Effects of sediment pulses on bed relief in bar-pool channels

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ABSTRACT: To further develop prediction of the range of morphological adjustments associated with sediment pulses in bar-pool channels, we analyze channel bed topographic data collected prior to and following the removal of two dams in Oregon: Marmot Dam on the Sandy River and Brownsville Dam on the Calapooia River. We hypothesize that, in gravel-bed, bar-pool channels, the response of bed relief to sand and gravel sediment pulses is a function of initial relief and pulse magnitude. Modest increases in sediment supply to initially low-relief, sediment-poor cross-sections will increase bed relief and variance of bed relief via bar deposition. Modest increases in sediment supply to initially high-relief cross-sections, characteristic of alternate bar morphology, will result in decreased bed relief and variance of relief via deposition in bar-adjacent pools. These hypothesized adjustments are measured in terms of bed relief, which we define as the difference in elevation between the pool-bottom and bar-top. We evaluate how relief varies with sediment thickness, where both relief and mean sediment thickness at a cross-section are normalized by the 90th percentile of observed relief values within a reach prior to a sediment pulse. Field measurements generally supported the stated hypotheses, demonstrating how introduction of a sediment pulse to low-relief reaches can increase mean and variance of relief, while introduction to high-relief reaches can decrease the mean and variance of bed relief, at least temporarily. In general, at both sites, the degree of impact increased with the thickness of sediment delivered to the cross-section. Results thus suggest that the analysis is a useful step for understanding the morphological effects of sediment pulses introduced to gravel-bed, bar-pool channels. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: sediment pulses; dam removal; bed relief; bar-pool channels

Introduction

While gravel supply is necessary for the formation of riffles and pools that form aquatic habitats (Lisle, 1982; Mossop and Bradford, 2006), episodes of atypically large sediment supply (i.e. sediment pulses [Lisle, 2008]) can produce morphological responses that may negatively impact habitat (Pizzuto, 2002) and increase flood risks (Downs et al., 2009). Whether from natural sources, such as landslides (Sutherland et al., 2002), or anthropogenic sources, such as dam removal (Shuman, 1995; Snyder et al., 2004), sediment pulses can be of concern for water resource managers (Shuman, 1995; Downs et al., 2009) through their potential for filling of pools, homogenization of habitats, forcing increases in width, or transitioning channels from single-thread to braided channels.

Past studies have found various and sometimes contradictory morphological responses to transient increases in sediment supply associated with sediment pulses. Some field and experimental data suggest that sediment pulses generally lead to reduction of bed topography, whether through pool filling (Lisle, 1982; Madej, 1999, 2001) or development of braiding conditions (Nicholas et al., 1995; Hoffman and Gabet, 2007). The post-pulse reduction of bed topography is supported by theory (Madej, 2001) that establishes a possible response trajectory, which includes the burial or diminishment of channel structure and the subsequent channel reorganization and recovery of bed topography. However, other field and experimental data (Sutherland et al., 2002; Downs et al., 2009; Kibler et al., 2011; Gaeuman, 2013) report increases in the range of channel morphologies, which include pools and bars of varying size and shape, in a reach. The increases result from a combination of scouring and filling pools and bar building. It is not yet clear which of these relief trajectories a channel may take in response to the introduction of a sediment pulse.

However, it appears that the initial relief, defined herein as the elevation difference between the deepest part of a cross-section and the highest feature (e.g. top of sediment bar), of a bar-pool channel may be an important control on its response to a sediment pulse. Several examples suggest that initially high relief may decrease in response to a sediment pulse. For example, a field-scale flume experiment (Podolak and Wilcock, 2013) showed that the introduction of a sediment pulse to a stable set of alternate bars (i.e. high initial relief) in a gravel-bed channel resulted in smaller, mobile, low-relief bars either superimposing on or replacing the initial alternate bar structure.
Similarly, flume experiments by Madej et al. (2009) demonstrated how the introduction of a moderate-sediment pulse to an alternate bar sequence (i.e. high initial relief) resulted in a decrease in the cross-channel relief as pools were filled and the introduction of an even larger sediment pulse resulted in a decrease in relief via the formation of low-relief, mid-channel bars. In both experiments, the relief in the pools recovered to the pre-pulse values with the subsequent passing of the sediment pulse (Madej et al., 2009). Following the release of a sediment pulse from a dam, Wohl and Cenderelli (2000) measured a decrease in the initially high alternate bar relief as the pools filled and a subsequent recovery of relief as the pools were later scoured out. Lisle (1982) also observed decreases in initially high relief to ‘riffle-like’ low relief due to the preferential pool filling during sedimentation associated with a large flood in California.

In contrast to the responses of high-relief initial conditions, low initial relief may increase with the introduction of a sediment pulse. For instance, Ikeda (1983) noted how the introduction of sand-gravel supply to a plane-bed flume (i.e. near zero initial relief) resulted in the development of small, mobile, low-relief bedforms that grew over time into a stable set of higher-relief alternate bars. Similar patterns of formation and evolution of high relief alternate bars following introduction of a sediment mixture to a steep plane-bed flume have been reported elsewhere (Lisle et al., 1991; Lanzoni, 2000b). Furthermore, Gaeruman (2013) chronicled the development of a high-relief alternate bar sequence following the injection of a slug of gravel into a low-relief bar-pool reach.

