

## **EVOLVING FLUVIAL RESPONSE OF THE SANDY RIVER, OREGON, FOLLOWING REMOVAL OF MARMOT DAM**

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**Abstract** The October 2007 removal of Marmot Dam on the Sandy River, Oregon, triggered a rapid sequence of fluvial responses as ~730,000 m<sup>3</sup> of sand and gravel that filled the former reservoir were suddenly exposed to an energetic river. Using direct measurements of sediment transport, photogrammetry, and repeat surveys between transport events, we monitored the erosion, transport, and redeposition of this sediment in the hours, days, and months following breaching. Measurements of suspended load and bedload documented an initial spike in the flux of fine suspended sediment in the minutes after breaching followed by high rates of suspended- and bedload transport of sand. Significant gravel transport did not begin at a measurement site 0.4 km downstream of the dam until 18–20 hours after breaching, when bedload transport achieved rates of about 60 kg/s—rates that greatly exceeded concurrent measurements of less than 10 kg/s at sites upstream and farther downstream of the dam. Bedload transport rates just below the dam site remained 10–100 times above upstream and downstream rates through subsequent high flow events during the winter and spring of 2007 and 2008.

Much of the elevated sediment load was derived from eroded reservoir sediment, which initially began eroding when a multi-meter-tall knickpoint migrated upstream 200 meters in the first hour. Rapid knickpoint migration triggered bank collapse in the unconsolidated fill, which swiftly widened the channel. Over the following days and months, the knickpoint migrated slowly upchannel, simultaneously lowering and becoming less distinct. By May 2008, a riffle-like feature approximately 1 m high, a few tens of meters long, and 2 km upstream from the breached dam persisted. Knickpoint and lateral erosion evacuated ~100,000 cubic meters of sediment from the reservoir in the first 60 hours, and by the end of high flows in May 2008 about 350,000 cubic meters (45 percent of the initial reservoir volume) had been evacuated. Large stormflows in November 2008 and January 2009 eroded another 39,000 cubic meters of sediment. Thus, within 15 months of breaching, about 55 percent of the impounded sediment (390,000 cubic meters) had been eroded. Two years after breaching, only another 10,000 m<sup>3</sup> (~400,000 m<sup>3</sup> total) had been eroded. About 30 percent of the eroded sediment has been redeposited in a tapered wedge of sediment that extends 2 km from the former dam site to the entrance of a confined bedrock gorge. Much of the balance of the eroded sediment is distributed along and

partly fills pools within the Sandy River gorge, a narrow bedrock canyon extending 2–9 km downstream of the former dam site, and along the channel farther downstream.

## INTRODUCTION

On 19 October 2007, a temporary cofferdam standing in place of the 15-m-tall, 50-m-wide Marmot Dam was breached, allowing the 80-km-long Sandy River to flow freely from Mount Hood, Oregon, to the Columbia River for the first time in nearly 100 years (Major et al., 2008, O'Connor et al., 2008; Figure 1). At the time it was breached (Figure 2), it was one of the largest dams removed (in terms of dam height and stored sediment) in the United States in the past 45 years, and also the greatest documented release of stored sediment from any US dam removal. Its removal subjected approximately 730,000 m<sup>3</sup> of impounded sand and gravel to erosion and downstream transport and deposition.

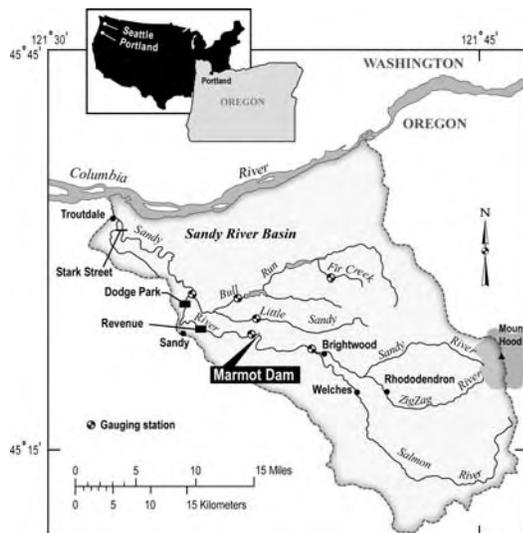


Figure 1 Location map of Sandy River basin, Marmot Dam, and measurement stations discussed in text. Confluence with Columbia River is located 20 km east of Portland, OR.



