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EVOLVING EXPECTATIONS OF DAM REMOVAL OUTCOMES: DOWNSTREAM GEOMORPHIC EFFECTS FOLLOWING REMOVAL OF A SMALL, GRAVEL-FILLED DAM[1]

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ABSTRACT: Dam removal is a promising river restoration technique, particularly for the vast number of rivers impounded by small dams that no longer fulfill their intended function. As the decommissioning of small dams becomes increasingly commonplace in the future, it is essential that decisions regarding how and when to remove these structures are informed by appropriate conceptual ideas outlining potential outcomes. To refine predictions, it is necessary to utilize information from ongoing dam removal monitoring to evolve predictive tools, including conceptual models. Following removal of the Brownsville Dam from the Calapooia River, Oregon, aquatic habitats directly below the dam became more heterogeneous over the short term, whereas changes further downstream were virtually undetectable. One year after dam removal, substrates of bars and riffles within 400 m downstream of the dam coarsened and a dominance of gravel and cobble sediments replaced previously hardpan substrate. New bars formed and existing bars grew such that bar area and volume increased substantially, and a pool-riffle structure formed where plane-bed glide formations had previously dominated. As the Brownsville Dam stored coarse rather than fine sediments, outcomes following removal differ from results of many prior dam removal studies. Therefore, we propose a refined conceptual model describing downstream geomorphic processes following small dam removal when upstream fill is dominated by coarse sediments.

(KEY TERMS: river restoration; dam removal; gravel-bed rivers; geomorphology; sediment transport; conceptual models.)

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INTRODUCTION

In the United States (U.S.), dam removal is increasingly implemented as a river restoration technique (Hart *et al.*, 2002; Gleick *et al.*, 2009), reflecting a growing concern over the adverse ecological and social impacts of dams (Pejchar and Warner, 2001). Safety concerns and impediments to fish passage associated with aging structures create the need for new policies and funding sources to support removal projects (Doyle *et al.*, 2003b). However, to date, scientific investigation of dam removal outcomes is limited. Although nearly 700 dams have been removed in the last 100 years (American Rivers *et al.*, 1999; Gleick *et al.*, 2009), outcomes from <5% of these removals have been documented as published ecological research (Hart *et al.*, 2002). Absence of monitoring at

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removal sites, inconsistent and incomplete experimental designs, and deficient baseline data have hindered the advancement of dam removal science (Heinz Center, 2002).

From a broader perspective, the scant quantity of published research is further limited by differences in the quality and type of information collected among sites. Moreover, physical settings and ecological constraints differ widely among rivers and dams, such that no single suite of dam removal effects can be universally projected. Lacking an extensive body of knowledge and experience, managers, stewards, and researchers often struggle to predict the magnitude, timing, and spatial extent of physical and ecological outcomes of dam removal (Hart *et al.*, 2002; Heinz Center, 2002). As tradeoffs exist between the restoration benefit and the potential for disturbance posed by dam removal (Stanley and Doyle, 2003), uncertainty about short- and long-term consequences complicates decision-making processes regarding whether and how to remove dams (Aspen Institute, 2002).

Existing research on the outcomes of dam removal has primarily occurred on low-gradient rivers that transport sand or silt (Stewart and Grant, 2005), documenting deposition of fine sediments downstream of dam failures and removals (Kanehl *et al.*, 1997; Evan *et al.*, 2000; Wohl and Cenderelli, 2000; Bushaw-Newton *et al.*, 2002; Stanley *et al.*, 2002; Doyle *et al.*, 2003a; Ahearn and Dahlgren, 2005; Cheng and Granata, 2007; Burroughs *et al.*, 2009). Past studies monitoring releases of stored reservoir sediments have reported a variety of morphological changes related to sediment routing and deposition through downstream reaches, including fining of channel substrates (Cheng and Granata, 2007), intrusion of fine sediments into channel substrates (Stanley *et al.*, 2002), filling of pools (Wohl and Cenderelli, 2000), decreased channel depth and increased width (Doyle *et al.*, 2003a; Burroughs *et al.*, 2009), and transition to simplified bed forms (Kanehl *et al.*, 1997; Bushaw-Newton *et al.*, 2002; Stanley *et al.*, 2002). Such reported geomorphic alterations imply direct and indirect effects to downstream aquatic biological communities. For instance, the fine sediments evacuated from Halligan Reservoir into the North Fork Poudre River filled pools and interstitial pore spaces within the channel's cobble and boulder bed, impairing spawning and holding habitats for trout (Wohl and Cenderelli, 2000).

Due in part to the preponderance of evidence from dam removals in which the reservoir has released fine materials, dominant conceptual representations of channel change downstream of dam removals often infer that sediments released from the reservoir homogenize downstream habitat structure, bed armoring and bar formations, and decrease substrate grain size, simplifying downstream habitats for many years after dam removal (Pizzuto, 2002). However, the number of studies documenting outcomes that fall outside of this expectation of habitat simplification is growing. Following the removal of two small Oregon dams that stored coarse material, Dinner Creek and Maple Gulch, Stewart (2005) observed that coarse sediments from the reservoir were deposited close to the dam, creating riffle-pool complexes in Dinner Creek where plane-bed morphology had existed prior to dam removal. In a physical model of a gravel pulse moving through a sediment-starved riffle-pool reach with alternating bars, Downs *et al.* (2009) observed that the gravel pulse increased the complexity of existing habitat, maintaining the riffle-pool morphology as the pulse moved through the reach and leaving a legacy of bar deposits and related areas of scour near bars that persisted after the pulse had passed. Though gravel deposited into pools as well as on riffles and bars, most deposition occurred in areas of low shear stress at the tail of the pool and pool depth was not significantly altered.

A considerable number of the 2 million-plus dams estimated to exist in the U.S. are less than 2 m in height (Graf, 1993; Shuman, 1995; Poff and Hart, 2002). Many of these structures have passed their design lifetimes, and in some cases, the reservoirs have completely filled with sediment. Due to the sheer number of such aging structures, decommissioning of small dams with full reservoirs is likely to become common in the near future (Doyle *et al.*, 2002, 2003b). The ecological effects of removing small dams are likely to differ from those associated with larger dam removal, just as effects of coarse sediment release may diverge from outcomes observed after releases of fine sediments. Thus, establishing a set of likely consequences and predictive tools targeted specifically to the various conditions in which dam removal may occur is an essential area of research to support decision making for future dam removals. In support of this research direction, we present downstream channel changes observed following removal of the Brownsville Dam from the Calapooia River in Western Oregon. A small structure (1.8-3.4 m in height, depending on season), impounding a reservoir filled with sediment, Brownsville Dam in many ways typifies the multitudes of defunct small dams that may be removed from American rivers in the future. However, unlike many reservoirs monitored in past studies of reservoir releases, the Brownsville Dam reservoir was filled with primarily coarse sediments. Adding to the breadth of knowledge regarding dam removal from rivers that transport gravels, results of the Brownsville Dam removal may be useful in predicting downstream channel changes following removal of other small dams that store coarse sediments.

METHODS

Brownsville Dam Background

A tributary of the Willamette River, the Calapooia River drains the Western Cascades of Oregon. Brownsville Dam was located in the mid portion of the 950 km^2 Calapooia River watershed, upstream of the town of Brownsville (Figure 1). The upper Calapooia basin is a moderately steep catchment (channel gradient ranges from 0.44 to 1.94%), dominated by private forest land, which transitions to a wider valley of low to modest grade (0.10 to 0.44%), comprised of primarily agricultural and low-density urban land uses. All peak flows and 90% of the Calapooia River's annual runoff occur between November and May (Runyon *et al.*, 2004).

