Post-Harvest and Post-Fire Watershed Response in the Little Creek Watershed, Santa Cruz County, California

Observations, Assessments, and Evaluations from 2001 through 2013

Swanton Pacific Ranch
Cal Poly State University – San Luis Obispo

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Chapter 1. Introduction

1.1 Background

The Little Creek Study officially began as a long-term effort to evaluate suspended sediment export and geomorphic conditions pre- and post-harvest as a means to help understand the effectiveness of the California Forest Practice Rules to protect water quality and watercourse conditions. The study included an eight-year calibration period before the 2008 selection harvest. A paired and nested watershed approach utilized event-based water quality sampling to monitor suspended sediment export. The channel geomorphic condition was monitored through repeated surveys of channel cross-sectional profiles and longitudinal profiles, in addition to sediment source surveys and channel substrate surveys. Each helped to characterize changes occurring within the system prior to and following timber harvest. In August 2009, following one year of the post-harvest evaluation, the study concluded abruptly when the Lockheed Fire burned 1,100 acres of the watershed, including both the control and treatment watersheds. Two approaches were used to analyze pre- and post-harvest conditions.

The Lockheed Fire started in a remote area near the northern boundary of the Scotts Creek watershed. During the first two days, the fire was strongly wind driven and progressed rapidly from north to south igniting mid slope areas along ridges trending predominantly from east to west. The upper hillslopes and ridge tops experienced the highest fire intensities attributed to the strongest wind effect; lower hillslopes typically experienced lower fire and burn intensities as a result of the fire back burning down toward riparian areas. Riparian areas of the mainstem streams were relatively unaffected by the fire, while tributary streams that were more in line with the wind direction during the fire experienced a greater effect. For example, much of the riparian vegetation along upper Berry Creek was completely consumed.

With over 90 percent of the Little Creek watershed extensively burned, the study was reconfigured to evaluate fire-induced changes to suspended sediment export and channel characteristics. The eight years of data from the pre- and post-harvest study provided the basis to help evaluate the post-fire response. In addition to the suspended sediment export and channel change monitoring efforts that remained consistent with the pre- and post-harvest analysis, new study goals were also identified to understand and document the watershed's response to the fire. This multidimensional approach is described in detail in Chapter 3.

The initial pre- and post-harvest study and the latter pre- and post-fire study collectively form what is now referred to as the Little Creek Study. Each will be treated separately in this report as stand-alone chapters.

1.2 Funding

The study to evaluate watershed and channel response to wildfire has been funded by three sources: the California Agricultural Research Initiative, a California Department of Forestry and Fire Protection (CAL FIRE) research agreement, and USDA McIntire Stennis research funding. Each grant or agreement have common project objectives and each differ somewhat with respect to goals and study areas.

1.2.1 California Agricultural Research Initiative Grant

Four California Agricultural Research Initiative grants funded both the pre- and post-harvest study and the pre- and post-fire study. The campus-wide grants were acquired beginning in 2001 to characterize sediment export and channel change prior to and following timber harvest.

This systemwide grant included collaborative agreements with University of California, Santa Cruz (UCSC), and Oregon State University (OSU). Subcontract agreements with UCSC and OSU established scopes of work that were largely independent of each other and of Cal Poly work. Cal Poly addressed suspended sediment event-based monitoring and repeat surveys that included soil hydrologic monitoring. Cal Poly also assumed project administration roles. The UCSC effort was focused on these watershed-scale goals: (1) evaluating mass-wasting processes within the Scotts Creek watershed and mapping historical mass-wasting within the watershed, and (2) using three generations of Airborne LiDAR data to create maps of erosion and deposition due to disturbance triggered by the Lockheed Fire within the Scotts Creek watershed. The OSU effort was focused on modeling efforts to evaluate post-fire suspended sediment export using a physically-based modeling approach and database development.

1.2.2 CAL FIRE Research Agreement

CAL FIRE provided funding for the pre- and post-harvest study, as well as the pre-and post-fire study, through service agreements. The CAL FIRE contracts, known as Little Creek Watershed Study Cooperative Instream Monitoring Project—Phase I and II, were particularly focused on hillslope erosion, channel change, and changes in suspended sediment export following timber harvest, and subsequently, following wildfire.

1.2.3 USDA McIntire Stennis Grant

Funding from McIntire Stennis further supported the effort to help answer the overall questions described above. The funded proposal identified the following study goals: (1) ascertain fire-induced changes in hydrologic flow pathways, (2) determine if suspended sediment export has increased following wildfire, and (3) determine if channel change is initiated following the Lockheed Fire.

1.3 Study Location

The study location is focused on the Little Creek watershed, which is part of the greater Scotts Creek watershed, located in the central part of the Coast Ranges in Santa Cruz County (Figure 1-1). Little Creek is one of seven subwatersheds that combine to form the Scotts Creek watershed. Scotts Creek provides habitat for four threatened or endangered aquatic species, and is highly regarded for its fishery resources and drains within the Monterey Bay National Marine Sanctuary. The Little Creek watershed, fourth in size and with over a mile of channel that supports these species, plays a vital role in the ecological function of the Scotts Creek watershed. The lower half of the Little Creek watershed is on Swanton Pacific Ranch, property owned by Cal Poly Corporation and managed by Cal Poly's College of Agriculture, Food, and Environmental Sciences. The upper half of the Little Creek watershed is predominantly on San Vicente Redwoods property, an 8,500-acre property acquired by a consortium of conservation groups in 2011. The current and previous property owners have been cooperators on the project and have agreed to not pursue any new timber harvests in the Little Creek watershed throughout the study period.

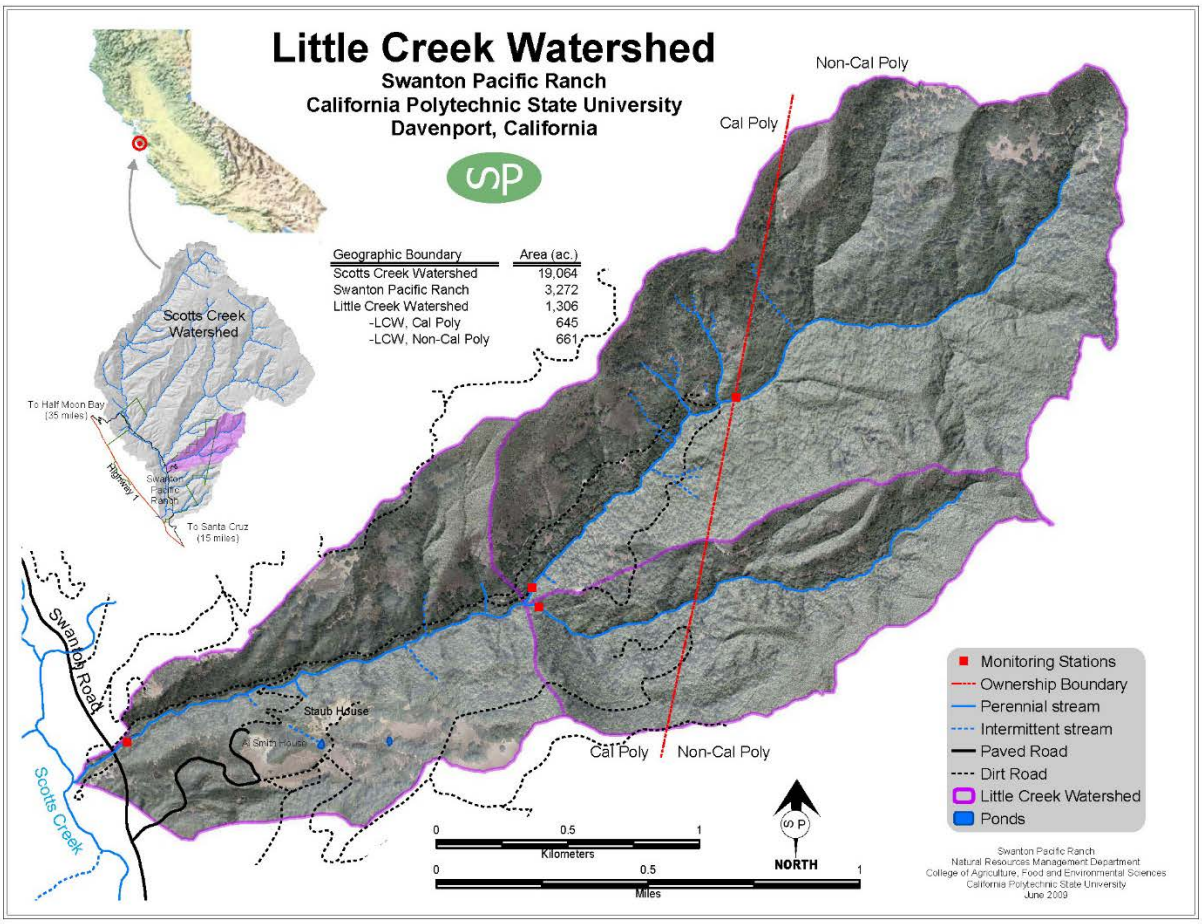


Figure 1-1. The Little Creek watershed.

