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RESEARCH ARTICLE

The influence of coarse particle mobility on scour depth in salmonid spawning habitat

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Abstract

This study examined the influence of flow hydraulics and coarse particle mobility on bed scour adjacent to coho salmon (*Oncorhynchus kisutch*) redds in a coastal California watershed for a bankfull flood. It was theorized that coarse particle mobility (i.e., mobility of particles larger than the median bed particle size, D_{50}) exerts a strong control on bed scour depth. Maximum scour depth at the study sites was found to be negatively correlated with flow shear stress, which is dissimilar to findings from previous scour studies in spawning reaches. This resulted from a relatively similar coarse particle size (D_{84}) for all study sites and a negative relationship between shear stress and coarse particle exposure to flow (or the D_{84}/D_{50} ratio), which together caused sites with low shear stress to have a high degree of localized coarse particle mobility and an associated high maximum scour depth. This study provides new insights into the vulnerability of spawning reaches with low flow energy to redd scour and highlights the need to consider the mobility of coarse particle sizes explicitly when examining the dominant controls on redd scour.

KEYWORDS

bed mobility, river management, salmon habitat, scour depth

1 | INTRODUCTION

Recovery of endangered Pacific salmon (*Oncorhynchus* spp.) populations requires an understanding of how geomorphic processes affect habitat characteristics and population dynamics. For Pacific salmon populations that spawn during the winter wet season, sediment mobility in spawning areas is a particularly important control on reproductive success (Montgomery, Buffington, Peterson, Schuett-Hames, & Quinn, 1996). During reproduction, female salmon excavate gravel nests or "redds" within the streambed where fertilized eggs are buried to incubate for weeks or months. Eggs are often buried to a depth that is approximately twice the diameter of the largest gravels present (DeVries, 2008). Scouring of redds during winter high flows can have considerable negative impacts on egg survival due to either egg evacuation and entrainment when scour depth exceeds egg burial depth (Kondolf, Cada, Sale, & Felando, 1991; McNeil, 1966; Shellberg, Bolton, & Montgomery, 2010) or egg entombment and suffocation caused by fine sediment in the active bed load transport layer depositing within gravels that lie just above buried eggs (Chapman, 1988; Lisle, 1989; Sear, Frostick, Rollinson, & Lisle, 2008). Understanding the controls on scour depth during commonly occurring high flow events that mobilize spawning gravel (e.g., bankfull floods with a recurrence interval of 1.5 to 2 years) can be useful for managers needing to develop effective spawning habitat improvement strategies for endangered winter spawning salmon.

Bed scour depth is often examined as a function of Shields stress (τ^*_{D50}; e.g., Cienciala & Hassan, 2013; DeVries, 2002; Hales, 1999; Haschenburger, 1999; May, Pryor, Lisle, & Lang, 2009; Shellberg et al., 2010; Wilcock, Barta, Shea, Kondolf, Matthews, & Pitlick, 1996), which is essentially the ratio of local boundary shear stress to the median bed particle size:

$$\tau*_{D50} = \frac{\rho_w gRS}{(\rho_s - \rho_w) gD_{50}} \tag{1}$$

where ρ_w is water density (kg/m^3), ρ_s is sediment density (kg/m^3), g is gravitational acceleration (m/s^2), R is flow hydraulic radius or average flow depth (meters), S is water surface slope (m/m), and D_{50} is the median particle diameter (meters). Some studies show a strong positive correlation between scour depth and τ^*_{D50} (e.g., May et al., 2009; Shellberg et al., 2010), whereas others show neither a strong positive or negative correlation (e.g, DeVries, 2002). Variability in the strength of correlation between scour depth and τ^*_{D50} may be driven in large part by additional factors that strongly influence bed particle mobility and subsequent scour such as bed particle structuring (Church, Hassan,

& Wolcott, 1998) and bed particle sorting (Carling, 1983). Further exploration into the relationship among shear stress, bed particle characteristics (e.g., size, structure, and arrangement), and bed scour is therefore necessary to clarify the connection between bed particle mobility and scour depth.

In principle, the mobility of the largest (or coarsest) bed particles should have a strong control on bed scour depth during sediment transporting flow events. As the coarsest particles mobilize, the active bed load transport layer becomes thicker, increasing the depth of scour (DeVries, 2002). The critical boundary shear stress required to mobilize coarse bed particles (i.e., particles larger than D_{50}) can be determined with the equation:

$$\tau_{\mathrm{crit}D_i} = D_i \left[a \left(\frac{D_i}{D_{50}} \right)^{b} \right] (\rho_s - \rho_w) g \tag{2}$$

where D_i is the bed particle size for which i% of the bed particles are finer (meters), a is a dimensionless parameter associated with critical τ^*_{D50} value for incipient motion ($\tau^*_{\mathrm{crit}D50}$; Andrews, 1983), and b is a dimensionless "hiding factor" between −1 and 0 that describes the degree of bed particle embeddedness (Parker, 1990). Focusing on the particle size variables, this equation can be reduced to

$$\tau_{\mathrm{crit}D_i} \propto D_i * \left(\frac{D_i}{D_{50}} \right) \tag{3}$$

