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SEDIMENT PULSE BEHAVIOUR FOLLOWING DAM REMOVAL IN GRAVEL-BED RIVERS

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ABSTRACT

As dams approach the end of their useful life, there is need to predict where and how accumulated sediment will move following dam removal to estimate and mitigate the impacts of this process on aquatic habitat and infrastructure. Flume studies suggest that sediment pulses disperse in place for most dams, but it is hypothesized that certain conditions (e.g., low Froude number, fine pulse grain size, small pulse sizes, and large peak discharge) may characterize pulses that translate downstream. However, quantitative analyses of sediment pulse behavior have not been widely conducted in field settings. We thus analyzed bathymetric data from four field sites in Oregon to investigate the reliability of flume-derived hypotheses (1) whether dispersion or translation dominates across a range of dam removal physiographies using multiple methods of evaluation and (2) if Froude number, pulse material grain size, relative pulse size, and discharge can predict reservoir sediment movement mode. Results indicated that dispersion generally dominated pulse behavior in the field setting, with some limited evidence of translational movement in individual years. The Froude number appeared to be the most reliable for anticipating pulse behavior. Further work is needed to link generalized sediment pulse behavior to sediment mobilization and transport processes. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: dam removal; dispersion; Froude number; Peclet number; translation

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INTRODUCTION

As more dams reach the end of their useful lifespans and the decommissioning of dams gains popularity as a river restoration strategy (Hart *et al.*, 2002; O'Connor *et al.*, 2015), it is increasingly important to understand how sites will respond to the removal of dams and weirs. While the literature is growing on the response of rivers to dam removal, particularly from the perspective of geomorphological processes and sediment transport (Kibler *et al.*, 2011; Wang *et al.*, 2014; Grant and Lewis, 2015; Zunka *et al.*, 2015), questions remain regarding the fate of sediment released from the reservoir. Understanding the distance and rate at which stored reservoir sediments may move following barrier removal will improve predictions for critical management concerns, including aquatic species habitat (Greig *et al.*, 2005), channel stability (Doyle *et al.*, 2003), flood risk and infrastructure (Born *et al.*, 1998) and water quality (Riggsbee *et al.*, 2007).

Researchers commonly analyse the sediment released with dam removal as a wave or pulse (*sensu* Lisle, 2008), which facilitates describing the timing and location of transported sediment in terms of translational and dispersive behaviour. Pulse movement may be tracked by delineating the apex and upstream and downstream edges of the sediment pulse. A pulse is considered to move by translation if the apex and both edges migrate downstream at uniform rates, whereas a dispersive pulse is characterized by diminishment of a longitudinally stationary apex and lengthening of the distance between edges (Lisle *et al.*, 2001). The impacts of dispersive pulse evolution will be concentrated in one area and diminish with time, while those of a translational pulse will propagate farther downstream and at a more constant intensity (Pizzuto, 2002; Cui *et al.*, 2003a). Flume studies indicate that dispersion generally characterizes pulses in gravel-bed streams, but some degree of translation may also occur (Cui *et al.*, 2003a; Lisle, 2008; Nelson *et al.*, 2015).

Past work has considered how site conditions affect translation of sediment pulses. Translational behaviour has been observed in flume experiments when the Froude number is 0.4 or lower (Lisle *et al.*, 1997, 2001), when the pulse material is finer than the ambient bed material (Cui and Parker,

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1997; Ferguson *et al*., 2015), when the pulse size is small relative to the channel width (Lisle *et al*., 2001; Sklar *et al*., 2009) and when peak discharge is at least three times the threshold for sediment entrainment (Humphries *et al*., 2012). Numerical models also support an inverse relationship between Froude number and translational behaviour (Cao and Carling, 2003; Cui *et al*., 2003b, 2005, 2008).

Froude number, sediment grain size, pulse volume and discharge values relate to pulse behaviour as descriptors of the stream's ability to transport sediment. The Froude number characterizes the velocity and depth interactions that influence a channel's ability to transport sediment (Grant, 2001). The pulse sediment grain size affects the mobility of the pulse material. When the pulse material is finer than ambient sediment, the pulse sediment is more mobile than the ambient material, making it relatively easier for the downstream edge to be transported downstream (Lisle *et al*., 2001) and creating conditions that are favourable to translational pulse behaviour. A large pulse volume may facilitate dispersive behaviour by obstructing flow, reducing sediment transport capacity upstream (Cui *et al*., 2003a) and encouraging deposition on the upstream edge of the pulse (Sklar *et al*., 2009). Large peak discharges likely promote translation, as the sediment transport rate increases with discharge (Wilcock and Crowe, 2003) and bed load transport zone increases with flow depth (Humphries *et al*., 2012).

It is unclear how closely the relationships observed in flume experiments and derived numerically match responses in the field setting. Natural channels are subject to substantial complexity that is generally not represented in physical models, including variability in network structure, channel geometry, planform and flow resistance from vegetation and large wood (Madej, 2001; Hart *et al*., 2002; Greimann et al., 2006; Gran and Czuba, 2015). Meanwhile, previous field studies have not quantitatively measured pulse movement, relying instead on patterns of erosion and deposition or changes in sediment transport rates to infer pulse behaviour (Meade, 1985; Wohl and Cenderelli, 2000; Sutherland *et al*., 2002; East *et al*., 2015).