1.3.1 Climate

The Santa Cruz Mountains have a Mediterranean climate with year-round coastal fog. The rain season from October through April is usually mild and wet, with the majority of rainfall occurring mid-November through February. Summers tend to be warm and dry with a fairly consistent fog bank situated at lower elevations along the coast. The mean annual precipitation at the lowest elevation in the Scotts Creek watershed is 76.2 cm (30.0 in). The mean annual precipitation ranges from 102-127 cm (40.2-59.0 in) along the ridgelines (Scott Creek Watershed Council 2005).

1.3.2 Geology and Soils

The Scotts Creek watershed resides in the tectonically-active Santa Cruz Mountains of the central part of the California Coast Ranges. Steep, narrow valleys characterize much of the watershed and its tributaries. This is due to the rapid uplift of the region in combination with the continual down cutting of streams and erosional events, such as landsliding, debris torrents, and rotational slumps.

The watershed overlies the Salinian block, which is composed of three main rock types: quartz diorite (Cretaceous), Santa Margarita Sandstone, and Santa Cruz Mudstone (Upper Miocene). The quartz diorite and some metamorphic marble and schist (Mesozoic or Paleozoic) make up the basement rock types, while the Santa Margarita Sandstone and Santa Cruz Mudstone makeup the overlying cover rock. As a result of continuous uplifting, the Salinian block has been tilted ocean-ward and has been subjected to surficial wind and rain erosion. The northeastern portion of the watershed is dominated by exposed granite while the rest of the watershed maintains a patchy distribution of sedimentary rock overlying granite (Taskey 2010).

Pedogenesis in the Scotts Creek watershed is strongly influenced by slope position, slope steepness, and parent material. There are numerous soil types within the Scotts Creek watershed but the dominant soil types include 113—Ben Lomond-Catelli-Sur complex, 30 to 75 percent slopes; 173—Sur-Catelli complex, 50 to 75 percent slopes; and 153—Maymen-Rock outcrop complex, 50 to 75 percent slopes.

1.3.3 Fisheries

Scotts Creek supports state and federally-listed coho salmon and federally-listed threatened steelhead trout. Scotts Creek is considered the most important fisheries system within the Santa Cruz Mountains because it is near the southern extent of historic coho populations, and the biologic and physical habitat conditions are among the least impacted found anywhere along the California Coast. Scotts Creek was identified as a core focus area for restoration (Figure 1-2) by NOAA Fisheries in the 2012 Central California Coast (CCC) Coho Recovery Plan (National Marine Fisheries Service 2012).

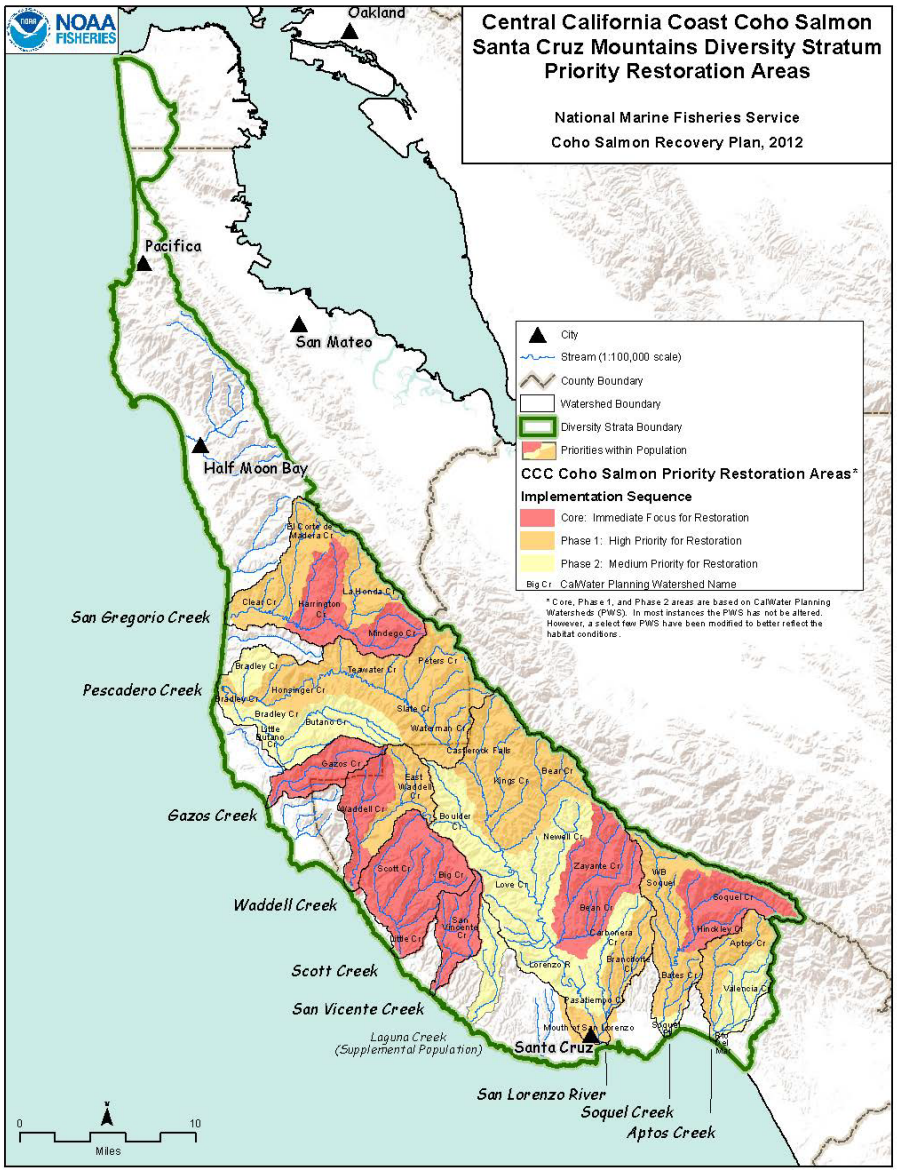


Figure 1-2. Priority restoration areas for Central Coast Coho Salmon featuring Scotts Creek as core focus area (National Marine Fisheries Service 2012).

1.4 Rainfall Monitoring

A network of rainfall gages have been established to support research goals on Swanton Pacific Ranch (Figure 1-3). Rainfall data have been collected throughout the network since the 1997-1998 winter. The first gages were installed at Landing 23 on the ridgeline upslope of the confluence of the North and South Forks (Landing or LD) and another on the porch of a caboose between College Station and the Red House area near the mouth of Little Creek (Red House or RH). In 2002, seven more gages were installed. Two are located in the Queseria Creek watershed, one near the Long Barn (Lower Queseria Creek or LQC) and another near the eastern

property line (Upper Queseria Creek or UQC). Five additional gages were also installed in the Little Creek watershed. The Ridgeline Smith (RLSM) gage is on the northern ridgeline of the Little Creek watershed near the Ranch northeast property corner. The Ridgeline North Fork (RLNF) gage is located at a log landing on the former CEMEX property just below the saddle on the eastern edge of the North Fork watershed. The Ridgeline South Fork (RLSF) gage is located at the headwaters of the South Fork Little Creek and Molino Creek watersheds. The Upper North Fork (UNF) gage is located at Landing 20 slightly north of the Upper North Fork bridge and streamgage. The Al Smith House rain gage (AL) is located near the Al Smith House on the southern edge of the watershed approximately equidistant along the mainstem of Little Creek. In February 2010, gages were also installed near the hillslope erosion study plots (HS) and at the Cowboy Shack (CS). In 2010, the Red House gage was relocated approximately 100 meters to the front of the Little Creek House.