where the shear stress required to move D_i is proportional to the absolute size of D_i as well as the size of D_i relative to D_{50}. For well sorted bed sediment mixtures, the shear stress required to mobilize high D_i value particles (e.g., D_{84}) and D_{50} particles can be similar because the particle sizes are similar (Andrews & Parker, 1987; Parker, Klingeman, & McLean, 1982; Wilcock, Kenworthy, & Crowe, 2001). In such instances, the mobility of high D_i value particles is primarily a function of the absolute size of the particles. For poorly sorted sediment mixtures, greater size differences between high D_i value particles (i.e., coarse particles) and D_{50} particles result in a higher D_i/D_{50} value and greater degree of coarse particle exposure to flow, which can promote a high degree of coarse particle mobility. Consequently, coarse particle mobility and subsequent bed scour depth are controlled by the interplay between exposure to flow and the absolute particle size. Although fundamentally important for understanding physical controls on bed scour and egg vulnerability, explicit connections between bed particle size variables that influence coarse particle mobility and bed scour depth in spawning reaches have not been adequately explored.

The goal of this study was to examine the relationship between flow hydraulics, coarse particle mobility, and scour depth around coho salmon (*Oncorhynchus kisutch*) redds for a bankfull flood event. The study investigated: (a) correlations between the bed particle size variables that influence coarse particle mobility and scour depth and (b) hydraulic controls on the bed particle size variables that influence coarse particle mobility. The results are intended to further the understanding of physical habitat features that control egg vulnerability to flood disturbance, thereby helping watershed managers focus restoration resources on priority areas.

2 | METHODS

2.1 | Study area

This study was conducted in the Lagunitas Creek watershed, Marin County, California, which originates on the northern slopes of Mt. Tamalpais (elevation ~785 m above mean sea level). The creek flows predominantly through rural oak (*Quercus* spp.), redwood forest (*Sequoia sempervirens*), and grassland (*Nassella* spp.) landscapes underlain by Franciscan mélange before entering Tomales Bay, a structural feature within the San Andreas Rift Zone (Jennings, 1994; Lawrence, Resh, & Cover, 2013; Figure 1). The watershed has a Mediterranean climate (i.e., dry summers and mild winters), with rain falling primarily between November and March and the largest annual floods typically occurring between December and February. Flow and sediment delivery are altered by a series of municipal water supply reservoir dams that regulate approximately 45% of the total watershed area.

The watershed supports coho salmon and steelhead trout (*Oncorhynchus mykiss*), and Chinook salmon (*Oncorhynchus tshawytscha*) in some years. The coho salmon population is included in the Central California Coast evolutionary significant unit, and is listed as endangered under the United States Endangered Species Act. The population is currently a fraction of its historical abundance due in large part to anthropogenic impacts on spawning and rearing habitat throughout the watershed (see Napolitano, 2014 and references therein).

Coho salmon return to Lagunitas Creek beginning in late November, with peak spawning in late December, as is typical of Central California Coast populations. Preferred spawning sites have loose, silt-free, coarse gravel, and nearby cover for adults (Moyle, 2002). Female salmon typically build redds in the transitional area at the downstream end (or tail) of pools where flow accelerates (Mull & Wilzbach, 2007). Coho salmon eggs incubate for 35–50 days at water temperatures of approximately 9 to 11 °C (Shapovalov & Taft, 1954). Coho salmon fry typically emerge from redds between late February and late March. Consequently, coho salmon eggs incubate in the streambed during the period with the highest annual stream flows.

2.2 | Study sites

We established study sites in channel reaches with newly built coho redds in early December 2004. We conducted redd surveys in known coho spawning reaches within mainstem Lagunitas Creek and Olema Creek (a major tributary that enters Lagunitas Creek near Tomales Bay) on December 13 and December 14, 2004 just after the first freshet of the 2004–2005 high-flow season. The surveyed reaches ranged in length from approximately 100 to 150 m. Coho redds were identified by direct observation of female salmon building redds and through discerning recently cleaned and mounded gravel. We sketched field maps, photographed spawning reaches, and flagged the stream banks to document the location of each redd.

In total, we established three study sites with a total of five redds on mainstem Lagunitas Creek (Site 1, Site 2, and Shafter site) and one study site with two redds on Olema Creek (Olema site; Figure 1). The sites were characterized by pool-riffle and riffle-run morphology,