Figure 2 Time lapse images of the breach of the temporary earthen dam at Marmot Dam. Times given in Pacific Daylight Time (PDT).

The removal of Marmot Dam provided an opportunity to systematically document sediment erosion from the reservoir and its downstream transport and deposition. This effort, involving Portland General Electric and several government agencies, academic institutions, and consulting firms, resulted in one of the most intensely monitored removals to date. Monitoring activities

included measurement of water discharge and sediment transport at multiple locations upstream and downstream from the dam site before, during, and after removal; repeat surveys of channel profiles, cross sections, and valley-bottom topography upstream and downstream of the dam site (including multiple acquisitions of LiDAR topography); photogrammetric measurements of the dam breach and subsequent knickpoint migration; and measurements of bed-sediment texture within the reservoir reach and at several downstream locations. From these measurements, we are able to document (1) volumes and rates of sediment erosion from the reservoir reach, (2) the position and migration rate of an upstream migrating knickpoint, (3) the volume, spatial extent, and character of downstream deposition, and (4) sediment transport rates associated with several episodes of erosion and deposition in the period immediately following dam breaching and in the subsequent two years.

### **SANDY RIVER BASIN PHYSIOGRAPHY AND HYDROLOGY**

The Sandy River drains 1300 km<sup>2</sup> of the rugged western Cascade Range in Oregon, including the west-southwest flank of Mount Hood volcano, before joining the Columbia River 20 km east of Portland (Figure 1). Basin elevation ranges from 3428 m (the summit of Mount Hood) to 3 m (at the river's confluence with the Columbia River). The basin is underlain by Miocene to Pleistocene volcanic and volcanoclastic bedrock (Trimble, 1963; Sherrod and Scott, 1995), and its headwaters contain abundant, coarse glacial and volcanic sediment (Crandell, 1980; Cameron and Pringle, 1986).

The mainstem Sandy River runs 80 km from its source on Mount Hood to its tidewater Columbia River confluence. Over its course, the river transitions from a high-gradient boulder-cobble mountain stream to a low-gradient (0.0007 m/m) sand-bed channel near the Columbia River confluence. The gravel/sand transition corresponds to the gradient decreasing below 0.001 at about river km (Rkm) 10 (Stillwater Sciences, 1999). A distinct bedrock gorge, beginning 2 km below Marmot Dam, confines the river between Rkm 46.3 and 39.5. In this high-gradient reach (0.01 m/m), the river flows over bedrock and boulder steps and through long, deep pools, and only patchy deposits of sand and gravel have accumulated (Stewart and Grant, 2005).

Flow in the Sandy River corresponds to the cool, wet winters and warm dry summers of the region. The annual hydrograph of the river is driven largely by prolonged, low-intensity autumn and winter rainfall augmented by spring melt of high-elevation snowpack; the greatest discharges occur when rain falls on thick snowpack. Mean annual flow of the Sandy River at Marmot Dam is about 38 m<sup>3</sup>/s, and the mean annual flood is about 460 m<sup>3</sup>/s. The 0.5 exceedance probability flow (2-year flood) is 415 m<sup>3</sup>/s, and the 0.01 exceedance probability flow (100-year flood) is 1425 m<sup>3</sup>/s.

Marmot Dam was the only dam on the mainstem Sandy River, and sited near the middle of the basin at Rkm 48.3. The dam was located 2 km upstream of the entrance to the Sandy River gorge. Through the site of Marmot Dam, and for several km above, the Sandy River is a high-gradient (~0.008 m/m) bedrock-and-boulder-controlled channel bounded by valley walls typically 0.2–0.5 km apart (Stewart and Grant, 2005). Below the Sandy River gorge, the river valley widens considerably and over the 10-km-reach between the gorge and the confluence with the Bull Run River, its average gradient declines to 0.006 m/m.

## RESERVOIR EROSION

A main focus of our monitoring was to document the rates and processes by which the  $\sim 730,000$  m<sup>3</sup> of sand and gravel stored in the 3-km-long reservoir reach was eroded, transported, and redeposited. Analysis of sediment evacuation from the reservoir is considered on two time scales: (1) rapid erosion during initial breaching and the ensuing  $\sim 60$  hours of high flow, and (2) the subsequent and much slower erosion during the winters of 2007–08 and 2008–09.

