Geomorphic Change in the Upper Carmel River, CA: Effects of the 2008 Basin Complex Fire

A Capstone Project

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Abstract

Wildfire plays an important role as a natural disturbance in chaparral communities, found commonly in Southern and Central Coast California; however, wildfire has the potential to increase flood risk, reduce reservoir capacity, and smother trout redds from accelerated post-fire sediment loading. A previous study conducted during the first winter following the 2008 Basin Complex fire reported that the fire did not impact sediment yield in the upper Carmel River, CA. The objective of this study was to quantify fire impact on sediment yield for the second and third winters following the Basin Complex Fire. I postulated that channel elevation would increase and particle sizes would decrease, thus indicating increased sediment yield. I compared mean channel elevations surveyed from 2008-2011 at six cross sections using multiple Wilcoxon Signed Rank tests. I conducted repeat pebble counts at eight locations in the active channel to compare grain size distributions through time. The results indicate that channel elevation did not change beyond non-fire variability, estimated to be ± 15 cm. Mean channel elevations did not increase and grain sizes did not decrease monotonically as expected. Geomorphic change in the upper Carmel River following the 2008 Basin Complex fire contrasts the pronounced channel aggradation detected following the 1977 Marble Cone fire. Fire history, pre-fire climate, and timing and magnitude of rainfall following each fire likely explain most of the variability between the two geomorphic responses.

Introduction

Carmel River is a valuable local resource for the Monterey Peninsula, California. The river provides recreational and aesthetic appeal for the region, critical habitat for federally threatened steelhead trout (*Oncorhynchus mykiss*), and a drinking water source for the cities of Del Ray Oaks, Pacific Grove, Carmel, Monterey, Seaside, and Sand City. A comprehensive understanding of the natural processes in the Carmel River watershed is vital for sustainably maintaining this resource. The Environmental Protection Agency (EPA) Healthy Watershed Initiative (2009) suggests that an integrated approach to managing watersheds will lead to healthy and sustainable water resources. One aspect of this systems approach managing watersheds is to understand the role of natural disturbances in the ecosystem, such as floods, wildfires, and landslides (Figure 1).

In Southern and Central Coast California, fire is an important episodic natural disturbance, necessary for the germination of many chaparral species found in this Mediterranean environment. However, fire poses direct threats to public health and safety including airborne ash and infrastructure damage. In addition, the sediment response following fire can dramatically change the morphology of a watershed and lead to damages associated with flooding. The Monterey County Water Resources Agency (MCWRA) has identified three rivers, including Carmel, as major flood hazards to the Peninsula. Even in absence of flooding following fire, fire-accelerated sediment transport to stream channels has the potential to aggrade steelhead trout spawning gravels and pool refugias with fine sediment, smothering redds and negatively impacting trout populations (Novak and White 1989). Spina and Tormey (2000) did not observe fine sediment aggradation in pools following a wildfire in the Malibu Creek...
watershed, California and attribute earthquake-induced recruitment of cobbles and gravels as a potentially important factor. In the steep, erodible Carmel River watershed, fire may play an important role in recruitment of a variety of particle sizes from the highlands (Figure 2). Rieman and Clayton (1997) suggest that fire may play an important role in increasing channel complexity, which may be important to salmonid survival. The indirect effects of fire on salmonid habitat are mixed, providing impetus for fire management strategies that consider the adaptations of local populations to fire disturbances. In addition to potential ecological impacts, large quantities of sediment may be deposited in reservoirs following fire, reducing the reservoir’s water storage capacity. The Los Padres Reservoir in the upper Carmel River watershed filled with 30 years worth of sediment in only 3 years time following the 1977 Marble Cone Fire (Hecht 1981). It is increasingly important to understand the past and present role of wildfire in the Carmel River watershed so that resource managers can balance the interests of the ecosystem with the interests and safety of the public.