In this study, we evaluate whether initial relief conditions can be used to predict the response of a bar-pool channel to the release of a pulse of sediment. To evaluate the proposed hypotheses (see later) for channel response, we compare the theorized and observed changes in bed relief as width-averaged sediment thickness varied following the release of sediment pulses with the removal of Marmot and Brownsville Dams on gravel-bed, bar-pool channels in Oregon.

**Conceptual Development**

**Analytical methods**

In order to represent changes in pool depths and bar heights in response to deposition or erosion, we operationally define cross-channel bed relief (r) as the elevation difference between the deepest part of a cross-section and the highest feature (e.g. top of a sediment bar) (Figure 1). Hereafter referred to as ‘relief,’ this difference is calculated within the central 70% (b) of the entire bankfull width (B). Fifteen percent of each cross-section’s width is removed from each boundary (Figure 1) in order to capture maximum bed elevations associated with in-channel bed sediment and exclude elevations associated with channel banks. These exclusions do not apply to the minimum bed elevations, because banks often abut thalwegs, particularly at steep outer banks of channel bends. Excluding the outermost 30% of the bankfull channel width will underestimate relief in situations where a sediment bar top connects smoothly with the top of a channel bank and may cause a bank bias towards higher relief in channels where parts of banks are included in b. As defined, relief is independent of stage, and changes in relief are dependent on evolving distributions of sediment depths in a cross-section.

We calculate mean sediment thickness at a cross-section (z) as 
\[ z = \frac{A}{B} \]
where A is the sum of the trapezoidally-integrated areas across the bankfull channel width (B) for each survey year (Figure 1). Bankfull width is determined from topographic indicators (e.g. ledges) in the pre-removal cross-section data (Dunne and Leopold, 1978), and the same width is used for each survey year for a given cross-section. For this study, where depth to bedrock is not known for most cross-sections, the minimum thalweg elevation of all survey years for each cross-section is used as the vertical datum. We do not distinguish in the analysis between types of bank and bed materials and refer to everything above the vertical datum as ‘sediment.’ Therefore, we also do not distinguish between sediment derived from the banks or pre-removal bed and sediment derived from upstream of the dams.

For each study site, we normalize z and r by the 90th percentile of the observed relief (R), measured in the respective study reaches prior to each dam removal, to form the non-dimensional variables: \[ z^* = \frac{z}{R} \] \[ r^* = \frac{r}{R} \]
The values of \( R = 1.2 \text{ m} \) and 4.9 m are calculated from the pre-removal surveys for Brownsville and Marmot, respectively. The 90th percentile is chosen to scale values by dimensions of larger bars that a channel is typically capable of forming, while avoiding bias by atypically large peak relief values, such as at a cross-section with considerable bank bias in the calculation of r. We somewhat arbitrarily use the terms ‘high’ (\( r^* > 0.5 \)) and ‘low’ (\( r^* < 0.5 \)) to describe relief in a reach relative to other values in that reach. For each field site, \( z^* \) and \( r^* \) are calculated for each surveyed cross-section from each survey period. In addition, the mean, standard deviation, and 95% confidence limits of each are calculated for each reach for each survey year (Tables I–III). The confidence limits are calculated using bootstrapping, whereby the populations of mean and standard deviation values are resampled (n = 1000) at random to establish the 95% limits of the resampled mean and standard deviation distributions. For each cross-section, the pre-removal \( z^* \) values are subtracted from the post-removal values at successive times to yield \( \Delta z^* \) values for each post-removal survey year.

**Hypothesis development**

When composed of coarse material (Lisle et al., 1997; Cui et al., 2003; Greimann et al., 2006) and introduced to gravel bed channels (Lisle et al., 2001; Lisle, 2008), sediment pulses are typically modeled and observed in the field as a one-dimensional stationary (i.e. not translating) dispersive wave (but see Sklar et al., 2009). This view has been incorporated into models of sediment pulse dynamics (e.g. Nicholas et al., 1995) and provides a reasonable description of the spatial and temporal trends that drive the changes in sediment thickness and relief posited by our hypothesis. If the maximum
thicknes of a wave is assumed to be located at a former dam or landslide deposition site, and the pulse evolves by spreading downstream, the sediment thickness at any location downstream increases with the arrival of the wave’s leading edge and subsequently declines as the pulse spreads out. A dispersion-dominated pulse is characterized by decreasing sediment thickness downstream of its initial location at the dam and zero effect downstream of the pulse toe at a given time (Lisle, 2008). Our hypotheses extend this previous work on sediment dispersion by proposing how spreading sediment will distribute across the width of channels as a function of initial sediment thickness, reaches with small pre-pulse thickness downstream of a cross-section depends on the initial bed relief and thickness of sediment delivered to a location.

We hypothesize that the change in relief due to the changes in sediment thickness at a cross-section depends on the initial value of \( r^* \). More specifically, we hypothesize that, in response to increases in sediment thickness, reaches with small pre-pulse relief will respond by filling pools and reducing bed relief. Both scenarios may impact the variance in relief among the cross-sections of a reach. Increases in variance are projected for reaches with low pre-pulse relief, and decreases in variance are projected for reaches with high pre-pulse relief.

