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Initial Fluvial Response to the Removal of Oregon's Marmot Dam

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A temporary, 14-meter-high earthen cofferdam standing in place of Marmot Dam was breached on 19 October 2007, allowing the 80-kilometer-long Sandy River to flow freely from Mount Hood, Oreg., to the Columbia River for the first time in nearly 100 years. Marmot Dam is one of the largest dams in the western United States (in terms of height and volume of stored sediment) to have been removed in the past 40 years, and its removal exposed approximately 730,000 cubic meters of stored sand and gravel to erosion and transport by the newly energetic mountain river. At the time, its breach represented the greatest release of sediment from any U.S. dam removal. (The March 2008 breaching of Montana's Milltown Dam exposed about 5–10 times as much sediment to potential erosion.) Ongoing, intensive monitoring of erosion, transport, and deposition of that sediment is providing the first detailed data from such a voluminous dam-removal sediment release, which will provide a basis for evaluating physical and numerical modeling of the effects of future dam removals from mountain rivers.

This article reports on the initial fluvial response to the breaching of the cofferdam, focusing on the first 48 hours following breaching, during which about 15% (100,000 cubic meters) of the stored sediment was eroded and transported downstream.

Marmot Dam

The Sandy River drains 1300 square kilometers of the western Cascade Range in Oregon—including the west-southwest flank of Mount Hood volcano—before joining the Columbia River 20 kilometers east of Portland (Figure 1). The river's volcanic and glaciated headwaters produce abundant coarse sediment. Marmot Dam, located 45 kilometers upstream from the Columbia River confluence, was the only dam constructed on the main stem Sandy River. It was originally completed in 1913 as a rock-and-timber crib structure but was replaced by a comparably sized 14-meter-high, 50-meter-wide concrete dam in 1989. Portland General Electric (PGE) owned and operated the dam and used it to divert water from the Sandy River as part of the company's 22-megawatt Bull Run Hydropower Project. At the time the dam was decommissioned, it was brimful with sediment and impounded 750,000 cubic meters (about 10 years of average annual sediment flux) of uncontaminated, mostly homogeneously mixed sand and gravel. Facing an expiring U.S. Federal Energy Regulatory Commission license and substantial fish passage upgrades and future maintenance costs, PGE opted to surrender its operating license and agreed in 2002 to a decommissioning schedule that culminated in the 2007 dam removal.

Of many possible options for decommissioning, PGE chose the informally termed "blow and go" option, in which the dam was removed as quickly as possible with minimal prior removal of stored sediment. PGE removed Marmot Dam between 1 July and 30 September 2007. Removal entailed building an earthen cofferdam on top of impounded sediment 70 meters upstream of the concrete structure, diverting the Sandy River around both the coffer and concrete dams, removing about 20,000 cubic meters of sediment between the dams, and then deconstructing and removing the concrete dam. While this approach was advantageous from the standpoints of low cost and minimal in-stream disturbance, it left the fate of the cofferdam and the remaining 730,000 cubic meters of reservoir sediment to an unfettered, high-gradient (0.006–0.009 meters per meter) river.

Breaching the Cofferdam

After PGE removed the last vestiges of the concrete dam, the cofferdam could be breached. The breaching was scheduled for late 2007, between seasonal fish runs, to minimize adverse consequences to resident and migratory fish. PGE desired a substantial flow at breaching to reduce the risk of blocking fish passage by incomplete incision of the sediment-filled reservoir reach, but a controlled breach was constrained by the 60-cubic-meter-per-second capacity of the diversion channel. On the morning of 19 October, heavy rainfall, a rising river, and a discharge forecast for 68 cubic meters per second prompted PGE to initiate the breaching procedure at about 1000 Pacific daylight time (PDT). Pumps dewatering the cofferdam and underlying sediment were removed sequentially beginning around 1200 PDT. At about 1330 PDT, water began seeping through the earthen dam, triggering small but growing mass failures on the dam's downstream face (Figure 1). At 1700 PDT, with the river flowing at nearly 50 cubic meters per second, crews carved a small notch in the cofferdam's crest and released flow over its top. By 1745 PDT, flow vigorously enlarged the breach (Figure 1), resulting in a flash flow peak of 136 cubic meters per second as the small volume of stored water rapidly drained (Figures 1 and 2a). By 1800 PDT, the river had incised through the earthen dam. By 2330 PDT, the river had removed it completely (see an online video in the electronic supplement to this *Eos* issue (http://www.agu.org/eos_elec/)).