Fire accelerates the natural flux of sediment through a watershed. Swanson (1981) depicts sediment yield following wildfire using a schematic (Figure 3); however, the scales of each axis are not labeled due to the inherent variability in comparing sediment yields from separate watersheds or fires. Even in absence of fire, sediment yield is highly episodic. Watson et al. (2003) found that in 1974 the Arroyo Seco watershed, a watershed adjacent to the Carmel, contributed about 1.4% of the Salinas River’s suspended sediment load, yet two years prior contributed approximately 60%. Despite such variability, fire tends to noticeably increase sediment yield. Suspended sediment in the Arroyo Seco River in the first winter following the 1977 Marble Cone fire was higher than the mean annual suspended load for the entire Salinas River watershed; the Arroyo Seco constitutes less than three percent of the Salinas River’s watershed area (Watson et al. 2003). Removing and burning vegetation increases the susceptibility of a watershed to erosional processes (Moody and Martin 2001). Removal of
hillslope vegetation liberates fine sediment stored in the leaf litter or on the uphill side of vegetation (Figure 4). As a result, previously stored sediment moves down slope under the influence of gravity, known as dry ravel erosion (Florsheim et al. 1991, Sugihara et al. 2006, Wondzell and King 2003). Dry ravel forms cones at the base of a slope, which in some cases may be in or adjacent to a stream channel (Figure 4). In mountainous chaparral dominated environments, burning hillslope vegetation creates a hydrophobic soil layer that reduces rainfall infiltration and increases runoff (Gabet 2003). Additionally, vegetation loss from fire reduces evapotranspiration, thereby increasing precipitation runoff or overland flow (Swanson 1981). Under similar rainfall events, recently burned areas can transport larger quantities of sediment and debris than in pre-fire conditions due to an increase in dry ravel supply and overland flow. Therefore debris flows, or mobilized large quantities of sediment and organic matter, are common following fire (Naiman & Bibby 1998). Large fluxes in sediment can create lasting effects on stream morphology (Eaton et al. 2010, Hoffman and Gabet 2007). As a result of fire’s landscape-changing impacts, rainfall events during the first winter following a fire have the potential to pose greater flood risks for downstream residents.

Figure 3. Expected sediment response in stream channels before and after a watershed-scale fire disturbance (Swanson 1981).
Post-fire geospatial models of a watershed’s potential to erosion are useful management tools for assessing high risk areas (Cannon et al. 2010). Accurate models are valuable for quick hazard assessments but are difficult to create due to the inherent variability in sediment responses following fire. Therefore it is increasingly important to quantify both sediment transport following fire and the intensity thresholds of external parameters driving the sediment response; these parameters include soil moisture, geology, topography, aspect, slope, precipitation, vegetation type, fire intensity, and fire frequency (Hecht 2000, Ryan et al. 2011). The external driving parameters not only influence the sediment response, but also the burn severity. Ecosystem appropriate frequent fire regimes minimize the available fuel load for fire and allow sediment and organic debris to be transported at moderate rates through a watershed. Infrequent fire events may lead to greater severity fires and more prolific sediment responses due to greater fuel loads and hillslope sediment storage (Naiman and Bilby 1998). Best land management strategies require increased understanding of the role of both anthropogenic impacts and natural, episodic landscape changes, such as wildfire (Naiman and Bilby 1998).

Steelhead trout and resident rainbow trout (*Oncorhynchus mykiss*) are an important species to consider in watershed assessments and management strategies in the Carmel River because of their threatened status and potential sensitivity to disturbance (Rieman and Clayton 1997). In
the Carmel River, approximately 50% of steelhead spawning habitat exists above the Lost Padres Dam, in the upper Carmel River (MPWMD 1994). Aquatic rearing habitat for steelhead trout may be adversely affected by fine grain sediment deposits, which are generally amplified following fire. Hecht (1981) captured 0.33 m of fine grain (sand) channel deposition of fine grain sediment (sand) in riffle sections of the upper Carmel River following the 1977 Marble Cone fire. Steelhead trout create redds, or nests for laying eggs, in the fast moving, riffle sections of streams; the median grain size preferred for creating redds is approximately 10% of the trout’s body length, usually between 10-46 mm (Kondolf and Wolman 1993). Fire-induced fine sediment deposition can disrupt the annual reproductive success of the steelhead trout by both preventing the emergence of fry and smothering trout redds, which require flow of oxygenated water (Lisle and Lewis 1992, Argent and Flebbe 1999). Quantification of fine grain sediment deposits following fire may be useful for assessing fire-related impacts on steelhead populations and aquatic habitat.

In 2008, the Indians/Basin Complex fire burned approximately 970 km² in the Santa Lucia Mountains, Monterey County, California, of which approximately 800 km² (~82%) burned within the Los Padres National Forest (USFS 2008) (Figure 5). The fire, ignited by lightning, mostly affected the Big Sur, Arroyo Seco, Carmel, and San Antonio watersheds and caused approximately $119.2 million in damages (USFS 2008). Due to the steep terrain, resource managers could not utilize agency recommended management techniques such as hydromulching and applying wood straw to burned slopes. Hydromulching generally consists of aerial spraying of grass seed or other quick growing plants on burned areas in attempt to reduce hillslope erosion. Based on the magnitude and severity of the 2008 wildfire, the U.S. Forest Service, California American Water (CalAm), and local residents anticipated a response to the fire similar to that of the 1977 Marble Cone fire. The aftermath following the Marble Cone fire included debris flows, threats of severe flooding, large woody debris & suspended organic matter at the Los Padres Reservoir, and fine sediment deposition in the upper Carmel River and Los Padres Reservoir (Watson et al. 2003, Hecht 1981). The U.S. Forest Service enforced public trail closures and managed emergency hazard communications for approximately a year following the Basin-Complex and Indians fires, to ensure public safety. Although the 2008 Basin Complex fire burned with similar severity as the Marble Cone fire, it did not produce the same observable large-scale landscape changes.