The response of a cross-section with minimal pre-pulse relief, low \( r^* \), to increasing sediment thickness depends on the nature of the reach. In alternate bar reaches, which are characterized by low \( r^* \) cross-sections at riffles and cross-overs between alternate bars but high variance in relief at the reach scale, we hypothesize that low relief will remain low in response to increasing sediment thickness. The aggradation in this low \( r^* \) case would be due to uniform deposition across the width of their characteristically planar form, and/or on the lateral margins in small amounts (Wohl and Cenderelli, 2000). In contrast, in plane-bed reaches that lack bars, pools, and riffles and are characterized by low \( r^* \) at cross-sections and low variance in relief at reach scale, we predict the introduction of a sediment
pulse to build bars and associated riffles and to increase the mean and variance of relief along the reach. The magnitude of the increase in relief will vary with the sediment thickness delivered to the cross-section, generally as a function of the distance from the dam and the morphology of the reach.

In a plane-bed channel, relief may be built, first, by the development of low-relief, mobile mid-channel bars upon introduction of a sediment pulse, and, second, by subsequent channel reorganization to form higher-relief, stable alternate bars (Ikeda, 1983). This transition from plane-bed to mid-channel bars to alternating bars has been extensively studied (see Venditti et al., 2012) for a summary of previous work and may be explained with instability theory (Lanzoni, 2000a, and references cited therein). This relief-building trajectory is likely influenced by many geomorphic processes, including selective transport and sorting of varying grain sizes (Lanzoni, 2000b), secondary flow (Nelson, 1990), bed reorganization during flood events (Rodrigues et al., 2012), and variations in sediment supply (Church, 2006; Venditti et al., 2012). In short, the relief-building sequence appears to follow some variation on the following trajectory: migrating bars with short wavelengths develop, then elongate, then stabilize at some longer wavelength into alternate bars (Ikeda, 1983; Nelson, 1990).

Alternatively, if a reach has an initially high relief due to existing alternate bars prior to the arrival of a sediment pulse, even small increases in the sediment thickness generated from a sediment pulse may decrease the relief mean and variance by filling bar-adjacent pools. From a process-based perspective, this pool filling may be associated with greater bed mobility, even at relatively low flows (Lisle, 1982; Lisle and Church, 2002), as a result of decreased bed armoring and sediment caliber accompanying greater sediment supply (Buffington et al., 2002). The presence and geometry of a pool are reliant on the dynamic balance between local hydraulic scour and the incoming sediment load. An increase in the sediment load, such as by the release of a sediment pulse, would tend to disrupt this balance, resulting in new pool geometries, likely with smaller volumes (Buffington et al., 2002). The subsequent evacuation of sediment from a reach as the pulse disperses could again increase the mean and variance of relief as the previously-aggraded pools are scoured (Wohl and Cenderelli, 2000; Madej et al., 2009). In response to sufficiently large increases in sediment thickness, such as those large enough to completely fill existing pools and even aggrade the bed over the entire bankfull channel width (Madej et al., 2009), a similar sequence of building bar relief on a plane-bed channel (Ikeda, 1983) may occur. For example, the flume experiments by Pryor et al. (2011) and Madej et al. (2009) both documented the formation of a multi-thread channel with low-relief, mid-channel bars in response to an increase in sediment supply. Both studies noted the subsequent development of a high relief alternate bar sequence if the channel was given time to equilibrate or degradation occurred following the reduction in supply.

Field Study of Oregon Dam Removals

The data collected before and after the removal of the Brownsville Dam on the Calapooia River and the Marmot Dam on the Sandy River provide the opportunity to investigate the relationship between bed relief and sediment thickness changes associated with a sediment pulse. Both rivers, located in western Oregon, are predominantly gravel-bed, single-thread channels with alternate bar morphologies. Both run-of-river dams formed reservoirs that provided head for flow through diversions. Impounded sediment filled both reservoirs to meet the tops of both dams, so that they allowed passage of bedload sediment for most of the time since construction. Relative to both the Brownsville Dam, Marmot Dam was taller and impounded 50× the sediment volume, which took 10 to 20× longer to accumulate. For both sites, we refer to the ‘water year’ (WY) as the time period from October 01 of one year to September 30 of the next year, with the labeled year (e.g. 2008 WY) being the latter year that marks the end of the water year (e.g. September 2008) rather than the year in which it begins (e.g. October 2007). For the sake of brevity, ‘water year’ is implied after all numerical years referred to hereafter.

Brownsville Dam on the Calapooia River, Oregon

The Brownsville Dam, near the town of Brownsville, Oregon, impounded the Calapooia River within its existing banks for diversion of flow to a canal (Figure 2). This small dam (1.8 m height × 33.5 m width × 4 m breadth) impounded approximately 14 000 m$^3$ of sediment with a median grain diameter in the gravel size range ($D_{50} = 0.059$ m), based on excavator-extracted bulk samples. According to local lore, the impounded sediment surface was flush with the top of the dam after two years. The dam was removed with an excavator and without dredging in August 2007. Dam removal and sediment evacuation revealed an older, smaller log-crib dam (1 m height × 10 m width) at the same location, and this dam was left in place.

Pre- and post-removal data were collected over a reach of 1.8 km in length (0.4 upstream and 1.4 downstream of the dam); based on the predominance of erosion upstream and the lack of significant deposition more than 720 m downstream, only that first 720 m downstream of the dam are included in the analysis (‘the study reach’). Within that 720 m, the gradient is 0.3%, and the channel has a single thread, a mixed ‘bedrock’ (resistant silt hardpan) and gravel bed, and low sinuosity (=1.04). In the first 400 m downstream of the dam, the bed is largely underlain by hardpan (partially lithified Missoula flood deposits), and the channel has a plane bed. In the remainder of the study reach, hardpan is exposed in some pools and alternate-bar morphology predominates. The floodplain and channel banks are composed of silt and gravel. The dam was built into a basalt intrusion outcropped on the right bank only at and immediately upstream of the dam site.