Erosion of Reservoir Sediment

As the earthen dam washed away under a 40- to 50-cubic-meter-per-second flow, the Sandy River eroded impounded sand and gravel through a combination of headward and lateral erosion (Figure 1). Headward erosion began after a 1- to 2-meter-high knickpoint (an abrupt change in the channel profile) developed near the cofferdam crest. The knickpoint enlarged and advanced 150 meters upstream at nearly 200 meters per hour, but over the next 250 meters, the knickpoint's advance slowed to a tenth of that initial rate and its height diminished to less than 1 meter.

Within 12 hours of breaching, the Sandy River incised through the sand and gravel fill in the lower 300 meters of the reservoir reach, nearly attaining its predam profile. The rapid incision led to nearly continuous collapse of meters-high vertical banks of unconsolidated fill, which swiftly widened

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the channel, especially in the 24 hours following breaching. Preliminary analyses of oblique terrestrial photographs and traditional ground surveys indicate that about 100,000 cubic meters of sediment (the approximate mean annual load of the Sandy River at Marmot Dam) was eroded within 48 hours of breaching, mostly from the lower 500 meters of the reservoir reach. A noteworthy aspect of this erosion is that it occurred under a median flow of about 50 cubic meters per second, a discharge just 30% greater than the river's mean flow at Marmot Dam.

Downstream Sediment Transport and Deposition

In anticipation of considerable sediment transport, we fielded research teams before, during, and after breaching to measure flow, suspended load, and bed load at two gauging stations: one 10 kilometers upstream of the dam near Brightwood, Oreg. (Figure 1), and another 450 meters downstream of the dam. The downstream gauging station was also outfitted with an automated pump sampler to collect frequent samples of suspended sediment—although its intake position at the channel margin and occasional clogging owing to bed aggradation temper sample caliber and continuity.

The first measurements on 19 October show prebreach suspended-sediment and bed load mass fluxes upstream and downstream of the dam of the order of a few to a few tens of kilograms per second (Figures 2c and 2d). Suspended sediment upstream was composed chiefly of fine sand, in contrast to the mostly silt and clay (<63 microns) passing the station below the dam. In both reaches, bed load consisted chiefly (>90%) of sand.

Breaching of the cofferdam released a pulse of turbid water, with an instantaneous suspended-sediment flux to 5200 kilograms per second (Figure 2c). The initial sediment pulse consisted predominantly of silt and clay, presumably eroded 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 stored sand and gravel. Following the initial peak value, median fluxes of sand-rich suspended sediment hovered around several tens (80 kilograms per second, pump samples) to hundreds (465 kilograms per second, midchannel and transverse samples) of kilograms per second for at least 24 hours, whereas the upstream median suspended sediment flux remained about 30 kilograms per second (Figure 2c).

Bed load transport also increased following breaching, but its response was slower than for suspended sediment. Bed load flux below the dam site increased from approximately 1 kilogram per second before breaching to 60 kilograms per second by 6 hours after breaching and to about 70 kilograms per second by 18 hours after (Figure 2d), in

