed in the appendix. Values in brackets represent residual calculations.

[2]The sediment budget balances reasonably well if the sediment distribution within the reservoir is about 60 percent sand and 40 percent gravel. Limited sampling of the reservoir sediment, however, suggests a mean distribution of about 45 percent sand and 55 percent gravel (Squier and Associates, Inc., 2000). For purposes of the sediment budget presented here, we assume a roughly equal distribution of sand and gravel within the reservoir and acknowledge that this causes uncertainty within the sediment budget.

as measured from aerial photographs. Inferences of as much as 60,000 m^3 of deposition within the gorge are based on uncertainties in fluxes and changes in storage measured upstream and downstream (table 7). Before dam removal, the pools in the gorge were about 2 to 3 m deep and contained only patchy deposits of sand and gravel (Stewart and Grant, 2005; G.B. Stewart, oral commun., 2011). A float trip through the gorge in April 2009 revealed that many of the pools had accumulated sediment and that new lateral bars of sand and gravel locally flanked the channel. The total sediment accumulation in the pools and flanking bars appeared to be less than the averaged 1.2-m pool filling required to account for the maximum plausible estimate of 60,000 m^3 of sediment deposition in the gorge. From these observations, we conclude that although sand and gravel storage in the gorge significantly affected local channel morphology, the total volume of sediment storage in this reach is probably represented by the lower end of the range indicated in table 7—on the order of a few tens of thousands of cubic meters.

Differential sediment transport and deposition produced significant spatial variations in the distributions of gravel, sand, and fines mobilized after breaching. Flux estimates suggest that about four times as much gravel entered the reach below the Marmot Dam station than exited the Sandy River gorge (tables 6, 7; fig. 35). Channel surveys and grain-size analyses suggest that about 70–90 percent of the gravel passing the Marmot Dam station was deposited in the 1500-m-long channel reach between that station and the entrance to the gorge (tables 4, 6, 7; fig. 35). Along the 9-km-long channel reach between the exit of the gorge and Dodge Park, nearly all of the mobile gravel that exited the gorge was lost to deposition and attrition (tables 6, 7).

In contrast to the gravel, the sand mobilized by reservoir erosion largely passed downstream (tables 6, 7). Within the uncertainty of our measurements, equal amounts of sand passed both the Marmot Dam and Revenue Bridge sites. Downstream of Revenue Bridge, however, about half of the sand load that emerged from the Sandy River gorge was deposited before reaching Dodge Park, assuming that no additional sand was entrained between those two sites. The remainder of the sand (about 300,000 Mg) moved farther downstream. The load of silt and clay that entered the reach below the Marmot Dam station passed through the gorge and mostly continued downstream past Dodge Park (tables 6, 7).

The differential mobility of the sand and gravel fractions of the sediment load are reflected in the compositions of the gravel bars that developed and grew in the channel reach between the site of the dam and the entrance to the gorge. In general, the bars are composed of 80–90 percent gravel and 10–20 percent sand (fig. 36) despite being derived from reservoir sediment composed of approximately equal proportions of gravel and sand (45–65 percent gravel, 35–50 percent sand, 2–5 percent fines; Squier and Associates, 2000; di Leonardo and others, 2009). The marked difference between the composition of sediment supplied to the reach and the sediment deposited within the reach reflects the preferential deposition of gravel from the mixed sand-and-gravel sediment load. Most of the disparity between sediment source composition and bar composition can be attributed specifically to evolution of the bedload component of the total sediment transport.

Although gravel was transported solely as bedload and the fines were transported solely as suspended load, sand transport was mixed and the proportions of sandy bedload and suspended load varied spatially (table 6). At Brightwood, nearly ten times as much sand was transported in suspension than as bedload. Immediately downstream of the dam site and at the exit of the gorge, the load of sand in suspension was only about 2–3 times greater than that in the bedload (table 6). Farther downstream at Dodge Park the percentage of sand transported in suspension relative to bedload was similar to that at Brightwood. The change in mechanism and magnitude of sand transport at Dodge Park compared to that exiting the gorge mainly reflects deposition of sand that was transported as bedload rather than an increase of the amount transported in suspension. At Dodge Park the amount of sand transported as bedload dropped by 80 percent compared to the load that exited the gorge, whereas the amount transported in suspension decreased by only 30 percent (table 6).

Discussion

As does dam emplacement, dam removal represents a fundamental perturbation to the geomorphic behavior of a river system. The geomorphic effects of dam removal propagate both upstream and downstream from the removal site: upstream, sediment erosion is the dominant process, whereas downstream, sediment transport and deposition predominate. These two zones are coupled in that erosion of sediment stored behind the former dam is the principal source of sediment transported and deposited downstream. The removal of Marmot Dam and subsequent release of stored sediment provides insights relevant to interactions among fluvial processes. Key findings pertain to (1) relations among the timing and rate of sediment erosion from the former reservoir and magnitude and sequencing of river discharge; (2) the nature and pace of knickpoint migration through the sediment reservoir; (3) temporal relations among the transport of constituent components of the reservoir sediment, river discharge, and channel morphology; (4) spatial and temporal relations among downstream sediment deposition, river discharge, and channel morphology; and (5) the adequacy of current physical and numerical models to predict timing, location, magnitude, and duration of sediment-related impacts.

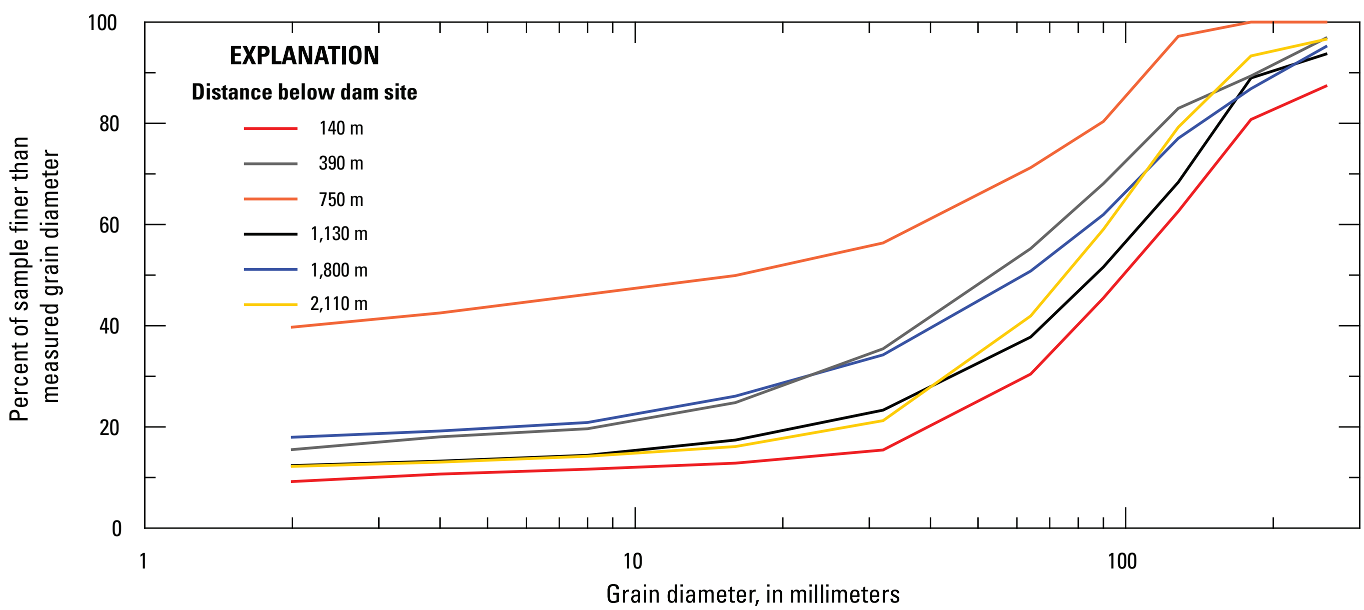


Figure 36. Grain-size distributions of bulk sediment samples of gravel bars collected along the 2-kilometer-long channel reach downstream of the Marmot Dam site.

Timing, Rate, and Processes of Reservoir-Sediment Erosion

Because the fate of sediment impounded behind a dam is a principal issue surrounding dam removal (Heinz Center, 2002, p. 85; Randle and others, 2010), identifying the factors that control sediment erosion and deposition following removal may assist in guiding removal strategies. Observations and measurements associated with removal of Marmot Dam document key processes, rates, and controls on erosion of coarse-grained reservoir sediment in a high-gradient fluvial environment.