The Calapooia River watershed comprises headwaters in the Western Cascades, the predominant source of basalt and andesite gravel bedload (Sherrod and Smith, 2000), and lowlands of the Willamette Valley, and is tributary to the Willamette River. At the dam site, upstream contributing area is 394 km$^2$, and annual peak flows range from 68 m$^3$/s (recurrence interval, RI, of one year) to 515 m$^3$/s for the flood of record in December 1964. The annual peak flow record is based on regressions between the Brownsville Dam site, where a gage has been in operation since 2006, the historical flow record at the former US Geological Survey (USGS) gage at Holley (#14172000) located 15.3 km upstream of the dam and draining 272 km$^2$, and the active gages on the nearby South Santiam and Mohawk Rivers (see Walter and Tullos [2010], for further details). Peak flows generally occur during the rainy season in October through May. Low base flows occur in the summer and are typically less than 2 m$^3$/s (see Supplementary Material, Figure A). The study reach has one small tributary, Wiley Creek, which enters the former reservoir from river right at 90 m upstream of the former dam.

Topographic data comprised cross-sections, longitudinal thalweg profiles, and bar surfaces surveyed at summer baseflow in 2007, 2008, and 2009, or one year before and
two years after dam removal (Walter and Tullos, 2010; Zunka, 2011). Prior to the removal, Walter and Tullos (2010) divided the study reach into habitat units (i.e. pool, riffle, run, or glide) of varying lengths, and cross-sections divided each unit into three equal lengths of 0.25 to 2× the bankfull channel width, so that, through the whole study reach, cross-section spacing is non-uniform.

Marmot Dam on the Sandy River, Oregon

The Marmot Dam was a privately-owned concrete dam located on the Sandy River between the confluences with the Salmon River and Bull Run. The dam (15 m height × 50 m width) was constructed in 1913, renovated in 1989, and diverted flow into a canal and aqueduct system for hydropower generation (Major et al., 2012). The reservoir sediment, which had accumulated over an estimated period of 30 years, consisted of 730,000 m³ of sand and gravel, 328,500 m³ of which was gravel (Cui and Wilcox, 2008). A temporary cofferdam was built to retain the reservoir sediment as the dam was removed, and the cofferdam was breached on October 19, 2007.

Pre- and post-removal data were collected over a 1.6 km reach (the ‘study reach’) downstream of the dam. In the study reach, the gradient is 0.6% and the channel has a single thread, a boulder-cobble bed, and low sinuosity (=1.05). The channel banks and floodplain are composed of a combination of volcanic and sedimentary rocks, lahars deposits, and Pleistocene terrace gravels (Major et al., 2012). There are no tributaries in the study reach.

The Sandy River watershed comprises 1300 km² of the Western and High Cascades of Oregon (Cui and Wilcox, 2008) (Figure 2, inset) and is tributary to the Columbia River. The Sandy River sediment load consists of sand and coarse volcanic gravel derived from the river’s origins at the base of Reid Glacier on the western slopes of Mt Hood and Pleistocene terraces bordering the river (Major et al., 2012). Among various bedrock controls along its length, the most notable is the steep (1%) and narrow (average width 30 m) Sandy River Gorge, which begins 2 km below the Marmot Dam and continues for a distance of 7 km (Cui and Wilcox, 2008). Peak flows in the Sandy River basin occur during long-duration, low-intensity precipitation in fall and winter and snowmelt and glacial melt in spring and summer. At the USGS gage site near Marmot Dam (#14137000), approximately 48 km upstream of the confluence with the Columbia River, the Sandy River has a drainage area of 684 km², a mean annual flow of 38 m³/s, and a mean annual flood of 460 m³/s, based on the 93-year gaging record (1912–2007) (Major et al., 2012).

Topographic cross-section surveys were conducted annually by David Evans and Associates at summer baseflow in 2007, 2008, 2009, and 2010, or one year prior to and three years following removal. The cross-section spacing was 14 m, approximately 20% of the 65 m average bankfull width, in the 660-m reach downstream of the dam and 30 m, approximately 20% of the 130 m average bankfull width, in the reach from 1.0 to
1.6 km downstream of the dam site. Cross-sections were not surveyed from 660 to 1000 m. See Major et al. (2012) for a detailed description of data collection at the Marmot Dam site.

Results

Brownsville Dam removal

The moderate flows following the removal of Brownsville Dam (see Supplementary Material, Figure A), including several one-year RI floods but no two-year RI events, and the low volume of sediment stored behind the dam resulted in only small morphological changes downstream. The Calapooya River evacuated 29% of the reservoir’s 14 000 m³ of sediment in 2008 and an additional 10% of the original sediment volume in 2009. By 2009, the released sediment covered the previously exposed hardpan in the first 400 m downstream of the dam site with a high-relief alternate bar sequence, although changes in sediment thickness were modest in magnitude and limited in spatial extent, with Δz* values exceeding 0.3 (Figure 3) at only the first and third cross-sections (XS1, XS3) at 10 and 100 m downstream, respectively (Figure 2).

