The Importance of Being Gravelly:
Lagunitas Creek Streambed Sediment in 1988 and 2011

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ABSTRACT

Streambed sediment quality is important for Coho salmon (*Oncorhyncus kisutch*). Lagunitas Creek, in Marin County, northern California, has experienced habitat degradation and declines in salmon populations that may be related to altered sediment regimes. I explored bed sediment composition of a 500 m reach in Lagunitas Creek that is below Peters Dam. It straddles Shafter Bridge, and includes the junction with San Geronimo Creek. To compare my results to those in a study done roughly 20 years ago, I conducted facies mapping, pebble counts, subsurface sampling, and longitudinal and cross-sectional surveys. I calculated percent coverage of various patch types, stresses experienced by the bed, and stresses needed to mobilize the subsurface and the surface layers of the streambed. The upstream sediment patches are more coarse than the downstream sediment patches. The streambed is also coarser than it was in 1988. The streambed experienced some localized spatial changes in the subsurface, surface, and bed shield stresses. Some coarse areas that previously had been composed of cobble or large gravel expanded in patch size. The pools and some runs had large amounts of fine sediment and sand on top of coarsened areas. The variability in spatial distribution, but not in diversity of patches, suggests that this section of Lagunitas Creek remained relatively stable over the past 20 years.

KEYWORDS

patches, gravel, salmon, shield stress, dam

INTRODUCTION

Coho salmon (*Oncorhyncus kisutch*) and sediment in mountainous gravel bed streams along the Pacific Northwest Coast are intricately related. Salmon require streambeds composed of gravel of a specific size in order to form and protect redds, depressions in which they lay their eggs (Galbraith, MacIsaac, Macdonald, & Farrell, 2006). Salmon egg survival also depends on subsequent sediment transport and water flows. The reduction of water flow and the loss of replenishing upstream sediment experienced by dammed streams can lead to the gradual coarsening and armouring of streambeds (Kondolf, 1997). If armouring occurs, the buried eggs risk being crushed (Kondolf, 1997). On the other hand, when stream power is low and a stream carries too much fine sediment, the stream deposits the sediment (Montgomery & Buffington, 1997). The settling of fine sediment into the cracks of gravel streambeds causes entrapment, which suffocates the eggs and reduces the likelihood of fertilization by decreasing the amount of dissolved oxygen present (Galbraith et. al., 2006). Because of the multitude of potential effects of the sediment upon the highly desired continuance of salmon spawning, the examination of sediment conditions is crucial in streams, like Lagunitas Creek, that serve as prime salmonid spawning habitat.

Historically a vibrant spawning habitat for the federally protected California Central Coast Evolutionarily Significant Unit of Coho salmon (Miller, 2010), Lagunitas Creek now experiences habitat degradation and losses in salmon spawning rates that may be related to altered sediment regimes (Cover, pers. comm.). Interest in this charismatic and economically profitable species has led to restoration efforts focused on decreasing fine sediment inputs from roads, mimicking of natural water flows through timed dam releases, and creating beneficial habitat structures like artificial pools and riffles through the installation of strategically placed woody debris and boulders (Hecht & Glasner, 2002). Despite these efforts, spawning surveys in the last few years suggest the Coho salmon population continues to be at an all-time low (Miller, 2010). One possible reason is the lack of mitigation efforts dealing with the effects that dams have upon sediment patterns in downstream reaches.

Figure 1. Peters Dam, Lagunitas, Marin, California. Downstream of Peters Dam on Lagunitas Creek

Built on Lagunitas Creek in 1954 to create the Kent Lake Reservoir for Marin County (Hecht & Glasner, 2002), Peters Dam serves as a major physical barrier, affecting subsequent geomorphological changes over time (Figure 1). In other study systems, the loss of replenishing upstream cobbles and gravels due to dams has led to the gradual coarsening and armouring of streambeds (Kondolf, 1997). Streambed armouring is detrimental to salmon spawning because the substrate is no longer loose enough for salmon to dig redds (Kondolf, 1997). Decreased water flow due to dams also aids the spread of larger aquatic plants that compete for space and increase entrainment on the gravel beds, leading to the overall reduction in suitability of the area for spawning (Merz, Smith, Workman, Setka, & Mulchaey, 2008). Despite the potential long-term impacts of Peters Dam upon sediment and salmon spawning habitat in Lagunitas Creek, comparison studies evaluating present day streambed sediment conditions as compared to past conditions have not been done. Such information could help guide future restoration efforts and contribute to the repository of information about mountainous stream response to major interventions like dams.