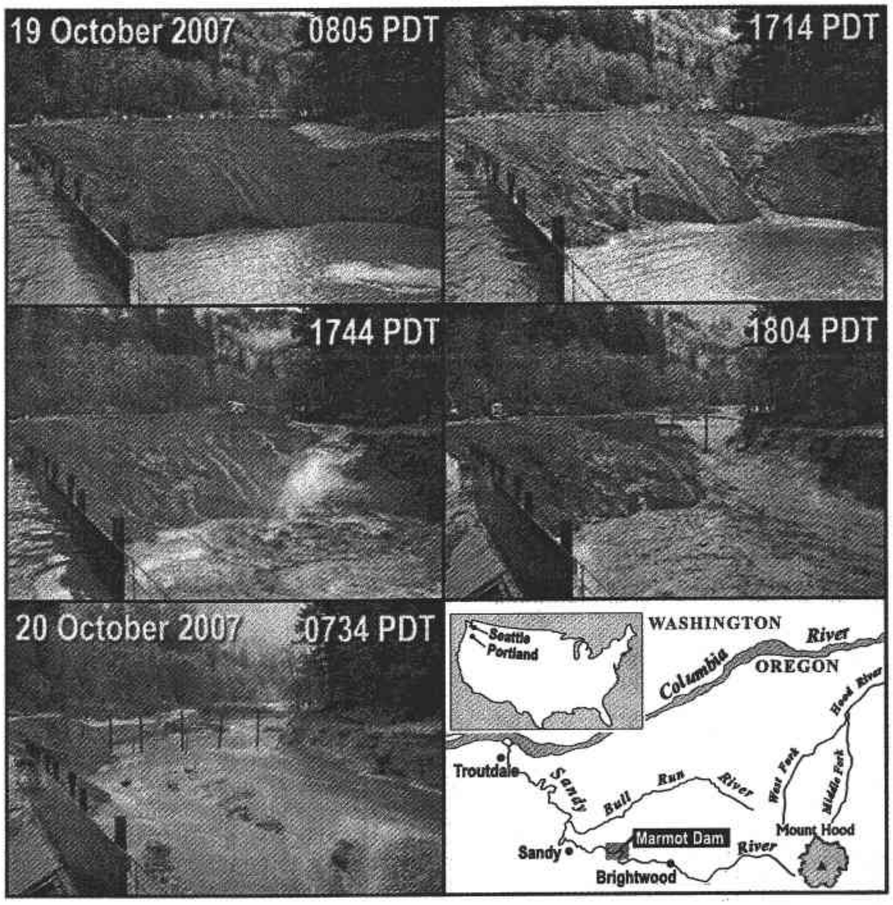

Fig. 1. Location of Sandy River, Marmot Dam and time-lapse images of breaching of the temporary earthen dam. The first image, at 0805 Pacific daylight time (PDT), was taken before the pumps dewatering the earthen dam were removed. Shortly after the pumps were shut off, water began seeping through the dam, gradually triggering small mass failures. Once all of the pumps were removed, crews carved a small notch in the dam crest and released the impounded water. Note the seepage and mass failures on the dam's downstream face evident by 1714 PDT, the channel and small knickpoints that developed as water overtopped the dam after it was notched, and the migrating headcut in the reservoir following breaching. By the following morning, the earthen dam and a substantial volume of stored sediment had been removed. Exposed well casings are about 10 meters tall. Note people for scale in some images. Data shown in Figure 2 were collected at U.S. Geological Survey gauging stations near Brightwood, Oreg., and 450 meters downstream of Marmot Dam. Portland, Oreg., is located 20 kilometers west of the Sandy River/ Columbia River confluence.

contrast to the steady, low (<10 kilograms per second) flux of sandy bed load passing Brightwood before and after breaching. Considerable bed load flux below the dam site continued throughout much of the next 48 hours. Initially, the bed load consisted predominantly of sand (<2 millimeters) sweeping past the gauging station in large dunes. Significant gravel transport past the station did not begin until 18–20 hours after breaching, in conjunction with rapid bed aggradation and downstream propagation of midchannel gravel bars.

Erosion and transport of reservoir sediment rapidly modified channel morphology in a 2-kilometer-long reach below the dam. At the gauging station, the channel bed had aggraded about 1.5 meters 18 hours after breaching (Figure 2b) and almost 4 meters after 66 hours. In conjunction with this aggradation, the former single-thread boulder-cobble channel evolved into multiple channels flanking mobile gravel bars. An early November 2007 survey—conducted after breaching but before subsequent stormflows—revealed that this deposition was part of a sediment wedge 4 meters thick at the former dam site and tapering out 1.5–2 kilometers downstream. This wedge accounted for about 85% (85,000 cubic meters) of the sediment volume initially eroded from the reservoir. The balance of the sediment, mostly sand, moved farther downstream, but it was not detected at measuring sites 8 and 18 kilometers downstream.