**Knickpoint Migration and Initial Sediment Erosion** Photogrammetric measurements from fixed-camera imagery, on-site observations and measurements, and a post-breach survey of the reservoir reach document the rates and processes of reservoir sediment evacuation during the 19–22 October 2007 high flow associated with breaching of the coffer dam. Erosion occurred chiefly through incision, knickpoint migration, and lateral erosion. Headward erosion began after a 1- to 2-m-high knickpoint developed at the dam crest following breaching. The knick enlarged and advanced 150 m upstream at nearly 200 m/hr (Wallick et al., 2008), but over the next 250 m its advance slowed to a tenth of that initial rate and its height diminished to less than 1 m.

Within 12 hours of breaching, the Sandy River had incised through much of the sand and gravel fill in the lower 300 m of the reservoir, and its gradient recovered a significant proportion of its pre-dam profile (Keith et al., 2009; Figure 3). This rapid incision led to nearly continuous collapse of meters-high vertical banks of unconsolidated fill, which swiftly widened the channel, especially in the first 24 hours following breaching.

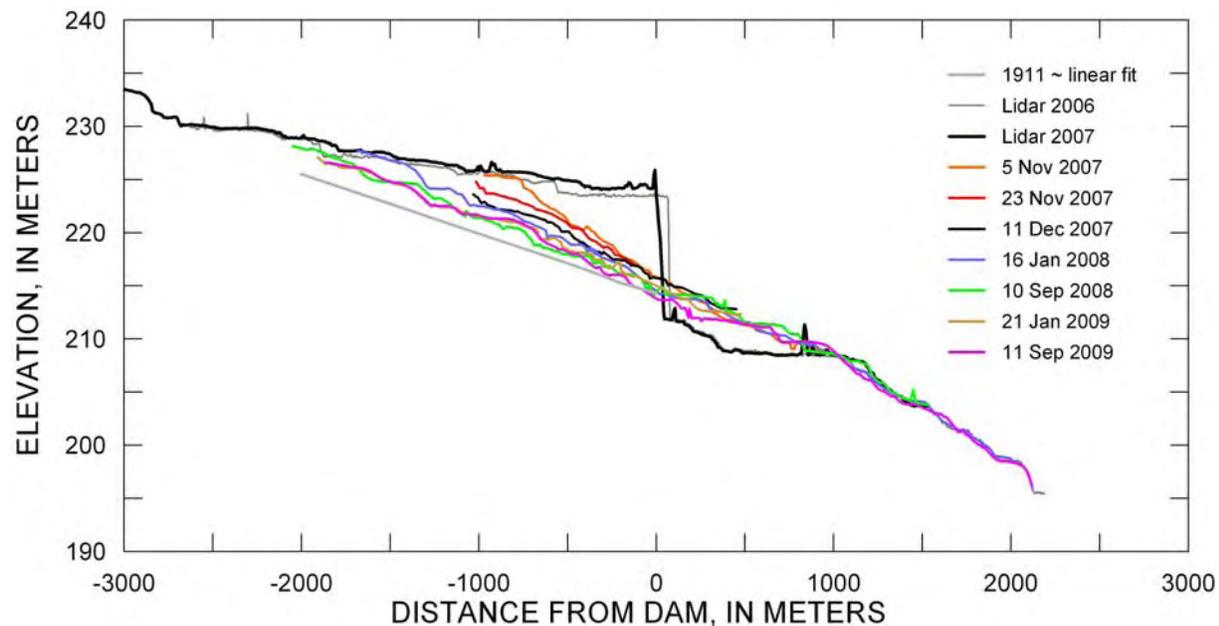


Figure 3 Longitudinal water-surface profiles of Sandy River before and after breaching of Marmot Dam.

Our measurements and observations show that approximately  $100,000$  m<sup>3</sup> of sediment was evacuated from the reservoir reach within 60 hours of breaching, primarily from the lower 500 m

of the reservoir reach (Figures 3 and 4). This volume was about 15 percent of the total volume of sediment impounded at the time of the breach, and approximates the average annual sediment load of the Sandy River at this location. All of this erosion was associated with a peak flow of  $\sim 80 \text{ m}^3/\text{s}$ —roughly twice the mean annual river flow and only 20 percent of the 2-year-recurrence-interval flow.