This research sought to bridge the gap between flume and field methodology by quantifying field-observed behaviour of sediment pulses following barrier removal at four gravel-bed rivers. The objectives of this study were to (1) investigate whether dispersion or translation dominates pulse behaviour observed in the field across a range of dam removal physiographies and (2) evaluate if Froude number, pulse material grain size, pulse size and discharge can explain pulse behaviour. We evaluated the hypothesis, derived from flume studies, that dispersion dominates pulse behaviour except in conditions of Froude number less than 0.4 and pulse material finer than ambient bed material. In addition, we expected that large pulse volumes were likely to move by dispersion, whereas high post-removal discharge was associated with translation. Finally, the assumptions and limitations of each technique to characterize pulse behaviour were discussed.

METHODS

Field data collection

Data collection, repeated annually, was comprised of topographic, bathymetric and bed texture surveys at four barrier removal sites on Oregon streams (Figure 1; Table I).

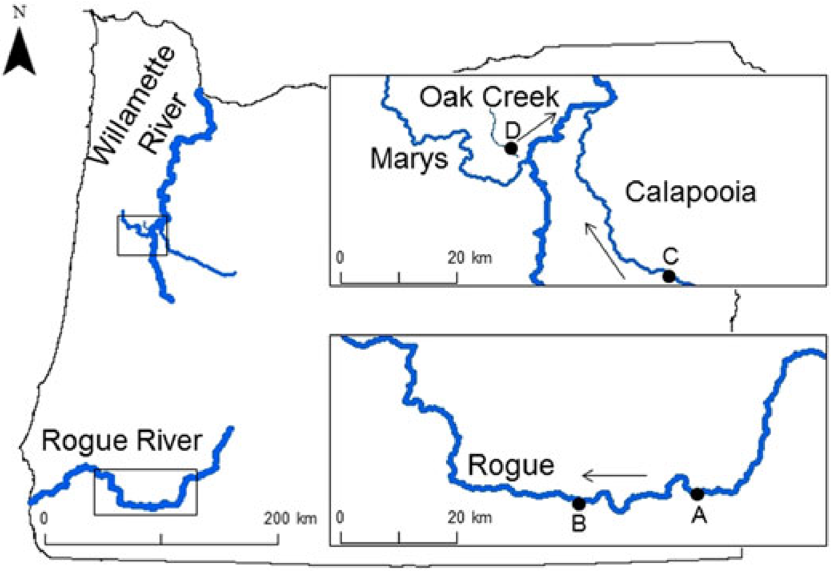

Figure 1. Locations of Gold Ray Dam (A), Savage Rapids Dam (B), Brownsville Dam (C) and Oak Creek culvert (D). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Table I. Barrier and site characteristics

Site characteristic	Gold Ray	Savage Rapids	Brownsville	Oak Creek
Dam height (m)	12	12.5	1.8	n/a
Dam width (m)	110	142	33.5	n/a
Removal year	2010	2009	2007	2007
Pre-removal data collection	July 2010	—	August 2007	July 2007
Post-removal data collection	June 2011, June 2012, July 2013	August 2010, June 2011, June 2012, July 2013	July 2008, August 2009	September 2008, June 2009
Stream name	Rogue River	Rogue River	Calapooia River	Oak Creek
Channel gradient (%)	0.21	0.27	0.23	0.65
Reservoir material	Gravel	Sand	Coarse gravel	Fine gravel
Discharge source (USGS gauge number)	#14359000	#14361500	Local gauge and #14172000	Local gauge and #14171000
Mean annual precipitation (cm)	103	100	173	150
Mean discharge ($m^3 s^{-1}$)	83	98	12	2.6
Drainage area (km^2)	5309	6294	394	31
Average channel width (m)	60	90	35	12
Initial apex height (m)	9.7	3.9[1]	1.8	2.0
Initial pulse volume (m^3)	526 000	71 000[1]	17 100	444
Period of discharge record (years)	108	75	54	59
1.2 Return interval discharge ($m^3 s^{-1}$)	348	456	100	14

[1] Topography and bathymetry from the first year following dam removal ('year 1') are substituted for the missing pre-removal data.

Bathymetric and topographic surveys upstream and downstream of the dams were conducted using Real Time Kinematic (RTK) Global Positioning System (GPS), total station, and a raft-mounted acoustic Doppler current profiler (ADCP) yielded elevations along cross sections, the thalweg profile and on bar surfaces (refer to Walter and Tullos, 2010; Kibler *et al.,* 2011; Tullos e*t al*., 2014; Pace, unpublished thesis, 2015 for bathymetry details). Grain-size data were comprised of surface particle counts (Wolman, 1954) on exposed bars. Discharge time series were retrieved from the nearest United State Geological Survey (USGS) gauge records where these spanned periods of data collection and, otherwise, reconstructed from regressions based on records from nearby gauges (Table I).