Reservoir sediment was eroded and entrained by the interacting processes of knickpoint retreat, vertical incision, and lateral migration. The location of the knickpoint within the reservoir sediment defined the locus of erosion, as most erosion was concentrated downstream of this point. Consequently, the locus of intense erosion shifted continuously upstream, although at a diminishing rate, as the migrating knickpoint locally increased the channel gradient and exposed new sediment to incision. Vertical incision associated with knickpoint passage simultaneously removed sediment and deepened the channel, which exposed vertical banks to toe erosion and consequent lateral widening.

Two key factors contributed to the rapid erosion of sediment from the Marmot Dam reservoir: (1) sediment composition and (2) establishment of extraordinary river competence. The reservoir sediment was composed mainly of sand and gravel (Squier and Associates, 2000). More importantly, however, even the modest 50–80 m^3/s flow of the Sandy River in the hours following breaching had sufficient energy to transport all of the available sizes of sediment, due in large part to the steep hydraulic gradient resulting from the abrupt 15-m drop as the cofferdam breached. Gross calculations based on the depth-slope product of the momentum equation and the Shields stress equation (Henderson, 1966), although valid strictly for one-dimensional steady-state turbulent flow, suggest that as the cofferdam eroded, the river was competent to mobilize particles at least an order of magnitude larger than those stored in the reservoir, which explains the rapid erosion and knickpoint migration in the first hours following breaching.

River competence diminished as the channel in the reservoir reach incised and widened and the river gradient declined. Although our first reservoir survey on November 5, 2007, was not started until 17 days after breaching, by which time the reservoir channel in the vicinity of the dam site had widened to 40 m with a slope of 0.010 m/m, time-lapse photography (Major and others, 2010) shows that much of that widening and slope adjustment occurred during the 24 hours following breaching. Assuming the channel geometry determined in the November 2007 survey is representative of the conditions in the days after breaching, approximate calculations similar to those for the time of breaching show that flow competence had diminished to a value consistent with the approximate median grain size of the channel bed at that time (fig. 17*A*).

Larger flows (as much as 231 m^3/s) in the months following breaching (fig. 12) continued to erode reservoir sediment but their effectiveness diminished over time (table 3; fig. 15). The reduced capacity of these flows resulted from a combination of factors, including (1) initial incision that isolated sediment on bedrock ledges, requiring increasingly larger discharges to access and entrain these deposits; (2) winnowing and selective transport, which coarsened and armored the bed and active bars and required progressively larger flows to initiate transport; (3) vertical incision that exposed coarse sediment buried at depth within the reservoir, which contributed to bed and bank coarsening; (4) progressive channel widening and floodplain development that further marginalized and isolated easily entrained sediment; and (5) a channel gradient that progressively diminished and became more uniform, which further reduced river competence. The combined result is that even the much larger flows in WY 2009 (which had peak discharges as much as 10 times larger than the peak discharge achieved during the breach storm) entrained only 13 percent of the sediment volume eroded by flows in WY 2008 (table 3). In sum, rates of reservoir erosion were high initially but diminished rapidly, consistent with erosion processes such as knickpoint migration and channel widening, which can enable substantial erosion when combined with an abrupt discontinuity provided by breaching. These erosion processes, however, quickly become less effective as the gradient declines and the channel widens and armors. In circumstances where other erosion processes such as channel migration or gully network extension are more important (for example, where the reservoir width is much greater than the pre-dam channel width), it is likely that the relative rates and durations of reservoir erosion may be slower and longer.

A key challenge to predicting short-term sedimentologic response to dam removal is uncertainty regarding the sequence of future flows (Cui and Wilcox, 2008). We infer that the sequence of generally increasing high flows after breaching (fig. 15, table 3) influenced erosion at the time scale of individual events but had negligible effect on the ending state after 2 years. The effects of an opposite sequence of initially large flows followed by smaller flows would likely have had a similar outcome after 2 years—a channel flanked by a coarse bed and banks and having a gradient approaching the pre-dam river profile (figs. 14, 17, 22)—but that outcome would have been achieved by a different erosion sequence. In the case of Marmot Dam, the flow sequence demonstrated the effectiveness of the first postbreach flows, even if relatively small, to trigger substantial geomorphic response. In this case, the initial response was governed mainly by the very high (slope driven) stream power of even relatively small flows. Had the largest flows been during the first year following breaching rather than the second, the state of erosion achieved after 2 years might have been reached sooner, but the total amount of sediment removed probably would have been similar. In the exceptional case whereby breaching coincided with an extreme discharge, most of the erosion might have happened within a single flood. Even so, the state of erosion achieved, controlled largely by reestablishment of a slope profile approaching the pre-dam gradient, coarsening of the channel bed, and isolation of sediment along the channel margin, may have been similar. Future large flows are more likely to redistribute sediment already deposited downstream of the dam site rather than to remove significantly more sediment from the reservoir reach. We make this inference because the remaining reservoir sediment is mostly isolated in thin bands along the valley margin or perched on bedrock benches and separated from most flows by an armored channel bed and banks. Indeed, just such an adjustment was observed during a large flow (peak discharge about 1,020 m^3/s at Marmot Dam) in January 2011 as the river incised the channel at the Marmot Dam cableway station by about 1 m and distributed the sediment farther downstream.

Knickpoint Evolution

Knickpoint development and migration are important consequences of dam breaching because of their influence on upstream erosion rates (Brush and Wolman, 1960; Gardner, 1983; Straub, 2007; Grant and others, 2008; Schippa and Pavan, 2009) and because of the potential that knickpoints pose as barriers to migration of aquatic species. During and after breaching of Marmot cofferdam, sediment erosion was closely related to knickpoint migration.

Knickpoint evolution and migration have been subjects of much analysis (Gardner, 1983). Experimental and numerical studies show that following a drop in base level, the water surface profile over the knickpoint lip steepens, flow velocity increases, and channel width narrows, leading to incision and accelerated channel-bed erosion above the knickpoint (Gardner, 1983; Schippa and Pavan, 2009). Such accelerated erosion causes the knickpoint lip to migrate upstream rapidly and to increase channel slope at the head of the knickpoint. In contrast, the knickpoint face migrates upstream more slowly and simultaneously decreases inclination (Brush and Wolman, 1960; Gardner, 1983). As a result, the original knickpoint is replaced by two morphologically distinct erosional regimes until a uniform slope is achieved (Gardner, 1983). In noncohesive sediment, the imposed shear stress near the knickpoint lip typically triggers rapid and substantive erosion, and the entrained sediment is deposited downstream of the knickpoint along a lower channel gradient (Brush and Wolman, 1960; Pickup, 1975; Schippa and Pavan, 2009). As a result, knickpoints in noncohesive sediment typically evolve rapidly, and an extended reach of uniform slope is swiftly achieved.

The Sandy River followed this general evolutionary sequence after breaching of the Marmot cofferdam. Knickpoint migration rates varied from as much as 200 m/hr in the first hours following breaching to less than 2 m/d by the end of the first year (fig. 10), and an extended uniform slope swiftly developed (fig. 14). These averaged rates of knickpoint retreat and consequent erosion, however, obscure what was actually an episodic process driven by short-duration high flows and locally influenced by subsurface conditions. For example, on the day after breaching, the very rapid upstream movement of the knickpoint was held up temporarily by a bedrock ledge 400 m upstream of the cofferdam; the knickpoint subsequently moved off this ledge within hours and continued its upstream migration.

The temporary stalling of the migrating knickpoint in the reservoir reach had little effect on sediment erosion, but it highlights an important consideration when formulating forecasts of reservoir erosion. In some settings, erosion of reservoir sediment may expose bedrock or hidden structures that have the potential to stall or even halt knickpoint retreat. This is more likely where reservoir width is much greater than the pre-dam channel width. In such a setting, the channel may incise and reestablish a position displaced laterally from its pre-dam location—as has been observed following removals of some small dams (Stewart, 2006) and after natural dam failures (Hewitt, 1998; Ouimet and others, 2008)—which might halt knickpoint retreat and possibly pose a passage barrier. Consequently, knickpoint location and rates of lateral erosion are additional important factors influencing the erosional trajectory of reservoir deposits, and those processes in turn depend on relationships between exerted and critical shear stresses, the nature of bedload transport, the stability of channel banks, and reservoir and underlying valley geometry (Gardner, 1983; Stefanovic and Bryan, 2007).

Spatial and Temporal Trends in Sediment Transport

The magnitude and rate of sediment transport, and size of sediment transported, following breaching of Marmot Dam varied in both space and time. Synoptic sampling of suspended-load and bedload fluxes during and following breaching, and analysis of temporal variations in the grain-size distributions of the transported sediment document the evolution and fate of the components of sediment eroded from the reservoir. Sediment transport patterns in turn influenced changes in channel and valley bottom morphology downstream of the dam site.