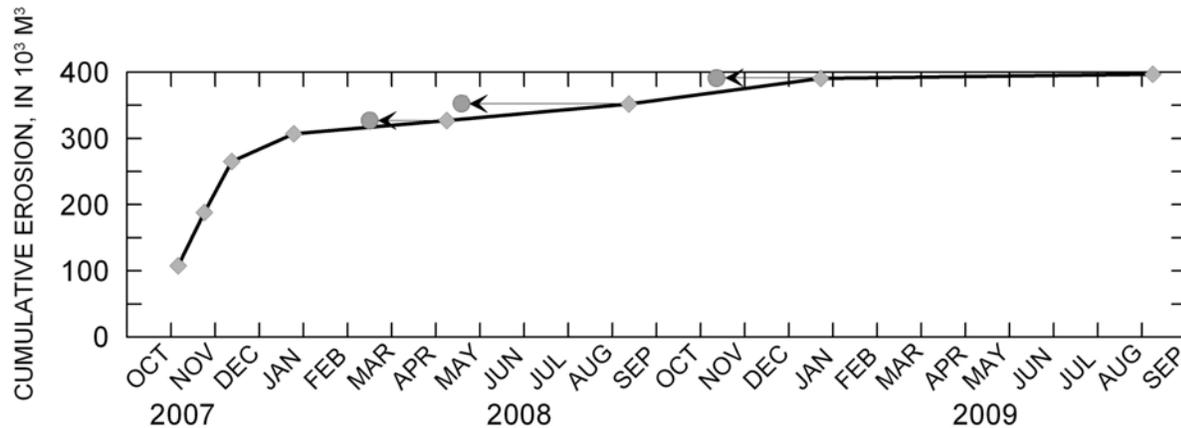


Figure 4 Cumulative erosion of reservoir sediment. Diamonds represent volume eroded at time of survey. Circles represent periods of high-flow that probably eroded the volume removed. For example, measured erosion between January and May 2008 occurred chiefly during a high-flow in March 2008.

**Longer Term Reservoir Erosion** The trajectory of erosion in the reservoir reach and changes in channel gradient were monitored by an additional seven surveys following the initial post-breach survey, extending the record to September 2009. The extent of an individual survey varied depending on flow conditions, but all surveys at a minimum extended at least 1 km upstream of the dam site (Figure 3). Each survey provided sufficient data to estimate the volume of additional erosion since the prior survey.

The sequence of surveys shows progressive incision and decreasing channel gradient in the reservoir reach (Figure 3), and rapidly diminished rates of volumetric sediment loss (Figure 4). Our surveys show that reservoir erosion initially was very rapid—within 2 months 265,000  $\text{m}^3$  of sediment had been removed. Much of the post-breach erosion occurred during two stormflows in November ( $Q_{\text{peak}} = 176 \text{ m}^3/\text{s}$ ) and early December ( $Q_{\text{peak}} = 231 \text{ m}^3/\text{s}$ ) 2007 (Figure 4). The magnitude and rate of erosion subsequently diminished; after one year 350,000  $\text{m}^3$  had been evacuated, and by September 2009, nearly two years after the breach, nearly 400,000  $\text{m}^3$  had been removed from the reservoir reach, about 55 percent of the initial  $\sim 730,000 \text{ m}^3$  stored. The minimal erosion in the second year following the breach was despite two large flows in November 2008 ( $570 \text{ m}^3/\text{s}$ ) and January 2009 ( $620 \text{ m}^3/\text{s}$ ), both of which approached the 5-year-recurrence-interval flow of  $632 \text{ m}^3/\text{s}$ .

## SEDIMENT DEPOSITION

Erosion from the reservoir reach triggered substantial deposition in the 2-km-long channel reach below the dam site and above the Sandy River gorge. Similar to the consideration of reservoir

erosion, we separate the discussion of sediment deposition into the initial 60 hours following the breach and subsequent annual changes.