The cross-sections were grouped into two reaches (Figure 3, Table I) based on the observed spatial and temporal patterns in net erosion and deposition following the removal. Reach I, comprising the first four cross-sections (Figure 2A), had relatively low initial relief (mean r* < 0.5, Figure 4, Table I), due to sparse sediment cover over the relatively planar silt-hardpan bed. The largest Δz* and most dramatic adjustments in channel morphology were in this near-dam Reach I over the first year following dam removal (Figure 3). Reach II, comprising cross-sections 5–24 (XS5–XS24), had a much wider range of relief prior to dam removal than Reach I (Figure 4). Following the removal of Brownsville Dam, Reach II was generally degraded in 2008 (Δz* < 0) relative to the pre-removal surface, and aggraded (Δz* > 0) in 2009 (Figure 3). The increases in sediment thickness for Reach I corresponded to the development, and subsequent modification, of sediment bars that increased initially low relief and decreased initially high relief. A mid-channel bar, which developed at XS1–XS4 (e.g. Figures 5A and 5C), increased mean relief from low to high and increased variance of relief values nearly 150% relative to pre-removal (Table I). This increase from initially low relief (r* < 0.5) was especially evident at XS3 (Figures 5C and 5D); XS2 exemplifies the decrease from initially high relief (r* > 0.5) (Figures 5A and 5B).

The development of an alternate bar sequence from 2008 to 2009 illustrated the local impacts of channel reorganization. The mid-channel bar deposited in Reach I in 2008 attached to the left bank at its lower extent and formed a river-left bar in Reach II in 2009. Despite the negligible to small changes in sediment thickness at the upstream end of Reach II in 2008 (Figure 3), the bar deposition, and accompanying scour of the bar-adjacent pool, led to greater r*. Farther downstream (>200 m distance), an alternate bar ~100 m in length formed at river right in 2009. With bar formation, relatively small increases in sediment thickness (e.g. Δz* = 0.05 at 258 m distance) led to relatively large increases in relief (e.g. r* = 0.64 in 2007 to r* = 0.89 in 2009 at 258 m distance).
The growth of this bar-pool morphology was accompanied by riffle formation (at 150 to 180 m distance, Figure 3), where $r^*$ decreased by 0.25 or more relative to initial conditions of $r^*$, which ranged 0.55 to 0.93. Thus, despite only minor changes in $\Delta z^*$ in the upstream portion of Reach II, bar growth increased relief and the creation of cross-over morphology decreased relief.

Downstream of 300 m distance, changes were characterized by relatively uniform degradation and aggradation across the width of the cross-sections in 2008 and 2009, respectively, with little alteration of bar morphology, so that changes in relief from initially high mean $r^*$ values were generally small (Figure 4) and not statistically significant (Table I).

### Marmot Dam removal

The removal of the earthen cofferdam upstream of Marmot Dam caused substantial and rapid channel responses in the Sandy River. The breach occurred during the rising limb of a moderate (<100 m$^3$/s) flow event (see Supplementary Material, Figure A), and the reach immediately downstream of the dam transitioned, literally overnight, from a single-thread, boulder-bed channel into a multi-thread channel with mobile sandy bars (Major et al., 2012). In 2008, the first year following the removal, more than 50% of the sediment left the former reservoir, and 110,000 m$^3$ was deposited in the first 2 km downstream of the former dam (Major et al., 2012). This deposition corresponded to a maximum $\Delta z^*$ of 0.6 near the dam site to a minimum of nearly zero at the distal end of the 2 km reach (Figure 6). Sediment thickness near the dam site declined in 2009 (smaller $\Delta z^*$ in Figure 6) but remained nearly constant downstream. Moreover, the entirety of the near-downstream (NDS) reach remained aggraded ($\Delta z^* > 0$) through 2010.

The cross-sections downstream of the Marmot Dam site were grouped into two reaches, a NDS reach, with large, statistically significant increases in sediment thickness, and a farther-downstream (FDS) reach, with small, insignificant changes in sediment thickness (Figures 2 and 6, Table II). In addition, we further subdivided the NDS reach into four sub-reaches (Reaches I–IV in Figure 6, Table II) based on the following patterns in $\Delta z^*$: Reach I had the largest increases in sediment thickness in 2008 and, relative to that ‘high stand,’ degradation in 2009; in Reach II, the sediment thickness changed little after initial deposition in 2008; Reach III experienced continued aggradation in 2009 after initial deposition; Reach IV experienced only small changes in sediment thickness after initial deposition. In the FDS reach, there was limited impact on relief, primarily through the modification of existing bars and pool filling.

The evolution of the NDS sub-reaches at Marmot demonstrated several morphologic variations of decreasing initially high relief in response to the large increases of sediment thickness (Figure 7). In Reach I where pre-existing relief was high, the large increases in $z^*$ in the year following removal decreased relief (Figure 7A, Table III). The mean relief then in-

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**Figure 6.** Longitudinal profile depicting normalized change in mean sediment thickness ($\Delta z^*$) with distance downstream of Marmot Dam on the Sandy River. Profiles are divided into near-downstream (NDS) and farther-downstream (FDS) reaches, and NDS reach is subdivided into four sub-reaches: I, II, III, and IV. See text for explanation of sub-reach divisions. Select cross-section locations are shown. No survey data exist for downstream distances between 660 and 1000 m.