Brownsville Dam was a hollow concrete dam, initially constructed in the 1880s as a summer diversion structure for a local woolen mill and rebuilt in the 1960s to maintain aesthetics in the diversion canal. The 33.5 m wide dam raised the level of the Calapooia River by 1.8 m during the high-flow season (October-May). During summer months, removable flashboards were installed, impounding the river level to 3.4 m above its historic elevation. When the flashboards were removed for the high-water season, channel-forming flows passed over the dam with little regulation.

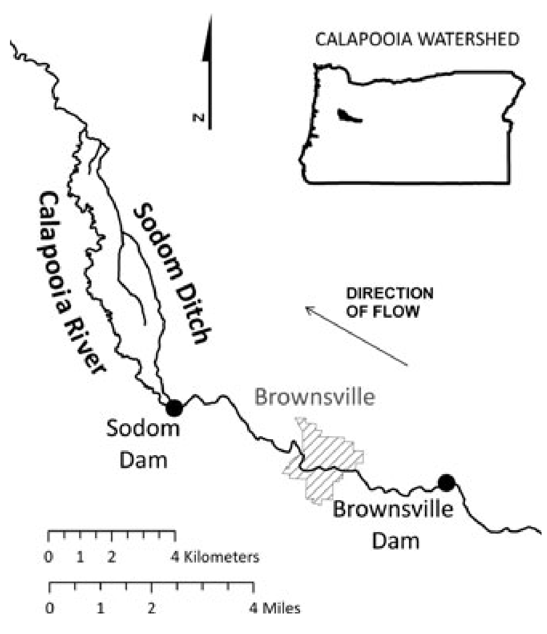

FIGURE 1. Location of the Calapooia River and Brownsville Dam.

After the reservoir filled with sediment, water and gravel-sized bed load passed over the dam, eventually undermining the structure on the downstream side, making the aging dam a liability for the owners. In addition to reducing the hazard risk presented by the Brownsville Dam, the 2007 removal was also justified in large part as removing a barrier to fish migration. Winter steelhead trout (*Oncorhynchus mykiss*) and spring Chinook salmon (*Oncorhynchus tshawytscha*), both of which are designated as Threatened under the Endangered Species Act (ESA), seasonally migrate through this section of the Calapooia to spawning and rearing grounds in the upper Calapooia basin. Although a fish ladder was constructed along the right abutment of the Brownsville Dam, it was not functional at all flows and was considered a barrier to migrating salmon. Twelve kilometers downstream of the Brownsville Dam, the Calapooia River is bifurcated for another mill diversion and approximately 60% of the flow is diverted through the Sodom Ditch (Figure 1), which is regulated by Sodom Dam. Also identified as a migration barrier for fish, Sodom Dam is slated for removal during the summer of 2011.

Data Collection

We conducted a preremoval baseline survey of channel morphology and habitat in the Calapooia River study area during the summer base-flow season (July-August) leading up to the late-summer removal of the Brownsville Dam. In the reservoir reach (0-400 m upstream of the dam), the reach downstream of the dam (0-1,600 m), and an upstream control reach (650 m in length, located 1,600 m upstream of the reservoir), we surveyed channel cross-sections (103 total), longitudinal thalweg profiles, and bar margins and cross-sections, using a Nikon DTM-352 Total Station (Nikon, Tokyo, Japan).

We collected and analyzed bulk sediment samples from surface and subsurface bed materials (Church *et al.*, 1987), and conducted pebble counts (Wolman, 1954) in riffles and bars of all study reaches. We sampled four bars and five riffles in the reach downstream of the dam, two bars and two riffles in the reservoir reach, and two bars and two riffles in the upstream control reach. Surface bulk samples were collected to the depth of the intermediate axis of the largest surface particle while subsurface samples were collected to twice the depth of the surface layer.

We characterized aquatic habitat using the Oregon Department of Fish and Wildlife (ODFW) Aquatic

Habitat Inventory methodology (Anlauf and Jones, 2007), which includes visual estimation of substrate composition (McHugh and Budy, 2005; Faustini and Kaufmann, 2007), and characterization of channel unit types as riffles, glides, and pools (Nielson and Johnson, 1983). We established a streamflow-gauging station, which recorded stage data at 15 min intervals, and developed a stage-discharge rating curve based on flow measurements over a range of discharges.

The baseline surveys of channel cross-sections, longitudinal profile, depositional features, ODFW Aquatic Habitat Inventory, and bed material sampling were repeated during the base-flow season one and two years after removal. All results reported herein are based on comparison of one year of preremoval data and two years of postremoval data. Using data collected from the upstream control reach, we implemented a Before-After-Control-Intervention (BACI) experimental design to detect changes to the downstream reaches with respect to channel substrate, area and volume of depositional features, and number and types of channel units. The control reach was selected based upon similarity to the downstream reach in terms of broad geomorphic characteristics (e.g., valley width, slope), yet was far enough upstream of the dam to be morphologically unaffected by the reservoir and dam removal.

Data Analysis

We plotted particle grain-size distributions for bar and riffle sediment samples, and extracted D_{50} (grain size at which 50% of material is finer), and the percentage of material finer than 4 mm. We used published values of measurement error associated with the applicable sediment sampling methodologies to estimate uncertainty of D_{50} and percent fines estimates derived from Wolman pebble counts (Wolman, 1954), and bulk sediment sampling (Ferguson and Paola, 1997; Shirazi *et al.*, 2009). Using visual estimates of benthic substrate composition from ODFW Aquatic Habitat Surveys, we calculated reach-level averages of substrate composition. We applied empirically derived measurement errors published by ODWF (Anlauf and Jones, 2007) to visual substrate estimates as characterizations of uncertainty associated with the visual substrate classification method.

We used Ordinary Kriging to generate bar surfaces based on surveyed bar perimeters and cross-sections. We processed mapped bar areas to correct for fluctuations in discharge between survey years, using the highest water level at the time of surveying (which occurred in 2008) as a constant datum. We then calculated three-dimensional bar area and estimated bar volume by computing the volume of material between the generated bar surface and the temporally constant datum.

We performed repeat surveys of wetted bar perimeters to determine within-year survey error associated with estimated bar areas. We computed uncertainty associated with bar volumes considering two potential error sources: errors in approximating bar surfaces using Ordinary Kriging of surveyed coordinates, and errors in bar volume stemming from the uncertainty of true bar areas. Volumetric uncertainty estimates associated with the Ordinary Kriging method were generated for each bar, and we combined these estimates with volumetric uncertainty arising from calculated ambiguities in bar area to propagate the total measurement error associated with estimated bar volumes.

As variability of many monitored parameters was high and sample sizes were relatively small, use of statistical hypothesis testing to determine significance of changes observed in monitored parameters was not appropriate for this study (Kibler *et al.*, 2010). In order to establish significance of results, we present our results with explicit articulation of parameter uncertainty, including assessment of measurement error and interannual parameter variability documented within the upstream control reach. Within this analysis, change that cannot be attributed to error in parameter estimation and that cannot be explained within the context of variability expected in the absence of disturbance is attributed to disturbance caused by the dam removal and recovery of the channel.

RESULTS

Baseline Assessment and Prediction of Postremoval Effects

Within the reservoir, a seismic refraction survey was used to estimate the depth of accumulated alluvium over bedrock (Northwest Geophysical Associates, Inc., 2006). Integrating cross-sectional surveys with sediment depth derived from the seismic refraction survey, and approximating cross-sections as trapezoids sitting on an average channel slope (Randle and Daraio, 2003), we estimated the volume of sediment stored behind Brownsville Dam to be 11,000 m^3. Bulk samples of sediment stored behind the dam, collected to a depth of 1.8 m, indicated that the stored material was primarily very coarse gravel (D_{50} = 59 ± 1.5 mm).