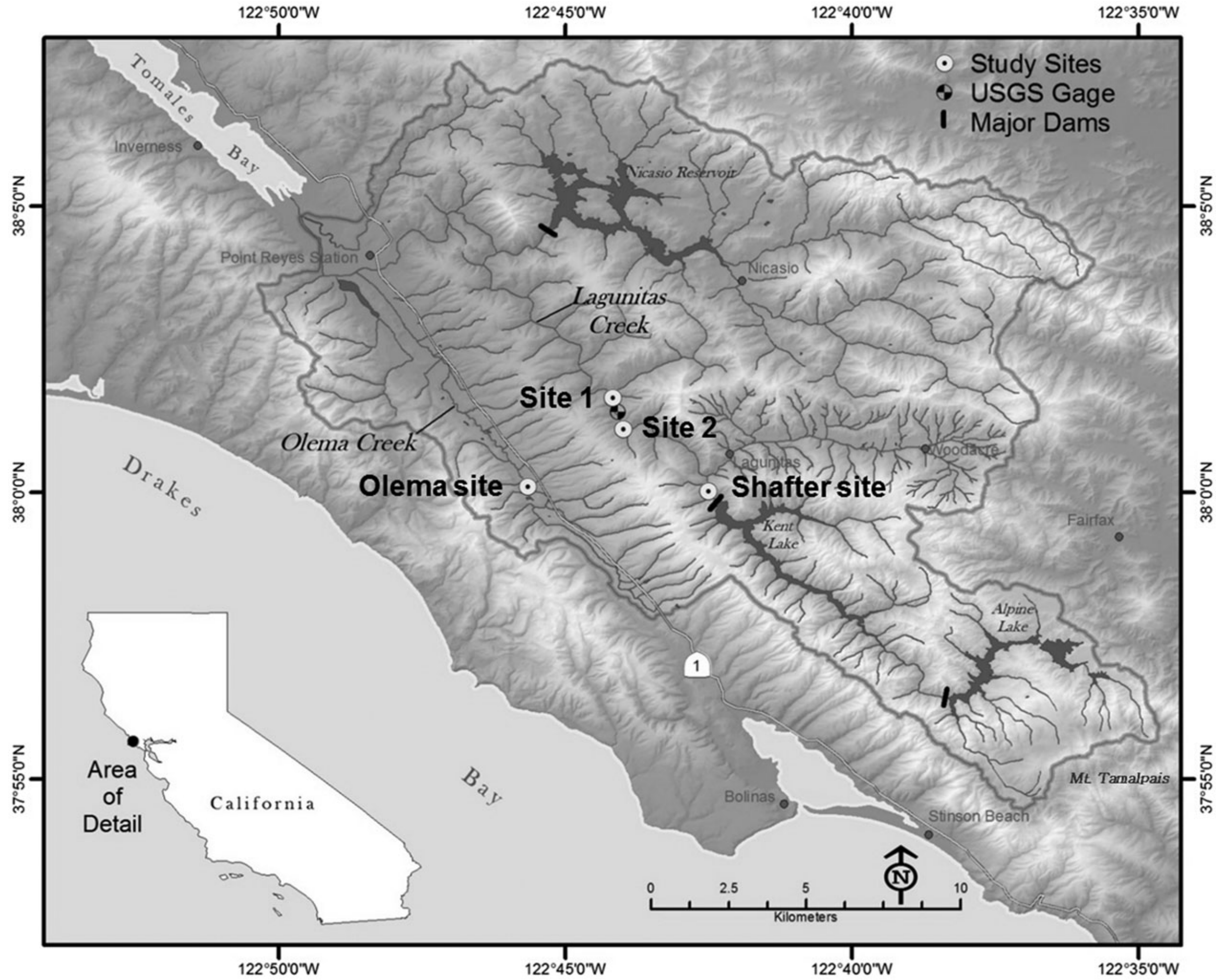

FIGURE 1 Location map of Lagunitas Creek watershed and study sites

median bed particle sizes in the coarse to very coarse gravel (16–64 mm) range, and reach-average channel bed slopes less than 0.01, typical of coho spawning reaches throughout the watershed (Table 1). We selected only the redds away from major flow obstructions that could impact local flow hydraulics and bed scour dynamics (e.g., large wood and bedrock outcrops).

2.3 | Hydrology

The relative magnitude (or recurrence interval) of storm flows at the study sites during the 2004–2005 high-flow season was determined using flow data from United States Geological Survey (USGS) gage 11460400 between Sites 1 and 2 (Figure 1). We first calculated the exceedance probability and associated recurrence interval for the gage's annual maximum instantaneous discharge values for water year 1983 to water year 2004. We then generated the gage's flood frequency curve (i.e., the fitted curve through the relationship between annual maximum instantaneous discharge and recurrence interval) using the log-Pearson Type III distribution method (Water Resources Council, 1981). Finally, we used the flood frequency curve to determine the recurrence intervals of the largest hourly storm flows recorded at the gage between December 1, 2004 and January 30, 2005, which in turn were used as estimates of storm flow recurrence interval at all four study sites.

TABLE 1 Key physical characteristics of the study sites

	Site 1	Site 2	Shafter site		Olema site	
Morphology	Pool-riffle	Pool-riffle	Riffle-run		Pool-riffle	
Reach-average channel slope	0.0021	0.0032	0.0041		0.0075	
Number of discrete bed sediment facies	1	1	2		2	
Bed particle sizes for discrete bed sediment facies (mm)						
D_{50}	31	30	23	30	36	43
D_{84}	60	54	52	68	55	64
D_{90}	74	58	59	70	70	78
Number of study redds within discrete bed sediment facies	2	1	1	1	1	1

2.4 | Geomorphic characteristics

At each study site, we surveyed a longitudinal profile of the streambed and channel cross-sections using a laser total station and rod-mounted prism. Longitudinal profiles captured thalweg elevations from the pool or run upstream of the study redds to the pool or run downstream, covering a channel distance between 130 and 185 m. One cross-section was surveyed through the "mound" of each study redd (i.e., the area with mounded gravel on top of buried eggs) in the portion of the channel presumed to be inundated during bankfull floods. We used depositional bar features, scoured bank vegetation, debris lines on banks, and distinct breaks in bank angle as the key channel indicators for identifying the approximate bankfull flood water surface elevation (Harrelson, Rawlins, & Potyondy, 1994). To ensure that redds were not disturbed during the cross-section surveys, we measured bed surface elevations by lowering the prism rod from a platform suspended above the channel bed. Longitudinal profile and cross-section elevations were measured at approximately 1-m intervals with an accuracy of ±0.5 cm.