During and after breaching of Marmot Dam, the sand and gravel entrained from the reservoir, as well as that entering from upstream, was sorted in transit. Although the flow incising the cofferdam and underlying sediment was competent to transport meter-sized boulders, its competence declined markedly within a few hundred meters downstream as the channel gradient flattened abruptly (fig. 14). At the Marmot Dam measurement station, 400 m downstream of the dam site, sampled bedload was at first composed almost entirely of sand; significant amounts of gravel did not arrive until 18 hours after breaching. Thus, between the cofferdam site and the Marmot Dam measurement station, gravel aggradation propagated downstream at a rate of about 20 m/hr, an order of magnitude slower than the rate at which a knickpoint initially migrated upstream through the reservoir reach.

The rapid sorting of the sediment transported past the Marmot Dam measurement site into sand and gravel phases presaged the distinct differences of their transport rates and downstream fates. Sand is readily transported by the Sandy River at virtually all flows as both suspended load and bed load (tables A1, A2), and although we have few low-flow bedload samples, the minor gravel transport at Brightwood and Revenue Bridge at the breach discharge of ~50 m^3/s (fig. 33) suggests that this may be close to the threshold for gravel transport. These very different transport thresholds for sand and gravel resulted in high rates and volumes of sand transport from the reservoir reach, and much faster and farther downstream transport of sand than gravel.

Although we measured passage of first sand and then later gravel at the Marmot Dam station, we cannot determine precisely the arrival of eroded sand and gravel at locations downstream of the Sandy River gorge. Our measurements of suspended-sand transport indicate, however, that sand eroded from the reservoir moved downstream rapidly; rates and magnitudes of suspended-sand transport at the Revenue Bridge measurement site, 9 km downstream of the dam site, were similar to those at the Marmot Dam measurement site within a month after breaching (figs. 29, 30). By mid November 2007, a substantial increase in the amount of suspended sand in transport was measured at Dodge Park, 18 km downstream of the dam site (fig. 30, tables A1, A2). This suspended sand may have been sand eroded from the reservoir, but higher flows at this time and abundant sand sources along the valley below the Sandy River gorge would be expected to produce more abundant sand transport, so we cannot say with certainty that the sand passing this station at that time was sand derived from the reservoir reach. Sand was also transported as bedload past the Marmot Dam measurement station in the hours following breaching (figs. 27, 33). The downstream signal of enhanced bedload transport of sand, however, is restricted to the Revenue Bridge measurement site where transport estimates indicate high ratios of bedload-to-suspended-load transport beginning by December 2007 (table 8) and bedload transport predominantly of sand throughout WY 2008 (figs. 35, 37). Neither anomalous transport rates nor amounts of sand transported as bedload were evident farther downstream at Dodge Park during WY 2008 (figs. 29, 30; table 8).

Except at the Marmot Dam station, downstream transport measurements do not show enhanced gravel transport. At both the Revenue Bridge and Dodge Park sites, the gravel contents of the bedload samples are consistent and do not increase after breaching (figs. 33, 34, 37). The only definitive evidence of gravel transport through the Sandy River gorge are the clasts of the Marmot Dam facing found on fresh gravel bars near the Revenue Bridge measurement site 18 months after breaching.

The sorting of sediment eroded from the reservoir is also evident in relations between bedload and suspended-load transport measured during WY 2008 (table 8). At both the Marmot Dam and Revenue Bridge stations, transport estimates indicate that bedload composed at most a sixth of the total load for the high flows of October and November 2007, presumably because sand eroded rapidly from the reservoir was initially transported mainly as suspended load. By December 2007, however, bedload approximately equaled the suspended load at both the Marmot Dam and Revenue Bridge stations, reflecting the substantial gravel transport at the Marmot Dam station and abundant sand bedload at Revenue Bridge (figs. 34, 37). High bedload transport rates at the Marmot Dam measurement station are consistent with calculations of river competence and observations of transient, high-amplitude sand dunes and highly mobile gravel bars. Concurrent transport estimates at Brightwood and Dodge Park indicate bedload composed a fourth or less of the total sediment transported. By January 2008, bedload transport at the Marmot Dam station may have exceeded suspended-load transport (table 8). This finding suggests a relative depletion from the reservoir reach of sand available for suspended transport but continued erosion and perhaps enhanced mobility of gravel as the river profile evolved and sediment supply rates remained elevated (table 3). The relative increase of suspended load at Revenue Bridge by January 2008 (table 8) possibly indicates that coarse sand entrained and transported from the reservoir reach as bedload had made its way past the Revenue Bridge measurement station. By May 2008, about twice as much sediment was transported as suspended load than as bedload at the Marmot Dam measurement station, probably reflecting diminishing bedload transport rates (as indicated by the transport ratings shown in fig. 32) owing to bed and bank armoring (fig. 17, 22), evolution of the longitudinal profile toward a pre-dam gradient (fig. 14), and increasing channel stability (fig. 22).

Experimental studies have shown that magnitudes, size distributions, and rates of sediment supply affect bed composition, sediment transport, and channel geometry in gravel-bed rivers. In particular, they have shown that increasing the sediment supply, especially the supply of sand, can greatly increase bedload flux, enhance gravel mobility, and alter channel morphology (Ikeda and Iseya, 1988; Madej and Ozaki, 1996; Curran and Wilcock, 2005; Vendetti and others, 2010). The breaching of Marmot Dam abruptly increased the sediment supply to the Sandy River, and similar to experimental results, the rate of bedload flux immediately downstream of the dam site increased substantially, the median bed-surface size sharply declined, and both sand and gravel were highly mobile even under very modest flow. However, we cannot say that the increased supply of sand to the river specifically enhanced gravel mobility, because supplies of both sand and gravel were increased simultaneously by erosion of reservoir sediment and because discharge also affects gravel mobility. At the Marmot Dam measurement station, the fraction of bedload sediment composed of gravel increased with discharge (fig. 37), even though the rate of sediment

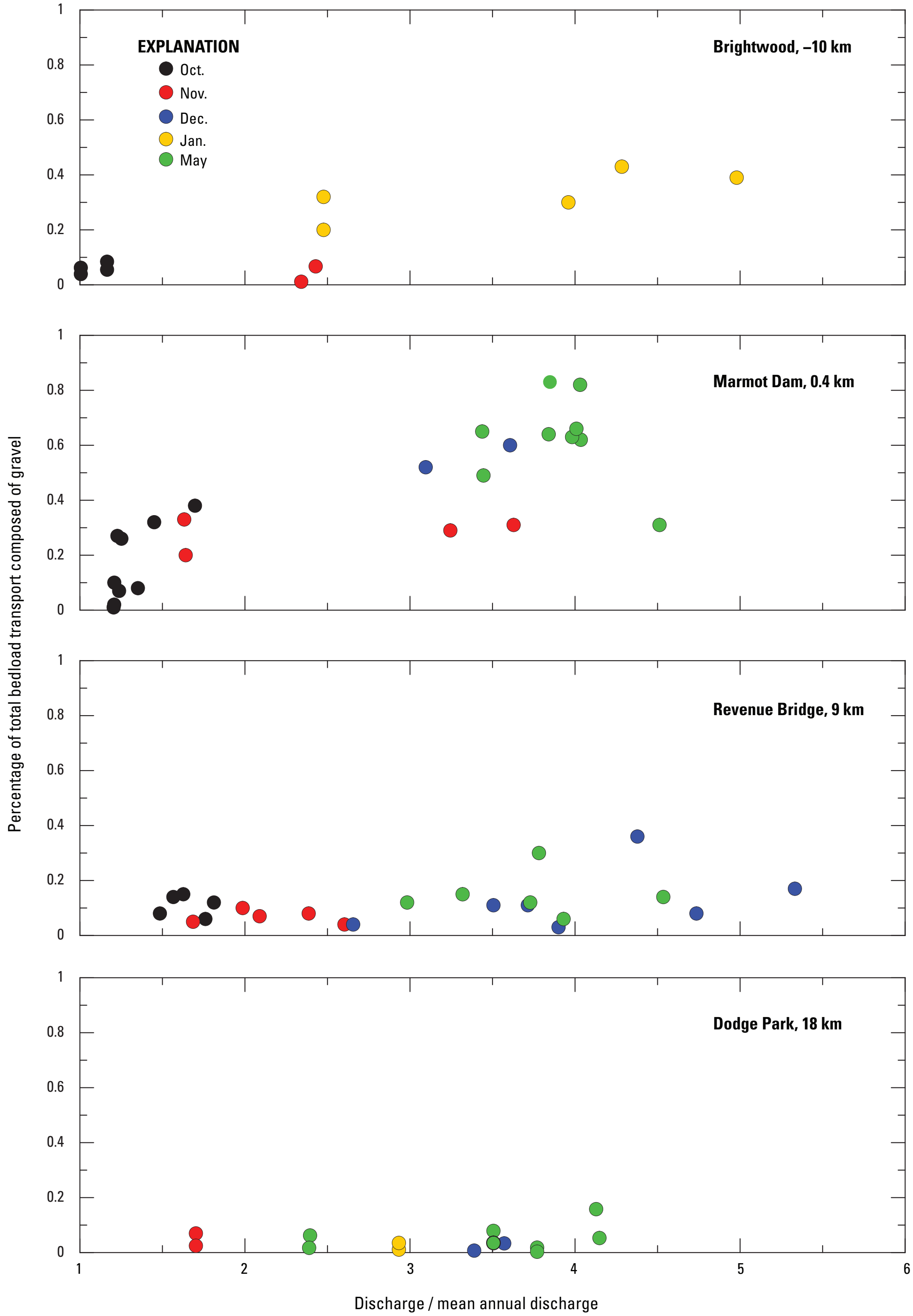


Figure 37. Percentage of total bedload transport composed of gravel as a function of normalized water discharge following breaching of Marmot Dam. The water discharge at which transport measurements were made is normalized by the mean annual discharge of the Sandy River at the measurement site. See figure 1 for station locations. Distances are station distance from Marmot Dam; positive values are downstream.