Processing of field observations

Changes in bed elevation and sediment volumes were used to evaluate pulse movement. Annual bathymetric data were imported into ESRI ArcMap and used to build triangular irregular networks (TINs) of the channel bed. The natural neighbour interpolation method was used to convert the TINs to digital elevation models (DEMs), with the resolution of 1 m (Wheaton, unpublished thesis, 2008). The geomorphic change detection tool was applied to calculate the difference between pre-removal and post-removal DEMs (Wheaton *et al*., 2009). Changes in topography and point density contributed to the estimation of uncertainty in the DEMs of difference (DoDs) through the application of a fuzzy inference system (Wheaton *et al*., 2009).

From the DoDs, pulse volumes were calculated within equally spaced polygons restricted to the survey area (i.e. the extent of surveyed points for both compared years). The location of each polygon was measured as the distance between the polygon's downstream boundary and the most upstream survey location. The longitudinal length of each polygon equalled the average channel width for each reference site (Table I). The net volume was calculated for every polygon by multiplying the mean change in elevation by the polygon area. The gross volume of each polygon corresponds to the sum of the net volume and the pre-removal gross volume.

The pre-removal gross volume was assumed to be zero downstream of the barrier and was calculated in the reservoir as the volume between a valley surface and the pre-removal DEM. The valley surface was constructed on the Rogue River and Oak Creek by linearly interpolating between two cross sections. The cross sections were located at riffles upstream and downstream of the reservoir, outside the expected area of sediment deposition such that valley slope points likely represent the historical elevations of the channel (White *et al*., 2010). The Brownsville valley surface was calculated based on the results of a seismic refraction survey conducted in 2006 (Northwest Geophysical Associates, Inc., unpublished report, 2006). At Savage

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Rapids, topography and bathymetry from the first year after removal ('year 1') were substituted for missing pre-removal data (Tables I and II).

Methods of predicting pulse behaviour

Froude number. With one exception, the possible predictors of pulse behaviour are dimensionless numbers. The Froude number (Fr) is a dimensionless description of flow conditions in an open channel based on mean stream velocity (v) and hydraulic radius (R).

$$Fr = \frac{v}{\sqrt{gR}} \tag{1}$$

We calculated R over the initial pulse area by using the geometric mean of bankfull channel dimensions measured at reservoir cross sections. The effective discharge (Q, Volume ratio section) and the geometric mean of bankfull channel dimensions were used to calculate v based on the continuity equation. We evaluated the hypothesis that translational movement exceeds dispersive movement only for sites characterized by a Froude number less than or equal to 0.4.

Median grain size, D_{50}. The relative pulse grain size was represented as the ratio of mean D_{50} pulse grain size, collected from the reservoir and assumed to represent accumulated pulse material to the mean D_{50} grain size from bed material, based on pre-removal particle counts collected downstream of the barriers. A resulting ratio less than 1 (i.e. pulse material finer than the bed material) was expected to reflect greater mobility of pulse sediment that can result in translation. In contrast, a ratio greater than 1 (i.e. pulse material coarser than the bed material) was expected to result in the downstream edge of the pulse remaining in place.

Relative pulse size. The size of the pulse relative to channel geometry was calculated as a ratio of the initial pulse apex height to active channel width. The apex height was estimated as the maximum change in elevation measured between the valley and the pre-removal DEM. While no thresholds have been established regarding the maximum pulse size for translation, we included the comparison of pulse size to investigate if such thresholds are evident in the field data.

Volume ratio. The volume ratio compared the initial pulse volume to the volume of flow conveyed by the channel. The 1.2 return interval (RI), calculated from annual peak flow series from USGS gages, was applied as a proxy for the channel's effective discharge (Biedenharn *et al.*, 2000). The flow volume was calculated by identifying all instantaneous flow rates greater than the 1.2 RI in the first

Table II. Quantitative indicators to evaluate pulse behaviour

Site name	Gold Ray				Savage Rapids				Brownsville			Oak Creek		
Year	Pre	1	2	3	1	2	3	4	Pre	1	2	Pre	1	2
Median location (metres from upstream survey boundary)	1734	1895 (T)	1800 (-)	1821 (T)	734	795 (T)	752 (-)	801 (T)	232	238 (T)	242 (T)	83	127 (T)	224 (T)
Length of middle 50% of volume (m)	1505	1970 (D)	1704 (-)	1636 (-)	667	675 (D)	729 (D)	464 (-)	144	155 (D)	152 (-)	81	221 (D)	200 (-)
Mean location (metres from upstream survey boundary)	1675	2458 (T)	2139 (-)	2210 (T)	678	732 (T)	695 (-)	757 (T)	232	257 (T)	274 (T)	88	162 (T)	194 (T)
Standard deviation (m)	2000	2830 (D)	2650 (-)	2830 (D)	770	820 (D)	800 (-)	829 (D)	250	240 (-)	250 (D)	100	200 (D)	500 (D)
Péclet number		0.2 (D)	(-)	(-)		0.07 (D)	(-)	0.2 (D)		(-)	0.7 (D)		0.4 (D)	0.2 (D)
Ratio of changing median to length		0.3 (D)	0.4 (D)	(-)		7.6 (T)	(-)	(-)		0.6 (D)	(-)		0.3 (D)	(-)
Ratio of changing median to standard deviation		0.95 (D)	(-)	0.39 (D)		0.99 (D)	(-)	2.1 (T)		(-)	10 (T)		0.38 (D)	0.19 (D)
Percent change in cumulative volume linear coefficient		−67 (D)	−1.6 (D)	2.8 (-)		−34 (D)	−1.3 (D)	87 (-)		−68 (D)	−5 (D)		−65 (D)	18 (-)

Evidence of translation is marked (T), evidence of dispersion is marked (D), and inconclusive results are marked (-). Evidence of translation exceeding dispersion is shaded.