To characterize local bed texture, we conducted Wolman (1954) pebble counts within discrete homogenous sediment patches (or sediment facies) surrounding each study redd. Site sediment facies were delineated on the basis of visual estimates of significant bed texture changes (e.g., a shift from predominately sand to predominately gravel). Sites 1 and 2 each had one dominant bed sediment facies type, while Shafter site and Olema site both had two dominant types (Table 1). Pebble counts within each of the sediment facies consisted of measuring the intermediate axis (or *b*-axis) of 100 bed particles to the nearest millimeter.

Pebble count data were compiled to determine D_{50}, D_{84}, and D_{90} values for the sediment facies adjacent to each redd (Table 1). The D_{50} and D_{84} values were used to determine the degree of bed particle sorting (D_{84}/D_{50}) and the associated degree of coarse particle (D_{84}) exposure to flow. We used the D_{84}/D_{50} ratio because it is commonly used in studies investigating the influence of bed particle sorting and coarse particle exposure to flow on flow resistance and sediment mobility (e.g., Ferguson, 2012; Millar, 1999; Wiberg & Smith, 1991). The D_{90} values were used to normalize bed scour values (described below).

2.5 | Flow hydraulics

Flood peak water surface elevations were monitored at each study site using a pair of crest gages. Crest gages were 1.2 m-long, 5 cm-diameter perforated PVC pipe encasing a 1.2 m × 2.5 cm × 4 cm piece of wood and crushed cork. At Site 1, Shafter site, and Olema site, we installed crest gages adjacent to the most upstream and downstream study redds and located 20 to 65 m apart. At Site 2, we installed gages approximately 80 m apart at the upstream and downstream ends of the reach that contained the one study redd. The bottom of each crest gage was surveyed and tied to the same local datum as the nearby channel cross-sections. Flood peak water surface elevation at each gage was recorded on the encased wood by floating crushed cork. At Site 1, Site 2, and Olema site, water surface elevations of the largest flood event (i.e., the bankfull flood event) were corroborated by water surface elevations recorded at nearby channel cross-sections (described above). At Shafter site, local vegetation interference during the bankfull flood caused the crest gage data to be unusable so we relied solely on the bankfull flood water surface elevations from the channel cross-sections.

Water surface elevation data were combined with cross-section elevation data to determine the bankfull flood water surface slope and average flow depth at each study redd. These data were then used to calculate bankfull flood boundary shear stress ($\tau_{bf} = \rho_w gRS$) and bankfull Shields stress (τ^*_{D50bf}) at each redd. At all sites, similarity in the bankfull flood water surface slope and the reach-average bed slope provided an indication of relatively uniform flow, a requirement for using the depth–slope product to determine boundary shear stress (Sime, Ferguson, & Church, 2007).

2.6 | Bed scour dynamics

Bed scour depths adjacent to each study redd were monitored using a network of scour chains (Lisle & Eads, 1991). Scour chains were 100 cm-long heavy gage steel links installed to a depth of approximately 30 cm, which was below the anticipated depth of bed scour for a bankfull flood event and approximately twice the anticipated average coho egg burial depth (on the basis of data from DeVries, 1997). It was not possible to install scour chains within the coho redds without damaging incubating eggs, so we installed chains around the redds. At most redds, we installed a chain upstream, downstream, and on left and right sides of the redd within 10 cm of the delineated redd boundary (Figure 2). The upstream redd (redd 1) at Site 1 was the only exception, where a chain could not be installed to the left of the redd because the redd boundary was against the left bank. The monitoring approach assumed that bed scour depth immediately adjacent to each redd was similar to scour depth in the redd, which has been shown in previous redd scour studies (e.g., Rennie & Millar, 2000). Upon installation, we measured the length of exposed chain above the bed to the nearest 0.5 cm and then placed the chain horizontally on the bed surface oriented downstream. The length of exposed chain was re-measured to the nearest 0.5 cm after the bankfull flood to assess the storm-induced scour depth. At locations where bed scour was followed by sediment deposition, we carefully excavated the chain prior to measuring the horizontal length.

For each study redd, maximum bed scour depth was selected for subsequent comparisons with adjacent bed particle size data and local hydraulics. Following recommendations from previous redd scour studies, maximum scour depth at each redd was normalized by the D_{90} value for the surrounding bed to indicate the magnitude of scour relative to the thickness of the surface bed layer (~1D_{90}) and the anticipated average egg burial depth (~2D_{90}) (DeVries, 2008; Shellberg et al., 2010; Wilcock et al., 1996).