Table 8. High flow and annual (water year 2008) ratios of suspended-sediment load to bedload estimated from Monte Carlo simulations of sediment transport by the Sandy River following removal of Marmot Dam.

[km, kilometers]

Period	Brightwood [1] (–10 km)	Marmot (0.40 km)	Revenue bridge (9 km)	Dodge Park (18 km)
Oct. 19–Nov. 1, 2007	188:1	8:1	24:1	47:1
Nov. 16–23, 2007	65:1	8:1	6:1	55:1
Dec. 2–8, 2007	4:1	1:1	1:1	8:1
Dec. 22–27, 2007	4:1	1:1	1:1	8:1
Jan. 10–17, 2008	4:1	0.5:1	4:1	8:1
May 14–31, 2008	4:1	2:1	4:1	8:1
Annual transport ratio	7:1	2:1	3:1	10:1

[1]Distance is location of station relative to site of dam. Negative numbers are upstream.

supply from the eroding reservoir declined with time (fig. 15). In contrast, gravel mobility below the Sandy River gorge at the Revenue Bridge and Dodge Park measurement sites shows little trend with discharge (fig. 37). At those stations, the fraction of bedload composed of gravel appears to be restricted to a narrow range regardless of discharge, from about 5 to 20 percent at Revenue Bridge and about 2 to 5 percent at Dodge Park.

At comparable discharges relative to mean flow, the fraction of bedload composed of gravel was greatest at the Marmot Dam measurement station and decreased downstream (fig. 37). At similar times and at comparable relative discharges, the fraction of bedload composed of gravel at the Marmot Dam site was about 2 to 6 times greater than that at Revenue Bridge and about 10 to 20 times greater than that at Dodge Park, even though channel gradients are similar (fig. 3). Although the greater fraction of gravel in the bedload measured at Marmot Dam compared to that measured at Revenue Bridge might reflect the influence of sediment supply, a more likely cause of that disparity is sediment sorting and selective deposition of gravel in the channel reach above, and within, the Sandy River gorge.

Spatial and Temporal Trends in Sediment Deposition

As is the case for transport rates, knowledge of sediment-deposition patterns following dam removal is relevant with regard to possible issues of contaminant transport, effects on aquatic and riparian habitats, and flood inundation. For the case of the Marmot Dam removal, potential sediment deposition was evaluated before breaching by use of a one-dimensional sediment transport model (Stillwater Sciences, 2000a; Cui and Wilcox, 2008), which provided estimates of reach-averaged deposit thicknesses through time for different hydrologic scenarios. However, understanding of the multidimensional character of deposition was of keen interest, particularly with respect to potential impacts on fish habitat (Esler, 2009).

Following breaching, channel profile and valley morphology emerged as dominant controls on sediment deposition. In particular, geometry of the 2 km of channel immediately downstream of the dam site strongly controlled near-dam deposition and influenced overall sediment transport farther downstream. Specifically, the preremoval longitudinal profile had a relatively low-gradient (0.004 m/m) reach extending from about 0.4 to 1.3 km downstream of the dam site (fig. 14) and included several large pools. It is along this reach that a large proportion of the eroded sediment was initially deposited, increasing the mean local slope from 0.004 to 0.009 m/m (fig. 14) and filling most of the large pools. Subsequently, once the profile anomaly was filled, this reach became mainly a transport zone.

Near the distal end of the depositional reach, approximately 1.3 km downstream of the dam site, the preremoval channel gradient abruptly steepened to about 0.011 m/m. This increase in slope persisted after dam removal and ultimately governed the downstream extent of the aggradation immediately below the dam site. Most of the gravel transported to the end of the depositional wedge continued to be transported the additional 1 km to the head of the Sandy River gorge because of the increased transport competence associated with the greater channel slope. Aside from minor pool filling, there has been little discernible change in the longitudinal profile within this steeper reach leading to the entrance of the gorge (figs. 14, 19). At present, the inflection point in the preremoval longitudinal gradient represents the farthest downstream extent to which the channel gradient has adjusted at the reach scale to sediment released by the dam removal. The channel gradient of the sediment wedge gradually declined in the 2 years following breaching, mainly in conjunction with incision of the uppermost part of the sediment wedge beginning after the high flows in May 2008 (fig. 14). The fixed location of the channel-gradient inflection appears to be the convergence at which the evolving postremoval channel gradient upstream has become coupled to the preremoval channel gradient downstream.

Within the Sandy River gorge observations are qualitative because of the difficulties in conducting measurements within this reach. Nevertheless, an April 2009 float trip (18 months after breaching and including participants who had floated through the gorge before dam removal) revealed (1) unchanged riffle and boulder-rapid crests; (2) pools that were at least partly filled with sand and gravel compared to their preremoval state; (3) fresh small gravel bars (less than 100 m^2) along the channel margin and accumulation of sand (and minor gravel) in high-flow eddy zones, especially in the first 2 km of the gorge; and (4) bed material toward the downstream end of the gorge composed predominantly of sand but including clasts of concrete from the Marmot Dam facing. Overall, the Sandy River gorge appeared to have experienced pool filling and local deposition in hydraulically controlled areas but little reach-scale profile change.

Downstream of the Sandy River gorge we did not detect any substantial deposition attributable to dam breaching, although our measurements were not widespread. Surveys and grain-size measurements conducted in July in 2007, 2008, and 2009 at 13 km (Cedar Creek) and 30 km (Oxbow Park) downstream from the dam site (fig. 1) found no overall change in river-bed elevation (see fig. 26) but showed about a 10 percent increase in surface sand content that may owe to sand eroded from the reservoir (Podolak and Pittman, 2011). Repeat water-surface and channel-bed surveys conducted in 2007 and 2009 from the Dodge Park measurement site at RK 30.2 downstream to RK 20 also showed little change in either water-surface or bed elevation (Bauer, 2009). Repeat channel soundings at the Dodge Park and Stark Street Bridge measurement sites, 18 and 39 km downstream from the dam site, showed bed elevation fluctuations of as much as 0.5 m but with no apparent trends. These surveys and cross-section measurements show no clear evidence for downstream aggradation between 2007 and 2009, despite passage of approximately 550,000 Mg of sand at the Revenue Bridge measurement site in WY 2008, of which 300,000 to 400,000 Mg is attributable to reservoir erosion (table 7, fig. 35). Thus, the sand eroded from the reservoir has been (1) conveyed through the river system and into the Columbia River, (2) deposited in locations lacking measurements, such as downstream of the Stark Street Bridge measurement site, or (3) broadly but undetectably dispersed along the channel. Some sand may also have infiltrated gravel deposits without producing any bed elevation change (for example, Wooster and others, 2008; Evans and Wilcox, 2010).

Observations and Measurements Compared to Prebreach Modeling

Measurements of sediment erosion, transport, and deposition during and following breaching of Marmot Dam provide a check for prebreach physical and numerical modeling studies addressing key sediment-related questions. As summarized in more detail by Downs and others (2009), Podolak and Wilcock (2010), Stillwater Sciences (2011), and Cui and others (2011), the one-dimensional sand-and-gravel routing model applied by Stillwater Sciences before breaching (Stillwater Sciences, 2000a; also Cui and Wilcox, 2008) broadly predicted the location and magnitude of reservoir incision and downstream sediment deposition, particularly the evolution of the river profile in the 4-km distance spanning the reservoir reach and the depositional sediment wedge above the Sandy River gorge. Actual rates of reservoir erosion and downstream deposition, however, appear to be underestimated by the numerical modeling (fig. 38). For example, channel gradient in the breach area declined to less than 0.02 m/m within about 48 to 60 hours of breaching and to less than 0.01 m/m within 30 days, whereas predicted times (Cui and Wilcox, 2008) to reach these states, under average hydrologic conditions, were 5 and 90 days, respectively (fig. 38). Similarly, the channel profile actually attained within a year of breaching was predicted to take from 4 to 10 years, depending on flow conditions. These discrepancies may, in part, be the result of (1) differences between the actual postremoval sequence of flows and those simulated; (2) the actual versus estimated sediment composition and distribution in the reservoir reach; (3) the inherently two-dimensional nature of erosional and depositional processes; and (4) differences between predicted and actual erosion processes. Local discrepancies between actual and predicted deposit thicknesses at the downstream end of the depositional wedge possibly resulted from complex hydraulic conditions produced by a large logjam near the entrance to the Sandy River gorge (Podolak and Wilcock, 2010).