Figure 5. Representative photos of the Carmel watershed pre-fire, fire, and post-fire (courtesy of Richmond 2009 and USFS 2008).
The Basin Complex fire provided an opportunity for U.C. Berkeley student Sarah Richmond to replicate the work of Hecht (1981) in the upper Carmel River and examine similarities and difference in sediment yield following the two wildfires. Richmond (2009) repeated the methodology of Hecht (1981) for the first winter following the Basin Complex fire and found no significant sediment deposits in the river. The results of Richmond (2009) greatly contrasted with the significant filling (0.33 m) of riffle cross sections recorded by Hecht (1981). The results of Hecht (1981) captured an influx of fine sediment during the first winter following the fire, followed by two years of scour and degradation. These results were characteristic of an episodic disturbance; the watershed’s response to the fire’s impact lasted three years, similar to other montane and Mediterranean watershed responses to fire (Moody and Martin 2001, Inbar et al. 1997). However, some watersheds have less pronounced sediment responses as reported by Ryan et al. (2011). Sediment yield following wildfire can be highly non-linear and vary in space and time (Moody and Martin 2009). Although hillslope and channel erosion rates generally increase following wildfire, the timing and magnitude of sediment pulses through a watershed are poorly understood, especially at the catchment scale (Shakesby and Doerr 2005). Heterogeneities in soil type, burn severity, vegetation, geology, topography, and climate often make it inappropriate to deduce that similar watershed-scale fires will generate comparable sediment yields. Inherent variability in the timing and magnitude of rainfall events likely drives the lag time and intensity of the sediment response to fire in similar landscapes (Moody et al. 2007, Wondzell and King 2003). Richmond (2009) observed no sediment pulse following the 2008 Basin Complex fire; however, she did not capture changes beyond the first winter rains following the fire. Therefore, the questions arise: Did significant channel filling and/or a reduction in particle sizes (fining) at depositional surfaces occur after the first winter following the Basin Complex fire? If so, what was the lag time between the fire and the peak sediment yield and what was the magnitude of the sediment yield in the upper Carmel River?

This study attempted to identify the timing of sediment pulse(s) following the 2008 Basin Complex fire and to quantify the relative magnitude of sediment yielded through surveys of in-channel elevation changes. Indicators of increased sediment yield include changes in channel morphology, specifically channel aggradation, measured using repeat cross sections, and changes in sediment grain size, specifically fining of particle sizes, detected from repeat pebble counts. I postulated that pools and riffles would aggrade monotonically and depositional surfaces such as gravel bars and floodplains would be comprised of finer grain sediment. The overarching goals of this work were 1) to improve current understanding of the sediment yield following the 2008 Basin Complex fire; 2) explain any observed variability in sediment yields following two wildfires at the upper Carmel River through qualitative comparisons of rainfall and fire histories; and 3) potentially guide management strategies by increasing current knowledge of the role of fire in the upper Carmel River watershed.
Methods

Study Area

The Carmel River is 43 km long and drains 656 km², eventually reaching the Pacific Ocean along Central California’s Coast (Smith et al. 2004). The Carmel River watershed is a desirable study area as it is well characterized (Hecht 1981, Kondolf 1986, Hecht 2000, Smith et al. 2004, Richmond 2009). The river is regionally important and serves as a key local natural resource, providing recreational and aesthetic value, drinking water to the Monterey Peninsula, and habitat refugia for federally threatened steelhead trout and resident rainbow trout (*Oncorhynchus mykiss*). In 2008, the Watershed Institute at California State University Monterey Bay conducted a high resolution bathymetry survey of the Los Padres Reservoir (Smith et al. 2008a, Smith et al. 2008b). My research in the upper Carmel River, which drains into the reservoir, was used to determine the need for a repeat bathymetry survey at Los Padres Reservoir.