Baseline surveys indicated that the reach immediately below the Brownsville Dam (0-400 m) was an incised, plane-bed channel, dominated by clay hardpan (31 ± 2% of channel substrate), with few depositional features. Further downstream of the dam, the channel transitioned to a wide and unconfined channel, which we characterized using historical aerial photography as highly dynamic, with frequent shifts in thalweg location and changes in channel width, as well as sizes and positions of depositional features (Walter and Tullos, 2009). We predicted that initial deposition of mobilized reservoir sediments would occur in the incised plane-bed reach immediately downstream of the dam. Because the reservoir had filled with gravel shortly after construction and had passed bed load since that time, we expected that the majority of the initially deposited sediment would eventually transport out of the reach. Within the more dynamic reach downstream, we expected that any effects of the sediment pulse associated with dam removal would be obscured by high natural variability, making the detection of dam removal-induced changes difficult.

To further refine predictions of deposition, we estimated channel competence with distance downstream of the dam, using the following equation after Lorang and Hauer (2003):

$$\tau_0 = \gamma h \sin \vartheta, \qquad (1)$$

where τ_o is the applied shear stress, γ is the specific weight of water, h is the water depth at the 1.2RYI flow (129 m^3/s), and $\sin \vartheta$ is bed slope.

The channel profile displayed a distinct break approximately 400 m downstream of the Brownsville Dam (Figure 2). Above this point, the channel gradient was 0.08%, and calculated shear stress (τ_o = 18-25 N/m^2) was lower than the critical shear stress (τ_c = 32 N/m^2; Chang, 1988) for the dominant reservoir grain size (D_{50} = 59 ± 1.5 mm), making this reach a likely locus of initial deposition. Beyond 400 m downstream, the channel gradient increased to 0.33% (τ_o = 46-126 N/m^2), and we expected this reach to transport the gravel supplied with minimal storage. Thus, we defined a likely depositional reach, DS-A, from 0-400 m downstream of the dam, within which transient storage of reservoir sediments was expected. Beyond this point, we defined the remainder of our downstream monitored reach as DS-B (400-1,600 m downstream of the dam), and predicted

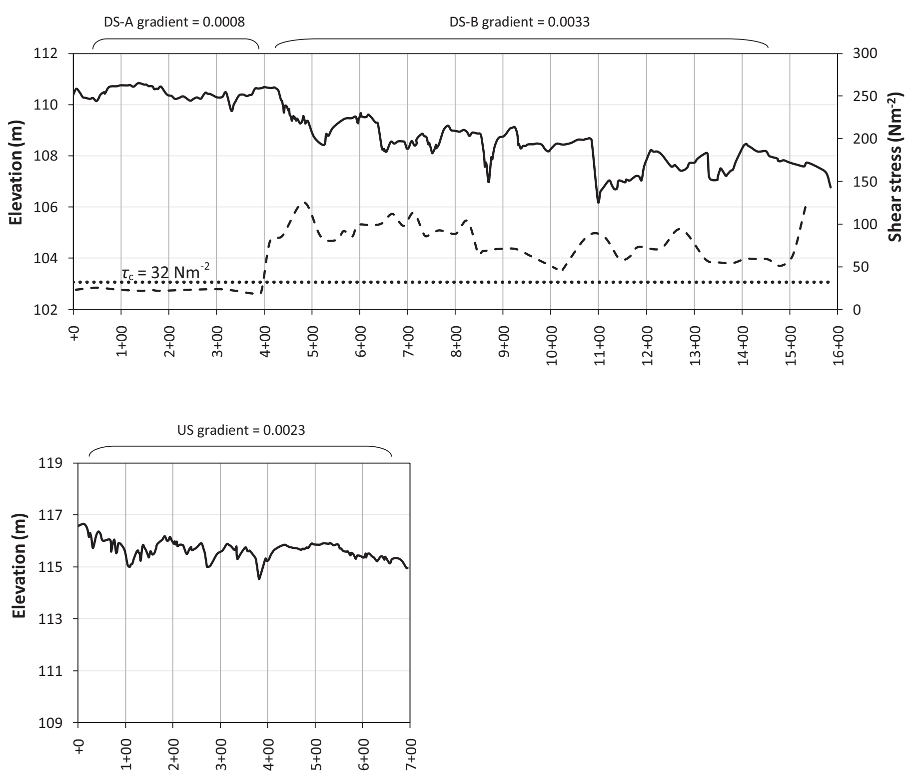

FIGURE 2. Longitudinal Elevation Profiles (solid lines) and Gradients of the DS-A, DS-B, and US Reaches. Shear stress (dashed line) is displayed for a 1.2 return year interval discharge in DS-A and DS-B, relative to the critical shear stress required to transport the median grain size of reservoir sediments (dotted line). Note that shear stress in the DS-A reach is lower than that necessary to transport the median grain size of reservoir sediments.

minimal detection of sediment-related effects in this reach.

Baseline data from surface bulk samples taken from DS-A bed features indicated that surface materials were fine to coarse gravel (bar D_{50} = 6 ± 1.5 mm, riffle D_{50} = 23 ± 1.5 mm), with median grain size smaller than that of the very coarse gravel comprising reservoir sediments. Furthermore, percentages of material finer than 4 mm were greater in DS-A than in reservoir sediment samples. We thus predicted that the very coarse gravel stored in the reservoir would deposit into DS-A, and that the channel bed grain size would initially increase. As this reach of the Calapooia River had limited access to the floodplain and contained no pools, we projected that bar formation along channel margins would be the primary response for storing the released sediment. Considering the relatively small volume of stored reservoir sediments, and that bed load had passed over the dam for many years, we anticipated that, outside of grade recovery at the dam site, changes in downstream substrate condition and gravel storage would primarily be transient effects.

Postremoval Observations

Floods Following Dam Removal. In the year following dam removal, flows during the high-water season did not exceed the 1.2 return year interval flow. However, several hydrologic events exceeded this approximation of the channel-forming discharge in the second year after dam removal (Figure 3).

Median Substrate Grain Sizes. In the year following dam removal, we observed an increase in median grain size (D_{50}) of bars and riffles closest to the dam (Figure 4). The increase of D_{50} in bars displayed a trend that attenuated in the downstream direction, with D_{50} of the bar closest to the dam (DS-A, +150 m) increasing by 600% the year following dam removal, D_{50} of the two most upstream bars of DS-B (+550 m, +780 m) increasing slightly (13 and 15%, respectively), and D_{50} in the bar furthest from the dam (+960 m) decreasing slightly (22%). Likewise, changes to D_{50} of riffles were most pronounced in sites closest to the dam and were absent in far downstream riffles.

Two years following dam removal, D_{50} in bars and riffles downstream of the dam decreased relative to the previous year, with sites closest to the dam returning to conditions similar to preremoval conditions. D_{50} in bars further downstream became slightly smaller than preremoval D_{50}, whereas D_{50} in some riffles were slightly larger than preremoval years. D_{50} in two riffles far downstream of the dam (+850 m and +1,270 m) did not increase the year following removal, but dropped perceptibly two years after removal. Fluctuations in bar and riffle D_{50} in the upstream control reach indicated that the natural variability of D_{50} in bars and riffles is high in water years that experience channel-forming flows, such that, with the possible exception of changes observed in DS-A at site +150 m, changes in D_{50} observed downstream of the dam fall into the range of interannual variability characteristic of this section of the Calapooia River.

Percentages of Fine Materials. Percentages of material finer than 4 mm decreased dramatically in bars and riffles of all reaches, including the upstream control reach, the year following dam removal (Figure 5). Two years after dam removal, fine materials in bars recovered to percentages similar to preremoval conditions, with the exception of the bar closest to the dam, where percentages of fine materials remained much lower than the preremoval condition. Conversely, percentages of fine materials in riffles remained low relative to the preremoval condition, with the exception of the most downstream riffle, where percentages of fine materials increased perceptibly.