3 | RESULTS

3.1 | Scour dynamics for a bankfull flood event

On December 27, 2004, one week after completing initial data collection and instrument installation, Lagunitas Creek experienced a flood

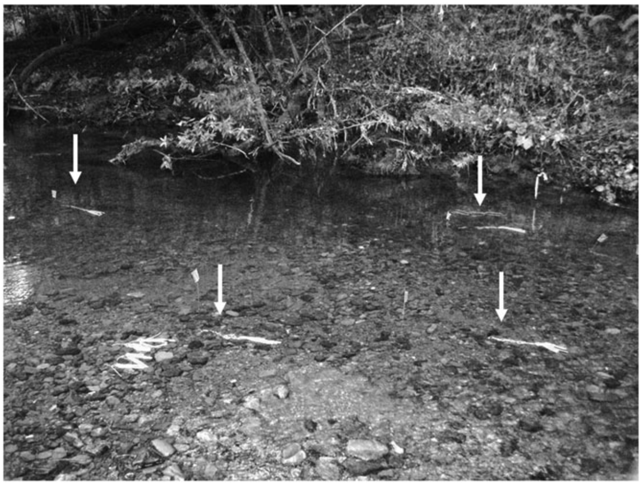

FIGURE 2 Scour chain installation design showing chains upstream, downstream, to the left, and to the right of a study redd. White arrows indicate scour chain locations. Flow direction is from left to right

event with a recurrence interval between 1.5 and 2 years (peak discharge ~50 m^3/s at the USGS gage; Figure 3). The observed flow stage at all four study sites around the time of the flood peak at the USGS gage closely matched bankfull flood stage indicators identified during the initial cross-section surveys, confirming that the flood was a bankfull flood event at all study redds. A subsequent storm flow (peak discharge ~22 m^3/s at the USGS gage) occurred on December 29 before the post-bankfull flood data collection could be completed, but it was assumed to have had a negligible impact on the December 27 flood scour depth recorded by the scour chains.

Table 2 summarizes the bankfull flood scour depths around the study redds indicated by increased scour chain length. We recovered 26 of the 27 chains installed, having to excavate one chain at Shafter site and all four chains at Olema site. The chains recorded scour depths ranging from <0.5 to 10 cm. The maximum scour depth was similar for the two redds within Site 1 (7 and 9 cm), Shafter site (8 and 10 cm), and Olema site (4.5 and 5 cm). As most redds were located near the channel thalweg, maximum scour depth was typically upstream or downstream of the redd within the zone of relatively high flow depth and velocity. Channel cross-sections through the study redds showing redd boundaries and bankfull flood stage are given in the Supplementary Information.

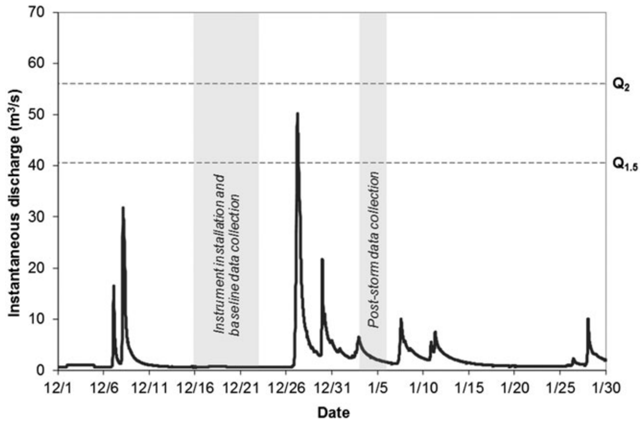

FIGURE 3 Instantaneous discharge during the 2004–2005 study period at United States Geological Survey (USGS) gage 11460400 (Lagunitas Creek at Samuel P. Taylor State Park) with the 1.5-year flood ($Q_{1.5}$) and 2-year flood (Q_2) discharge values. Pre- and post-storm data collection periods are also identified

Comparing normalized maximum scour depth adjacent to the seven study redds with local bankfull flood hydraulics shows an overall negative relationship (Figures 4 and 5). The correlation between τ_{bf} and maximum normalized scour depth shows a strong negative power-function relationship (R^2 = .87; p = .007), with a factor of ~2 increase between the lowest and highest boundary shear stress values (28.7 to 55.1 N/m^2) corresponding to a factor of ~3 decrease in maximum bed scour adjacent to the study redds (1.7 to 0.6 the local D_{90} value; Figure 4). The correlation between normalized maximum scour depth and $\tau^*_{D50\mathrm{bf}}$ is not as strong but does clearly show a statistically significant negative power-function relationship as well (R^2 = .62; p = .05), with a similar factor of ~2 increase between the lowest and highest Shields stress value (.048 to .095; Figure 5).

3.2 | Particle size characteristics associated with coarse particle mobility

The critical shear stress required to initiate coarse bed particle transport and local bed scour is driven by the relationship between absolute particle size (D_{84} in this study) and degree of particle exposure to flow (D_{84}/D_{50}). Examination of the D_{50} and D_{84} values adjacent to the study redds shows that D_{50} is positively correlated with τ_{bf} (R^2 = .68; p = .02), yet the D_{84} values show no consistent increase with an increase in τ_{bf} (Figure 6). The D_{50} values increase with τ_{bf} in a linear fashion from approximately 22 mm at 19.3 N/m^2 to approximately 36 mm at 55.1 N/m^2, while the D_{84} values show no correlation with an increase in τ_{bf} (R^2 = .01; p = .87) and a low degree of variance around a mean value of 59 mm (coefficient of variation = .1; Figure 6). These conditions result in the degree of D_{84} exposure to flow having a strong negative correlation with τ_{bf} (R^2 = .98; p = .00003; Figure 7). The site with the lowest τ_{bf} values (Shafter site) has D_{84} values approximately 2.3 times larger than D_{50}, while the site with the highest τ_{bf} values (Olema site) has D_{84} values approximately 1.5 times larger than $D_{50.}$