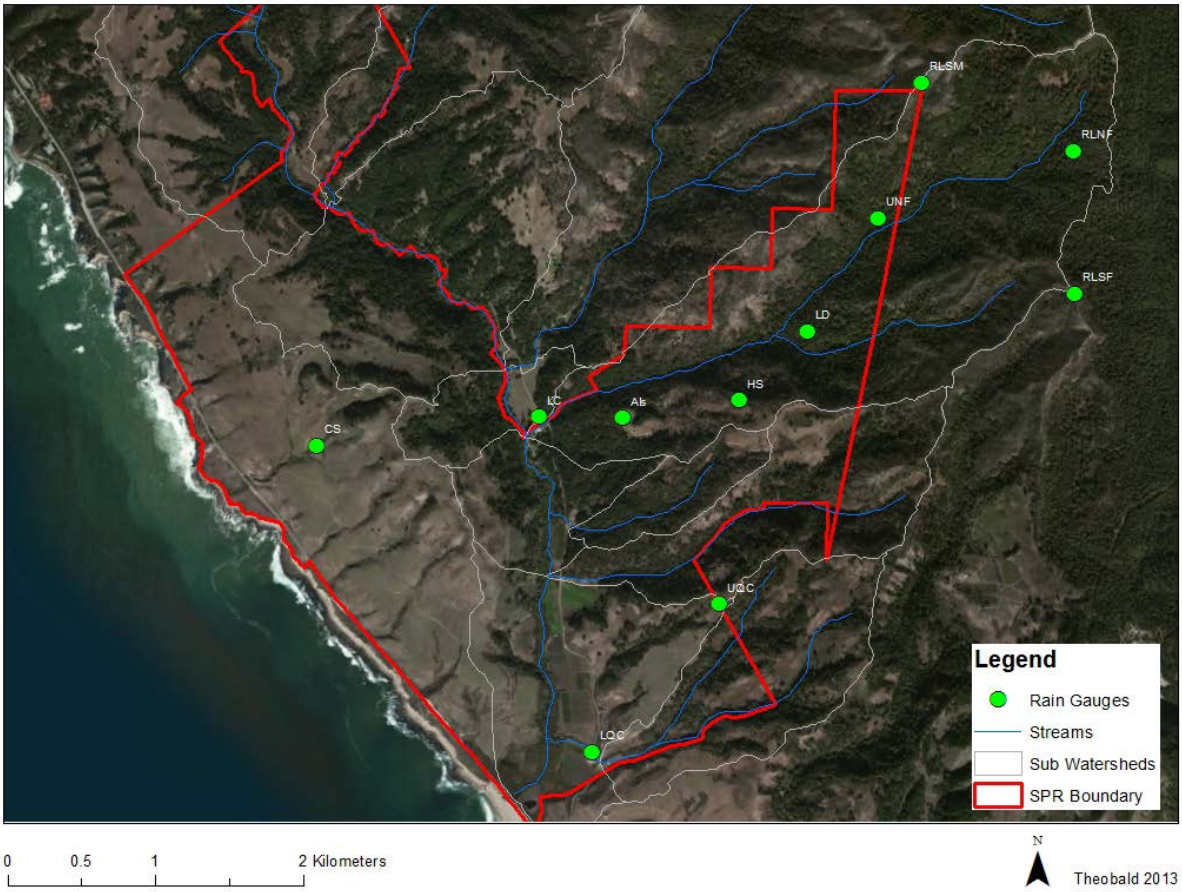


Figure 1-3. Location of rain gages distributed throughout Swanton Pacific Ranch and the Little Creek watershed, Davenport, CA.

Nine of the gages use Onset 6 inch tipping bucket rain gages with Onset event data loggers. Two gages currently use NovaLynx 8 inch tipping bucket rain gages (LD and HS) with Onset event data loggers. Each recording rain gage is also accompanied by a standard NWS 8 inch manual rain gage or a 4 inch Clear-Vu rain gage, which are used to calibrate tipping bucket data and fill

in gaps where the recording rain gage did not document accurate data. The rain gages are typically visited weekly, when the recording rain gage data is downloaded and manual gages are measured. Tipping bucket rain gages have been quality checked against the manual rain gages where those data are available (since 2005). Weekly and annual totals were checked and tipping bucket amounts were modified to match manual gages when there were significant discrepancies.

Cumulative annual rainfall plots show rainfall at the LD rain gage since WY 1998 (Figure 1-4). The LD rain gage is located in the center of the watershed, and previous work using Thiessen polygon averaging (Cichowski 2004) showed it was generally representative of basin-wide average precipitation.

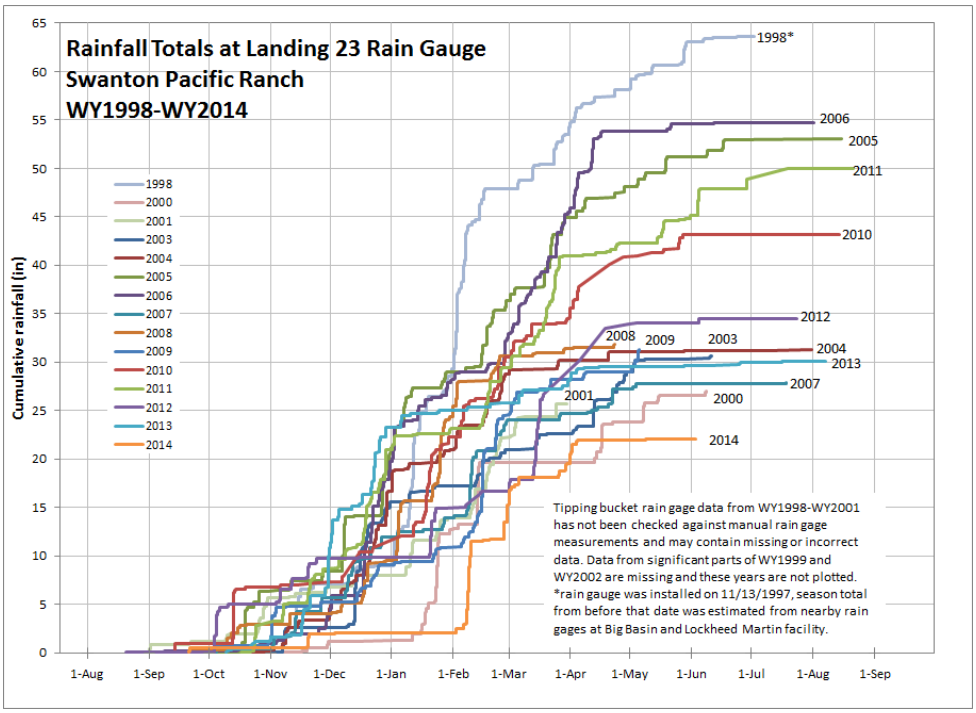


Figure 1-4. Cumulative annual rainfall plots from the rain gage located at Landing 23 for 1998-2013.

1.5 Streamflow Monitoring

Three streamflow monitoring stations were constructed from 1997-1998 in anticipation of long-term suspended sediment monitoring (Figure 1-1). The three rated section flumes (Main Stem, North Fork and South Fork) were constructed out of local redwood and instrumented initially with pressure transducers. In 2001, with the project funded to evaluate suspended sediment export and channel change, stage and flow data collection was initiated. A fourth monitoring station was added at this time at Upper North Fork to allow for a nested comparison. Stage was

monitored in stilling wells at each station with three methods: pressure transducers, ISCO Bubbler gages, and Belfort float and pulley water level recorders. Rating curves were established with repeated velocity-area flow measurements across the full range of stream stages and with additional measurements repeated frequently each rain season to ensure consistency.

Chapter 2. Pre-and Post-Harvest Evaluation

2.1 Background

The Little Creek Monitoring Project was designed as a long-term study to evaluate the water quality and geomorphic conditions of a coastal mountain stream located in the southern-most extent of the redwood/Douglas-fir forest region. The primary goal of this study was to provide valuable information documenting watershed conditions before, during, and after single-tree and small group selection harvests. Study goals included providing substantiated scientific documentation of suspended sediment impacts following timber harvests on forested watersheds. This information can be used to help determine the effectiveness of the current California Forest Practice Rules to adequately protect water quality and maintain healthy watersheds.

2.1.1 Setting

The Little Creek Monitoring Study setting is the Little Creek watershed, a 529 ha (1306 ac) subwatershed of Scotts Creek in the Santa Cruz Mountains. The climate is Mediterranean with mild temperatures and the majority of rainfall occurring in the winter. The annual precipitation is 100-300 cm in the upper portions of the watershed and 75 cm at lower elevations. The geologically-active watershed has steep inner gorges with an average basin slope of 45 percent and elevation ranging from 12 m to 488 m (White 2010). This watershed is composed of westward dipping Santa Cruz mudstone and a thin layer of Santa Margarita sandstone overlying quartz diorite, with some outcrops of schist. The Santa Cruz mudstone is found in the lower portion of the Little Creek watershed up to the confluence of the North and South Forks, while the quartz diorite and schist outcrops are found along the channel above the confluence and slowly expands to the upper slopes upstream through to the headwaters of the watershed. Little Creek contains first- and second-order channels (based on the USGS topographic map) and stream gradients are generally greater than 2%. Channel types according to Montgomery and Buffington (1997) include plane-bed, step-pool, cascade and bedrock, while the bed types are composed of gravel, cobble, boulder, and rock (Perkins 2012).

The Little Creek has been actively managed dating back to clearcutting operations of the latter 19th century and early 20th century. More recent harvests in the latter 20th century have followed the old-growth logging using modern forest practices, including a change to selection harvesting methods. Harvests in the Little Creek watershed are documented in Table 2-1.