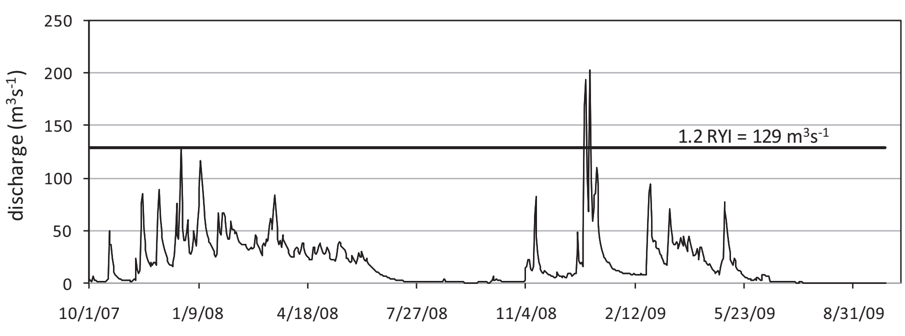

FIGURE 3. Calapooia River Flows. Discharge monitored downstream of the dam, for two years following dam removal, displayed relative to the 1.2 return year interval flow.

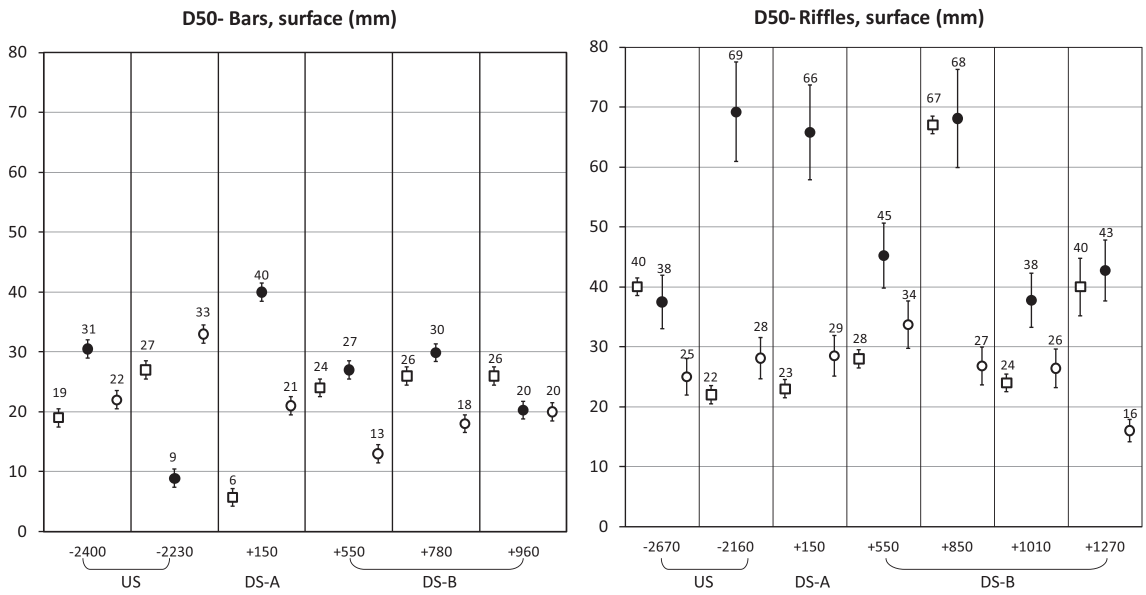

FIGURE 4. D_{50} in Bars and Riffles of the Control Reach (US) and Downstream Reaches (DS-A and DS-B) Before and After Dam Removal. The horizontal axis is position in the watershed relative to the dam. Negative numbers are distances (in meters) upstream of the dam; positive numbers are distances downstream of the dam. White squares are 2007 samples, black circles are 2008 samples, and white circles are 2009 samples. Error bars represent measurement error, calculated according to measurement error estimations given in Wolman, 1954 (pebble counts); Ferguson and Paola, 1997; and Shirazi *et al.*, 2009 (bulk samples).

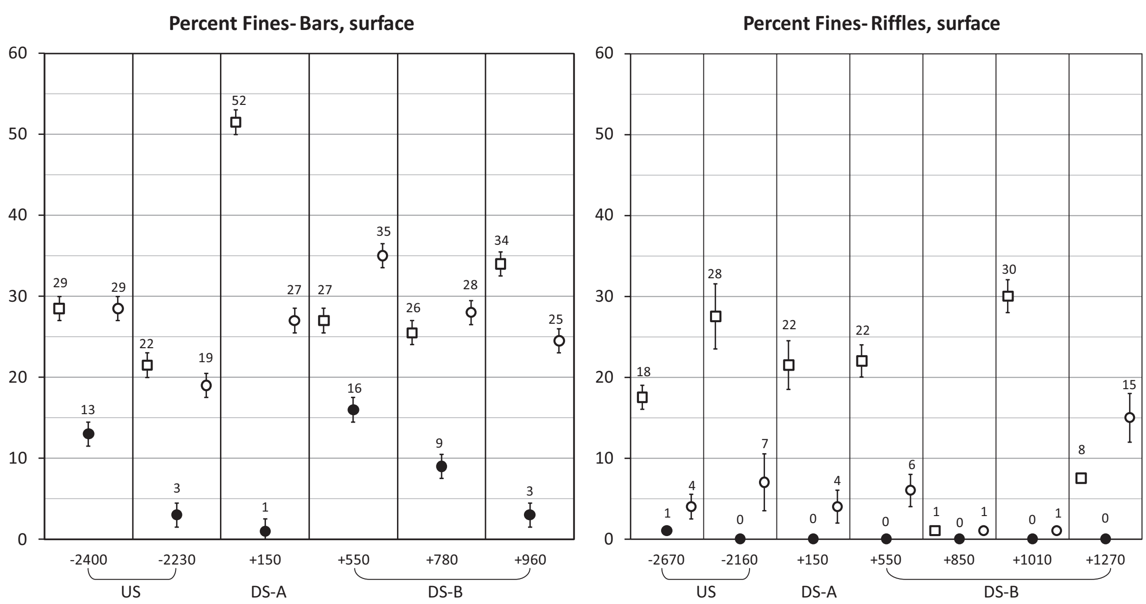

FIGURE 5. Percentage of Material Finer Than 4 mm in Bars (Surface and Subsurface) and Riffles (Surface) of the Control Reach (US) and Downstream Reaches (DS-A and DS-B) Before and After Dam Removal. The horizontal axis is position in the watershed relative to the dam. Negative numbers are distances (in meters) upstream of the dam, positive numbers are distances downstream of the dam. White squares are 2007 samples, black circles are 2008 samples, and white circles are 2009 samples. Error bars represent measurement error, calculated according to measurement error estimations given in Wolman, 1954 (pebble counts); Ferguson and Paola, 1997; and Shirazi *et al.*, 2009 (bulk samples).