My study aimed to fill this information gap by exploring the upstream and downstream differences in the streambed substrate and salmon spawning suitability of a reach below Peters

Dam that includes the entrance of San Geronimo Creek into Lagunitas Creek. My first objective was to determine how the composition of the sediment patches and subsurface substrate of the Lagunitas Creek changed since 1988 observations (Kinerson & Dietrich, 1990). Second, I sought to establish if a noticeable spatial distribution to these changes exists before and after an important sediment input source, the entrance of San Geronimo Creek. Last, I evaluated whether there has been overall deterioration or improvement in potential salmon-spawning gravel beds.

METHODS

Study site

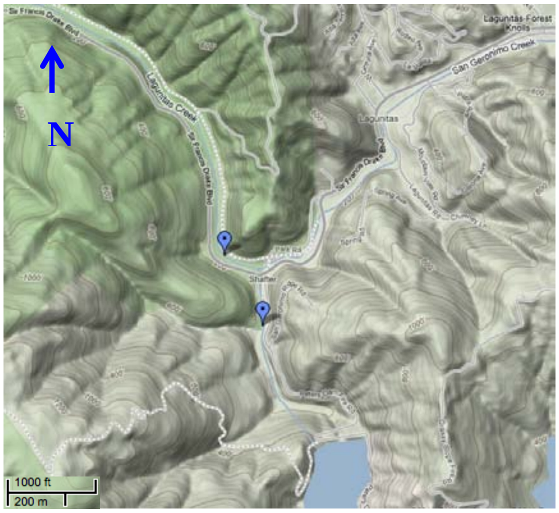

Figure 2. Topographic map of study site, Lagunitas Creek (Google Maps, 2011). The blue balloons approximately mark the study site with north directly up and flow to the north west.

I studied two sections of bed sediment within a 500 m reach of Lagunitas Creek where the San Geronimo Creek joins below Peters Dam (Figure 2). The downstream section starts about 250 m downstream of Shafter Bridge and extends upstream for 200 m. The upstream section extends about 100 m, including and extending up from the bridge. The headwaters of Lagunitas Creek begin on Mount Tamalpais, and the creek feeds into Tomales Bay. The watershed is made up of many mountainous streams with gravel as the primary bed surface substrate (Hecht & Glasner, 2002). Because of California's Mediterranean climate, the watershed experiences dry hot summers and cool rainy winters. The majority of sediment passes through the creek during the rainy winter season. Sediment transport at my study site is also affected by human interventions. Peters Dam, a major sediment flow obstruction, is about 300 m upstream of the study reach (Kinerson & Dietrich, 1990). The upstream reach reflects the effects of stopping the downstream sediment transport upon the streambed. San Geronimo Creek serves as an additional sediment source, and thus the downstream reach is different.

Data collection

Facies Mapping with Pebble Count

Facies mapping is a technique employed by geomorphologists and engineers to map surface sediment distributions. The facies maps I produced enabled me to assess the similarities and differences in sediment patches and average surface grain size, compared to the 1988 data (Kinerson & Dietrich, 1990) as a reference point. I used a 15 m tape to mark the longitudinal centerline of each section. I then proceeded to identify and map different patches by moving downstream to upstream and marking cross-sectional locations with a stadia rod, an instrument similar to a large extendable ruler. Each time the dominant grain size of the sediment changed, I marked a new section. Dominant is defined as roughly 80% of the composition is that grain size (Cover, pers. comm.). I based grain size on the following scale: sand (< 2 mm), gravel (fine [>2 mm - 8 mm], medium [>8 mm - 16 mm], large [>16 mm - 64 mm]), cobble (>64 mm – 256 mm), or boulder (> 256 mm) (Kondolf, Lisle &Wolman, 2005). Since I made several maps, I also took a compass reading down the centerline in order to be able to seam them together in the proper orientation at a later date. Although the facies mapping is a subjective process refined through practice of visual estimation, pebble counts helped to add greater degree of certainty by adding quantitative data about average grain size. I conducted pebble counts of 100 counts for poorly mixed patches and 50 counts for well-mixed patches (Kondolf et. al., 2005).