3.3 | Relationship between coarse particle exposure to flow and scour depth

Comparing the D_{84}/D_{50} ratio values adjacent to the study redds and the normalized maximum scour depth values for the bankfull flood event shows a strong positive relationship (R^2 = .81; p = .009; Figure 8). Combining the findings from Figure 8 with those from Figures 6 and 7 indicate that, in general, the study redds exposed to the lowest τ_{bf} values had the highest D_{84}/D_{50} ratios, considerable localized coarse particle mobility (i.e., τ_{bf} values that exceeded local $\tau_{\mathrm{crit}D84}$ values), and in turn the highest normalized maximum bed scour values. Figure 8 shows that D_{84}/D_{50} explains a high percentage (>80%) but not all of the variability in normalized maximum bed scour values. The remaining variability is explained in large part by factors controlling coarse sediment transport and subsequent scour not explicitly accounted for in this study, including the variables in addition to D_{50} and D_{84}/D_{50} that drive $\tau_{\mathrm{crit}D84}$ values (e.g., $\tau^*_{\mathrm{crit}D50}$ and the hiding factor associated with particle embeddedness).

TABLE 2 Scour depths (cm) for the 12/27/04 bankfull flood event indicated by scour chains installed directly adjacent to the study redds

	Site 1		Site 2	Shafter site		Olema site	
	Redd 1	Redd 2	Redd 1	Redd 1	Redd 2	Redd 1	Redd 2
Upstream	<0.5	9	<0.5	10	<0.5	4.5	<0.5
Downstream	7	8	4	<0.5	<0.5	1	5
Left	*No chain installed*	6	1	*Not recovered*	<0.5	4	<0.5
Right	0.5	8	<0.5	<0.5	8	2	<0.5

Note. The underlined values are for chains that needed to be excavated. Redd identification numbers within the study sites increase moving downstream.

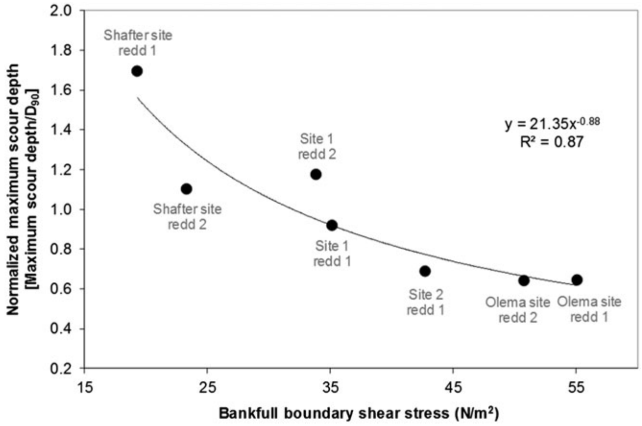

FIGURE 4 Maximum scour depth for each study redd normalized by the adjacent bed D_{90} versus boundary shear stress for the 12/27/2004 bankfull flood event. Redd identification numbers within the study sites increase moving downstream

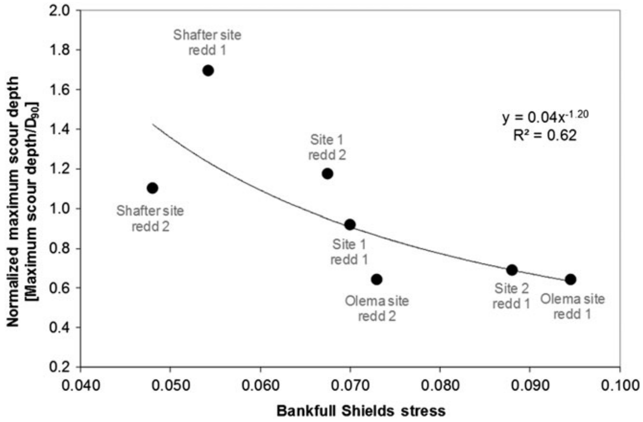

FIGURE 5 Maximum scour depth for each study redd normalized by the adjacent bed D_{90} versus Shields stress for the 12/27/2004 bankfull flood event. Redd identification numbers within the study sites increase moving downstream

4 | DISCUSSION

This study documents the importance of bed particle size characteristics in driving bankfull flood scour dynamics for coho salmon spawning areas in a coastal California watershed. The results show that maximum scour depth was negatively correlated with measures of shear stress (τ_{bf} and τ^*_{D50bf}) but positively correlated with coarse particle exposure to flow (as reflected by D_{84}/D_{50} ratios). Although the general setting for this study is similar to that of other studies examining hydraulic controls on redd scour (i.e., a modest-sized watershed with gravel-bedded reaches that support annual salmonid spawning), the results are quite different. Here, we discuss potential mechanisms underlying the results as well as the implications for management and monitoring of sediment dynamics in salmon-supporting watersheds.