**Sediment Deposition Following Breaching** Sediment deposition at the Marmot gaging station, 400 m downstream of the coffer dam, began within 3 hours of breaching, judging from a rise in water stage during a constant discharge. For the 39 hours between 2100 PDT on 19 October 2007 and 1200 PDT on 21 October, stage height (and the channel bed) rose at steady rate of 6.3 cm/hr before stabilizing early on 22 October at an elevation 3.2 m higher than that at the time of breaching (Figure 5). Bedload transport of sand accompanied channel aggradation during the first 18 hours after breaching, followed by transport and deposition of predominantly gravel beginning at 1200 PDT on 20 October 2007. During this 18 hour period after breaching, the channel transformed from a single thread, boulder-cobble bed to a multi-thread channel with a sand-and-gravel substrate flanked by mobile sandy bars.

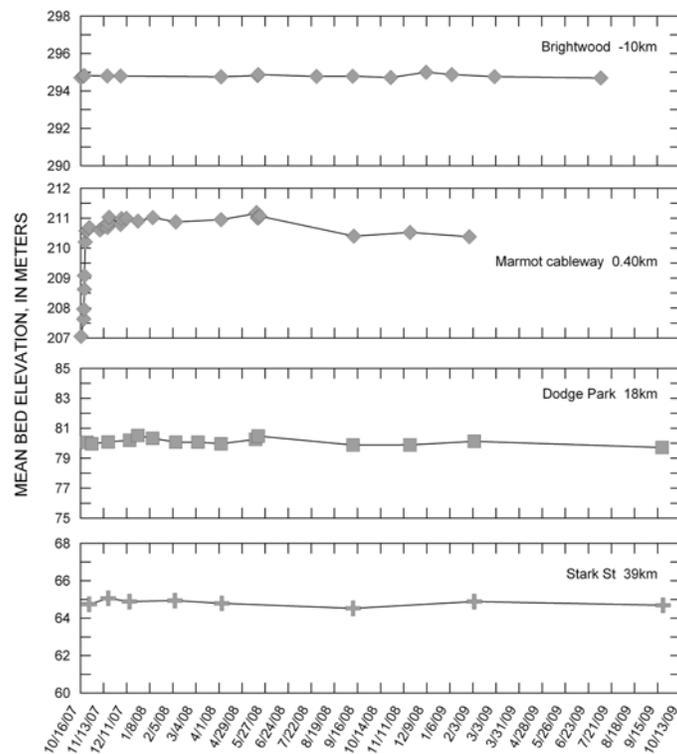


Figure 5 Time series of mean bed elevations at various measurement stations following breaching of Marmot Dam. See Figure 1 for station locations.

Aggradation at Marmot gaging station was part of a 1.25-km-long wedge of sediment, 4 m thick at the cofferdam site and tapering to the pre-breach channel bed at its distal end (Figure 3). About 65,000 m<sup>3</sup> of sediment—65 percent of the impounded sediment eroded from the reservoir reach in the first 60 hours—was deposited in this channel reach immediately after breaching. Channel soundings at measurement sites 9 and 18 km downstream showed no net aggradation during the first 60 hours following breaching, indicating that the balance (~40,000 m<sup>3</sup>) of eroded sediment not accounted for in the sediment wedge was deposited in the Sandy River gorge or broadly dispersed along the channel below the gorge.

**Longer Term Sediment Deposition** Surveys and soundings conducted after breaching show that the valley bottom between the dam and the Sandy River gorge rapidly evolved from an accumulation zone to a transport reach (Figures 3 and 5). High-flow events between November 2007 and September 2008 eroded about 245,000 m<sup>3</sup> of sediment from the reservoir reach (Figure 4), but deposited only an additional 45,000 m<sup>3</sup> of sediment in the 2 km of channel above the Sandy River gorge. Thus, approximately 110,000 m<sup>3</sup> of sediment accumulated in a 2-km-long wedge during the first year after breaching, accounting for about 30 percent of the volume evacuated from the reservoir reach.

In the second year after breaching, the channel reach immediately below the dam experienced net erosion of sediment. Most of the erosion occurred in the proximal part of this reach, where deposition had been greatest during the first year after breaching, and was largely accomplished by large stormflows in November 2008 and January 2009. Farther downstream, deposition during the two years following breaching was not channel wide; instead, sediment mainly accreted on existing gravel bars (Podolak and Wilcock, 2009).