Farther downstream, the sediment-routing model predicted local accumulation of as much as 1 m of gravel between the Sandy River gorge exit and Bull Run confluence, as much as 20 cm of sand accumulation along the Stark Street Bridge reach, and as much as 40 cm of sand accumulation in the lower 10 km of the valley, mainly within 2 years of breaching (Cui and Wilcox, 2008). Surveys at the exit of the gorge near Revenue Bridge, at Dodge Park, and at a site 13 km downstream from the dam site (Cedar Creek)—locations of predicted accumulation—have not detected any changes approaching this magnitude. Although soundings from Stark Street Bridge show bed-elevation fluctuations of a few tens of centimeters in the 2 years following breaching, the overall change is one of bed lowering (fig. 21). No measurements were obtained downstream of Stark Street Bridge. Discrepancies between model predictions and our observations may in part be due to unanticipated storage of sediment

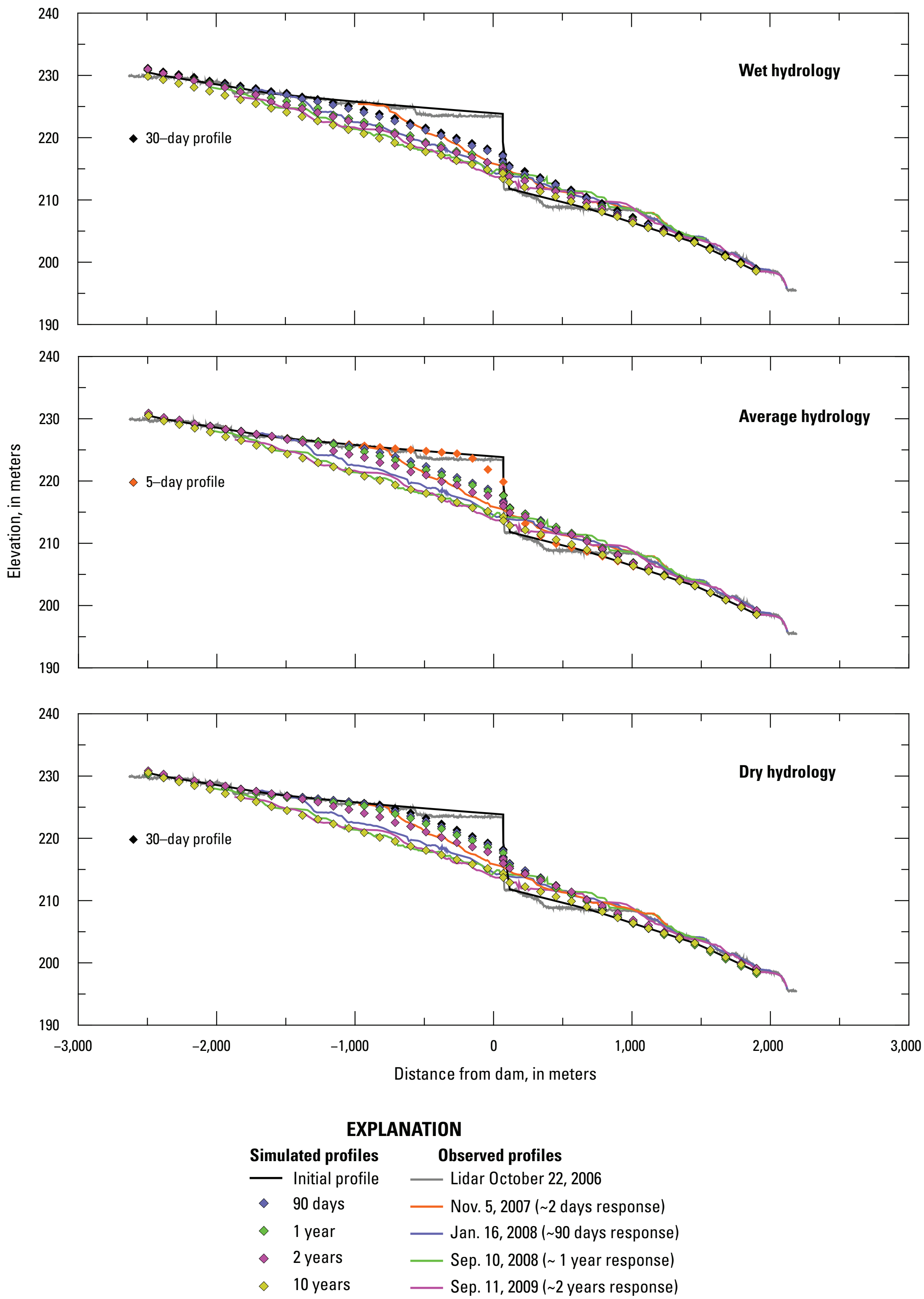


Figure 38. Comparisons of channel-profile development through the Marmot Dam reservoir reach predicted by a one-dimensional numerical simulation model (Cui and Wilcox, 2008) to measured water-surface profiles as a function of time. Numerical predictions are shown for various assumed hydrologic conditions. Positive distances from dam are downstream.

(perhaps a few tens of thousands of cubic meters) in the Sandy River gorge. Furthermore, the typically high transport rates and dynamic channel conditions of the Sandy River make channel-elevation changes of less than 1 m difficult to attribute clearly to dam removal.

Physical modeling was also conducted to help evaluate consequences of breaching the cofferdam, in particular to evaluate the location and behavior of knickpoint formation and reservoir sediment erosion (Marr and others, 2007; Grant and others, 2008). These scaled physical-model simulations indicated that knickpoint migration and consequent erosion of sediment depended largely on the position of the breaching notch (Marr and others, 2007; Grant and others, 2008). Owing to bedrock influence on the geometric alignment of the Sandy River through the reservoir reach, the physical experiments indicated that notching the center or north side (river right) of the cofferdam could pin the river against bedrock and promote a deep and narrow channel through the reservoir reach, or perhaps superimpose the channel onto bedrock, whereas notching the south side (river left) of the cofferdam could enhance the amount and rate of reservoir sediment erosion by forcing the river to migrate laterally within the bedrock confines of its pre-dam channel. These experiments guided the decision to notch the south end of the cofferdam.

The physical experiments predicted rates of erosion and the overall trajectory of knickpoint migration for various notching and flow scenarios (Marr and others, 2007). For model simulations similar to actual flow conditions—a scaled flow of about 70 m^3/s and the cofferdam notched on river left—the predicted advancement of the knickpoint at rates of meters per minute matched observed rates. The predicted percentage of initial sediment eroded (35–40 percent), however, was substantially greater than the percentage actually eroded (about 15 percent) within the first 60 hours of breaching. Imperfect scaling of grain sizes of stored sediment, modeled flow competence, and poor control on downstream boundary conditions may have affected the erosion results (Grant and others, 2008; Cui and others, 2011). Also, the rapid knickpoint migration along the left margin of the reservoir did not match model results for notching the cofferdam on river left, which generally produced knickpoints eroding laterally to the right as they moved upstream. Additionally, the initial formation of two competing knickpoints was not indicated by the physical models. However, the overall trajectory of knickpoint advancement farther upstream, as constrained by bedrock valley margins, followed paths indicated by the physical model runs.

Implications for Monitoring Dam Removals

The pace and scale of dam removals is accelerating. Despite this, few comprehensive postremoval monitoring efforts have been reported, mainly because most removals to date have been small structures, and resources for monitoring and evaluating responses have been scarce. The significant investments of resources and personnel required for monitoring efforts such as those conducted at Marmot Dam are neither practical nor merited for many removals (Randle and others, 2010). However, for removals of dams impounding significant amounts of sediment, such as the 2008 removal of Milltown Dam on the Clark Fork River, Montana (Wilcox and others, 2008), the 2011 breaching of the Condit Dam on the White Salmon River, Washington, and the 2011–2013 removal of two large dams on the Elwha River, Washington (Randle and Bountry, 2010), the fate of the stored sediment is of significant concern, and assessment of reservoir erosion, transport rates, and patterns and timing of downstream deposition may be valuable. Enhanced predictive capability will emerge from continued development of numerical models like that applied by Cui and Wilcox (2008) to the Sandy River, but predictions by such models require assessment by the types of measurements and monitoring performed with the decommissioning of Marmot Dam. Greater understanding of fluvial response to dam removal requires monitoring efforts that span a broad range of fluvial environments and dam and reservoir settings. Monitoring of fluvial responses to future dam removals could possibly benefit from aspects of the findings reported here, as well as from consideration of alternative, or more complete, monitoring and measurement activities.