4.1 | Controls on bed particle size factors that influence bed scour

Although we did not explicitly measure dominant local controls on the D_{84}/D_{50} ratio at the study sites, it is possible to infer these controls from site-scale geomorphic features and principles of hydraulic and depositional processes. Estimates of mean annual sediment yield to Site 1, Site 2, and Shafter site are similar at approximately 300 t/km^2/year when considering just the contributing watershed area below dams (Stillwater Sciences, 2010). These locations also have similar bedload particle size distributions during sediment transporting bankfull floods (as observed during this study). Field observations during this study also suggest similar conditions for the Olema site. Similarity in D_{84} values among the study sites, regardless of τ_{bf} value, therefore appears to be driven by similarities in long-term rates of coarse sediment delivery to and transport through the study sites. The increase in D_{50} at sites with greater τ_{bf}, along with its effect on decreasing the D_{84}/D_{50} ratio, appears to be driven by differences in local sediment transport and deposition dynamics. Lower boundary shear stress sites are inherently more depositional and accumulate finer sediment, resulting in smaller D_{50} values. These sediment delivery and deposition processes result in conditions in which sites with the lowest boundary shear stress have the highest D_{84}/D_{50} ratio values, greater localized coarse particle mobility, and deeper localized bed scour during bankfull floods.

The negative relationship between the D_{84}/D_{50} ratio and shear stress that we observed differs from previous research and may help explain our counterintuitive observation that bed scour depth was greater at sites with lower bankfull flood shear stress. Research in other watersheds in California (Pearce, O'Connor, McKee, & Jones, 2003), Colorado (Pitlick, Mueller, Segura, Cress, & Torizzo, 2008), and Maryland (Prestegaard, Dusterhoff, Stoner, Houghton, & Folk, 2000) found that both D_{50} and D_{84} values increased with greater τ_{bf}, but that D_{84} values increased at a higher rate, resulting in positive relationship between D_{84}/D_{50} and τ_{bf}. These physical characteristics could lead to situations where the interplay between D_{84} and the D_{84}/D_{50} ratio causes bed scour to be the greatest at sites with the greatest τ^*_{D50bf}

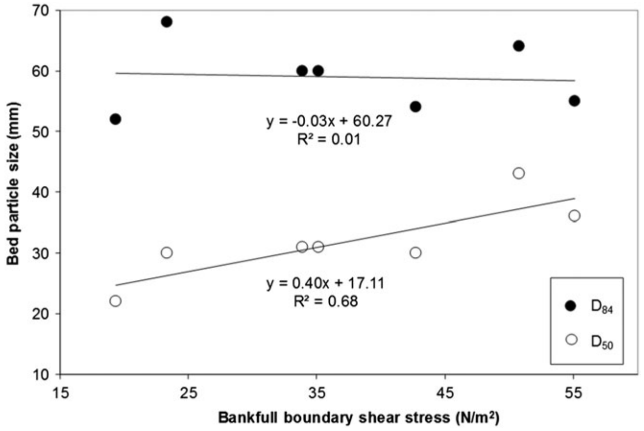

FIGURE 6 Median bed particle size (D_{50}) and coarse bed particle size (D_{84}) adjacent to the study redds versus 12/27/2004 bankfull flood boundary shear stress

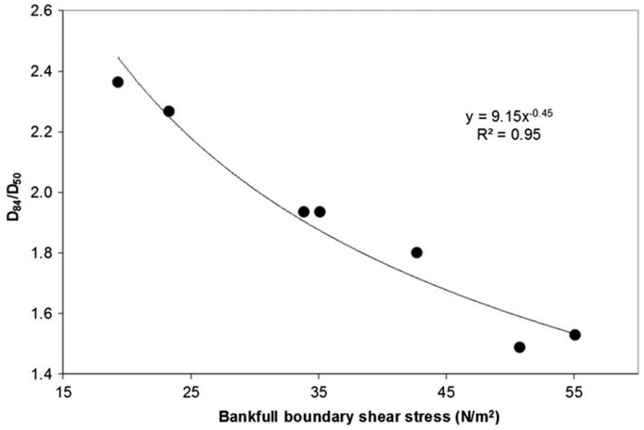

FIGURE 7 The D_{84}/D_{50} ratio (or degree of coarse particle exposure) for the bed adjacent to the study redds versus 12/27/2004 bankfull flood boundary shear stress

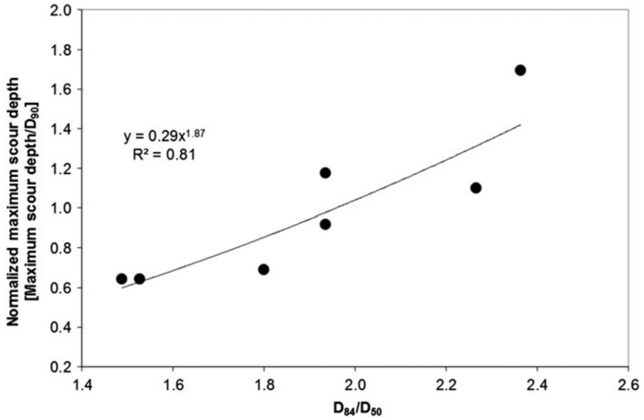

FIGURE 8 Maximum scour depth for each study redd normalized by the adjacent bed D_{90} versus the adjacent bed D_{84}/D_{50} ratio (or degree of coarse particle exposure)

(i.e., sites with high D_{84} values but also high D_{84}/D_{50} ratios), as has been shown in several previous redd scour studies (e.g., May et al., 2009; Shellberg et al., 2010). It is therefore likely that the positive relationship between τ^*_{D50bf} and scour depth for several sites shown in previous redd scour studies is controlled, at least in part, by the rate at which both D_{84} and D_{50} values increase with increasing boundary shear stress. More research is needed to understand how scour dynamics among sites differ in regions with different D_{84}/D_{50} ratio–shear stress relationships.