**Figure 7.** Normalized change in mean sediment thickness ($\Delta z^*$) and normalized relief ($r^*$) plots for sub-reaches Reach I, Reach II, Reach III, Reach IV (A–D, respectively) of the NDS reach for Marmot.
increased in 2009 and 2010 when erosion subsequently reduced \( z^* \) values. For example, the downstream 100 m of Reach I (e.g., XS12, Figures 8A and 8B) was characterized by high relief and a deep single-thread channel prior to dam removal. In 2008, this section underwent a decrease in \( r^* \) (Table III) due to over 3 m of width-averaged deposition, which was manifested as multiple shallow channels (Figure 8A). The degradation in 2009 then excavated a single channel on river left and increased mean relief relative to 2007 and 2008 values (Figure 7A). Reach II transitioned from the highest initial mean relief at Marmot to low mean \( r^* \) post-removal (Figure 7B, Table III). In this reach, all post-removal cross-sections registered lower \( r^* \) values than the lowest pre-removal value (Figure 7B). The key morphological response to the substantial deposition in Reach II was the creation of a low-relief, mid-channel bar in 2008 that completely filled the U-shaped pre-removal channel and deposited sediment on the tops of the banks (Figure 8C). This bar became attached to the right bank in 2009 (Figure 8C). The initially high relief of Reach III was reduced during each of two phases of aggradation in 2008 and 2009 (Figures 6 and 7C, Table III). The morphological responses included the deposition of a low-relief, river-left bar in 2008 and the creation of low-relief, riffle-like morphology in 2009 (Figures 7C and 8E, Table III). The additional increase in \( z^* \) in 2009 resulted in a planar channel (Figure 8E) with the smallest \( r^* \) values measured for any year (Figure 8F). Reach IV experienced a slight decrease from initially high mean relief to low relief following deposition of a river right bar in 2008 and limited subsequent modification of sediment thickness, morphology, or relief (Figure 7D, Table III). Thus in the initially high-relief sub-reaches, pre-removal morphology was completely buried by the deposition of new bars, which had lower relief than the pre-removal morphology.

The responses of bed relief in the NDS and FDS reaches demonstrated the substantial effects of large magnitudes of sediment deposition and limited effects of small magnitudes of deposition, respectively (Figure 9, Table II). In the FDS reach, reach-averaged \( \Delta z^* \) values were less than 0.04 for all survey years (Figure 6) and produced only small changes, both positive and negative, in mean relief (Figure 9, inset), but the changes were not statistically significant (Table II). In the Marmot NDS reach, over 90% of the post-removal cross-sections and all cross-sections from sub-reaches III and IV had \( \Delta z^* \) values greater than 0.3 (Figures 6, 7C, 7D, and 9). As a result, the mean \( r^* \) values in the NDS reach decreased substantially pre- to post-removal and did not recover during the survey period (Figures 7 and 9, Table II). Thus we observed an overall and persistent decrease in relief with large increases in \( z^* \) for the initially high relief NDS reach.

The sequence of decrease and subsequent increase in relief variance across the NDS reach was consistent with shallow bar deposition in 2008 and channel reorganization in 2009, respectively. In general, no statistically significant changes in relief variance occurred in any individual NDS sub-reach, except for the notable decrease in Reach III in 2009 to a near-zero value with the development of riffle-like morphology (e.g., Figure 8E) across all Reach III cross-sections (Table III). However, the NDS reach underwent a statistically significant decrease in the relief variance (Table II) associated with the aggradation and widespread development of shallow, mobile bars in the sub-reaches in 2008. Following channel reorganization in 2009, the sub-reaches spanned separate channel units, with Reaches I and II and Reach IV...
corresponding to two river-right bars, and Reach III corresponding to ‘riffle-like’ morphology. The development of this bar–riffle–bar sequence increased relief variance for the reach to pre-removal levels (Table II). Therefore the morphologic variability in the NDS reach decreased as only a single morphology (i.e. low-relief bars) was represented in each sub-reach, but increased as both bar and riffle morphologies appeared in the sub-reaches in 2009.

Discussion

The two case studies presented herein indicate that somewhat predictable behaviors of building or reducing relief may occur following the introduction of a sediment pulse. The specific behavior of pool filling or bar building appears to depend on the initial relief and the amount of sediment delivered to individual features. Like other studies (Sklar et al., 2009), this work confirms the importance of initial conditions and the magnitude of the sediment pulse on channel response. The Brownsville and Marmot Dam removal sites and respective sub-reach divisions provided useful contrasts in thicknesses of sediment introduced to the downstream channel, ranges of initial relief, and resulting morphological impacts with which the hypothesized responses were evaluated.

Effect of initial relief on channel response

Results from both study sites generally confirmed the hypothesis that initial relief is an effective predictor of the impacts of a sediment pulse on channel morphology. Increasing sediment thickness tended to increase relief in locations with initially low relief and decrease relief in locations where it was initially high. Several studies (Wohl and Cenderelli, 2000; Madej et al., 2009; Podolak and Wilcock, 2013) documented decreases in initially high relief with the introduction of sediment pulses through either pool-filling or development of low-relief mid-channel bars. These behaviors were both visible at Marmot, where the pools of the FDS reach were filled and where initially high relief of the NDS reach was decreased with the formation of mobile, sandy bars. In flume studies where sediment pulses were introduced to low relief plane bed reaches (Ikeda, 1983; Lisle et al., 1991; Lanzoni, 2000b), relief increased with the development of sediment bars. This behavior was evident in the first 300 m downstream of the Brownsville Dam, where low relief was increased with the development of an alternate bar sequence.