Below the Los Padres Reservoir, the lower Carmel River flows through Carmel Valley, adjacent to residential communities, agricultural lands, and commercial centers. I will define the upper Carmel River watershed as the area located upstream of the Los Padres Reservoir, draining approximately 116 km² of undeveloped lands (Smith et al. 2004). The upper Carmel River is located mostly within the Ventana Wilderness in the Los Padres National Forest. The Los Padres Reservoir, located approximately 30 km southeast of the city of Carmel, CA, serves as a convenient point of entry to the upper Carmel River, which is almost exclusively accessible by foot or mule. The two research sites in this study were established by Richmond (2009) using the methods of Hecht (1981) and are located near Bluff Camp and Carmel River Camp along the Carmel River Trail, roughly 7-8 km upstream of the Los Padres Dam (Figure 6).

Data collected near Carmel Valley Village, CA were used as proxies for discharge and climate data due to the remoteness and lack of data at the two sites. The mean discharge of the Carmel River at the Robles del Rio (USGS Gage 11143200) is 2.62 m³/s based on historic annual discharge measurements (1958-2009) (USGS 2010). The mean annual temperature and precipitation for the Carmel Valley, CA is 14.1°C and 443.5 mm, respectively (WRCC 2006). Actual values at the research sites likely differ from reported values.

The watershed geology is influenced by active faults, folding, and rapid uplift and erosion, creating steep hillslopes, up to 87% grade (Smith et al. 2004). The primary geology is underlain by Mesozoic igneous granitic bedrock, Paleozoic metamorphosed rocks, and overlain by Tertiary and Quaternary sedimentary rocks (SEAT 2008). The dominant vegetation type found on south facing slopes is montane chaparral with some annual grasslands, while the north facing slopes are generally characterized by oak woodlands and small pockets of montane conifers.
Field Techniques

I conducted repeat elevation surveys using a NWI802 Rotating Laser in 2010 and a Topcon Auto Level in 2011 at 6 benchmarked cross sections, 3 at Bluff Camp and 3 at Carmel River Camp, established by Richmond (2009) (Figure 7). I surveyed two riffles and one pool at Bluff Camp, referred to hereafter as Bluff Camp Upstream Riffle, Bluff Camp Middle Riffle, and Bluff Camp Downstream Pool; at Carmel River Camp I surveyed 2 pools and 1 riffle, hereafter referred to as Carmel Camp Upstream Pool, Carmel Camp Downstream Pool, and Carmel Camp Middle Riffle. I surveyed perpendicular to the stream banks at 0.33 m intervals along each cross section,
consistent with the methods of Richmond (2009); this methodology allowed for matched pair analysis of cross section elevation change. I surveyed before the onset of major winter rains in 2010 and 2011: October 30-31, 2010, November 6-7, 2010, and November 11-13, 2011. Note that I did not survey Carmel Camp Upstream Pool in 2010 because I was not able to identify the benchmarks. I used repeat surveys to capture the relative timing and magnitude of sediment pulse(s) following the fire.

I used a modified Wolman (1954) 100 particle sampling method, or pebble count, to analyze grain size (intermediate axis) composition of gravel bars, floodplains, and riffle cross sections at Bluff Camp and Carmel River Camp, four locations at each site. I sampled 5 randomly placed transects, with 20 random counts per transect, on floodplains and gravel bars (6 locations); transect sizes varied due to the area of each gravel bar and floodplain (Richmond 2009). In riffles, I made 50 random counts on each the upstream and downstream sides of Carmel Camp Middle Riffle and Bluff Camp Upstream Riffle cross sections. Particles were measured on their intermediate axis using a metric ruler (Figure 8). Particles larger than 30 cm were measured using a 30 m transect tape. I sampled seven pebble count locations from January 21-23, 2011 and eight locations on November 12, 2011; discharge was too strong to safely conduct the Carmel Camp Middle Riffle pebble count in January 2011. A schematic of pebble count locations and cross section locations at each site is displayed in Figure 9. I used pebble count particle size distributions of less frequently inundated surface such as floodplains as a supplemental method for detecting fire-related change. Indicators of increased sediment yield might only be captured in floodplains and gravel bars because of infrequent elevation surveys and the high grade of the Carmel River, which is primarily comprised of cobbles and boulders.

Figure 7. Surveying floodplain/right bank of Carmel Camp Middle Riffle using an auto level and stadia rod, November 2011

Figure 8. Measuring intermediate axis particle size using a metric ruler at Bluff Camp Small Gravel Bar, November 2011
Statistical Analysis

To statistically compare changes in cross section mean channel elevation from 2009 – 2011 I used a one-tailed Wilcoxon Signed Rank test; the data were not normally distributed, thereby failing to meet the assumptions of a paired t-test. I compared the March 26, 2009 surveys conducted by Richmond to the October/November 2010 surveys for Bluff Camp Upstream Riffle, Bluff Camp Middle Riffle, and Carmel Camp Middle Riffle. I did not have matched pairs.
for any of the pool surveys to test statistically. I compared spring 2009 data to fall 2010 data as a proxy for detecting major change from the second winter. I also compared the October/November 2010 surveys to the November 2011 surveys for all cross sections except Carmel Camp Upstream Pool, which I was unable to survey in 2010. I used information from Fall 2010 and Fall 2011 as proxies for surveys before and after the third winter following the Basin Complex fire. I used a Bonferroni correction, significance at $\alpha = 0.0625$, because I tested 8 related hypotheses. I plotted distance and elevation for each cross section using Microsoft Excel (2007) and preformed all statistical analyses using R (R Development Core Team 2011).