Longitudinal and cross-sectional surveying

Longitudinal and cross-sectional surveys yielded data needed to calculate slope. They also contributed to the data bank for future studies regarding bank stabilization. I used a stadia rod, a 100 m tape, a laser level, and a tripod to map elevation changes both along the cross section and along the longitudinal section. I marked bankfull height, which is an important parameter for the calculation of shear stress and as an indicator of water level during flood conditions.

Subsurface sampling

Subsurface sampling is used to determine the percent composition of the subsurface layer of the streambed, which approximates bed load (Kinerson & Dietrich, 1990) and average subsurface grain size. Martin Trso, a geomorphology consultant, and I processed two to three subsurface samples from both upstream and downstream sections of the reach (Trso, pers. comm.). We selected a 1 m^2 patch per sample and cleared the initial layer from the top of the site. We shoveled, sieved, and weighed roughly 100 kg worth of subsurface sediment. The sieves separated the following grain-sizes: greater than 32 mm, 16-32 mm, 8-16mm, 4-8mm, 2-4 mm, and 1-2 mm.

Data analysis

Facies map comparison

For 2011 data, I calculated percent coverage for each facies type for the reach as a whole, the downstream portion, and the upstream portion. I then compared the upstream and downstream site by evaluating change in percent coverage. I also calculated the mean percent coverage and standard deviation to assess significance.

Stress and Dimensionless Bedload Transport Ratio

I calculated the stresses experienced by the bed, the subsurface, and the surface of the bed, as well as the dimensionless bedload transport ratio, q^*, to determine whether or not the streambed is likely to experience bed sediment movement (Kinerson & Dietrich, 1990). I then compared the 2011 values to recalculated 1989 values. I recalculated the 1989 values because I found that the 1989 calculations (Kinerson & Dietrich, 1990) were incorrect by an order of magnitude. I used following equations (next page):

shear stress of the bed: $\tau_b = \rho g h S$

shear stress based on subsurface sediment: $\tau_{cs} = \tau^*(\rho_s - \rho)gD_{50s}$

shear stress based on surface sediment: $\tau_{css} = \tau^*(\rho s - \rho)gD_{50ss}$

dimensionless bedload transport ratio:

$$q' = \left[\frac{\left(\frac{\tau_b}{D_{css}} - \frac{D_{50s}}{D_{50ss}}\right)}{\left(\frac{\tau_b}{D_{css}} - 1\right)}\right]^{1.5}$$

τ_b *: bed stress.*

τ^* *: 0.0475*

τ_{css} *: critical subsurface stress*

τ_{cs} *: critical surface stress*

h : bankfull depth

ρ_s *: sediment density, 2600 kg/m*^{3}

ρ *: water density, 1000 kg/m*^{3}

g : gravity, 9.8 m/s^2

D_{50s}*: average surface sediment diameter*

D_{50ss} *: average subsurface sediment diameter*

RESULTS

Figure 3. Large woody debris on Lagunitas Creek. Two examples of large woody debris with some evidence of bank undercutting about 100 m upstream of Shafter Bridge.

Facies mapping

I found many instances of prior restoration infrastructure and substantial bank undercutting (Figure 3). Sand patches tended to line banks and occupy areas with large woody debris installations. The bed predominantly had cobble with some gravel (16.39%) and large gravel with some cobble (18.70%), indicating an overall coarser distribution of sediment (> 2 standard deviation from mean % coverage). The bed also had a moderate amount of medium gravel (9.56%) and sand (8.52%) (> 1 standard deviation from mean % coverage).

Upstream of Shafter Bridge

The upstream section was coarse, with more than half comprised of large gravel with some cobble (28.95%) and cobble with some gravel (27.26%) (> 2 standard deviations from mean % coverage).