Table 2-1. Harvests in the Little Creek watershed since 1990

Location		Harvesting	Harvest	Removed				
Little Creek	**Year**	**Method**	**Acres**	**Redwood (bf)**	**Douglas-fir (bf)**	**Trees/ac**	**Basal Area**	**BA/ac**
South Fork	1990	tractor	59	285,810	391,000	18	4,284	73
North Fork	1994	cable/tractor	120	615,790	326,830	12	5,966	50
North Fork	1995	cable/tractor	100	578,810	274,490	13	5,401	54
Lower	2004	tractor	102	588,000	82,000	7	3,499	34
North Fork	2008	cable/tractor	143	847,000	22,000	5	3,881	27
Lockheed Salvage	2010	helicopter	91	838,000	20	20	5,187	57
South Fork	2011	helicopter	84	632,000	12,000	10	3,192	38
TOTAL			**699**	**4,385,410**	**1,108,340**			

2.1.2 Study Design

Water quality monitoring utilized a combination of paired watershed and nested study designs. The study evaluated turbidity and suspended sediment concentration data collected during the pre-harvest or calibration period (2001-2007), and the post-harvest period (2008-2009) following the 2008 Little Creek – North Fork harvest. The post-harvest period was limited to one year due to the entire study area in the watershed being burned in the August 2009 Lockheed Fire.

In 1997, three monitoring stations equipped with rated-section flumes were first installed on Little Creek. In 2001, a fourth monitoring site was established in a natural channel cross section. At these locations, stage, turbidity, temperature, and event-based samples for lab analysis of turbidity and suspended sediment concentration were collected. Additionally, rainfall data from 11 gages were collected.

The geomorphic analysis included analysis of longitudinal profiles -and cross-sectional profiles from repeated surveys, LIght Detection and Ranging (LiDAR) analyses, roads and landslide inventories, streambank sediment source and channel stability surveys, and documentation of historic landslides throughout the watershed. The longitudinal profile and permanent channel cross section surveys described existing morphologic conditions and were used to evaluate channel changes over time. LiDAR provided high-resolution, three-dimensional mapping data. As part of the study, ground surveyed watershed and channel characteristics were compared with LiDAR data. The LiDAR studies were largely ancillary to the pre- and post-harvest analysis. Refer to White et al., 2010 and Dietterick et al., 2012 for additional information on these studies. The roads and landslide inventories were conducted as an initial attempt to identify the sources of sediment in the watershed. The Near Stream Sediment Source Survey documented actively eroding streambanks, smaller streamside landslides, and channel characteristics. These data were

to be used to monitor sediment source locations and characteristics throughout the study. The data offered an interpretative advantage for helping to explain observations made from event-based sediment export from one year to the next.

2.1.3 Calibration

The period from 2002-2008 served as the calibration period for the paired (North Fork Little Creek and South Fork Little Creek) and nested comparisons (North Fork Little Creek and Upper North Fork Little Creek). The calibration period included data from 31 events for the paired study and 30 events for the nested study (Table 2-2). When regressing the North Fork to the South Fork, the paired study showed significant variability ($r^2 = 0.648$) in the responses between the two watersheds (Figure 2-1). The nested comparison revealed a significantly better correlation ($r^2 = 0.955$) between events for the North Fork and the Upper North Fork (Figure 2-2). In addition to documenting the variability of the turbidity and suspended sediment response between periods of active management, the calibration was successful in showing the level of change that could be detected. Gaedeke (2006) showed using the calibration data through 2006 that it would take an average increase in suspended sediment concentration (SSC) of 30 percent to be statistically significant at the .05 level (Figure 2-3).

Table 2-2. Storm event load summary for WY2002-2008 for the paired study (North Fork vs. South Fork) and for the nested study (North Fork vs. Upper North Fork)

	North Folk vs. South Fork			North Fork vs. Upper North Fork		
Water Year	# Events	Station	Max load (kg)	# Events	Station	Max load (kg)
2002	4	NF	21934	n/a	NF	n/a
		SF	3975		UNF	n/a
2003	3	NF	19374	2	NF	19374
		SF	1287		UNF	25337
2004	5	NF	105052	7	NF	105052
		SF	546		UNF	56554
2005	5	NF	10411	4	NF	10411
		SF	1529		UNF	9568
2006	5	NF	24526	8	NF	24848
		SF	1911		UNF	19845
2007	2	NF	10382	3	NF	10382
		SF	1341		UNF	14525
2008	7	NF	59685	6	NF	59685
		SF	40478		UNF	56584

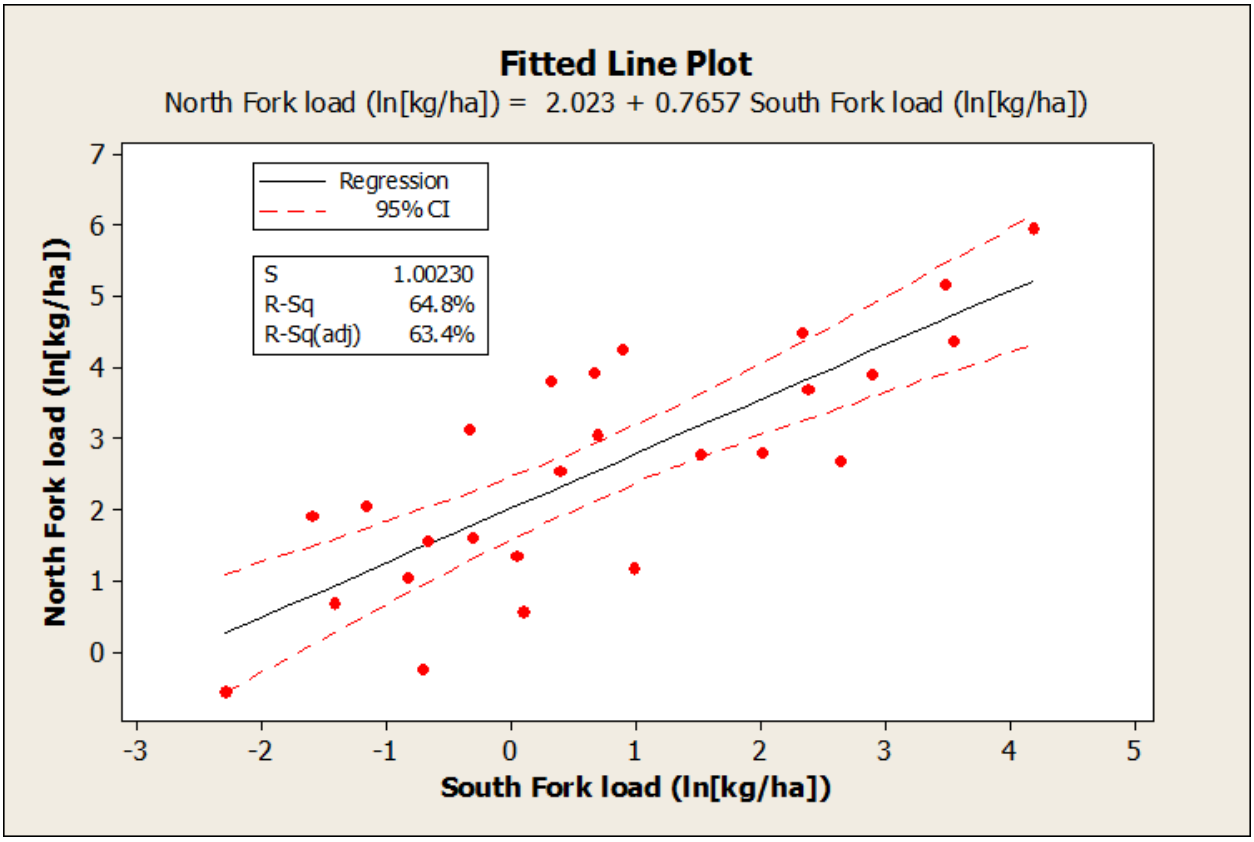


Figure 2-1. Fitted line plots and 95 percent confidence interval lines for paired study (North Fork vs. South Fork) sediment event loads (kg) for calibration period.