For the case of Marmot Dam, interacting, multidimensional processes drove sediment erosion and consequent transport. Knickpoint migration and lateral erosion processes largely controlled the rate and ultimate state of reservoir erosion. However, knickpoint formation, migration, and associated erosion are difficult to model. Although experiments show general profile changes and estimate potential erosion rates as knickpoints migrate (Brush and Wolman, 1960; Gardner, 1983; Grant and others, 2008) and some numerical modeling of knickpoint development and migration exists (Schippa and Pavan, 2009), little work has been done developing a detailed process-based understanding of knickpoint migration, especially in relation to movement through coarse-grained, noncohesive sediment. Consequently, monitoring of knickpoint formation and migration is important in future dam removals, but owing to the documented rapid pace of these processes, greater understanding will require more systematic and higher fidelity measurements of knickpoint position, height, sediment composition, and specific erosion processes than were achieved at Marmot Dam. The photographic monitoring and surveys reported here provided some quantitative data on initial rates and processes of erosion, and longitudinal and cross-section surveys provided the total volume of reservoir sediment eroded and information on lateral widening rates. These measurements, however, may not be of sufficient resolution to support improved dynamic models of knickpoint formation, migration, and consequent erosion. Continuous, or at least more frequent, tracking of knickpoint position, height, topographic profile, specific erosion processes, and evolving substrate conditions would have been better. For cases in which reservoirs are not completely full of sediment or where dams are removed incrementally, the processes by which local base-level fall is transmitted to reservoir sediment will control the rate at which sediment erodes; focused monitoring of these processes will enhance future capability to predict sediment erosion when a dam is removed.

Patterns and timing of downstream deposition were broadly predicted by the one-dimensional sediment-routing model of Cui and Wilcox (2008), but some aspects of fluvial response were not well predicted, owing mainly to local topographic influences that were not adequately characterized by reach-averaged analyses and to the multidimensional nature of flow and depositional processes. Enhanced predictive capability of transport and deposition of sediment associated with dam removals requires high-spatial-resolution application of two- and three-dimensional flow and sediment-transport models, but such modeling will require assessment at similar resolution and it may not necessarily provide more satisfactory results compared to simpler models (Cui and others, 2011).

A lack of baseline information hindered certain aspects of our analysis. Key uncertainties in our sediment budget perhaps could have been reduced by more complete three-dimensional topographic mapping of the valley bottom before and after dam removal, especially within the Sandy River gorge and farther downstream, and by better characterization of the composition and distribution of the reservoir sediment. From our surveys and those of DE&A, it is apparent that even the measured cross sections and channel-profile surveys were insufficient to fully document all deposition, especially far downstream from the dam removal where deposition was predicted to be patchy. Airborne lidar combined with comprehensive bathymetric surveys, repeated at appropriate intervals, are possible means for this type of monitoring. Accurate characterization of the reservoir sediment size and spatial distribution is especially important because, as shown here, gravel, sand, and fines are transported differentially and are deposited in distinct hydraulic and geomorphic environments. Predictions of the ultimate channel profile in the vicinity of Marmot Dam would have been aided by better information on the pre-dam topography. Such information would have provided for better estimates of the volume of sediment stored and of the channel profile that would be the logical endpoint of postremoval profile evolution. Given the age of the structure, however, extensive geophysical analyses would have been required to obtain higher-fidelity resolution of pre-dam topography. Nevertheless, systematic acquisition of baseline topography could streamline monitoring efforts and endpoint predictions for future dam removals.

Measuring sediment fluxes is an important aspect of monitoring river response to dam removals. The bedload and suspended-load measurements associated with removal of Marmot Dam are the most extensive so far reported following a dam removal and are unlikely to be matched in most monitoring efforts. Although difficult and expensive, such sediment transport measurements provide key data that support calculation and understanding of an overall sediment budget, rates of reservoir erosion and downstream sediment deposition, sediment-transport modes, the evolution of fluxes of different sediment sizes, and possibly development of better numerical sediment-transport models. Even with the extensive efforts here, in which most high flows during the year following breaching were sampled for bedload and suspended-load fluxes at multiple sites, developing transport-rating relations was challenging owing to temporal evolution of transport conditions, especially downstream of the dam site. Additional measurements could have helped reduce uncertainty; in particular, more measurements at lower flows would have helped to better constrain threshold transport conditions, more systematic synoptic sampling could have better defined spatial transport patterns, and sampling through an entire stormflow hydrograph and during additional high flows could have helped aid better understanding of how and when sediment is transported. Greater understanding of the effects of the Marmot Dam removal with respect to sediment-transport conditions would have been aided by measurements of suspended load and bedload for at least a year prior to removal, and ideally for multiple years prior to and subsequent to removal rather than the single postremoval wet season reported here.

Although the level of resources and effort expended to monitor response to the Marmot Dam removal is neither practical nor warranted for many dam removals, this removal presented an extraordinary opportunity to enhance understanding of fluvial responses to dam removal. It would have been difficult to understand the interactions among, and temporal evolution of, the suite of processes active during and following breaching without that effort, and as noted above, additional measurements would have been beneficial. Had we been interested only in broad scale morphologic changes with time, we could have conducted erosion and deposition surveys annually and ignored measurements of sediment flux and temporal evolution of sediment grain size. Such limited monitoring efforts, however, would have missed the details of system response and shed little insight on the processes by which this high-gradient, coarse-bedded river processed and redistributed the large sediment input.

Monitoring future dam removals may benefit from technological advances. Existing and emerging techniques that may be useful for monitoring fluvial response to dam removal include the following:

1. Bathymetric lidar, which would help better define preremoval channel geometry, postremoval erosion and deposition, and in the case of Marmot Dam could have helped obtain critically needed data on pool and channel geometry in the Sandy River gorge.

2. Proxy methods for estimating sediment flux. Suspended-sediment concentrations can now be estimated reasonably well on the basis of relationships with turbidity (Lewis, 1996), and emerging efforts are working on developing proxy measurements of bedload transport (Gray and others, 2010). Emerging advances in these areas

offer the possibility of making long-term, continuous measurements even in remote, inaccessible reaches.

3. Tracer technologies, specifically with regard to gravel tracers. Use of tracer technologies can advance understanding of when gravel is in motion, the conditions under which it moves, how rapidly it transports downstream, and where it is deposited as it migrates downstream.

4. Terrestrial laser scanning and Structure-from-Motion photogrammetry. These emerging technologies for acquiring high-resolution topography (for example, Westoby and others, 2012) can provide ways to obtain high-fidelity measurements of sediment erosion and deposition in areas where it could have critical consequences.

The duration required to monitor fluvial response to dam removal is a difficult question to address specifically, because it is a function of reservoir sediment composition, channel geometry, the length of the preremoval monitoring period, the randomness and sequencing of postremoval discharges, and the nature of dam removal. Minimal preremoval monitoring of channel complexity, sediment transport, and dynamic sediment distribution may provide some insights on baseline conditions, but the range of variability associated mainly with hydrologic randomness may take several years to establish. How long postremoval monitoring should extend could perhaps be addressed in terms of some metric of river system resilience. As we have seen at Marmot Dam, the river very rapidly recovered (within 1 to 2 years) a large percentage of many pre-dam physical factors, such as original river profile, channel and bar morphology, and channel complexity. Perhaps one metric of river system resilience might be quantified as some substantial percentage recovery of a robust physical characteristic such as original river profile or channel-bar planform, position, and composition. In high-gradient river systems transporting noncohesive sediment, the length of postremoval monitoring may be very short compared to low-gradient river systems transporting cohesive sediment, and the period of monitoring following single-stage removals may be shorter than that required for prolonged, staged removals.