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two water years post removal, multiplying each identified flow rate by its duration in seconds and summing the results. Where discharge time series were reconstructed from regressions based on records from nearby gauges, the 1.2 RI was compared with daily average flow rates instead of instantaneous flow rates. Discharge time series were not reconstructed at the Oak Creek culvert location. The DoD analysis comparing the pre-removal and valley surfaces was used to generate the initial pulse volume, except at Savage Rapids where previous researchers (U.S. Bureau of Reclamation, 2001) estimated the initial pulse volume. Like relative pulse size, no translation thresholds have been established in the literature.

Peak discharge. Post-removal peak discharges were compared to investigate how conditions following barrier removal may have affected pulse behaviour. We expected to see evidence of translation in relatively wet water years, when discharge exceeded the 1.2 RI. We considered full water years (1 October to 30 September) following barrier removal. The duration of high flow was calculated as the percent of time in a year when discharge exceeded the 1.2 RI, while the magnitude of the peak flow was normalized by dividing by the 1.2 RI.

Indicators of pulse behaviour

The methods for characterizing observed pulse behaviour in flume experiments (Sklar *et al.* 2009) were applied to the gross volumes for each field site. For the purposes of this study, dispersive behaviour was defined to dominate pulse behaviour when dispersive movement exceeded translational movement. As described in detail in the succeeding texts, dispersive and translational movement was evaluated by (1) visual observation of apex movement; or changes in (2) Péclet number; (3) the middle 50% of volume; (4) mean and standard deviation of the gross volume location; and (5) cumulative volume.

Visual observation. Pulse behaviour was evaluated visually from DoD results. Translation was identified by the shift of the pulse apex downstream over time, where the apex was identified as the location of maximum change in elevation. Dispersion was interpreted from the lengthening of areas of accumulated pulse sediment.

Péclet number. The Péclet number (Pe) is a dimensionless ratio (Equation 2) commonly used to model convective heat transfer, applied herein such that the advective and diffusive movements described by the Péclet number were analogous to translation and dispersion, respectively (Sklar *et al.*, 2009). Péclet numbers greater than 1 indicated the dominance of advection and therefore translational movement of the sediment pulse, whereas Péclet numbers less than 1 provided evidence of the dominance of dispersion. Negative Péclet numbers calculated from decreasing variance were considered inconclusive.

$$Pe = \frac{A_{\mathrm{eff}}}{D_{\mathrm{eff}}} \tag{2}$$

$$A_{\mathrm{eff}} = \frac{\left(\mu_{\mathrm{t}+1} - \mu_{\mathrm{t}}\right)^2}{L^{*}t} \tag{3}$$

$$D_{\mathrm{eff}} = \frac{1}{2}\frac{dm}{dt} \tag{4}$$

$$m = \frac{\sigma^2}{L} - \left(\frac{\mu}{L}\right)^2 \tag{5}$$

The numerator (A_{eff}), representing advection, was calculated from the mean locations of pulse volume at consecutive survey years, μ_{t} and μ_{t+1}, the total pulse length (L) and the time (t) between surveys (Equation 3). The denominator of the Péclet number is an effective dispersion coefficient (D_{eff}) that was calculated from the change in spatial moments (m) over time (Equation 4, Roberts and Goltz 1987). The first and second spatial moments were the mean location (μ) and variance (σ^2), respectively, described in the Mean and standard deviation section. Both the mean location and variance were normalized by L (Equation 5).

Length of middle 50% of volume. The middle 50% method was similar to the Péclet number method in that it was a ratio used to compare translational to dispersive movement. Downstream movement of the median location of cumulative volume provided evidence of translation, while the spreading of the length of the middle 50% of volume indicated dispersion (Sklar *et al.*, 2009). Trimming the outer 50% of volume removed the noisy, small accumulations on the upstream and downstream survey extents. The length of the middle 50% of the pulse was found by dividing the cumulative gross volume into quarters and measuring the longitudinal distance covered by the middle two quarters (Figure 2A). The pulse centre was represented by the median location at which half of the total gross volume occurred (Figure 2A). The spacing of polygons (described in the Processing of field observations section) determined the resolution of the gross volume values. When median locations fell within a polygon, they were linearly interpolated from the locations of polygon boundaries. A ratio of the change in median location to the change in pulse length, visualized as the slope of the line in Figure 2B, compared relative degrees of translational to dispersive movement.