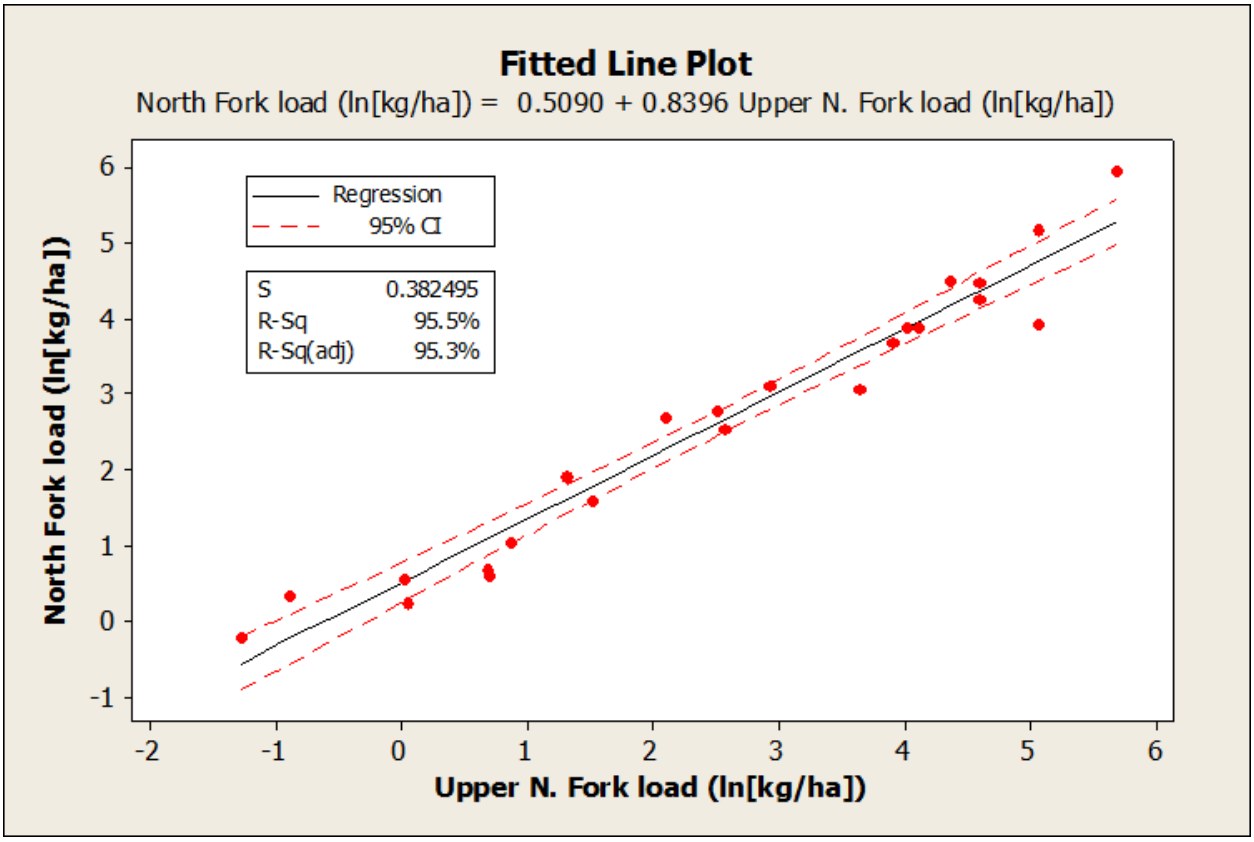


Figure 2-2. Fitted line plots and 95 percent confidence interval lines for the nested study (North Fork vs. Upper North Fork) for calibration period.

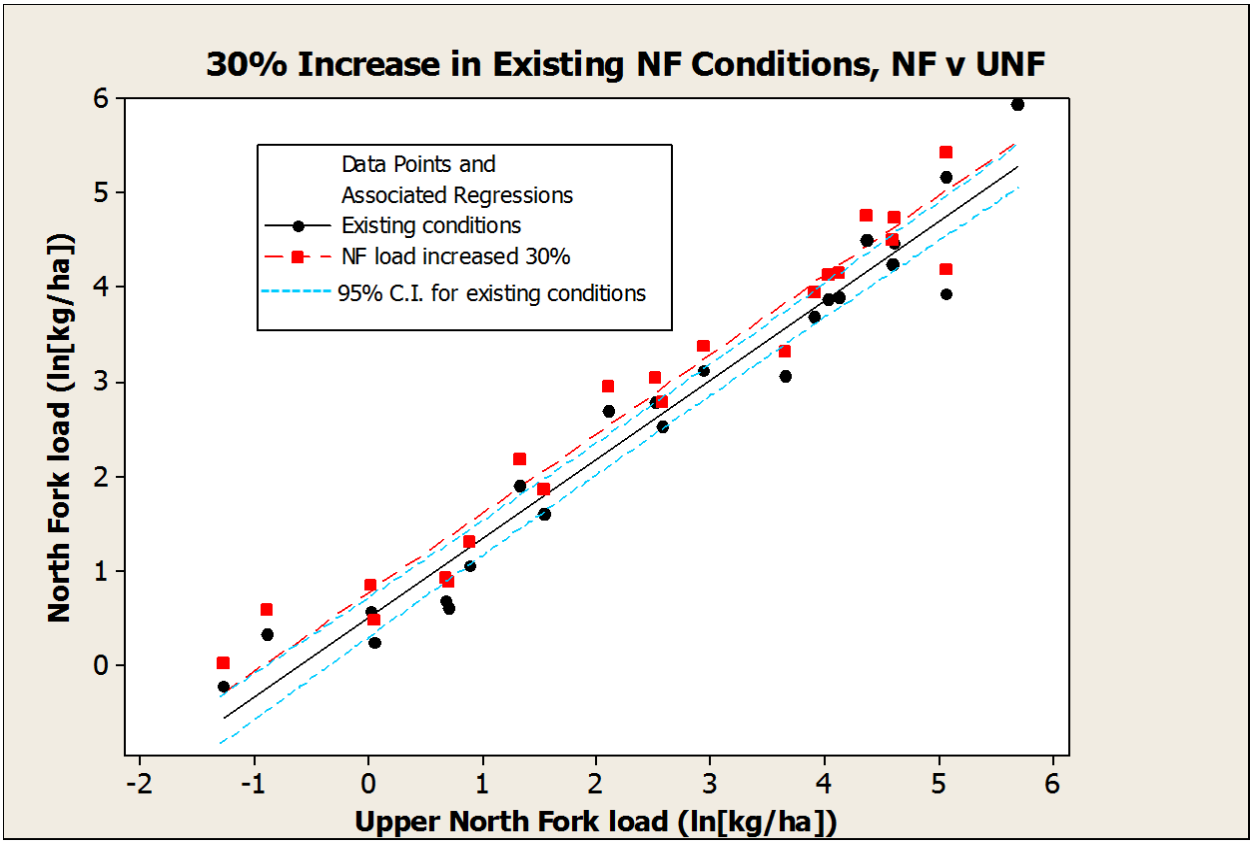


Figure 2-3. Comparison of best fit lines for calibration period and theoretical increase over existing conditions necessary to produce a statistically-significant change for the full range of event load responses.

2.2 Post-Harvest Analysis (from Skaugset et al., 2012)

2.2.1 Introduction

The impact of timber harvest on the hydrology and sediment yield of forested watersheds is a topic of ongoing concern and study. Research results from seminal paired watershed studies in the Pacific Northwest (PNW) show that timber harvest activities do affect annual water yield (Rothacher 1970, Harris 1973, Wright et al 1990), peak flows (Rothacher 1973, Jones and Grant 1996, Harr et al. 1975, Ziemer 1981), and sediment yield (Fredriksen 1970, Brown and Krygier 1971, Lewis 1998). These results, for the most part, chronicle the environmental impact associated with a bygone era. In that era the trees to be harvested were very large, roads were constructed commiserate with the harvest, the logging machinery was large and had a significant environmental footprint, and finally, there were no Best Management Practices (BMPs) applied. In the ensuing three to four decades forest practices have changed drastically. Contemporary managed forests are made up of smaller, more uniform, harvest-regenerated stands, the road systems exist, the logging machinery is smaller and has a smaller environmental footprint, most importantly, timber harvest activities are highly regulated and BMPs are used. This is certainly

the case for the Swanton Ranch in Santa Cruz County, California (Piirto et al 1999). Nonetheless, there is still ongoing concern regarding the environmental impact of timber harvest activities. The objective of this project was to investigate the impact of timber harvest activities in harvest-regenerated redwood stands with an individual tree selection silvicultural system on the hydrology and sediment yield of the Little Creek watershed.

2.2.2 Methods

This paired watershed study was carried out in the Little Creek watershed located on the Swanton Pacific Ranch, which is the school forest for the California Polytechnic State University in San Luis Obispo. Swanton Pacific Ranch is located 18 km Northeast of Santa Cruz near Davenport, California. The two watersheds that made up this study are the South Fork Little Creek (SF), which has an area of 116 ha and was the control watershed, and the North Fork Little Creek (NF), which has an area of 287 ha, was the treatment watershed (Figure 2-4).