Effect of variable sediment thickness on channel response

The magnitude of the impacts of the sediment pulses on channel morphology and relief at Brownsville and Marmot varied with the thickness of sediment delivered to each reach in patterns consistent with the literature. The impacts of sediment pulses are usually largest at the site of the former dam and decrease downstream (Lisle et al., 1997; Cui et al., 2003; Greimann et al., 2006; Lisle, 2008). Indeed, at both study sites, the largest changes in relief were nearest the dam site, where the largest increases in sediment thickness occurred, and impacts decreased with distance downstream. The contrasting relative sediment pulse size between Brownsville and Marmot resulted in the differences in the scaled responses in Δz*. Although magnitudes of change in Δz* were comparable in the reaches of both sites (Tables I and II), the larger Δz* at Marmot modified the morphology of the cross-sections more profoundly than the smaller Δz* at Brownsville, but the relief metric and comparative statistics did not capture these qualitative differences in morphological modification.

The depth of sediment delivered to a feature impacted the nature and degree of morphological response. Madej et al. (2009) showed that, when introduced to an alternate bar sequence, small sediment pulses tend to deposit in the bottom of pools and leave pre-existing bar structure intact, but larger sediment pulses tend to drown out pre-existing morphology and form, albeit temporarily, low-relief mid-channel bars. The analogous behaviors occurred at the Marmot FDS and NDS reaches, respectively, demonstrating the relative impacts of small versus large sediment thicknesses. The high relief pre-removal morphology of the NDS reach was thickly buried in 2008 by mobile, mid-channel bars that greatly reduced bed relief. In contrast, in the FDS reach, changes in sediment thickness were small and mean relief was minimally affected by the subtle bar growth and pool filling. At Brownsville, channel reorganization only occurred immediately downstream of the dam, where deposition of the largest sediment thicknesses resulted in the formation of alternate bars. The normalized increases in sediment thickness at Brownsville were not as great as the NDS reach at Marmot, and mobile, low-relief, mid-channel bars did not develop. The results suggest the hypothesis that the development of mobile mid-channel bars, effectively as a lesser degree of braiding, is related to the introduction of larger sediment thicknesses on the continuum of channel responses to sediment pulses.

Whereas the sediment thickness is the cross-sectional area divided by the channel width, the fact that widths in the FDS reach are nearly twice those in the NDS reach may account for some of the differences between the reaches. However, we would also expect that the velocity of the sediment flux would be lower in a wider channel, and the cross-sectional area of sediment is the volume flux divided by the velocity. These two effects on the sediment thickness would tend to cancel. Average Δz* values in the NDS reach are an order of magnitude greater than in the FDS reach, where that average is, statistically, indistinguishable from zero. It appears, then, that the sediment flux in the FDS reach is still much smaller than in the NDS reach.

Role of alternate bars in maintaining relief variance

The results from Marmot and Brownsville indicated that development of alternate bars during the processing of a sediment pulse can maintain, and even increase, the variance in relief at the reach scale. While the mean relief increased with bar deposition in the plane-bed Reach I at Brownsville, variance in relief increased as well with the creation of both high-relief bar-pool and low-relief riffle-like morphology of the alternate bar sequence. The prevalence of mobile, low-relief bars in most of the NDS reach at Marmot in 2008 represented a lack of morphologic variability and resulted in the decreased variance of relief observed. Then, in 2009, as alternate bars stabilized in Reaches I, II, and IV and the cross-over morphology appeared in Reach III, the relief variance in the NDS reach increased, consistent with our hypothesized models of channel change. The pattern of reorganization of mid-channel bar sediments to alternate bar morphology is consistent with the responses to increased sediment supply observed by Ikeda (1983) and is tied to measurable increases in relief variance and morphological diversity.
Study scope and further work

This study contributes to the understanding of potential morphological responses to sediment pulses in bar-pool morphology. Bar-pool systems are common throughout many rivers with gradients less than 2% (Grant et al., 1990) but are rare in steeper gradient streams (Buffington et al., 2002). Thus, the hypothesized trajectories are limited to bar-pool systems in rivers not characterized by steep gradients (<1% in sites examined herein) and should be evaluated in other initial conditions (e.g. morphological, hydrological, pulse characteristics) where the dominant sediment processes are different. As the hypotheses are further examined, several issues should be considered. First, the potential for decoupling the patterns of mean and variance of relief exists if a given study reach does not span more than a single alternate bar sequence. The hypotheses predicted that the development of alternate bars from a plane bed morphology would increase both mean and variance of relief and that the filling of pools would decrease both mean and variance of relief. However, if a study reach spans only a single bar, increasing relief uniformly for all cross-sections in the reach may actually decrease the variance in relief while increasing the mean. Given that variance in relief is highly dependent on the spatial scale (e.g. a single bar or an alternate bar sequence) over which it is measured, the morphological context of a set of cross-sections within the channel planform should be considered when evaluating these hypotheses.

Second, while small pulses are likely to follow the hypotheses outlined earlier, the introduction of a sediment pulse larger than those presented herein may fill the channel to generate major and unpredictable reorganization of the bed. The morphologic responses may be more variable in response to a larger pulse and could include channel widening, pool filling and/or deepening, the development of low-relief braided morphology (Buffington et al., 2002), streamwise shifting of riffle crests, or avulsion.

Third, rather than a retrospective analysis, it may be desirable to modify the approach outlined herein to predict potential channel responses prior to future dam removals. Such an analysis should modify the existing approach by: (1) using the pre-removal thalweg elevation, as opposed to minimum elevation, to establish the vertical datum for each cross-section, and (2) discretizing sub-reaches by initial relief or morphologies apparent from two-dimensional depositional patterns, such as alternate bars.