Repeat soundings at the Dodge Park and Stark Street bridges, 18 and 39 km downstream, show bed fluctuations of up to 0.5 m during the two years after breaching, but no systematic trends (Figure 5). These fluctuations may result from migration of low-amplitude, long-wavelength sandy bedforms, but it is not clear if such sand transport is directly attributable to release of the impounded reservoir sediment.

## SEDIMENT TRANSPORT

We measured discharge, suspended-sediment load, and bedload during six high flows in the year following breaching at a single station upstream of Marmot Dam and at four measurement sites downstream of the dam site (Figure 1). Measurements at Brightwood, 10 km upstream of Marmot Dam, and at three downstream sites—Marmot Dam gaging station (0.4 km downstream), Dodge Park (18 km downstream) and Stark Street bridge (39 km downstream)—were obtained by USGS staff. Measurements near Revenue bridge, 9.5 km downstream of the dam site, were made by Graham Matthews and Associates (GMA; Pittman and Matthews, 2008).

**Suspended-sediment Transport** Pre-breach measurements show suspended-sediment concentrations upstream and downstream of the cofferdam ranging from about 100 to 1000 mg/l (Figure 6c). The measurements show sediment concentrations at Brightwood, upstream of the dam site, about two to four times greater than those measured downstream of the dam site (Figure 6c). This difference in concentrations is largely due to the presence of the dam and its associated diversion of water. The measured concentrations, when combined with streamflow discharge, show that pre-breach suspended-sediment fluxes upstream and downstream of the dam were tenths to tens of kg/s (Figure 6d), fluxes probably typical of the Sandy River at a discharge approximating the mean annual flow. Suspended sediment at Brightwood consisted chiefly of fine sand. In contrast, mostly finer sediment (<63 μm) passed stations below the dam.