The elevation of the study watersheds ranges from 100 to 580 m and average annual precipitation ranges from approximately 450 to 1400 mm from the outlet to the higher elevations (Gaedeke 2006). For the period of study, 2002-2010, the average annual precipitation was 875 mm at the outlet of the study watersheds to 1060 mm on the ridgelines. The soils in the study watershed are deep to moderately deep, well drained to somewhat excessively drained, and have a surface layer of loam, sandy loam, or stony sandy loam (Bowman and Estrado 1976). The forest on the Swanton Ranch in lower Little Creek is a harvest-regenerated stand of redwood (*Sequoia sempervirens*) and Douglas-fir (*Psuedotsuga menziesii*). The stand is, nominally, 100 years old and before harvest has 280 ft^2 of basal area, 45 mbf/acre, and an incremental growth of 500 bf/acre/yr. The stands are comprised of 60 percent redwood, 25 percent Douglas-fir, and 15 percent tanoak *(Lithocarpus densiflora)* (Piirto et al. 1999).

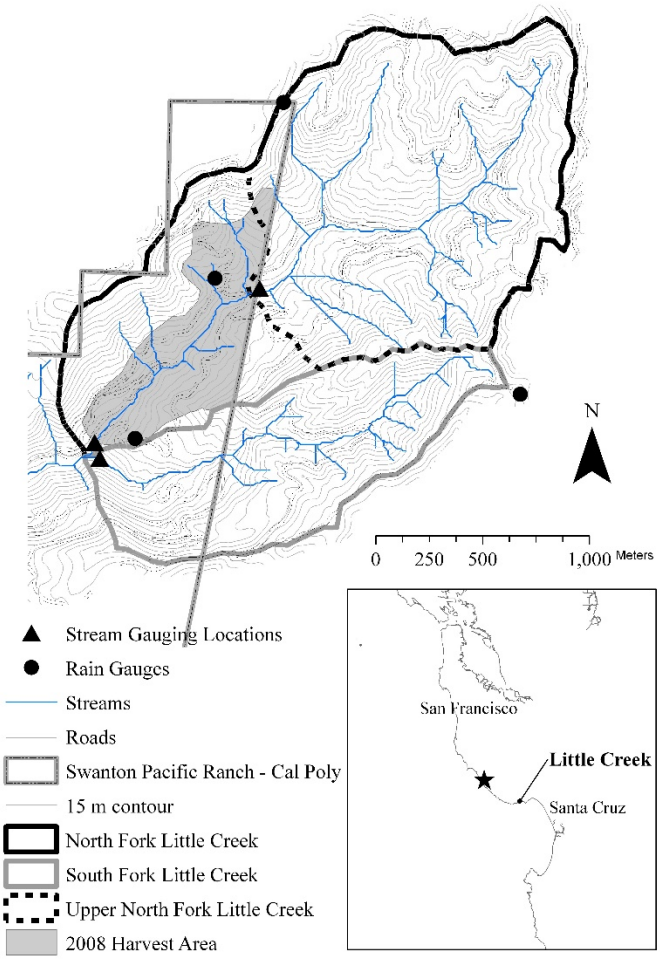


Figure 2-4. Little Creek study watersheds, California.

2.2.3 Timber Harvest Treatment

During the summer of 2008, timber harvest took place on 116 acres (47 ha) of the Swanton Pacific property above the gauging station on the NF Little Creek. The silvicultural system used was an individual tree selection system in compliance with the Santa Cruz County Rules of the California Forest Practice Rules. The timber harvest removed 728 trees that accounted for 3,882 ft^2 of basal area and 824 mbf (gross scale) of volume. Timber harvest removed, on average, six trees per acre that accounted for 33 ft^2 of basal area and 7,103 bf per acre. Those values represent 23 percent of the basal area and volume in unmanaged redwood stand in lower Little Creek. The harvest was carried out with ground based systems, tractors, and aerial systems, slackline skyline. Approximately 62 percent of the volume was harvested with tractor systems and 38 percent was harvested with cable systems. Harvest operations took place, for the most part, off of existing roads.

2.2.4 Post-Harvest Data Collection

Precipitation was measured with four tipping bucket rain gauges located in the Little Creek study watersheds (Figure 2-4). Streamflow, turbidity, and suspended sediment concentration (SSC) were measured at two gauging stations located at the outlets of the NF and SF Little Creek for the study period (Figure 2-4). Pressure transducers were used to measure stage that was stored on data loggers and converted to discharge with empirical stage vs discharge relationships. Turbidity was measured with real-time, instream turbidity probes. Automatic pump samplers were used to collect water samples during storms that were later analyzed for suspended sediment concentration. Streamflow was measured year round but values of turbidity and water samples for SSC were taken hourly just during storms.

2.2.5 Post-Harvest Data Analysis

Three parameters were selected to use for analysis of the streamflow and sediment yield data; peak flow, total storm quickflow volume, total storm sediment yield. Gaedeke (2006) described how storms were selected from the time series streamflow data. Subsequent analysis of the streamflow data used his approach. Once a storm was defined, the peak flow is the maximum hourly flow in the storm hydrograph and is reported in l/s/ha. A standard hydrograph separation (Hewlett and Hibbert 1967) was performed to determine the total storm quickflow volume and this value is reported in mm. Finally, turbidity vs SSC relationships were developed so SSC values could be estimated. SSC in mg/l were multiplied by hourly discharge in l/s to give an hourly sediment discharge, which were summed to give the mass of sediment for the storm, expressed in kg. Unique relationships between turbidity and SSC were storm and watershed specific. Examples of these relationships and how they were developed is presented in Gaedeke (2006).

For the calibration time period, 2002-2008, pairs of values from the control (SF) and the treatment (NF) watershed for peak flow, total storm quickflow volume, and total storm sediment yield were plotted. These data were not homoscedastic, thus a log transform was performed on the variable values to satisfy that assumption. A linear regression was performed on the transformed data and plotted with the data. Then values of the 95 percent prediction limit were calculated and added to the graphs. Log transform values for peak flow, total storm quickflow volume, and total storm sediment yield for the three storms that occurred during the post-harvest water year were added to the plots. The location of the post-treatment data points relative to the 95 percent confidence limits were used to evaluate if a statistically significant, post treatment effect occurred the first winter after timber harvest. During the summer of 2009 the Lockheed Fire occurred. Significant portions of the NF and SF of Little Creek were involved in that fire. The SF Little Creek no longer had value as a control watershed for the study. Thus, no further post-harvest data are available.

2.2.6 Post-Harvest Results

The data set that was analyzed for this study consisted of 38 storms that occurred between December 2002 and March 2009. Of these 38 storms, 35 occurred during the calibration period

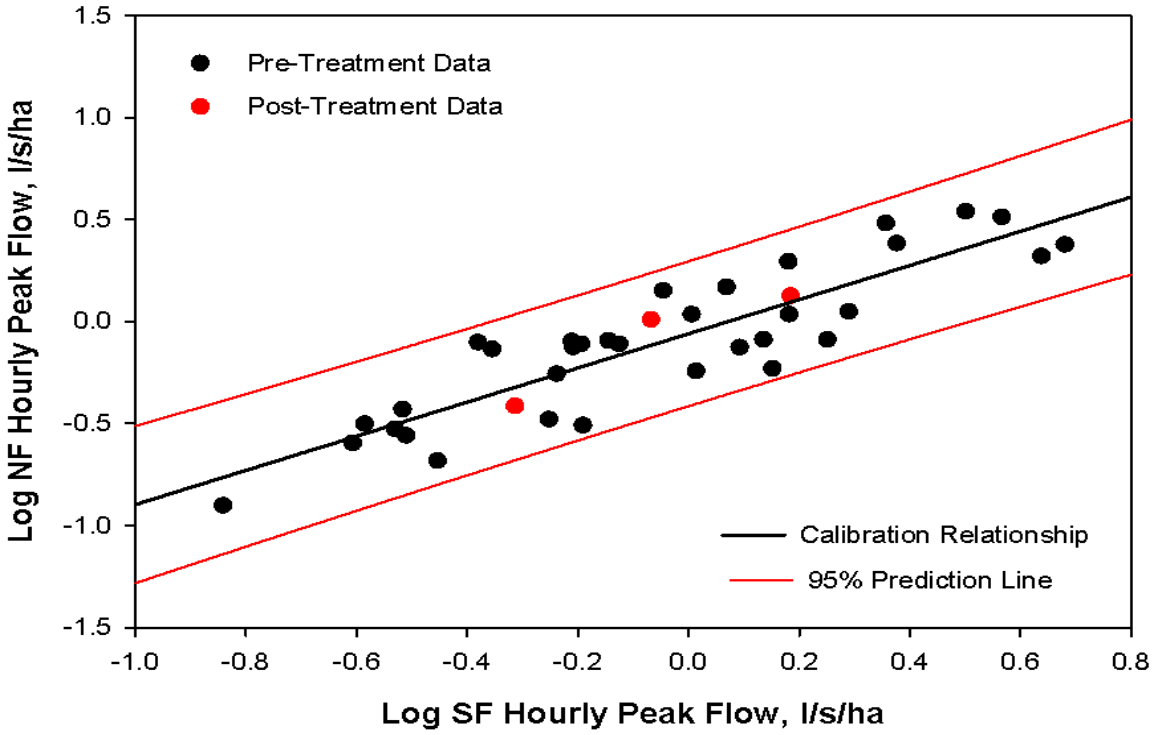
between December 2002 and February 2008. Three storms occurred during WY 2009 after timber harvest was carried out.