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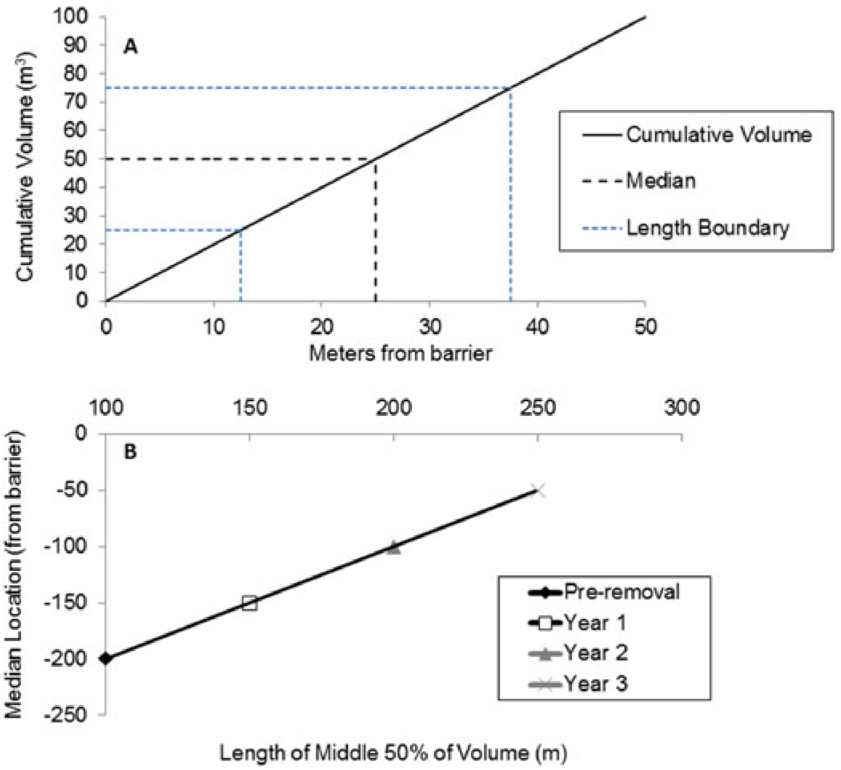

Figure 2. Conceptual graphs of (A) identifying the length of the middle 50% of volume based on the cumulative volume and (B) comparing the movement of median location, indicating translation, to increasing length of middle 50% of pulse volume, indicating dispersion. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Mean and standard deviation. Changes in the mean and standard deviation of pulse location between surveys were also used to describe pulse behaviour. The downstream movement of the mean location indicated degree of translation, while increasing standard deviation indicated dispersive movement. Volume values were represented by the gross pulse volume values measured within each equally spaced polygon (Processing of field observations section). The mean location of pulse volume (μ) was calculated by summing the products of each polygon's volume and location and then dividing by the pulse volume.

$$\mu = \frac{\sum(location*volume)}{total\ volume} \tag{6}$$

The standard deviation (σ) was calculated by summing the products of volume and squared location for each polygon and then dividing by the total cumulative volume.

$$\sigma = \sqrt{\frac{\sum(location^2*volume)}{total\ volume}} \tag{7}$$

The ratio of translational to dispersive movement was calculated by dividing the change in mean by the change in standard deviation for the pulse location.

Percent change in cumulative volume linear coefficient. Changes in the spatial distributions of annual cumulative gross volumes were analysed to classify pulse behaviour (Sklar *et al.*, 2009). As the apex of a dispersive pulse diminishes, the slope of its cumulative volume will decrease (Figure 3). Cumulative volume slopes that do not decrease between years indicate that the pulse shape does not

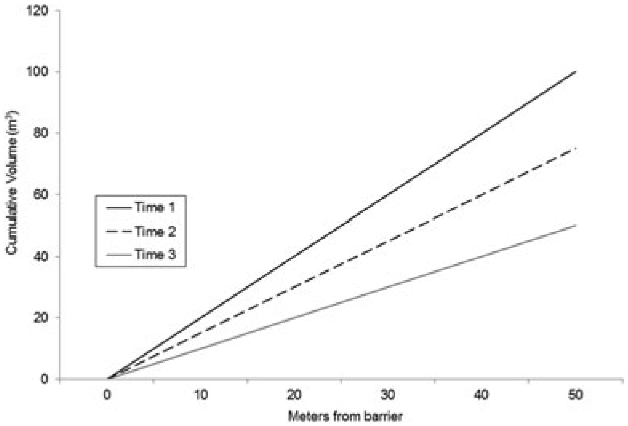

Figure 3. Conceptual graph of the flattening cumulative volume indicative of a dispersive pulse

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change, consistent with translation. The change in the cumulative distribution slope was measured by linear trendlines fit to each cumulative distribution. The strength of dispersion was noted by the magnitude of the percent of change in the trendline slope from 1 year to the next.

RESULTS

Observed pulse behaviour

Based upon visual inspection of net erosion and deposition (Figure 4), dispersion appeared to dominate at all sites except Savage Rapids (Figure 4B), as illustrated by the stationary apexes. At Savage Rapids, relative to the first year following removal, the peak height of deposition downstream was greatest in the third year following barrier removal and appeared to shift 50 m upstream by the fourth year, indicating neither translation nor dispersion.

Visual inspection of gross volumes (Figure 5) indicated a mix of translation and dispersion at all sites except Brownsville (Figure 5C), where dispersion dominated. At Gold Ray, Savage Rapids and Oak Creek, the apex of the gross volume both diminished and moved downstream, suggesting that both translational and dispersive behaviours were present. At Brownsville, the apex diminished but did not move downstream, indicating that dispersion dominated pulse behaviour. For all sites except Gold Ray (Figure 5A), the total volume of pulse sediment diminished as a result of more sediment eroding from the upstream survey area than was deposited in the downstream survey area, indicating a total net loss of recorded pulse sediment (Figure 6).