Downstream of Shafter Bridge

The downstream section was mostly sand, medium gravel, and large gravel. The largest facies coverage was sand (12.86 %, > 2 standard deviations from mean % coverage). Medium gravel (11.33%) and large gravel with some cobble (11.09%) also had a presence, followed by medium gravel with some cobble (8.46%), cobble with some gravel (8.32%), and exposed bed rock (7.91%) (>1 standard deviation from mean % coverage).

Comparison of upstream and downstream sections

The upstream reach was significantly coarser than the downstream reach, with more patches of cobble with some gravel (Δ% = 18.94%) and large gravel with some cobble (Δ% = 17.86%) (> 2 standard deviations from Δ% coverage).

The downstream reach was significantly sandier than the upstream reach (Δ% = 10.81%, > 2 standard deviations).

Shields stress

Compared with the 1988 data (Kinerson & Dietrich, 1990), the Lagunitas Creek section experienced an overall increase in stresses (Table 1). The downstream dimensionless bedload transport ratio also increased.

Table 1: Stress and dimensionless bedload transport ratio calculations. I calculated critical subsurface and surface stresses, the bed stress, and the dimensionless bedload transport ratio at one site upstream of Shafter Bridge and one site downstream of Shafter Bridge for 2011. I also recalculated 1988 values (Kinerson & Dietrich, 1990).

Site	Year	D_{50ss} (mm)	D_{50s} (mm)	D_{50}/D_{50ss}	Bankfull Height (cm)	Slope (m/m)	τ_{css} (Pa)	τ_{cs} (Pa)	τ_b (Pa)	τ_b/τ_{css}	q*
US	1988	9	43	4.78	47	0.005	6.45	30.81	23.03	3.57	0.
	2011	32	45	1.41	54	0.005	22.93	32.25	26.46	1.15	0.
DS	1988	5.5	8.8	1.60	45	0.002	3.94	6.31	8.82	2.24	0.44
	2011	12	11	0.92	49	0.001	8.60	7.88	4.47	0.52	0.79

Upstream of Shafter Bridge

The present subsurface critical stress increased from the 1988 value by 16.48 Pa (Table 1). The present surface critical stress increased from the 1988 value by 1.47 Pa (Table 1). The dimensionless bedload transport ratio remained 0 (Table 1).

Downstream of Shafter Bridge

The present subsurface critical stress increased from the 1988 value by 4.66 Pa (Table 1). The present surface critical stress increased from the 1988 value by 1.47 Pa (Table 1). The present dimensionless bedload transport ratio increased from the 1988 value by 0.35 (Table 1).

Other Observations

The mean subsurface diameter at the upstream site now falls in large gravel range (>16 mm – 64 mm). Previously, the upstream mean subsurface diameter was considered medium gravel (<8 – 16 mm) (Table 1). The downstream subsurface diameter also increased, indicating a shift from fine gravel (>2 mm – 8 mm) to medium gravel (<8 – 16) (Table 1).

DISCUSSION

By comparing streambed sediment and stress data for 1988 and 2010-2011, I was able to evaluate sediment composition. As explained earlier, salmon require streambeds composed of gravel of a specific size in order to form and protect redds, the depressions in which they lay their eggs (Galbraith et al., 2006). There are two specific concerns. First, if the bed substrate coarsens and forms armour, the substrate is no longer loose enough for salmon to dig redds (Kondolf, 1997). Second, if there is too much fine sediment, the entrainment of fine sediment in gravel leads to lowered dissolved oxygen levels, which then causes salmon eggs to suffocate (Galbraith et al., 2006). In addition, patch formation and distribution affect macrobenthic communities. Changes to this food source can then affect growth and survivorship of juvenile salmon (Bolliet, Bardonet, Jarry, Vignes, & Gaudin, 2005).

Bed sediment composition

The surface and subsurface sediments experienced expansion of coarse areas that previously had been composed of cobble or large gravel. In addition, pools, and to some extent, runs, had large amounts of fine sediment and sand on top of coarsened areas. Previous literature suggested that dams can cause streambeds to coarsen and become paved (Parker & Klingeman, 1982; Kondolf, 2007). Peters Dam either releases water in times of drought or overspills in times of flood. Dam-released water with little to no sediment load can scour existing sediment from downstream reaches of the dam, which also would contribute to overall coarsening of both the surface and subsurface sediment over time (Kondolf, 2007). In light of the fact that dams are impermeable barriers, coarsening can also be explained by flume studies in which cutting off sediment supply led to the formation of a coarse gravel bed (Dietrich, Kirchner, Ikeda, & Iseya, 1989). Another dammed, flow-regulated river noted a similar sediment pattern: the majority of riffles downstream of the dam have degraded, while the pools aggraded from the influx of fine sediment and lack of coarse sediment (Sear, 1995).