For the calibration period for the SF Little Creek, the control watershed, the average peak flow was 1.08 l/s/ha and the values ranged from 3.46 to 0.13 l/s/ha. The three peak flows for the post logging period were 0.39, 1.34, and 1.02 l/s/ha for an average of 0.92 l/s/ha. For the calibration period for the NF Little Creek, the treatment watershed, the average peak flow was 1.28 l/s/ha and the values ranged from 4.79 to 0.14 l/s/ha. The three peak flows for the post logging period were 2.20.49, 1.53, and 0.86 l/s/ha for an average of 0.96 l/s/ha. All three of the peak flows that occurred after logging during WY 2009 were within the variability exhibited by the population of calibration peak flows (Figure 2-5a). There was no observed impact of the timber harvest on peak flows.

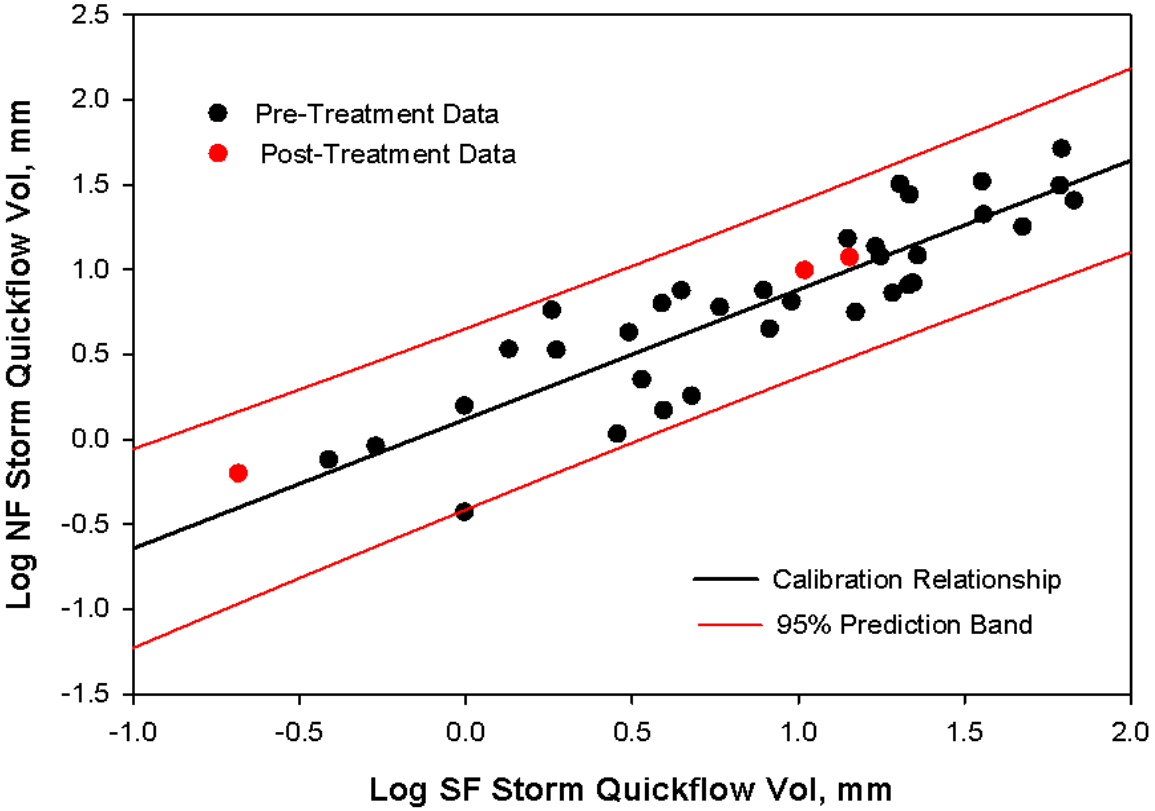
For stormflow volumes the control watershed, the SF Little Creek, for the calibration period had an average of 16.2 mm and the values ranged from 67.5 to 0.2 mm. The three storms for the post logging period had quickflow volumes of 0.6, 11.8, and 9.9 mm for an average of 7.4 mm. For the treatment watershed, the NF Little Creek, for the calibration period storm quickflow averaged 11.1 mm and the values ranged from 51.4 to 0.4 mm. The three storms in the post logging period had quickflow volumes of 0.2, 14.5, and 10.5 mm for an average of 8.3 mm. Once again, the values of storm quickflow for the three post logging storms fell within the variability exhibited by the calibration data (Figure 2-5b). There was no observed impact of timber harvest on storm quickflow volumes.

For total storm sediment yield the SF Little Creek, the control watershed, for the calibration period had an average of 31.8 kg/ha and a range from 396 to 0.1 kg/ha. The three storms for the post logging period had total storm sediment yields of 4.9, 64.9 and 9.5 kg/ha for an average of 26.4 kg/ha. For the treatment watershed, the NF Little Creek, for the calibration period the total storm sediment yield averaged 35.9 kg/ha and ranged from 331 to 0.1 kg/ha. The three storms during the post logging period had total storm sediment yields of 0.3, 5.2, and 1.5 kg/ha for an average of 2.3 kg/ha. The total storm sediment yield from the post logging period fits well within the variability exhibited by the calibration data (Figure 2-5c). There was no observed impact of timber harvest on total storm sediment yield.

a.


Pre-Treatment Data
Post-Treatment Data
Calibration Relationship
95% Prediction Line
Log NF Hourly Peak Flow, l/s/ha
Log SF Hourly Peak Flow, l/s/ha
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8

b.


Pre-Treatment Data
Post-Treatment Data
Calibration Relationship
95% Prediction Band
Log NF Storm Quickflow Vol, mm
Log SF Storm Quickflow Vol, mm
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

c.

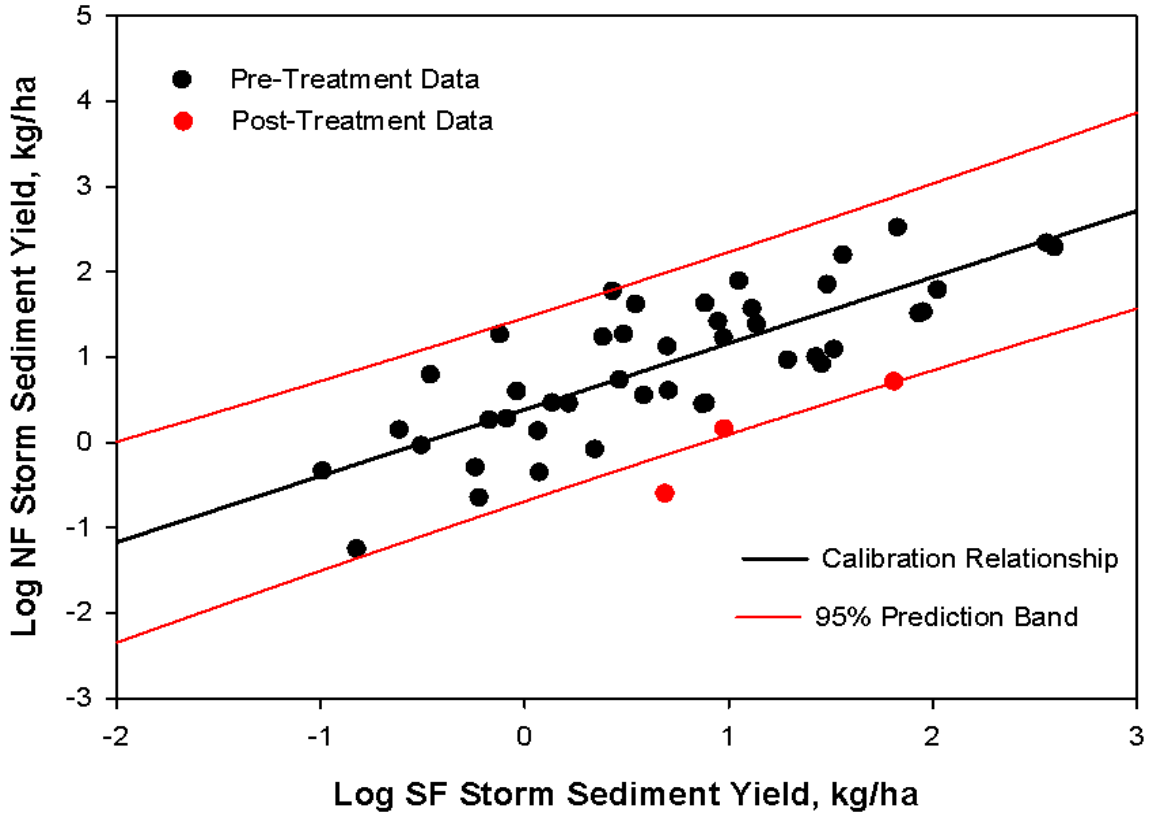


Figure 2-5. Three graphs showing data for the control (SF) vs. the treatment (NF) watersheds for the pre-treatment and post-treatment data for a) hourly peak flows, b) total storm quickflow, and c) total storm sediment yield.