The results of the quantitative methods to evaluate pulse behaviour (Table II) not only provided some evidence of translation at all sites but also suggest that dispersive movement exceeded translational movement. Increasing distances from the upstream survey boundary for the median locations indicated that translational behaviour occurred to some degree at all sites. However, the Péclet number was less than 1 for all survey years, suggesting that dispersive pulse behaviour was stronger than translational behaviour. Only in year 2 at Savage Rapids was the ratio of changing median location to pulse length greater than 1, indicating the dominance of translation (Table II). The ratio of changing mean to standard deviation suggested that the pulse translated in year 4 at Savage Rapids and in year 2 at Brownsville (Table II). The percent change in cumulative volume linear coefficient reliably indicated that the pulses decayed at the dam site without translation. Taken together, the indicators

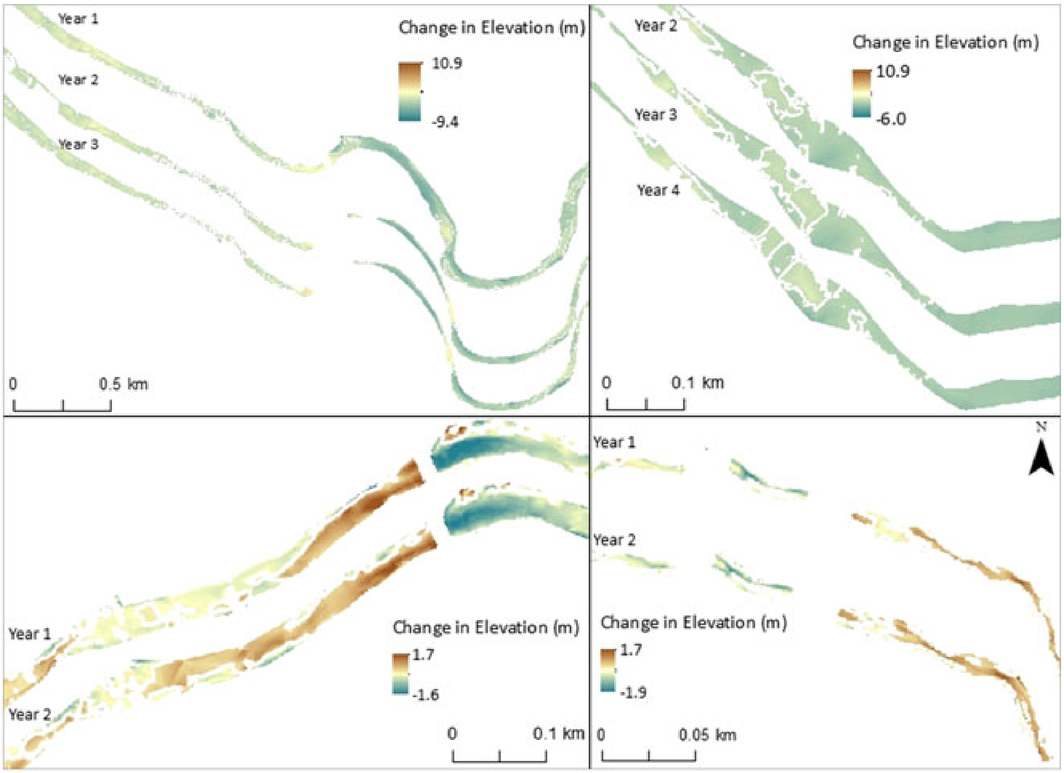

Figure 4. DoDs relative to pre-removal DEM at (A) Gold Ray Dam, (B) Savage Rapids Dam, (C) Brownsville Dam and (D) Oak Creek culvert. The uncertainty probability ranges from 2 to 48%. DoDs relative to year 1 DEM at Savage Rapids Dam and relative to pre-removal DEMs at all other sites. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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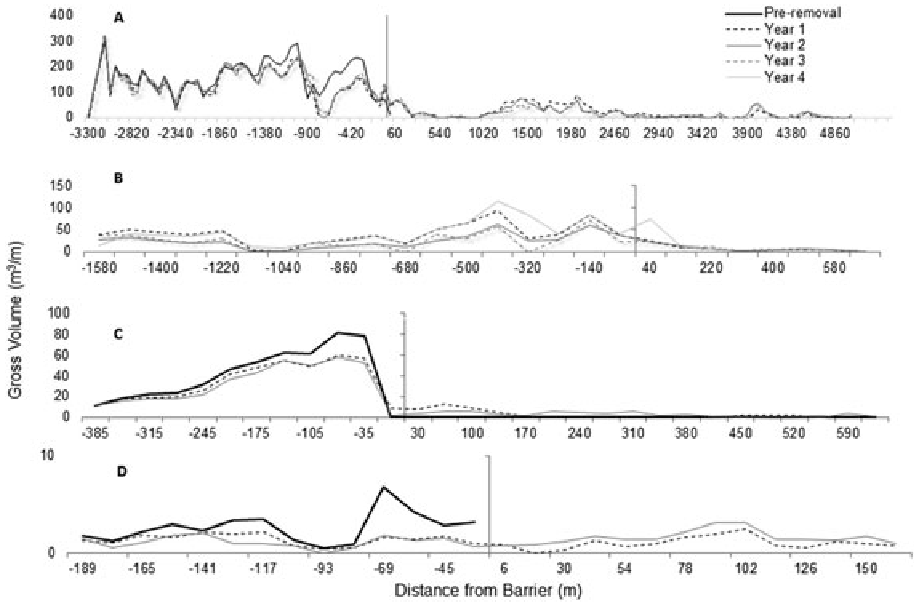

Figure 5. Gross volumes at (A) Gold Ray, (B) Savage Rapids, (C) Brownsville and (D) Oak Creek

suggest that dispersion was the dominant process at the sites, with individual years (e.g. year 4 at Savage Rapids) potentially displaying behaviour more consistent with translation.