In order to avoid disturbing spawning coho, we measured streambed scour dynamics immediately adjacent to redds. Consequently, there is some uncertainty whether the processes occurring adjacent to redds are representative of what occurred within the redds themselves. Redd building by salmon locally removes fine sediment, coarsens the substrate, and increases form drag, which are predicted to decrease sediment mobility and redd scour during modest flood events compared to the adjacent undisturbed bed (Montgomery et al., 1996). However, these effects may be counteracted by the excavation and loosening of streambed sediment during redd building, which can make coarse sediment more mobile compared to undisturbed conditions (Buxton, Buffington, Yager, Hassan, & Fremier, 2015; Gottesfeld, Hassan, Tunnicliffe, & Poirier, 2004). Therefore, in some instances, bed mobility within a redd may be greater than in the adjacent streambed (Buxton et al., 2015). We suspect however that differences in sediment mobility between redds and adjacent unmodified streambed areas will be greater for salmon species and populations where mass spawning aggregations are more common (i.e., where large numbers of spawning salmon considerably change channel textural and geomorphic characteristics; Hassan, Tonina, & Buxton, 2015). A previous comparison of substrate mobility within and adjacent to redds for spawning densities similar to those seen in this study found no statistical differences in scour depth in these locations (Rennie & Millar, 2000). Therefore, in the context of our study and similar situations where spawning salmon densities are modest, sediment transport dynamics in the streambed adjacent to redds seem to provide a reasonable, if not conservative, representation of the mobility within the redds themselves.

4.2 | Implications for salmonid habitat management

Overall, this study adds new insight into the potential vulnerability of low flow energy spawning reaches to excess scour. In general, spawning reaches with overall low flow energy during commonly recurring winter bankfull floods (as indicated by low values of boundary shear stress, Shields stress, or stream power) are known to be susceptible to fine sediment deposition, making them vulnerable to redd entombment and egg suffocation (e.g., Naden et al., 2016). At the same time, these types of spawning reaches are typically considered to have a low degree of coarse sediment mobility and have relatively low vulnerability to redd scour (e.g., May et al., 2009). However, the results from this study show greater bankfull flood scour depths at lower shear stress sites, a phenomenon that we attribute to greater exposure of coarse particles as a result of depositional processes that produce finer D_{50} values. Although the scour depths did not exceed the anticipated average egg burial depth of ~$2D_{90}$, sites with greater coarse particle exposure to flow and scour can be considered more vulnerable to egg loss due to the potential for scour or entombment of eggs buried at shallow depths <$2D_{90}$. These results therefore indicate the need to collect appropriate baseline bed particle size and bankfull flood shear stress data and assess both redd entombment and scour risk at low shear stress spawning sites before developing spawning habitat management priorities and monitoring schemes.

This study also underscores the importance of considering indices of coarse particle exposure to flow (e.g., D_{84}/D_{50}) when calculating bed particle mobility at a resolution appropriate for habitat management. The results show that during a bankfull flood event, sites with lower boundary shear stress had greater maximum depth of scour due to high D_{84}/D_{50} values. In other words, the lower boundary shear stress sites had higher ratios of bankfull flood boundary shear stress to critical boundary shear stress required to move D_{84} ($\tau_{bf}/\tau_{critD84}$). Equation 2 shows that $\tau_{critD84}$ is a function of D_{84} and D_{84}/D_{50} as well as $\tau^*_{critD50}$ and a hiding factor associated with particle embeddedness. If single, arbitrary values for $\tau^*_{critD50}$ and the bed particle hiding factor are taken from the literature and used with this study's data to determine $\tau_{bf}/\tau_{critD84}$ (similar to the approach used by Lapointe, Eaton, Driscoll, and Latulippe (2000) to determine $\tau_{bf}/\tau_{critD50}$), the relationship between normalized maximum scour depth and $\tau_{bf}/\tau_{critD84}$ is negative, which does not make physical sense in light of this study's findings. Under the assumption that the measured τ_{bf} values are well constrained, the relationship is likely driven by incorrect $\tau_{critD84}$ values due to improper selection of the $\tau^*_{critD50}$ value and (or) the bed particle hiding factor. Recent research has shown that $\tau^*_{critD50}$ is strongly correlated with D_{84}/D_{50} values as well as channel slope (Ferguson, 2012) and therefore needs to vary accordingly. Similar cautionary notes regarding the use of arbitrary $\tau^*_{critD50}$ values from the literature in sediment transports studies have been around for some time (e.g., Buffington & Montgomery, 1997). Thus, D_{84}/D_{50} should now be considered one of the key variables that influences coarse particle mobility and should be included explicitly in management studies seeking to understand spawning reach susceptibility to scour.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Fig A1 Channel cross-sections through study redds at Site 1 and Site 2 with the approximate redd boundaries and maximum stage during the 12/27/04 bankfull flood event identified. Station values increase moving towards the right bank.

Fig A2 Channel cross-section through study redds at Shafter site and Olema site with the approximation redd boundaries and maximum stage during the 12/27/04 backfull flood event identified. Station values increase moving towards the right bank.

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