Continued Monitoring and Analysis

While other researchers examine effects on fish and related aspects of the riverine ecosystem, we and colleagues continue to monitor the geomorphic effects of the

Marmot Dam removal. Subsequent stormflows eroded more sediment from the reservoir and moved it farther downstream. By mid-January 2008, about 300,000 cubic meters of reservoir sediment were eroded, a subtle knickpoint was 1.5 kilometers upstream of the former dam site, and sediment sampling and channel soundings as far as 18 kilometers downstream documented enhanced sand transport and possible channel aggradation. Comprehensive aerial and ground surveys during summer low flow will document the cumulative effects of this past winter's high flows on reservoir erosion, downstream changes to channel morphology, substrate characteristics, and fish habitat. Together, the analyses over coming years of transient, storm-driven changes and cumulative consequences should shed new light on the processes and rates by which a high-gradient mountain river can respond to dam removal and consequent voluminous sediment input.

Additional information is available at http://www.nced.umn.edu/Marmot_Dam_Portal.

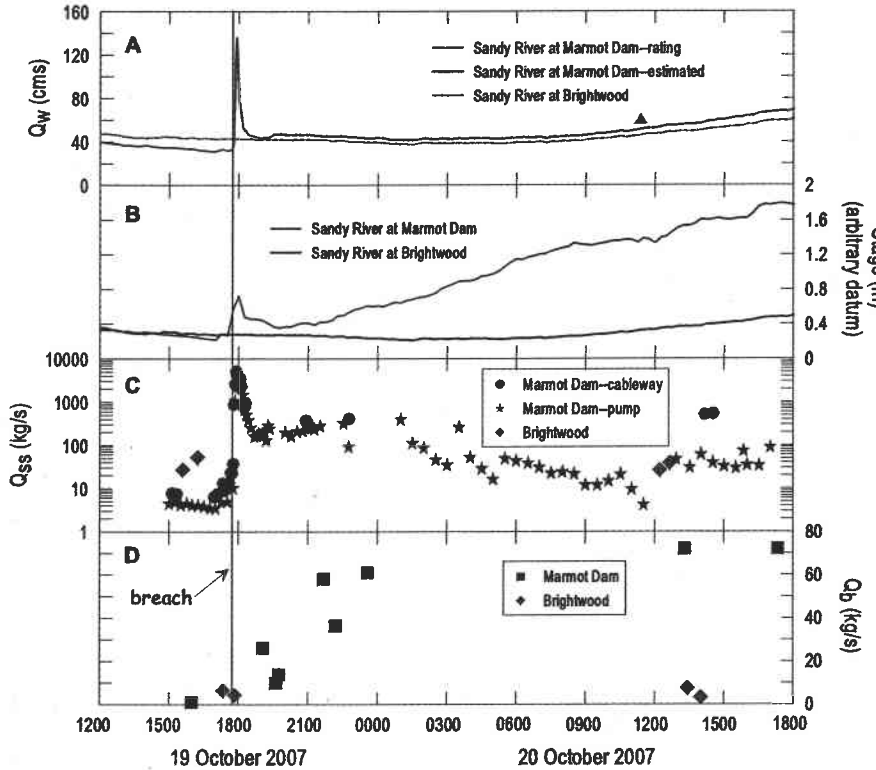

Fig. 2. Time series of stage (water surface elevation) and water and sediment fluxes above and immediately below Marmot Dam (see Figure 1). (a) Water discharge. Prior to dam breaching, some flow was diverted past the dam gauging station, and hence the measured discharge below the dam is less than that passing Brightwood upstream. After breaching, all flow passed the dam gauging station. Owing to channel aggradation at the dam gauging station, postbreach discharge below the dam had to be estimated from regional gauges. The triangle represents measured discharge below the dam. (b) Stage. Sediment deposition led to a rising stage at the dam gauging station beginning about 3 hours after breaching. (c) Suspended sediment flux. Below the dam, samples were collected manually from a cableway and by an automated pump sampler at the channel margin. At Brightwood, and from the dam cableway before breaching and the day after, samples were collected systematically across the channel every 3–6 meters. Immediately after breaching, however, dam cableway samples were obtained only at a single midchannel station. Similarity 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 flux. (d) Bed load flux. The mean flux was computed from samples collected systematically across the channel every 3–6 meters.

Acknowledgments

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