Fourth, bank bias in the calculation of relief values can overstate decreases in relief. Where deposition results in decreased relief, inclusion of banks in calculations of initial relief may simply exaggerate that apparent result. Where bars, either mid-channel or alternate, are initially absent, however, the results due to bank bias may be misleading. For example, many pre-removal Marmot cross-sections, particularly in Reaches II and III, exhibited a U-shaped morphology that lacked sediment bars (e.g. XS28; Figure 8E) but, nevertheless, produced high mean and variance of relief (Table II) because significant bank relief was included in the central 70% of the cross-section.

Fifth, the effect of the hardpan in Reach I at Brownsville on channel morphology in response to increased sediment load is uncertain. This resistant surface would limit the erosion of the bed and therefore may stunt potential pool growth. Indeed, in cross-sections where hardpan was known to be exposed in the bed (e.g. Brownsville Reach I), there was no evidence degradation below the hardpan. Alternatively, the smooth hardpan surface may inhibit pool-filling by efficiently passing bedload to rougher, sediment-covered patches of bed downstream (Iseya and Ikeda, 1987). However, provided the volume of sediment introduced to Reach I, it is likely that this effect would be insignificant to, or overwhelmed by, the substantial deposition that occurred.

Finally, the hypothetical at-a-cross-section responses in this study, when examined collectively, generated a rough three-dimensional portrait of reach response to sediment pulses. These responses corresponded to the hypotheses that bar-pool channels will build bars where bars are lacking and fill pools where bars are developed. However, a more complete model based on three-dimensional topography may provide additional insight regarding channel responses and the sediment processes driving them. The hypotheses and simple heuristic model in this study are intended to establish expectations for how channels evolve in response to sediment pulses; they are not intended to supplant more detailed morphodynamic models or to provide an exhaustive description of the dominant sediment transport processes and mechanisms driving morphological responses.

While the body of literature on evolving fluvial topography is growing richer from flume studies (e.g. Ikeda, 1983; Lanzoni, 2000a, 2000b; Venditti et al., 2012) and field studies (e.g. Welford, 1994), some critical questions remain regarding the impacts of a sediment pulse on the sediment dynamics that build bars (Church, 2006; Venditti et al., 2012) and that are responsible for the filling and scouring of pools (Lisle and Hilton, 1992; Sear, 1996; Buffington et al., 2002; MacWilliams et al., 2006). For example, the importance of the hydrologic sequence post dam removal is increasingly reported (Pearson et al., 2011; Sawaske and Freyberg, 2012) to be of limited relevance in the rates and sequences of sediment dynamics, with process-based erosion of the reservoir sediments initially dominating, while initial bed slopes are large and grain sizes small, until event-based dynamics take over (Pizzuto, 2002). And yet, within-year hydrologic variability has been shown to drive variability in the caliper and quantity of sediment being transported to pools and the strength of the flow field that is responsible for scouring sediment from pools (Sear, 1996). The continued evolution of the understanding of sediment transport in gravel-bed streams and the mechanisms that drive the building and elimination of relief with a transient sediment pulse will facilitate understanding of where the hypotheses developed herein apply and when other trajectories are likely to occur, as well as advance the fields of geomorphology and river management.

Conclusion

Reasoning that, in so far as bed relief is a reasonable proxy for the kind of ‘channel complexity’ often associated with high-quality aquatic habitat, we addressed the importance of initial bed relief and changes in sediment thickness on channel response to sediment pulses. Specifically, we examined the hypotheses that deposition from a sediment pulse would increase relief by building bars in channels with initially low relief, whereas pool filling would reduce relief in channels with initially high relief. Additionally, we hypothesized concomitant increases and decreases in the variance of relief in response to the growth of alternate bar sequences and filling of pools, respectively.

The results generally supported these hypotheses. Following the introduction of a sediment pulse, high relief generally decreased and low relief increased, and greater changes in sediment thickness produced greater changes in the mean and variance of relief. Whereas relief variance either changed little (as in the Sandy River) or increased (as in the Calapooya) following dam removal, the results suggest that dam removal may have limited negative impacts on, or even increase heterogeneity in, channels over the long-term. The range of
responses, including eventually increasing relief following short-term reductions, suggest that, even where sediment pulses initially reduce bed relief by filling pools, diversity of aquatic habitat may soon recover with the development of alternate bar morphology. While the hypotheses did not explain the full range of responses observed at the two field sites, this work does provide a starting point for estimating the range of responses to dam removal of alluvial channels that exhibit bar-pool morphology and for developing more physically detailed and site-specific hypotheses.

The results advance the understanding of the range and types of morphological responses possible in bar-pool channels to the introduction of small- and medium-sized pulses and have several implications for managers concerned about homogenization of aquatic habitats. First, the potential for new deposition to fill pre-existing pools is linked to initial relief and expected changes in sediment thickness. In the cases examined here, pools that filled typically had high initial relief, as hypothesized. Second, bank erosion and channel widening are not necessary conditions for decreased bed relief. Third, where bars are initially lacking, sediment additions may increase or sustain relief through the formation of alternate bars, as was observed downstream of both the Brownsville and Marmot Dam sites. Fourth, the development of low-relief, mobile, mid-channel bars as a first response to a moderate increase in sediment thickness, as was observed in the Sandy River downstream of the Marmot Dam site (in the NDS reach), is a temporary feature on the path towards the formation of alternate bars, consistent with flume and field studies.

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**Supporting Information**

Additional supporting information may be found in the online version of this article at the publisher’s web site.