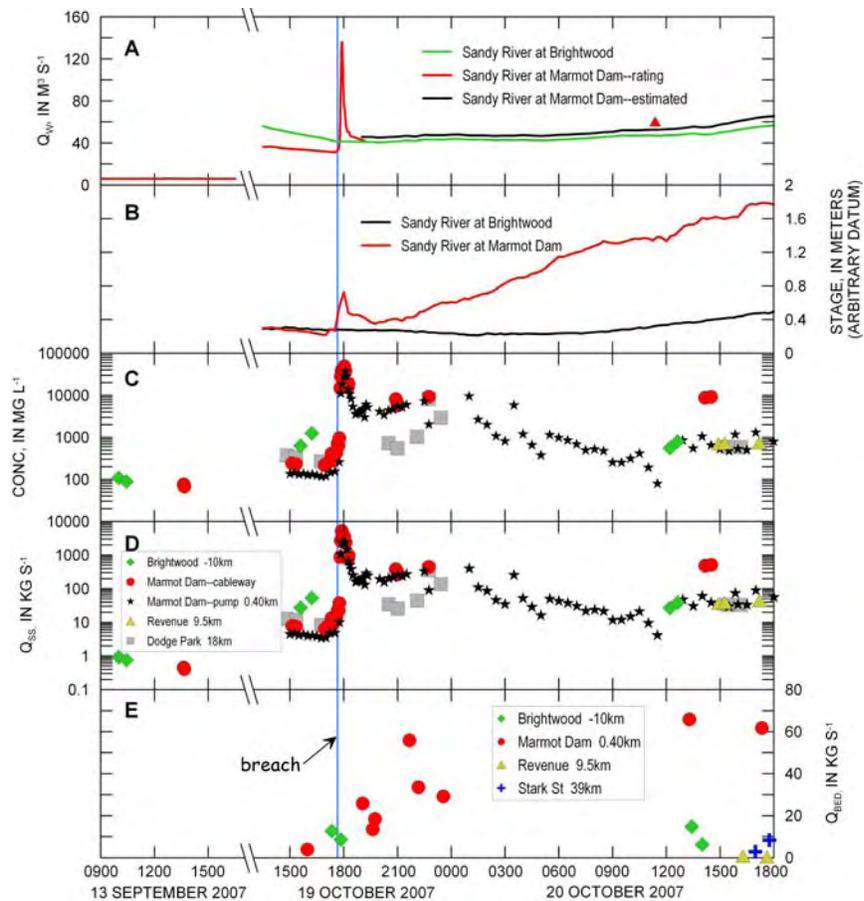


Figure 6 Time series of stage (water-surface elevation) and water and sediment fluxes above and below Marmot Dam site (see Figure 1 for station locations). (A) Water discharge. Prior to dam breaching some flow was diverted past the Marmot gauging station, and hence the measured discharge below the dam is less than that passing Brightwood upstream. After breaching, all flow passed the Marmot gauging station. Owing to channel aggradation at the Marmot gauging station, postbreach discharge immediately below the dam had to be estimated from regional gauges. The triangle represents a measured discharge at the Marmot gauging station. (B) Stage. Sediment deposition led to a rising stage at the Marmot gauging station beginning about 3 hours after breaching. (C) Suspended-sediment concentration measured above and below the dam site. At the Marmot gauging 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 by cataraft. All samples were typically collected at equal intervals across the channel. Immediately after breaching, samples collected from the Marmot cableway were obtained only at a single midchannel station. 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 systematically across the channel. Revenue bridge data from Pittman and Matthews (2008). Distances identify station distance from Marmot Dam; positive values are downstream.

Breaching of the cofferdam released a pulse of turbid water having an instantaneous suspended-sediment flux as great as 5200 kg/s as it passed the Marmot gaging station (Figure 6d). The initial sediment pulse passing the station consisted predominantly of fines (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—but the suspended load coarsened rapidly as the Sandy River incised into the stored sand and gravel. Following the initial peak value, the flux of the sand-rich suspended sediment stabilized between several tens (80 kg/s for the pump samples) to hundreds (465 kg/s for the 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 about 30–50 kg/s (Figure 6d).

Event-driven suspended sediment fluxes declined rapidly following dam removal. By December 2007, suspended-sediment concentrations, fluxes, and compositions measured at the Marmot station were similar to those measured farther downstream (Figure 7). By May 2008, measured suspended-sediment concentrations, fluxes, and compositions were similar among all sites upstream and downstream of the dam site (Figure 7).

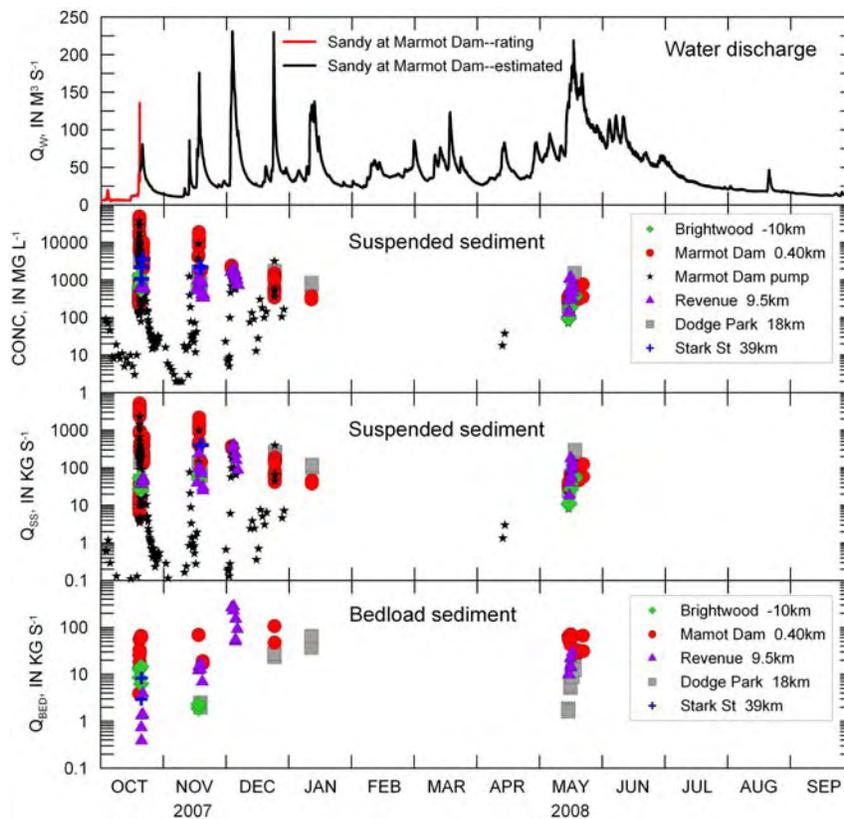


Figure 7 Time series of water discharge and sediment fluxes measured during high-flow events in the months following breaching of Marmot Dam. Data from Revenue bridge from Pittman and Matthews (2008). See Figure 1 for station locations. Distances identify station distance from Marmot Dam; positive values are downstream.