Substrate Size Class Composition. Substrates in DS-A transitioned from hardpan-dominated (31 ± 2%) before the dam removal to largely comprised of gravel and cobble (48 ± 15% and 28 ± 8% respectively) the year following removal, with gravels continuing to dominate substrates (70 ± 22%) two years after removal (Figure 6). Comparatively minor changes in substrate composition were observed in

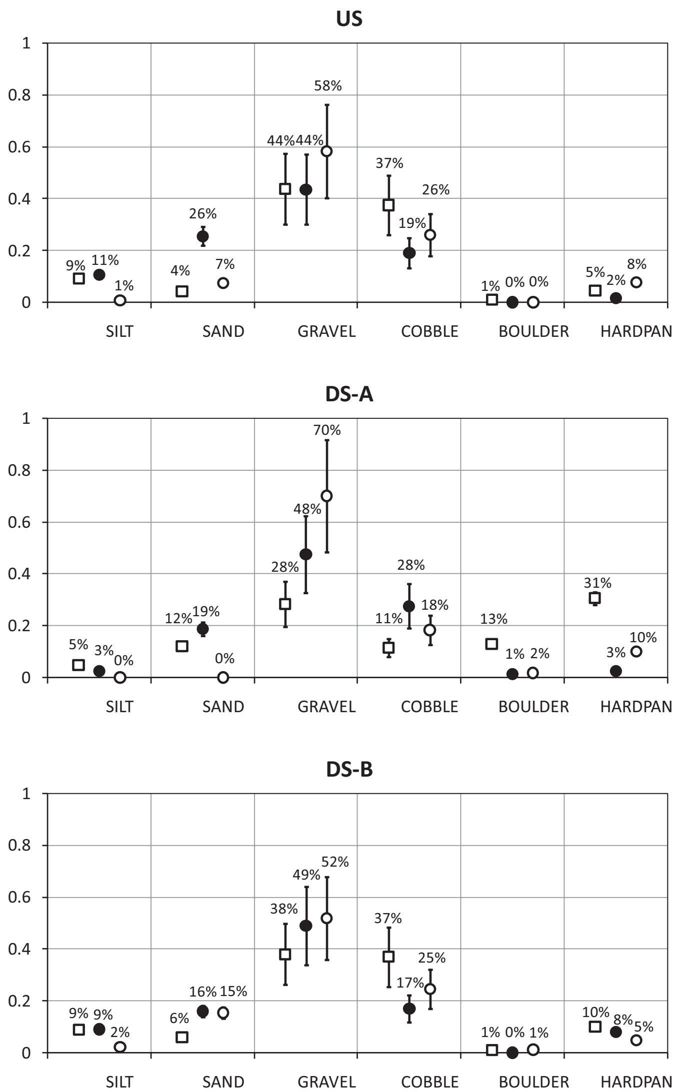

FIGURE 6. Substrate Size Class Composition by Percent in the Control Reach (US) and the Downstream Reaches (DS-A and DS-B), Before and After Dam Removal. White squares are 2007 samples, black circles are 2008 samples, and white circles are 2009 samples. Error bars represent measurement error, calculated according to measurement error estimations given in Anlauf and Jones, 2007.

the DS-B reach, although sand and gravel percentages did increase slightly, associated with an observed loss of cobble and hardpan. The upstream control reach displayed a measureable increase in percentages of sand in the low-water year following dam removal, a trend that was evident in downstream reaches as well. However, percentages of gravels and hardpan were relatively consistent in the upstream control reach throughout the study period.

Bar Area and Volume. Detailed bar surveys taken before and after dam removal reveal a 120 to 700% increase in bar area in DS-A between the time of dam removal and the survey one year after removal (Figure 7). Likewise, bar volume in DS-A increased 6- to 96-fold one year following dam removal. Two years following dam removal, bar areas and volumes in DS-A were similar to the year after dam removal (changes did not exceed measurement error), remaining high relative to the baseline condition. In contrast, we measured a small (1 to 33%) increase in bar area and virtually no change to bar volumes in DS-B the year following dam removal, both within measurement error. Comparative analysis in the upstream control reach indicates negligible change in bar area and volume over the same time period. The change in bar area and volume in DS-A one year after dam removal exceeds parameter uncertainty, and is large relative to changes in the upstream control reach, thus we report an increase to bar area and volume in DS-A one year after dam removal that persisted at least two years after dam removal.

Geomorphic Channel Units. Prior to dam removal, DS-A displayed relatively simple channel morphology when compared with DS-B and the US control reach (Figure 8). Devoid of depositional features and riffle-pool structure, we characterized a majority of the channel (92% of channel length) as glide channel units. One year following dam removal, the number of channel units in DS-A had increased from three to five, representing creation of a new riffle and two pools, where pools comprised 73% of the channel length. Comparatively, in the same time period, the number of channel units in the upstream control reach decreased from 11 to 10 and in DS-B from 15 to 13. Two years after dam removal, the number of channel units in DS-A dropped from five back to three, though the new riffle and pool structure created in the first year after dam removal was partially retained. In DS-B, channel area characterized as glide channel units decreased in the two years following dam removal: two years after dam removal, glide channel units in DS-B had decreased from 43 to 16% of channel length, while percentage of the channel length defined as riffles and pools increased from 20 to 28% and from 32 to 56%, respectively.

DISCUSSION

Interpreting the Significance of Monitoring Results

To support decision making and engineering design with regard to dam removals, there is a need

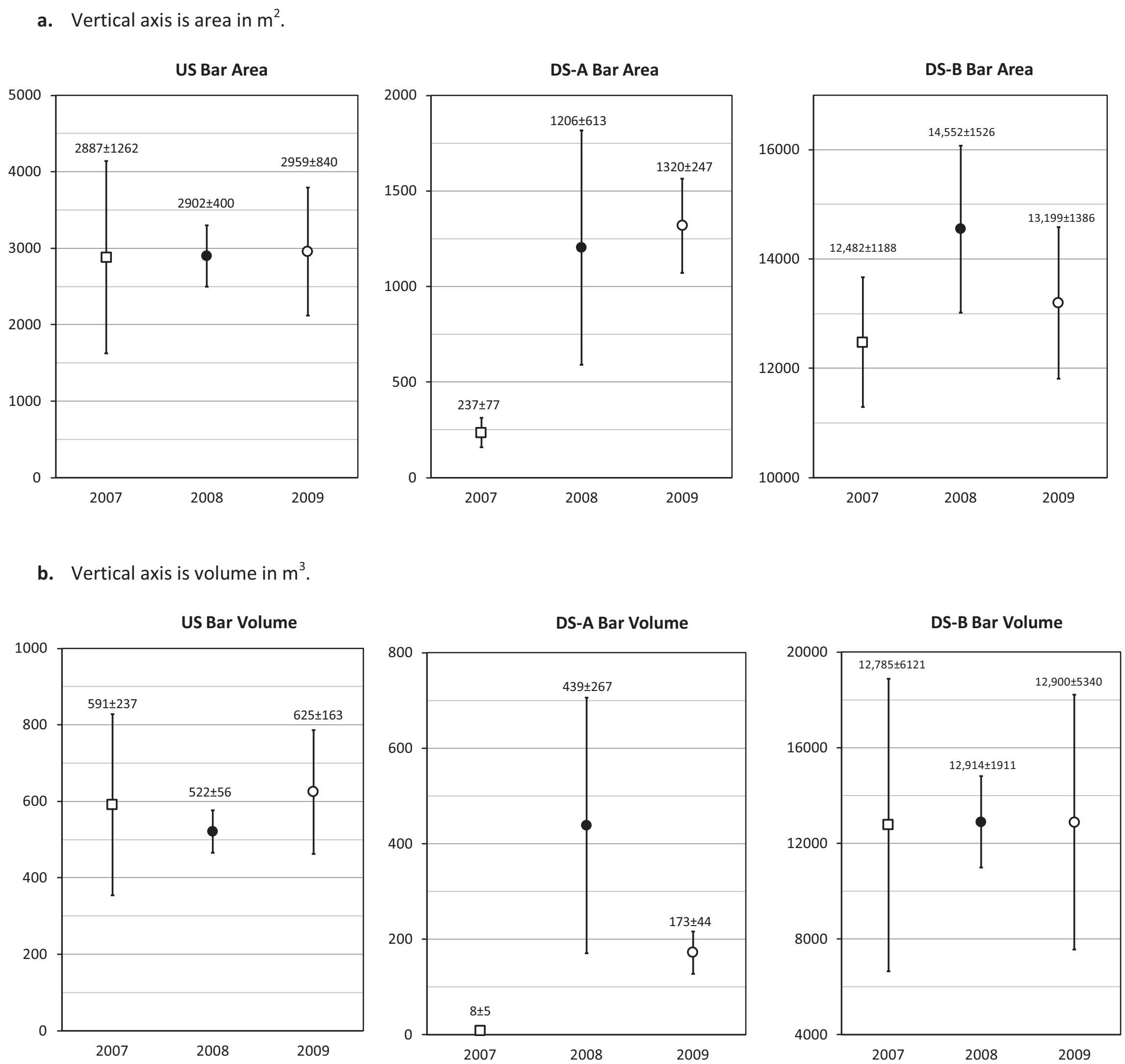

FIGURE 7. Area (a) and Volume (b) of Bar Features in the Control Reach and Downstream Reaches Before and After Dam Removal. Error bars represent measurement error.