I graphically displayed all available pebble count data from November 2011, January 2011, October/November 2008, January 2009, and March 2009. I plotted the data as percent finer than versus log scaled grain sizes in Excel to make ocular comparisons of fining at each pebble count location. I also reported D-50 particle size and percent finer than 4 mm. Shifts in grain size between the pebble counts of Richmond (2009) and the early and late 2011 pebble counts may indicate fining associated with the fire. I was unable to employ the methods of Bevenger and Rudy (1995) to statistically compare particles sizes from 2008, 2009, and 2011 using contingency tables because of differences in methodologies between Richmond and Bevenger and Rudy (1995).

**Results**

The sediment pulse expected to follow the 2008 Basin Complex fire did not occur in the upper Carmel River according comparisons of cross sectional surveys. Each of the six cross sections varied slightly in morphology from 2008 - 2011 (Figures 10-17). Mean channel elevation did not vary beyond 15 cm between surveys and generally channel elevation change was within ±5 cm (Figure 18). Mean elevation increased at Carmel Camp Middle Riffle between November 2010 and November 2011 surveys, suggesting significant aggradation occurred ($V = 742.5$, $p < 0.001$, $n = 76$). However, seven other mean elevation comparisons between 2009 and 2010 and 2010 and 2011 indicated no significant aggradation ($p > 0.05$); see Appendix 1 for detailed analyses of each comparison.

Particle size distributions do not indicate monotonic fining with respect to time at all sampled locations (Figures 19-26). At Bluff Camp point bar grain size coarsened between October 2008 and January 2009, fined between January 2009 and January 2011, and remained relatively the same between January 2011 and November 2011 (Figures 19, 27, 28; Tables 1 & 2). Carmel Camp small gravel bar monotonically fined with respect to time (Figures 25, 27, 28; Tables 1 & 2). Bluff Camp Upstream Riffle fined between January 2011 and November 2011 but fining was not captured as aggradation since mean channel elevation decreased between November 2010 and November 2011. There appears to be no consistent trends in fining of D-50 and percent finer than 4 mm among and between all locations with respect to time (Tables 1 &2). However, fining was observed in small grain size classes, but not at the D-50 level (Figures 19-26). From initial pebble counts conducted by Richmond (2009) in 2008/2009 to later pebble counts in 2010/2011 the percentage of grain sizes finer than 4 mm increased at all sampled locations except for Bluff Camp Point Bar (Figure 28).
Figure 10. Bluff Camp Upstream Riffle cross section surveys from 2008 – 2011; all cross sections are relative to the left bankpin, set to an arbitrary elevation of 100 m.

Figure 11. Bluff Camp Middle Riffle cross section surveys from 2009 – 2011; all cross sections are relative to the left bankpin, set to an arbitrary elevation of 100 m.
Figure 12. Bluff Camp Downstream Pool cross section surveys from 2008 – 2009; all cross sections are relative to the left bankpin, set to an arbitrary elevation of 100 m.

Figure 13. Bluff Camp Downstream Pool cross section surveys from 2010 – 2011, plotted separately from 2008-2009 surveys because of uncertainty as to which left benchmark Richmond referenced; all cross sections are relative to the left bankpin, set to an arbitrary elevation of 100 m.
Figure 14. Carmel Camp Upstream Pool cross section surveys from 2009 – 2011; all cross sections are relative to the left bank pin, set to an arbitrary elevation of 100 m.

Figure 15. Carmel Camp Middle Riffle cross section surveys from 2008 – 2011; all cross sections are relative to the left bank pin, set to an arbitrary elevation of 100 m.
Figure 16. Carmel Camp Downstream Pool cross section surveys from 2008 – 2009; all cross sections are relative to the left bankpin, set to an arbitrary elevation of 100 m.