The remaining indicators provided inconclusive evidence regarding the dominance of translation or dispersion at each site. The length of the middle 50% of volume indicated that the pulse length decreased in the final survey year at all sites, which did not provide support for translation or dispersion. Measurement of upstream movement of the pulse median locations during year 2 at Gold Ray and year 3 at Savage Rapids suggested sediment accumulation upstream of the sediment pulses, which was likely associated with dispersion. However, these cases of upstream movement of pulse median were accompanied by shortening of the pulse length, which was inconsistent with dispersive pulse behaviour.

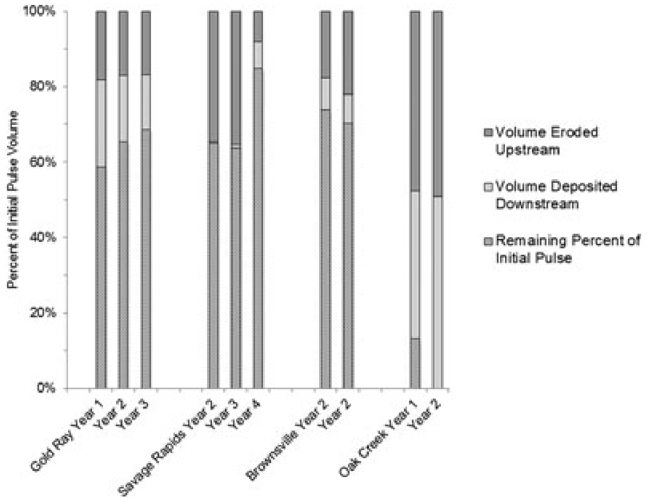

Figure 6. Eroded and deposited volumes as percentage of initial pulse volume. The grey hatched area represents the remaining percent of the initial pulse volume that either remains upstream, erodes downstream or is lost to the downstream barrier

Predicted pulse behaviour

Based on previous experiments, we expected that translation would occur where Froude numbers were less than 0.4, grain-size ratios were less than 1.0, pulse size ratios were small and volume ratios were large. At least one of these conditions (Table III) occurred at every site, although most sites had only one condition indicative of translation. Consistent with the absence of established thresholds for

Table III. Results of methods to predict pulse behaviour at each site

	Gold Ray	Savage Rapids	Brownsville	Oak Creek
Froude number	0.82	0.23	0.40	0.93
Grain-size ratio	0.40	0.38[1]	1.3	0.23
Pulse size ratio	0.16 (2)	0.04 (1)	0.19 (4)	0.17 (3)
Volume ratio	205 (3)	1280 (2)	1720 (1)	[2]

Shaded boxes indicate a prediction that translational movement will exceed dispersive movement. Numbers in parentheses indicate ranking of predicted translation relative to others sites.

[1] Topography and bathymetry from the first year following dam removal (‘year 1’) are substituted for the missing pre-removal data.

[2] Flow data were not estimated at culvert location.

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distinguishing between dispersion and translation in the literature, the ranges for pulse size and volume ratios did not provide a definitive pulse size or volume associated with dispersive pulse behaviour, but the larger volume ratios were associated with evidence of translational movement. The Froude number was equal to or below 0.4 for Savage Rapids and Brownsville, which are also the only two sites where there was evidence of stronger translational movement than dispersive movement (Table II). The grain-size ratio inaccurately suggested that translation should have been evident at all sites but Brownsville, indicating the reliability of small relative pulse material grain size as a predictor of translation may be low.

If high flows supported translational behaviour, and the 1.2 RI event was adequately high to translate a pulse, then all sites during most years should have had adequate flows for translation of the pulse (Table IV). Gold Ray, Savage Rapids and Brownsville all experienced at least one wet water year when peak discharge exceeded the 1.2 RI. The duration of flows greater than the 1.2 RI was longest in the second year following dam removal at Brownsville and first year at Oak Creek. The magnitude of peak discharge relative to the 1.2 RI was largest in the first year at Oak Creek. Neither the duration nor magnitude appeared to predict years in which translation was most strongly expressed.

DISCUSSION

Anticipating how a pulse of sediment will move following dam removal can support managers and planners in designing strategies for sediment management, stabilization and/or excavation to protect downstream infrastructure and habitat. Improving predictions of pulse behaviour according to variables that are measurable in the field prior to dam removal would enable future removals to confidently plan for the effects of either translational or dispersive pulse behaviour.