Conclusions

Removal of Marmot Dam provided an extraordinary opportunity to evaluate effects of dam removal on an energetic fluvial system. Our measurements and observations show that the primary, and highly interrelated, factors affecting the fluvial system were (1) creation of a short-lived but significant profile discontinuity—a knickpoint—at the site of dam breaching, which migrated rapidly upstream; (2) interactions among knickpoint migration, channel incision, and channel widening, which led to rapid entrainment of sand and gravel from the former reservoir reach; and (3) consequent transport and deposition of that sediment, patterns of which were controlled strongly by channel and valley bottom morphology. Interactions among these fluvial processes as well as external factors promoted strong spatial and temporal variations in sediment erosion, transport, and deposition. Key aspects of our observations and analyses of the effects of dam removal include the following:

1. Knickpoint retreat and channel incision followed by channel widening acted to rapidly erode the noncohesive, coarse-grained reservoir sediment. Knickpoint formation resulted from the abrupt channel discontinuity that formed by breaching the 15-m-tall sediment pile comprised of the temporary cofferdam and underlying reservoir sediment. The 2-m-tall knickpoint retreated at rates first exceeding several meters per minute but then slowed and evolved to a more subtle gradient discontinuity 500 m upstream within 17 hours of breaching. The knickpoint continued migrating upstream, primarily during subsequent high flows but at an overall decreasing rate, until eventually becoming a low-relief riffle 2 km upstream of the dam site, near the upstream extent of the former reservoir, within a year of breaching. After a year, the slope discontinuity became indistinct and difficult to follow. Channel widening followed knickpoint passage through the reservoir and greatly enhanced sediment erosion and entrainment. The rapidly diminishing height and upstream migration rate of the knickpoint with time largely explain the simultaneously diminishing rate of reservoir sediment erosion, although bed coarsening and progressive isolation of sediment in narrow bands along the channel margin were also contributing factors.

2. Because of the stream-profile discontinuity associated with the knickpoint, only modest discharges were necessary to entrain substantial volumes of noncohesive sediment from the reservoir reach, resulting in exceptional sediment transport rates downstream of the dam site. At Marmot Dam, 17 percent of the stored sediment volume eroded within the first 60 hours, and that erosion was associated with a peak flow just twice the mean annual flow. Peak flows 2 to 3 times larger maintained high rates of erosion for about 2 months before erosion rates declined notably despite even larger flows. Over the 2-year analysis period, about 60 percent of the reservoir sediment was evacuated, but the rate of erosion decreased logarithmically with respect to cumulative flow.

3. The sequence of transporting flows affected the specific trajectory of reservoir erosion and downstream sediment transport during the 2 years following breaching of Marmot Dam. However, because overall erosion was largely a consequence of knickpoint retreat and channel widening, which in the 2 years after removal had affected most of the reservoir reach, it is unlikely that the specific sequence of flows significantly affected the overall

outcome. For other dam-removal situations, where reservoir erosion may be controlled by a different suite of processes or proceed more slowly, the sequence of high flows may have more influence on the overall outcome.

4. Channel and valley-bottom morphology can strongly influence rates of transport and distribution of sediment released by dam removal. For the case of Marmot Dam, valley morphology, especially in the 2-km reach downstream of the dam site, controlled specific patterns of deposition and transport. Moreover, the channel and valley morphology facilitated strong differences in the transport of sand and gravel.

5. The ratio of the volume of sediment stored in the reservoir reach to the average annual sediment load can affect the nature and duration of response to dam removal. The removal of Marmot Dam exposed about 5 to 10 years worth of average annual sediment load to renewed erosion by an energetic river. As a result, the river rapidly eroded and redistributed the sediment, water quality approached ambient levels within several months, and the heavily impacted 2 km of channel downstream of the dam site became relatively stable within 2 years of dam removal. Although large flows (many times the mean annual flow) will likely rework deposited sediment over the coming years, the basic preremoval channel morphology in terms of position and composition of the gravel bars has been largely reestablished, and large-scale channel change is unlikely except by exceptionally large flows.

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Appendix—Methods for Assessing Sediment Erosion, Deposition, Water Discharge, and Sediment Transport

Sediment Erosion and Deposition

A variety of methods were used to assess sediment erosion and deposition along the Sandy River following breaching of Marmot Dam. Here we describe the data used to assess erosion and deposition and the uncertainties associated with those data.

Data

Data available to measure the volumes of sediment eroded from the Marmot Dam reservoir reach and its subsequent downstream deposition include repeat ground and airborne lidar surveys, oblique terrestrial photographs, and bulk sediment samples. Three nonbathymetric airborne lidar surveys, using a Leica ALS50 Phase II laser scanner, were flown during low-water conditions on the Sandy River: October 22, 2006; September 29–October 7, 2007; and September 29–October 1, 2008 (Watershed Sciences, 2006, 2009a,b). At the times of those surveys, discharges were near annual low flows (8.6–9.0 m^3/s, 2006 survey; 5.7–19.3 m^3/s, 2007 survey; 11.0–13.1 m^3/s, 2008 survey), minimizing data loss from water covering the bed. The lidar data were provided as 1-m-resolution digital elevation models (DEMs). Simultaneous aerial photography was collected in 2006 and 2008 and was provided as orthorectified images. The accuracy of the lidar data involves two components: (1) an absolute accuracy (deviation of the lidar point altitude from a ground survey altitude) and (2) a relative accuracy (variation among multiple lidar measurements of the same point). The Sandy River lidar data had a median relative accuracy of 0.046 m (2σ value of 0.052 m) and a Root Mean Square Error (RMSE) of the absolute accuracy of 0.051 m (2σ value of 0.090 m) (Watershed Sciences, 2009a). The laser had an illuminated footprint of 0.15 milliradians (Leica, 2007), which translated into a spot size on the ground of about 0.18 m, and it returned between 0.48 and 1.17 points per square meter in the vicinity of the dam (Watershed Sciences, 2009a). In addition to airborne laser scanning, several ground surveys using a total station were collected in the reaches immediately upstream and downstream of the dam site. A series of annual channel cross-section surveys from 2005 through 2010 (commissioned by Portland General Electric through David Evans and Associates) extends from 2,200 m above the dam site to 1,700 m below the dam site. Monumented cross sections are spaced an average of 13 m apart downstream of the dam site and 200 m apart through the reservoir reach. However, there is a 400-m-long gap in the downstream section. We made a second series of total-station surveys intermittently from 2007 through 2009 that captured the intra-annual development of erosion and deposition. These event-based surveys (November 2007, December 2007, January 2008, May 2008, September 2008, January 2009, September 2009; fig. 12) did not specifically measure channel cross sections but instead measured the locations of significant topographic breaks (for example, bank tops and bases, the channel thalweg, bar tops, edges of water). The spatial extent and point density of these surveys varied with the topographic change from storm to storm. A third set of total-station surveys was conducted in August 2009 and followed the same survey protocol as used for the DE&A cross-section surveys, with the goals of filling in the 400-m-long topographic gap in their surveys and extending the cross-section surveys downstream an additional 500 m (Podolak and Pitman, 2011).

A multicamera network, consisting of five high-resolution (10 megapixel), digital single-lens-reflex cameras, was placed around the lower reservoir reach to monitor sediment erosion associated with breaching of the cofferdam and the subsequent fluvial response (Major and others, 2010). The cameras were driven by external timers, and images were stored on site. During breaching, each camera captured images at 10-minute intervals; subsequently, the intervals were changed to 30 minutes. One camera was positioned downstream of the cofferdam looking upstream, two were positioned near the cofferdam with views across the reservoir, and two were positioned approximately 300 m upstream of the cofferdam, before the reservoir turned southward and out of view of the dam site, with views looking downstream. Placement of the cameras permitted a 3-dimensional spatial analysis of erosion rates and processes in the lower reservoir reach using commercial photogrammetric software. The software, Photomodeler Pro 5, uses overlapping, but not necessarily stereoscopic, imagery in conjunction with camera-calibration parameters to solve for the spatial coordinates of points manually tagged in the photographs. The combination of camera locations, sensor elements, and lens characteristics affects feature resolution. Major and others (2009) provide a discussion of camera calibrations, the types of errors inherent in using oblique terrestrial photography, and the general methodology for measuring process rates from oblique imagery. We imposed control on the imagery through a combined process of camera calibrations and determination of external spatial coordinates. External spatial control was imposed on the imagery through the use of fixed control points. Multiple orange plywood targets (measuring approximately 50 cm × 50 cm) having known spatial locations were placed around the lower reservoir within the fields of view of the cameras.

Postremoval bulk sediment samples were collected from 1m^3 pits at 6 locations in the 2 km of channel downstream of the dam site (fig. 36), and at two locations 600 m upstream of the site to assess in-situ grain-size distributions. An average of 1,300 kg of sediment was excavated from each pit and field processed into half-phi size classes for particles larger than 64 mm (>256 mm, 180–256 mm, 128–180 mm, 90–128 mm, 64–90 mm) and full phi size classes for finer particles (32–64 mm, 16–32 mm, 8–16 mm, <8 mm). One subsample of the <8 mm size class from one pit was further sieved into 4–8 mm, 2–4 mm, and <2 mm size classes. The <8 mm size distribution was applied to all pit samples.