Figure 17. Carmel Camp Downstream Pool cross section surveys from 2010 – 2011, plotted separately from 2008-2009 surveys because of uncertainty as to which left benchmark Richmond referenced; all cross sections are relative to the left bankpin, set to an arbitrary elevation of 100 m.
Figure 18. Mean channel elevation change between matched pair surveys (2008 – 2011), grouped by study site

*Statistically significant aggradation (V = 742.5, p < 0.001, n = 76)

Figure 19. Bluff Camp point bar percent finer than versus particle size; black arrow shows the direction of the shift needed to indicate particle size fining between surveys

Figure 20. Bluff Camp large gravel bar percent finer than versus particle size
Figure 21. Bluff Camp small gravel bar percent finer than versus particle size

Figure 22. Bluff Camp Upstream Riffle cross section percent finer than versus particle size

Figure 23. Carmel Camp large gravel bar percent finer than versus particle size

Figure 24. Carmel Camp floodplain percent finer than versus particle size
Figure 25. Carmel Camp small gravel bar percent finer than versus particle size

Figure 26. Carmel Camp Middle Riffle cross section percent finer than versus particle size

Figure 27. D-50 grain size (mm) for each pebble count location and each sampling date; error bars represent the range of sizes in which the D-50 particle size exists (for pebble counts that recorded grain size categorically).
Figure 28. Percent finer than 4 mm represented at each pebble count location through time.

Table 1. D-50 grain size (mm) for each pebble count location and each sampling date; green indicates smaller D-50 grain size than previously sampled, red indicates larger D-50 grain size, and yellow indicates no change.

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<th>Bluff Camp Large Gravel Bar</th>
<th>Bluff Camp Small Gravel Bar</th>
<th>Bluff Camp Upstream Riffle Cross Section</th>
<th>Carmel Camp Large Gravel Bar</th>
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Table 2. Percent finer than 4 mm represented at each pebble count location through time; green indicates an increase in percent finer than 4 mm and red indicates a decrease in percentage of grain sizes less than 4 mm.

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Discussion

Cross section surveys spanning three years (October 2008 – November 2011) following the Basin Complex fire detected no fire-generated sediment pulses. Only the Carmel Camp Middle Riffle cross section indicated significant aggradation between 2010 and 2011 surveys (Figure 18). However, this change was less than 5 cm, which is not geomorphically relevant. The Carmel Camp Middle Riffle, like most of the Carmel, has a boulder and cobble bed. The D-50 grain size in this cross section is greater than 8 cm and therefore greater than the statistically detected elevation change (Table 1). Bluff Camp Middle Riffle scoured approximately 15 cm from 2009 to 2010, but Bluff Camp Upstream Riffle and Carmel Camp Middle Riffle did not exhibit scouring at this scale (Figure 18); filling and scouring varies not only between riffles at different sites but also between riffles within the same site. Furthermore, no site exhibits a filling then scouring cycle across the sampled years (Figure 18). The variability in filling and scouring cycles suggests that cross section morphologies at all cross sections did not change beyond normal variability in the years following the fire (Figure 18). Study results indicated that filling and scouring even in absence of fire occurs on the scale of approximately 15 cm, and more commonly ≤5 cm changes occur in mean channel elevation. The results did not indicate monotonic aggradation and therefore contrast the postulate that the upper Carmel River channel would aggrade monotonically in pools and riffles following the 2008 Basin Complex Fire. There are several plausible explanations for why a sediment pulse was not observed in the measured surveys: 1) surveying cross sections was not an appropriate proxy for detecting and measuring sediment yield at this scale, 2) the sediment pulse has not occurred yet (Figure 29), 3) the sediment pulse occurred in a single, almost instantaneous (i.e. smaller than our surveying interval) event, on the order of days or weeks as observed by Watson et al. (2003), or 4) there was no sediment pulse beyond normal background variability following the 2008 Basin Complex fire.

Repeat pebble counts did not clearly indicate increased sediment yield spatially among and temporally within sampled locations. Fining appears to be most evident in small grain sizes (e.g. 2-10 mm) and less observed at the D-50 grain size, which is expected given that the Carmel River has a boulder and cobble channel bottom (Figures 19-26, 28). However, grain size analyses indicate that there were approximately as many occurrences of fining when observing changes in D-50 as there were when comparing the percentage of clasts finer than 4 mm (Tables 1 &2). Some locations sampled had a larger D-50 but a greater percentage of clasts finer than 4 mm while other locations exhibited an opposite trend. This variability in fining is further amplified when put in the context of surveyed cross sections. The D-50 particle size at Bluff Camp Upstream Riffle decreased by approximately one third and the percentage of particles less than 4 mm more than doubled between January 2011 and November 2011. However this fining in grain size did not equate to net channel aggradation; the cross section appears to have scoured during this period (Figure 18). The Bluff Camp Upstream Riffle is boulder and cobble bedded, therefore scouring is unlikely to expose fines. There are two plausible explanations for why the pebble count indicated fining, and thus deposition, while the cross section indicated scouring: 1) the channel scoured during a high flow event, such as the March 25, 2011 winter storm, and lower flows following the storm deposited a thin layer of fine sediment or 2)
surveys and pebble counts were not precise enough methods to be used as indicators for changes in grain size.