Hypothesized and observed pulse behaviour

The results agreed with past work that dispersion dominates pulse behaviour (Cui *et al*., 2003; Lisle, 2008) and found limited evidence of translational movement exceeding dispersive movement in the first year following dam removal. Following the first year post removal, individual indicators of translation suggested that flow conditions may lead to some downstream movement of the pulse median.

The results provided some support for the application of Froude number as a predictor of pulse behaviour. The two sites with limited evidence of translation exceeding dispersion were also the only sites with Froude numbers less than or equal to the 0.4 threshold observed in flume studies (Lisle *et al.* 2001; Cui *et al.* 2003a), and the two sites characterized by Froude numbers greater than 0.4 have no evidence of translational movement exceeding dispersive movement. Although the increased mobility of finer pulse grain size can lead to translational behaviour of the pulse (Lisle *et al.* 2001), our results did not support the use of grain-size ratio as a predictor of pulse behaviour in these systems. The grain-size ratio was less than 1 for all sites except Brownsville, leading to the incorrect expectation for these sites that translational behaviour should be evident in the changing pulse over time. Comparison of observed behaviour to hydrologic year indicated no clear connection between evidence of translation and wet water years, although it is possible that the 1.2 RI was not adequately high (e.g. Humphries *et al.* 2012) to trigger translation. Comparison of observed behaviour with volume ratio suggested a connection between evidence of translation and large flow to pulse volume ratios, but no applicable threshold was identified. Finally, the results did not support the application of pulse size ratio as a predictor of pulse behaviour.

Critique of methods for investigating pulse behaviour and further research

The methods to characterize pulse behaviour defined herein offer quantitative approaches to evaluate sediment pulse behaviour, but the results highlight limitations in accurately measuring initial volume and assessing translation in field settings. The limitations also inform further development of quantitative methods to evaluate pulse behaviour.

The measurement of initial pulse volume in the field was limited by the typical absence of pre-dam data. The methods

Table IV. Peak discharge, percent of post-removal water year with flows exceeding the 1.2 RI and peak discharge as a multiple of the 1.2 RI

	Gold Ray			Savage Rapids				Brownsville		Oak Creek	
Year	1	2	3	1	2	3	4	1	2	1	2
Peak discharge (cm)	530	550	1080	320	710	810	1080	85	123	49	18
% WY	0.4%	0.4%	0.7%	0	0.5%	0.6%	0.4%	0	0.8%	0.8%	0.3%
Peak/1.2 RI	1.5	1.6	3.1	0.6	1.6	1.7	2.4	0.8	1.2	3.5	1.3

Water years that exceed the 1.2 RI discharge are shaded.

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assumed that the pre-removal gross volume equals the volume between a linear valley surface and the pre-removal DEM and is zero downstream of the barrier, despite the fact that all the barriers were known to pass sediment. If some of the initial volume were to include the channel bed material upstream of the dam, the initial volume would be overestimated. The volume of sediment deposited downstream following dam removal would appear to be a smaller percent of the initial volume, causing an underestimation of translational movement.

The length of middle 50% of volume results reflects another key challenge in measuring pulse movement in the field. The decrease in pulse length that causes an inconclusive measurement of dispersion in some survey years may be explained by the loss of pulse material from the downstream edge of the pulse across the survey boundary, as documented at Savage Rapids, Brownsville and Oak Creek. This transport of pulse material out of the study reach can result in underestimating the pulse length. A loss of pulse material to the downstream boundary may also explain the inconclusive Péclet numbers found at Gold Ray, Savage Rapids and Brownsville, which are the result of decreasing variance in the spatial distributions of gross volume.

In order to better link generalized sediment pulse behaviour to sediment mobilization and transport processes, it would be useful to investigate how pulse behaviour changes throughout the hydrologic year and river network. Consistent with other studies (e.g. Tullos and Wang, 2014; East *et al.*, 2015), our results indicate that the largest rate of scour from the initial pulse occurs in the first year following dam removal. More sub-annual study within both phases of reservoir erosion, representing the initial base level lowering and the subsequent event-driven erosion (Pizzuto, 2002), may support refining predictors by more fully explaining the processes associated with translational and dispersive pulse behaviour. In addition, network position can influence pulse behaviour by transitioning a translational wave into a dispersive wave in reaches with substantial storage (Gran and Czuba, 2015). Future work should integrate network position and available storage in predictors of pulse behaviour.

CONCLUSION

Flume experiments suggest that sediment pulses disperse in place for most dams, although results from flume studies indicate that sites with a Froude number less than 0.4, fine pulse grain size, small pulse size and large discharge may be dominated by translation. Flume experiments lack realism of *in situ* variability in geometry and roughness, whereas field studies of pulse behaviour lack application of quantitative methods to the prediction and evaluation of pulse movement. We thus evaluated the evidence for dispersion and translation at four case studies and the ability of Froude number, grain size, pulse size and discharge to explain pulse behaviour.

While results provided some limited evidence of translational movement at all four sites, dispersion generally dominated pulse behaviour. The Froude number appeared to be the most reliable metric for anticipating pulse behaviour. The analysis of sediment pulses may be skewed by errors in establishing boundary conditions, particularly the pre-dam bed elevations and the longitudinal extent of the field survey. Finally, further work is needed to link generalized sediment pulse behaviour to sediment mobilization and transport processes.

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