to predict dam removal outcomes and the temporal and spatial scales over which effects are likely to occur. Acquiring information needed to inform such predictions requires monitoring of ongoing dam removals using rigorous study designs, which occurs infrequently due to factors such as unpredictable timelines for removal, lack of funding for monitoring, and insufficient baseline data. Additionally, dam removals, by their very nature, defy some assumptions of robust study designs and challenge traditional methods of evaluating the significance of results (Kibler *et al.*, 2010). For instance, BACI experimental designs implemented on longitudinal river systems violate the assumption that experimental sites are independent of control sites (Hurlbert, 1984; Norris and Hawkins, 2000). However, in addition to the difficulty of finding an appropriate control site outside of the river basin in question, choosing a reach from another basin may introduce parameter variability, a potential impediment to detecting small to moderate changes.

Due to the small sample sizes of our monitored parameters, the likelihood of generating Type II errors in statistical hypothesis testing is high. Therefore, we do not consider statistical hypothesis testing to be appropriate for determining significance of changes observed downstream of the Brownsville Dam removal. Rather, we choose to establish significance of results using a standard of practical significance based upon change exceeding parameter uncertainty, which we characterize as a combination of measurement error and background variability documented within the control reach. We then use these evaluations of preremoval versus postremoval differences to make inferences regarding the processes driving changes in the channel.

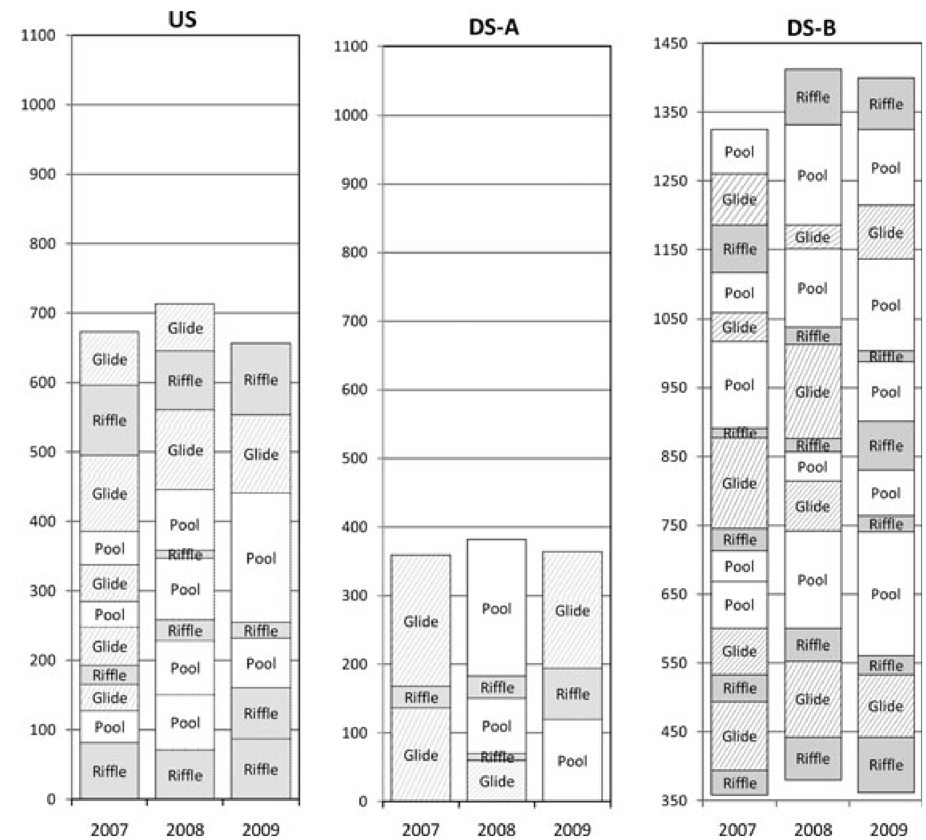

FIGURE 8. Channel Units in the Control Reach (US) and Downstream Reaches (DS-A and DS-B) Before and After Dam Removal. Vertical axis is distance moving downstream, in meters.

One year after dam removal, we observed that median grain sizes (D_{50}) of bars and riffles in the reach directly below the dam (DS-A) had increased, and noted that the signal diminished with distance downstream. However, as D_{50} was relatively variable in the control reach as well, it is difficult to attribute high significance to the changes observed downstream of the dam removal. We conclude that, although the point sediment samples provide suggestive evidence for a shift in grain size directly below the dam, the changes that we observed further downstream are within the realm of interannual variability one may expect to see in this section of the Calapooia River. Although interannual variability of grain sizes is stronger than the signal of grain-size increase that we observed following dam removal, there is no evidence that median grain sizes of bars and riffles downstream of the dam decreased following dam removal, as has been observed in dam removals releasing fine sediment.

Likewise, our evidence does not suggest that removal of the Brownsville Dam caused percentages of fine materials to increase in downstream reaches. One year after dam removal, we observed a substantial drop in percentages of fine sediment in bed materials below the dam and in the upstream control reach. Because the upstream control reach behaved comparably to the reach below the dam, the changes in the downstream reach cannot be attributed to local effects of the dam removal. More likely, some change in fine sediment supply from the catchment or sequencing of sediment delivery and clear-water flows in the low water year following removal influenced both sites in a similar way. Nonetheless, it is evident that the dam removal did not contribute to a detectable increase in percentages of fine sediment.

According to visual substrate classifications, DS-A was dominated by clay hardpan prior to dam removal, whereas only 3% of the channel was composed of hardpan after removal. Given the corresponding increases in gravel and cobble substrates and based on field observations, coarse sediment that evacuated from the reservoir appears to have deposited above the hardpan in DS-A following dam removal. Visual documentation of substrate size classes is a method that encompasses much uncertainty, as empirical evidence from Oregon streams suggests, particularly with regard to discerning percentages of gravel and cobble (Anlauf and Jones, 2007). We present strong observational evidence that one year after dam removal percentages of hardpan and boulders decreased in DS-A, and that percentages of cobble and gravel increased. However, although percentages of gravel substrate increased by 250% in the two years following dam removal, the changes do not exceed potential errors in characterizing this parameter, and therefore lessen our certainty in concluding that the changes observed are beyond measurement error. We also note an increase in percentages of sand in both DS-A and DS-B, though given the simultaneous increase in sand in the control reach, it is difficult to attribute this increase to the dam removal.

The shift in substrate texture from hardpan to gravel and cobble immediately downstream of the dam was documented by visual estimation, yet not explicitly detected by bulk sampling and pebble counts, methods that preferentially sample nonaggregated materials. As reaches directly downstream of dams may often scour to resistant layers comprised of boulders, hardpan, or bedrock (Williams and Wolman, 1984), dam removal monitoring should include methods that allow estimation of bedrock or hardpan in analyses of substrate change below dams. The facies map (Wolman and Schick, 1967; Kondolf *et al.*, 2003) is such an approach, in that the patterns of surficial sediment deposits, exposed bedrock, and other features are mapped to scale, such that significant changes in distribution of such features may be detected in repeat mapping.