Stresses and dimensionless bedload transport ratio

The dimensionless bedload transport ratio in the upstream section is very low (0), indicating that there is little to no sediment supply (Kinerson & Dietrich, 1990). This value also remained unchanged from 1988. While a previous study suggested that streams with low values would naturally aggregate (Dietrich et al., 1989) this section has not done so. The steadfast and impermeable nature of Peters Dam may be the reason. Downstream, however, the dimensionless bedload transport ratio increased by .35, indicating that the downstream portion of the creek is more likely to experience channel instability than it was 20 years ago (Kinerson & Dietrich, 1990).

Both upstream and downstream bedload transport ratio values are relatively low, which is consistent with the diversity of patches in the given reaches. Patches form as the natural response to reduced sediment supply. The interaction of different grain sizes causes an uneven distribution of shear stress, resulting in the movement of only some sediment present in the bed load and leaving the rest to form patches (Dietrich, Nelson, Yager, Venditti, Lamb, & Collins, 2006). Further flume studies also implicate size-selective cross-stream bed load transport as the defining mechanism for continued, forced patches in gravel streams (Nelson, Dietrich, & Venditti, 2010). My results suggest that since there were no major upheavals in patch distribution and the reaches coarsened as anticipated, the dominant bed load transport regime in this section of Lagunitas Creek remained fairly constant over the last 20 years.

Limitations

Poor timing of data collection, as well as framing of my study, resulted in greater margins of error and prevented conclusive observations. In particular, the heavy rains during March 2011 may have affected surface sediment observations. Furthermore, the heavy volunteer turn-over and the nature of the methods, like pebble counts, increase the possibility of user-dependent bias in recording sediment sizes (Marcus, Ladd, Stoughton, & Stock, 1995). Also, since my study focused on sediment, salmon observations fell outside of my scope of research.

Future Directions

Future studies in this system should combine sediment patch distribution data with salmon spawning surveys over at least six years to ascertain if any correlation does exist. Since coho salmon come in cycles of three years, analyzing six years' worth of salmon surveys would allow for a full generation of turnover. By situating the sediment results with the salmon surveys, researchers would be able to more comprehensively assess the association between salmon spawning and streambed sediment. Researchers should also consider following a holistic approach that incorporates many habitat-defining parameters, as some studies suggest that sediment may not even be the major defining criteria (Mull & Wilzbach, 2007; Stillwater Sciences, 2008).

Salmon Habitat and Restoration Implications

A coarsened sediment bed, both on the surface and subsurface, suggests a decrease in available salmon-spawning habitat. The accumulation of fine sediment poses a worrying trend because a recent flume study implied that fine sediment may actually increase active bed transport and mobilize coarse layers (Venditti, Dietrich, Nelson, Wydzga, Fadde, & Sklar, 2010), resulting in an unstable bed unsuitable for salmon. Current restoration techniques have not visibly improved the sediment quality, although impacts may not be seen for several more years. Because of the potential time lag, ongoing monitoring studies should continue. One of the major restoration efforts, large woody debris installations, collects fine sediment and may weaken and release this sediment all at once later (Haschenburger & Rice, 2003). As noted previously, fine sediment influxes jeopardize the well-being of spawning gravels and salmon egg survivorship by affecting dissolved oxygen levels (Galbraith et al., 2006). Furthermore, while a sediment budget could offset coarseness and recharge surface sediment, it should be carefully implemented. Adding gravel often is a costly and ineffective restoration method, as 11-24% can be lost annually (Merz, Pasterneck & Wheaton, 2006). To summarize, additional restoration may be necessary to offset the dam effect upon bed sediment and to prevent a chain reaction of coarsening, fine sediment and bed instability. Any additional restoration measures should be carefully evaluated for potential negative consequences to salmon habitat.

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