Analysis

The area of focus for the analysis of erosion and deposition extends from 3,100 m upstream to 2,200 m downstream of the dam site. No single source of altitude data covers the entire area during any one time period, so altitude changes were calculated using various methods according to data availability. In the reservoir reach, the most extensive sources of preremoval altitude data were the 2006 and 2007 lidar surveys. The digital elevation model (DEM) created from the dry land imaged by the 2007 lidar survey was used as the preremoval surface. In the wetted channel, the bed elevation was estimated using the water-surface elevation of the lidar survey, a channel width from the aerial photographs, and an average wetted area from the measured cross sections. Postremoval surfaces were generated from the event-based and annual topographic surveys, and volume changes were computed by measuring the differences between sequential surfaces. Finally, to establish a pre-dam topographic surface, a 1911 topographic map was digitized and rectified (Mount Hood Railway and Power Company, 1911; Keith, 2012).

Downstream of the dam site, estimates of volume changes were made primarily by computing changes in surveyed bed altitudes from cross-section surveys. Changes in areas lacking surveyed cross sections were estimated from lidar. For reaches of channel having limited wetted area, average depths were calculated from nearby cross sections and subtracted from the lidar water surfaces. Finally, to fill the 400-m-long gap in the cross-section surveys, a linear fit was used to estimate a downstream decrease in the average change in cross-section area.

In the reservoir reach, volume changes were computed by comparing lidar elevations to surfaces interpolated from high resolution topographic point data. This interpolation was augmented with cross-section survey data when possible. Additionally, interpolated cross-section areas below lidar water-surface altitudes provided a basis from which to compare subsequent topographic surveys.

To assess error in the cross-section comparisons, a stable reach of river was analyzed between 2006 and 2007. Although repeat cross-section surveys of this reach should produce zero elevation change, the RMSE between the consecutive surveys was 0.094 m. To evaluate errors inherent in differencing lidar surveys, the elevations of 28 fixed points (such as buildings and road intersections) were extracted from the 2007 and 2008 lidar DEMs and differenced, yielding a RMSE of 0.079 m. To compare the accuracy of elevations obtained from lidar DEMs to survey point elevations, 269 surveyed point elevations were compared to elevations extracted from a lidar DEM. Differences in those elevations yielded an RMSE of 0.33 m. The surface grain sizes of the bars on which several points were compared are coarse (the diameter at which 84 percent of the size distribution is finer, d_{84}, ranged from 71 to 230 mm), and this coarse grain size posed problems for interpolating lidar points within a DEM. The coarse grain sizes of the bars fall between the absolute accuracy of the lidar elevation data (0.051 m) and laser spot size (0.18 m) on one end, and the DEM grid-interpolation scale (1 m) on the other. Owing to this mismatch in size scales, the most conservative RMSE (0.33m) was applied to all volume computations derived using lidar DEMs.

Water Discharge

We estimated postbreach discharge near Marmot Dam by combining the rated discharge at Brightwood with estimates of discharges from the principal unmeasured tributaries (Wildcat, Alder, and Whiskey Creeks) entering the Sandy River between Brightwood and Marmot Dam. To estimate the discharge, we first computed the unit-area discharge for the measurement station on Fir Creek near Brightwood (fig. 1) using the USGS 15-minute-discharge time series for that station. Fir Creek is a tributary to the upper Bull Run River and has a drainage area that is comparable to the drainage areas of the unmeasured tributaries. We assumed that the unit-area discharges for the unmeasured tributaries are similar to that of Fir Creek. Hence, we applied each 15-minute unit-area discharge value computed for Fir Creek to the combined areas of the unmeasured tributaries and estimated a combined discharge contribution from those basins to the Sandy River. We then added that estimated discharge contribution to the rated discharge at Brightwood to estimate the discharge of the Sandy River below Marmot Dam (fig. 12). This approach does not account for potential water storage in the channel between Brightwood and Marmot Dam, nor does it account for the time lag in the passage of flow past the two sites. Given the relative proximity of the two sites (about 10 km) and the generally uniform and steep slope of the reach (fig. 3), we assumed that channel storage is minimal. Furthermore, the time lag between the two sites is less than 1 hour at high-flow velocities and less than 2 hours at low-flow velocities. Because the discharges at Fir Creek and Brightwood are monitored only every 15 minutes, we did not make minor time-lag corrections.

Pittman and Matthews (2008) developed a stage-discharge relation at the Revenue Bridge measurement site and applied it to the record of continuous stage they recorded from November 18, 2007, through May 17, 2008. When computing annual sediment fluxes, we augmented the discharge record of Pittman and Matthews (2008) with our estimate of discharge at the Marmot Dam measurement station to construct the annual hydrograph at Revenue Bridge.

Although river stage was measured at Dodge Park when sediment samples were collected, we had to estimate the annual hydrograph at the site to compute an annual sediment load. Because Dodge Park is located just above the Bull Run River confluence (fig. 1), we estimated the annual hydrograph at Dodge Park by subtracting the flow coming in from the Bull River from that passing along the Sandy River below Bull Run, as measured by the long-term station just downstream from the Bull Run confluence (Sandy River below Bull Run; fig. 1). We estimated the inflow of the Bull Run River as the combined flows measured on the Bull Run River near Bull Run and Little Sandy River measurement stations. The estimated discharges at Dodge Park are within 5 percent of the five discharges measured.

Computation of Annual Sediment Fluxes and Their Uncertainties

We used relations between suspended-sediment concentrations and water discharges, bedload transport rates and water discharges, annual hydrographs, and bootstrap Monte Carlo simulations to estimate annual mean sediment fluxes in water year 2008, as well as the ranges of uncertainty about those mean fluxes, at the various measurement sites. Grain-size analyses of sediment samples (tables A1, A2; note that tables A1–A3 are provided only as online electronic supplements at *http://pubs.usgs.gov/pp/1792/*) allowed us to perform Monte Carlo simulations of fluxes of the constituent loads of gravel, sand, and fines in addition to fluxes of total sediment loads.

Bootstrapping analysis is a procedure that involves repeatedly assembling data sets by randomly sampling with replacement from a sample population and analyzing each data set in the same manner (Efron and Tibshirani, 1986; Rustomji and Wilkinson, 2008). The number of elements in each bootstrap sample equals the number of elements in the original sample set. The range of estimates of some quantity obtained from repeated assembly of datasets provides an estimate of the uncertainty of the quantity of interest. The bootstrap method for estimating annual suspended-sediment fluxes entailed converting suspended-sediment concentrations to suspended-sediment loads (kg/s) and then randomly sampling with replacement paired sediment load–water discharge values to build a data set of n pairs equal to the original sample population. A power function, $Q_s = aQ^b$— where Q_s is suspended-sediment load in kg/s, Q is water discharge in m^3/s, and a and b are regression coefficients—was then fit to the bootstrapped sample. That power function was then applied to the annual hydrograph, based on 15-minute discharge values, and the results summed to estimate one realization of the annual suspended-sediment flux. In total, 1,000 realizations were implemented for a single computational experiment, and between three and six computational experiments were executed for each sample population of interest. Because the populations of paired sediment-concentration and water-discharge data were small ($n \leq 10$ for various monthly groupings discussed in the text; table A3), results were sometimes highly variable. We provide the estimated 5th, 50th, and 95th percentile values of the Monte Carlo simulations, and use the median (50th percentile) value as our estimate of annual flux. For some very small sample sets, the 95th percentile value was extreme, and we do not present its value.

A procedure similar to that used to estimate annual fluxes of suspended sediment was used to estimate annual fluxes of bedload sediment. First, relationships between bedload transport rates and water discharges for various time periods were determined for each measurement site. Those relationships were then applied to appropriate periods of the annual hydrographs which best corresponded with the time periods for which the transport relationships were valid. Fluxes for each time period were then summed to estimate the annual bedload flux. Shortly after breaching, bedload discharge past the Marmot Dam measurement station increased rapidly with little change in water discharge. Thus, rather than using the full set of data collected immediately after breaching in the bootstrapping process, when transport was highly disequilibrated and rapidly increasing, we used only those measurements that began 2–3 hours after breaching (see figs. 27, 32) when bedload flux had already increased significantly. Separate bootstrap analyses were made for the combined data collected in November–December 2007 and in May 2008, because those data are displaced significantly toward larger water discharges (fig. 32). Those displacements indicate that the bedload flux rate past the Marmot Dam station had diminished within a month or two of breaching and by May had declined further (fig. 32). In our analysis using the May 2008 data, we ignored two data points that lie far to the left of the overall data trend. Although those data appeared to have been collected appropriately, for reasons unknown they are significant outliers and hence are excluded from the data analysis. Discussions regarding data collected at Brightwood, Revenue Bridge, and Dodge Park are provided in the main body of the report.

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