The results of this study greatly contrast the results of Hecht (1981) who captured 30 cm of fine-grained sediment channel aggradation in the same study reach, using similar methods following the 1977 Marble Cone fire. Additionally, the Marble Cone fire generated 30 years’ worth of deposition in just three years at Los Padres Reservoir (Hecht 1981). It is likely that the timing and magnitude of rainfall events leading up to and following each fire contributed to the two contrasting observed sediment yields. The winter of 1974 produced a wet snowstorm, which caused limb breaks, thereby increasing the fuel load for the 1977 Marble Cone Fire. In addition, the summers of 1976 and 1977 were drought years, while the winter of 1978 was the fourth wettest winter on record. The 2008 Basin-Complex Fire pre- and post-fire climate was less extreme (Figure 30). Additionally, the Marble Cone Fire occurred after a 61 year period without fire, while the Basin-Complex Fire was preceded by the 1999 Kirk-Complex Fire and the 1977 Marble Cone Fire (Figure 31). Frequent fires reduce fuel loads as well as hillslope sediment storage (Florsheim et al. 1991). It is possible that the Carmel River watershed generated less dry ravel following the Basin Complex Fire than the Marble Cone as a result of less hillslope storage and thus less sediment mobilized following the Basin Complex Fire. There is no way to test this hypothesis at present; however, future studies may want to incorporate dry ravel volume estimates into research methods to better emulate the methods of Richmond (2009) and potentially better detect the impact of fire.

![Figure 29. Observed three-year trend in “sediment yield” following the Marble Cone Fire (left) and Basin-Complex Fire (right); future sediment yield is unknown and may or may not follow the depicted trend (dashed-line).](image-url)
The observed variability in sediment yields following two comparable burn severity wildfires suggests that sediment yield following wildfire has a range of possible magnitudes. It seems that rainfall and fire history are important in determining the magnitude of these impacts. Opportunistic studies following future wildfires in the upper Carmel River are suggested. These studies could incorporate more frequent surveying in their methodologies and establish more cross sections at a greater spatial scale in order to better characterize the sediment yield associated with fire at the watershed-scale. Use of remote sensing in future studies is encouraged. A bathymetry survey of the Los Padres Reservoir, while potentially costly, could provide future students with sediment volume estimates. Monitoring reservoir filling through repeat bathymetry surveys could verify whether or not cross section surveys and pebble counts are accurate methods for capturing sediment pluses associated with fire. Continued monitoring that includes existing methodologies is important for cross referencing future methods and for further understanding the natural variability of sediment yields in absence and in presence of wildfire in the upper Carmel River watershed. If future studies in the upper Carmel River watershed continue existing methods following future fires the relative importance of burn severity, rainfall timing and magnitude, and fire history to sediment yield could be incorporated into future analyses. An improved understanding of the range of sediment yields following wildfire may help inform regional land use planning and protection, including fire management in the Los Padres National Forest and operation of the Los Padres Reservoir.

Figure 30. Annual precipitation at Big Sur, California (BGS) National Weather Service Gage from 1960-2010; 1977 Marble Cone fire and 2008 Basin Complex fire are denoted by grey shading (Warrick et al. 2012).
Figure 31. Fires that have affected the upper Carmel River watershed since 1906; acres burned reflects the total area of land affected by the fire and is not exclusive to the Carmel River watershed.

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Literature Cited


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Appendix 1

2010 and 2011 Comparison
1) BLUFF CAMP UPSTREAM RIFFLE CROSS SECTION
Paired Samples
Continuous (Interval or ratio scale) (yes)
Random (yes)
Normally Distributed

Shapiro-Wilk: not normal (W = 0.7938, p-value = 6.597e-08, n = 62)

Not normally distributed so use nonparametric Wilcoxon Signed Rank Test:

Fail to reject null; No significant change between 2010 and 2011 at Bluff Camp Upstream Riffle Cross Section (V = 1439, p-value = 0.9998, n = 62) Alternative: $\mu_{2011} > \mu_{2010}$, Null: $\mu_{2011} \leq \mu_{2010}$
2) BLUFF CAMP MIDDLE RIFFLE CROSS SECTION

Paired Samples
Continuous (Interval or ratio scale) (yes)
Random (yes)
Normally Distributed

Shapiro Wilk: not normal (W = 0.6328, p-value = 2.769e-11, n = 63)

Wilcoxon Signed Rank Test:

Fail to reject null; No significant change between 2010 and 2011 at Bluff Camp Middle Riffle Cross Section (V = 1294, p-value = 0.9871, n = 63) Alternative: $\mu_{2011} > \mu_{2010}$, Null: $\mu_{2011} \leq \mu_{2010}$
3) BLUFF CAMP DOWNSTREAM POOL CROSS SECTION

Paired Samples
Continuous (Interval or ratio scale) (yes)
Random (yes)
Normally Distributed

Shapiro Wilk: not normal (W = 0.9664, p-value = 0.02845, n = 83)

Wilcoxon Signed Rank Test:

Fail to reject null; No significant change between 2010 and 2011 at Bluff Camp Downstream Pool Cross Section (V = 1816, p-value = 0.7025, n = 83) Alternative: \( \mu_{2011} > \mu_{2010} \), Null: \( \mu_{2011} \leq \mu_{2010} \)
4) CARMEL CAMP MIDDLE RIFFLE CROSS SECTION

Paired Samples
Continuous (Interval or ratio scale) (yes)
Random (yes)
Normally Distributed

Shapiro-Wilk: not normal ($W = 0.6135$, $p$-value $= 7.733 \times 10^{-13}$, $n = 76$)

Wilcoxon Signed Rank Test:

Reject null; statistically significant change between 2010 and 2011 at Carmel Middle Riffle Cross Section ($V = 742.5$, $p$-value $= 0.0004191$, $n = 76$)

Alternative: $\mu_{2011} > \mu_{2010}$, Null: $\mu_{2011} \leq \mu_{2010}$; doesn't look geologically significant based on boxplot and mean elevation change (error bars btwn 0 and 5 cm)
Histograms for Carmel Middle Riffle 2010 and 2011 surveys are not strikingly different; in fact they look pretty similar overall. Odd that test is statistically significant.

5) CARME CAMP DOWNSTREAM POOL CROSS SECTION

Paired Samples
Continuous (Interval or ratio scale) (yes)
Random (yes)
Normally Distributed

Shapiro-Wilk: not normal (W = 0.8241, p-value = 3.246e-08, n=79)

Wilcoxon Signed Rank Test:
Fail to reject null; No significant change between 2010 and 2011 at Carmel Camp Downstream Pool Cross Section \( (V = 1180.5, \ p\text{-value} = 0.05183, \ n=79) \) Alternative: \( \mu_{2011} > \mu_{2010} \), Null: \( \mu_{2011} \leq \mu_{2010} \)

**2009 (March 26 & 27) and 2010 Comparison**

1) **BLUFF CAMP UPSTREAM RIFFLE CROSS SECTION**

- Paired Samples
- Continuous (Interval or ratio scale) (yes)
- Random (yes)
- Normally Distributed

Shapiro-Wilk: \( (W = 0.9728, \ p\text{-value} = 0.3251, \ n=48) \) Normally Distributed!!!

F-Test for Homogeneity of Variances: \( (F = 1.1703, \ num \ df = 47, \ denom \ df = 47, \ p\text{-value} = 0.592); = var!!! \
Paired T-Test:

Fail to reject null; No significant change between 2009 and 2010 at Bluff Camp Upstream Riffle Cross Section \( (t = -0.154, df = 47, p\text{-value} = 0.4391) \) Alternative: \( \mu_{2010} > \mu_{2009} \), Null: \( \mu_{2010} \leq \mu_{2009} \)

2) BLUFF CAMP MIDDLE RIFFLE CROSS SECTION
Paired Samples
Continuous (Interval or ratio scale) (yes)
Random (yes)
Normally Distributed

Shapiro-Wilk: \( W = 0.6255, p\text{-value} = 6.636e-11, n=58 \); not normally distributed

Wilcoxon Signed Rank Test:
Fail to reject null; No significant change between 2009 and 2010 at Bluff Camp Middle Riffle Cross Section ($V = 1580.5$, $p$-value = 1, $n = 58$) Alternative: $\mu_{2010} > \mu_{2009}$, Null: $\mu_{2010} \leq \mu_{2009}$

3) **CARMEL CAMP MIDDLE RIFFLE CROSS SECTION**

- Paired Samples
- Continuous (Interval or ratio scale) (yes)
- Random (yes)
- Normally Distributed

Shapiro-Wilke: ($W = 0.6787$, $p$-value = 2.173e-09, $n = 52$); not normally distributed

Wilcoxon Signed Rank Test:
Fail to reject null; No significant change between 2009 and 2010 at Carmel Camp Middle Riffle Cross Section (V = 881.5, p-value = 0.9909, n=52) Alternative: $\mu_{2010} > \mu_{2009}$, Null: $\mu_{2010} \leq \mu_{2009}$