Strong evidence of an increase in area and volume of depositional features downstream of the dam, combined with observations of changing bed-form morphology, lead to the conclusion that aquatic habitats became more complex in DS-A following dam removal. As habitat unit classification tends to be somewhat subjective, it is possible that year-to-year variability between field crews may be partially responsible for some of the changes observed. ODFW reports that identification of channel units using this methodology is characterized by a moderate degree of measurement uncertainty, with an error of approximately 30% (Anlauf and Jones, 2007). Considering the subjectivity associated with this parameter, it is difficult to interpret quantitative estimates of change (Poole *et al.*, 1997). Acknowledging that these data should be interpreted semiqualitatively, we suggest, based on the observed transition from a plane-bed channel with few depositional features to more complex structure including riffles, pools, and multiple bars, that channel morphology in the reach directly below the dam became more heterogeneous following removal.

As preferred gravel grain sizes for some local organisms, such as steelhead trout and Chinook salmon, have been reported, we also may comment on the ecological significance of some of the changes observed. According to a meta-analysis of salmonid spawning gravel preferences undertaken by Kondolf and Wolman (1993), steelhead prefer to spawn in gravels with D_{50} ranging from 31 to 46 mm, whereas Chinook prefer gravels with D_{50} between 16 and 54 mm. The D_{50} in the riffle immediately downstream of the dam increased to a size that is greater than that preferred by Chinook and steelhead, though only for one year. Given that median grain sizes of all other bars and riffles remained within the preferred size range and that we did not detect increases in percentages of fine materials after the dam removal, we conclude that, at least with regard to grain sizes of spawning gravels, the Brownsville Dam removal did not impair the quality of spawning gravel habitats. Further, the documented shift from hardpan to gravel and cobble substrates, indicating creation of new potential spawning habitats, may also constitute an ecologically significant benefit to quantity of habitat in the reach downstream of the dam. Although water temperature was not monitored throughout the dam removal study, we speculate that removal of the shallow impoundment, replacement of hardpan substrate with gravel and cobble, and creation of pools indicate that the dam removal may have fashioned a more favorable thermal environment for cold-water salmonids when compared with preremoval conditions, through facilitation of thermal exchange between surface water and substrates, particularly around the newly deposited bars (Burkholder *et al.*, 2008) and creation of thermal refugia (Ebersole *et al.*, 2003).

Revising Conceptual Models of Channel Change Downstream of Small, Gravel-Filled Dam Removals

Conventional perceptions of geomorphic change downstream of dam removals often forecast smothering of the channel bed by a large volume of fine sediments released from the reservoir, leading to dramatic fining of substrate texture and homogenization of habitat structures and bed forms that will persist for years after the dam is removed. The prevalence of these perceptions is based on documentation of such outcomes after the removal of many dams that contained a large volume of fine sediments, whereas observation of alternative scenarios has been less common. However, development of numerical models for predicting the erosion and deposition of sediment released with dam removal (Cui *et al.*, 2006a,b; Wong *et al.*, 2004) and introduction of new dam removal case studies reporting alternative scenarios (Stewart, 2005; Downs *et al.*, 2009;

this study), are beginning to expand the breadth of outcomes observed and expected after dam removal.

Refining the conceptual models that facilitate prediction of dam removal outcomes is a process that is likely to direct dam removal management toward enhanced decision making with regard to whether and how to remove a dam. Often, particularly in reference to small dam removals, limited funding is available for detailed study or modeling aimed at predicting potential outcomes, and decisions thus may be made with relatively sparse information. For this reason, the availability of well-developed conceptual models informed by past observation can be invaluable to the decision-making process. To that end, oversimplified ideas of one-size-fits-all dam removal effects have the potential to dominate stakeholder perceptions, and fears of detrimental effects may influence decision making, even when such concerns are unfounded. As an example, during discourse leading up to the decision to remove Brownsville Dam, stakeholders voiced anxiety that downstream aquatic habitats might be negatively impacted by dam removal as a consideration to not remove the dam (Elston, 2009), perhaps due in part to the prevailing conception that dam removals result in persistent simplification of downstream habitats. However, given that Brownsville Dam was a low structure that stored a small volume of coarse sediment relative to flow competence, these conventional perceptions surrounding dam removal did not create realistic expectations for outcomes of this particular removal. A thorough preremoval baseline assessment predicted an alternative outcome of limited and transient impacts to downstream habitats, which was confirmed by three years of monitoring. This pattern of spatially limited and transient responses, described in detail below, may apply to other small dam removals in gravel-bed rivers with limited fines, and can be verified for individual sites through baseline assessments and basic hydraulic calculations. Such analyses may serve to inform stakeholder expectations, or as a screening tool for distinguishing low- from high-risk projects. For the case of small dam removal in which the reservoir is filled with gravel, we suggest that the following pattern of responses (Figure 9), based on evidence from the sparse number of documented small dam removals from gravel-bed rivers and from channel effects observed following sediment pulses introduced to gravel-bed rivers, may be expected after removal.

At the Time of Removal. The reach below a dam may be armored or simplified, particularly if the reservoir actively trapped sediment until the removal, but also due to scour from an artificially steep gradient at the dam site. In the case of full reservoirs that had passed bed load prior to dam removal, sediment starvation may not be evident in the reaches below the dam, though scour may still be observed near the dam. Reservoir sediments may begin to transport into the reach below the dam during base flows and reservoir dewatering, however, in the case of dams that store coarse sediments, the first flows competent to transport the dominant reservoir grain size may not occur immediately. In this case, depending on the timing of dam removal relative to the high-flow season, a temporal lag between dam removal and movement of reservoir sediments may occur. For instance, though the structure of Marmot Dam was removed from the Sandy River in Oregon in July, during base-flow season, breaching of the cofferdam and substantial evacuation of reservoir sediments did not occur until the first storm of the year on October 19 (Grant *et al.*, 2008).

Initial Sediment Transport. As reservoir sediments move into the downstream channel, substrates shift toward the distribution of grain sizes found in the reservoir. Other immediate channel responses typically include a decrease in depth and reduction in variability of bed topography, effects that diminish with time and the number of channel-forming flows since the introduction of the sediment pulse (Madej, 2001). Reservoir sediments initially deposit into pools (if any exist) or form and expand depositional features along channel margins. The volume and texture of stored sediments relative to the river's sediment transport capacity will dictate the rate and patterns of substrate and channel form changes and provide a control to the magnitude of immediate change to be expected following dam removal. For instance, as small reservoirs store comparatively small volumes of sediment (e.g., the Brownville Dam stored approximately 1.5 years of sediment), the magnitude of changes observed even immediately following removal may be subdued when compared with immediate observations following removal of larger dams that stored decades of sediment.