**Bedload Transport** Bedload flux was very low prior to breaching of the cofferdam, but increased substantially soon after. Immediately prior to breaching, bedload flux upstream and just downstream of the cofferdam was  $\leq 6$  kg/s, and consisted chiefly (>90%) of sand (Figure 6e). Within 2 to 3 hours of breaching, bedload flux at the Marmot station increased 10–20 fold. Within 6 hours of breaching, it increased ~40-fold (from 1 kg/s before breaching to about 40 kg/s). It then increased another 50 percent (to about 60 kg/s) over the next 6–18 hours. This rapid increase in bedload flux at the Marmot station was in contrast to the steady, low (<10 kg/s) flux of sandy bedload that passed Brightwood (10 km upstream) and that emerged from the Sandy River gorge (9.5 km downstream; Pittman and Matthews, 2008) (Figure 6e). Considerable bedload flux continued past the Marmot station for much of the next 60 hours; simultaneously, bedload flux of less than 5 kg/s emerged from the Sandy River gorge (Pittman and Matthews, 2008).

Initially, the bedload passing the Marmot gaging station consisted chiefly of sand (< 2 mm). Minor amounts of gravel began passing the site within 4 hours, but significant gravel transport past the station did not begin until 18–20 hours after breaching, in conjunction with rapid bed aggradation and growth of mid-channel gravel bars.

Bedload transport past the Marmot gaging station remained significantly elevated during subsequent high-flow events in water year 2008 compared to transport upstream and farther downstream of the dam site. When bedload was actively transported, the flux immediately downstream of the dam site was persistently 4 to 10 times greater than fluxes measured upstream and farther downstream (Figure 7). During the year following breaching, bedload passing the Marmot station contained substantially more gravel than that passing the other measuring sites.

## CONCLUSIONS

The fluvial response of the Sandy River to abrupt sediment loading caused by removal of Marmot Dam was characterized by rapid and significant erosion of stored sediment (>50% of stored volume), enhanced sediment transport under modest discharges, and substantial (to 4 m thick) deposition of sand and gravel in the few km of channel below the dam site during the two years following breaching. In the first 60 hours following breaching, lateral and vertical erosion of the stored sediment advanced rapidly 500 m upstream from the dam, and removed nearly 100,000 m<sup>3</sup> of sediment (~15 percent of the stored volume). Sediment transport rates immediately below the dam site increased by more than an order of magnitude. The channel below the dam site changed from a single-thread, boulder-studded channel to a multi-thread channel flanked by mobile sand-and-gravel bars as about 65 percent of the sediment eroded from the reservoir was deposited along the 2 km of channel below the dam site. Through the remainder of the year following dam removal, rates of sediment erosion, transport, and deposition diminished. Within a year of removal, about half of the stored sediment had been removed, but at progressively diminishing erosion rates. Within a few months of dam removal, suspended-sediment loads largely returned to pre-removal levels, but bedload transport rates just below the dam site remained 10–100 times above upstream and downstream rates. Also by this time, the channel reach between the dam site and the Sandy River gorge had stabilized into a single thread flanked by gravel bars and had evolved from chiefly an accumulation zone to a transport reach. After one year, about 40 percent of the eroded reservoir sediment had been

deposited in this reach. Within two years of breaching, about 55 percent of the reservoir sediment had eroded, channel morphometry remained stable, and the volume of sediment deposited in the channel reach below the dam site remained constant. The eroded sediment not deposited in the 2-km-long channel reach below the dam site has been largely distributed along, and partly fills, pools within the Sandy River gorge, a narrow bedrock canyon extending 2–9 km downstream of the dam site, and is also broadly distributed along the channel farther downstream. However, beyond the river gorge, few if any of the measured variations in channel geometry and sediment transport are clearly attributable to the release of sediment from dam breaching and the ensuing two years of sediment transport.

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