Locations and Timing of Sediment Deposition. Approximate locations, magnitudes, and timing of sediment deposition in downstream reaches may be loosely predicted by theories of sediment pulse movement and comparative grain sizes of reservoir sediments and existing downstream substrates. Results from flume experiments undertaken by Lisle *et al.* (2001) and Downs *et al.* (2009) suggest that sediment pulses comprised of coarse material evolve primarily by dispersion, decaying in place, rather than translating downstream. Thus, in the case of small reservoirs filled with noncohesive material that is

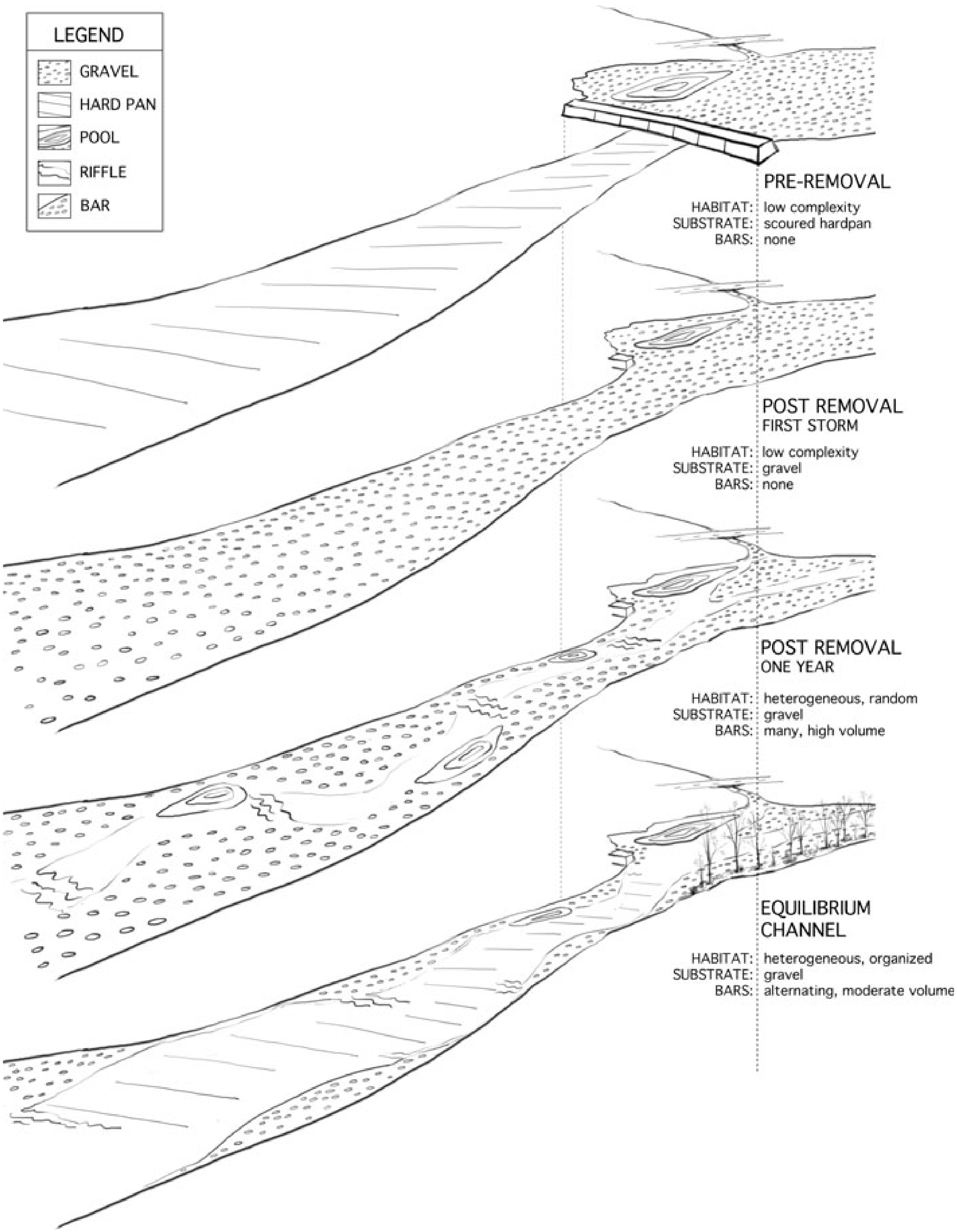

FIGURE 9. Stages of Channel Change Downstream of a Small, Gravel-Filled Dam Removal. Illustrating benchmark stages in channel evolution following removal of the Brownsville Dam. The equilibrium channel was not observed in this study, but is a prediction of conditions likely to be observed many years after removal.

coarser than downstream sediments, detectable downstream responses to dam removal will likely be localized to the reach directly downstream of the dam, and will be detectable shortly after dam removal, with the magnitude of detectable effects diminishing through time and with distance downstream. As the sediment pulse decays, the wavelength (spatial extent of effect) increases whereas amplitude (magnitude of effect) decreases, such that impacts beyond the reach immediately downstream of the dam are likely to be negligible, particularly if the dam had passed bed load before removal. A pulse of sediment may progress as described above, moving as a detectable wave with a well-defined amplitude and wavelength. However, it is more frequently the case that the movement of well-defined wave is not evident, and thus the evolution of a pulse of sediment instead may be evaluated through changes in bed forms and channel organization (Pitlick, 1993; Madej, 2001).

Establishment of Channel Complexity. Complexity of physical habitats may develop soon after a small release of coarse sediment (Madej, 2001; Stewart, 2005; Downs *et al.*, 2009; this study). A moderate to high amount of available sediment relative to transport capacity creates opportunity for differential rates of deposition and scour through space and time, potentially increasing heterogeneity of hydraulic habitats on the subreach and reach scale (Yarnell *et al.*, 2006). As subsequent flows rework initially deposited sediments and the sediment pulse passes through the reach, sediments deposited into pools are scoured and bars, floodplains, and channel margins become enduring locations of depositional storage (Downs *et al.*, 2009; this study). For example, patterns of flow convergence and divergence within the Calapooia River sculpted sediments deposited after removal of the Brownsville Dam into alternating bars and pools. As bed forms and depositional features develop, differential sorting also creates heterogeneity with respect to patches of different substrate grain sizes, as fines are winnowed from riffles and deposited into pools, bars, and downstream of large wood or boulders.

Establishment of Channel Organization. Outcomes from the Brownsville Dam removal indicate that complexity of habitats immediately below a small dam removal may recover relatively quickly, in this case, within one year. However, long-term analysis of sediment pulses indicates that although heterogeneous random bed forms may develop soon after introduction of the sediment pulse, more time is required before the channel organizes into regularly spaced bed forms (Madej, 2001). Again, timing of sediment evacuation from the reservoir reach and reorganization of released sediments into regularly spaced alluvial channel structures is largely controlled by flow competence, as well as valley and channel-forcing features. In the case of reservoirs that store extremely coarse fractions that are infrequently mobilized or when dam removal occurs before a series of low water years, a lag in release of reservoir sediments and the recovery of channel organization may occur.

In summary, the consequences of a small release of gravel from a full reservoir following small dam removal may diverge from past observations of relatively large releases of fine sediments that have caused persistent downstream substrate fining and habitat degradation. As such, conceptual models based on evidence from releases of coarse sediments may provide more accurate predictions of potential downstream effects of sediment release following removal of small dams from gravel-bed rivers.

CONCLUSIONS

Outcomes observed following removal of the Brownsville Dam provide valuable confirmation of the range of possible geomorphic responses to dam removal, and support the need for sufficient baseline data in future work. In the case of this small dam with a gravel-filled reservoir, significant changes to downstream channel morphology were difficult to detect due to the small magnitudes of change relative to measurement error and background variability. However, we present strong evidence that removal of Brownsville Dam did not have a negative impact on downstream aquatic habitats. Rather, within 400 m of the dam, we observed a coarsening of substrate grain sizes in bars and riffles, a shift in substrate type from hardpan to gravel and cobble, an increase in area and volume of bars, and creation of riffles and pools that replaced a simplified plane-bed channel. Amalgamation of detected outcomes leads us to conclude that the gravel released from the Brownsville Dam reservoir increased habitat heterogeneity close to the dam and had little detectable effect to channel morphology further downstream. Because the relatively minute, localized, and ecologically beneficial changes that we observed are not well described by some conceptual perceptions of dam removal outcomes, the Brownsville Dam removal offers a case study for verifying an alternate conceptual model for downstream channel response to the removal of small, gravel-filled dams. Through continual verification and revision of established conceptual models as new information becomes available, dam removal monitoring has the potential to inform and influence decision making with regard to future restoration.

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