2.2.7 Post-Harvest Discussion

It should not be surprising that there is no detectable impact of the timber harvest that occurred in the NF Little Creek in 2008 on the hydrology and sediment yield of the NF the first winter after logging. The reasons for this are the scale and intensity of the timber harvest operations in the NF Little Creek watershed. In published results from the seminal watershed studies the size of the treatment watersheds were often very small, 70 to 101 ha, compared to the size of the NF Little Creek watershed, 291 ha (Rothacher 1970, Brown and Krygier 1971). The Caspar Creek study watersheds had comparable sizes, 508 and 425 ha (Lewis 1998).

But more important than the scale of the timber harvest activities is the intensity. In all of the seminal paired watershed studies the silvicultural system was clearcut and the percent area affected ranged from 30 to 100 percent (Fredriksen 1971, Brown and Krygier 1971). The exception, again, is the Caspar Creek Study where the South Fork was harvested with an individual selection system but 100 percent of the area supported operations and 59 percent of the volume was removed (Lewis 1998). The silvicultural system for the NF Little Creek was individual tree selection, harvest operations were conducted on only 20 percent of the area above

the gauging station and only three percent of the volume and basal area of the forest above the gauging station was removed.

Bosch and Hewlett (1982) report that it takes removal of forest canopy on at least 20 percent of the area of a watershed to detect an impact on annual water yield. While this analysis did not investigate annual water yield, the three percent volume and basal area removed is well below the published threshold of 20 percent. The scale and intensity of the harvest operations essentially precluded a significant effect on hydrology.

There is a concern that given the paucity of post-harvest data this study may not give a true test of the impact of the forest practices used in the NF Little Creek on the hydrology and sediment yield of the watershed. This is not the case. While there are differing opinions regarding the impact the timber harvest on peak flows, those differing opinion are usually with regard to large peak flows (Grant et al 2008). There is widespread agreement that timber harvest can and does affect small peak flows (Ziemer 1981) or the peak flows that may occur many times a year, the first winter after timber harvest occurs. The mean annual flood (MAF) for the NF Little Creek during the period of record, was 1.94 l/s/ha and the three post-harvest peak flows, 0.49, 1.53, and 0.86 l/s/ha, were all below the value of the MAF. These are the size flows that could and should be affected by timber harvest the first winter after logging occurs. These flows represent an excellent opportunity to evaluate the impact of timber harvest on the hydrology of a watershed.

While the scale and intensity of the harvest combined with the size of the post-harvest peak flows may help explain the lack of an impact to the hydrology of the NF Little Creek, it doesn't necessarily explain away the lack of significance in the sediment yield data. It does explain part of the lack of significance in the sediment yield data because sediment yield and streamflow are very tightly correlated. In all of the seminal paired watershed studies an increase in sediment yield was always accompanied by an increase in water yield and storm flow. However, the degree that the increased sediment yields are a function of increased stream power versus an increase in the erosion rate of the watershed has never been fully investigated.

Nonetheless, the two harvest entries for the Caspar Creek Watershed Study did conclusively exhibit the importance of contemporary Best Management Practices in mitigating increases in sediment yield associated with timber harvest. Accelerated erosion associated with timber harvest was reduced by roughly an order of magnitude when contemporary BMP's were used in the 1990's compared with the practices used in the 1960's and 1970's. A compelling hypothesis to put forward is that the combination of the reduced scale and intensity of timber harvest activities in conjunction with the use of contemporary BMP's resulted in levels of accelerated erosion, which must occur, that remained within background variability.

2.2.8 Post-Harvest Conclusion

Hourly peak flows, total storm quickflow volume, and total storm sediment yield were analyzed for 35 storms that occurred prior to timber harvest activities and three storms that occurred during the winter after timber harvest occurred. There is no evidence in any of the results that the timber harvest activities had any impact on the hydrology or sediment yield of the NF Little Creek watershed. This finding should not be surprising given the scale and intensity of the timber

harvest activities. Timber harvest removed only about two percent of the basal area in the NF Little Creek watershed above the gauging station effectively negating a discernable impact on the hydrology. It is hypothesized that in the absence of a significant impact on the hydrology, the forest practice regulations and BMPs were effective in keeping the accelerated erosion, which must occur, within background variability.

Chapter 3. Pre- and Post-Fire Evaluation

3.1 Purpose and Need

One of the major concerns expressed by the public and land managers in the California Coast Ranges is whether disturbed conditions following wildfire increase the risk for debris flows and surface erosion during significant storms. Debris flows and surface erosion occur naturally in the Santa Cruz Mountains; the need exists to identify areas at greater risk following intense wildfire and determine the appropriate mitigation treatments to prescribe. Mitigation can be cost prohibitive and a number of studies have documented that post-fire erosion control measures have been marginally successful, unsuccessful, or provided a net negative effect in reducing surface erosion or channel erosion (Taskey et al. 1989; Booker et al. 1993; Robichaud 2000; Santi 2006; Wohlgemuth 1996). An increase in surface erosion, delivery of sediment to channels, and subsequent risk of debris flows can pose an extreme hazard to human life, property, and habitat conditions for salmonids and macroinvertbrates (Cleveland 1973).

Sediment yield increases have generally been found to be the greatest during the first year following fire, with the increases often attributed to increased runoff efficiency due to fire-induced soil-water repellency (Robichaud et al. 2009). The results of recent studies debate the influence of fire-induced soil water repellency on hydrologic flowpaths in streamflow generation and the erosion processes (Larsen et al. 2007). Although data related to soil-water repellency conditions are often unavailable before fire, it is possible to examine similar conditions in unburned areas for comparative purposes. The extent to which the fire-induced soil-water repellency forms within the soil profile is a function of burn intensity, pre-fire vegetative composition, litter composition, physical soil properties, and soil moisture conditions (Huffman et al. 2001). The hydrologic recovery after wildfire can be attributed to vegetative recovery, along with successive episodes of wetness, that promote the breakdown of the soil-water repellent layer and a return to near pre-burn infiltration rates (Kunze and Stednick 2006).

Post-fire sheet erosion has not been shown to be the dominant source of erosion and sediment delivery to channels (Santi et al. 2006), and rills are a more dominant hillslope source of sediment delivery (Benavides-Solorio and MacDonald 2005). The extent by which surface erosion may contribute to sediment to stream channels from the steep (>60 percent) and excessively steep (>90 percent) mountain hillslopes of the Coast Ranges is still questioned. Immediately following wildfire where litter/duff is consumed, ash and the bare mineral soil are at risk to surface erosion processes, particularly on excessively steep slopes.

These erosion products have a higher likelihood of being delivered to stream channels where steep slopes and inner gorges exist. Inner gorge conditions are common in the Santa Cruz Mountains. There are also pre-fire conditions on manzanita-dominated upper slopes of Little Creek where infiltration rates are naturally very low. The questions regarding how wildfire affects hydrologic processes include: (1) does fire-induced soil-water repellency exist and what

effect is there on surface erosion processes, and (2) how are erosional processes affected when soil water repellency exists without the presence of fire?

Catastrophic channel erosion and deposition commonly occur after wildfires in mountainous catchments in the western U.S. (e.g., Meyer et al. 2001). Erosion can be triggered by increases in runoff on burned soils that become impervious to water after heating (e.g., Debano 2000). Because alluvial channels evolve to convey flood runoff generated upstream (Leopold and Maddock 1953), they must deepen and/or widen to accommodate increases in runoff (Booth 1990) following fires. Expansion of headwater channels upstream into previously un-channelized hillslopes occurs frequently after burning (Moody and Kinner 2005). Erosion of channels combined with dry ravel, in turn, generates sediment which is then conveyed downstream. In this way, upstream erosion can fuel channel-derived debris flows and/or catastrophic sedimentation downstream (Cannon et al. 2001). Such deposition poses significant hazards for populations and infrastructure downstream of recent burns. Additionally, changes in bed surface grain size that accompany erosion and deposition (Parker 1990) have dramatic and often detrimental effects on downstream aquatic habitat (Reiser and White 1988).

The confidence in understanding the potentially adverse impacts on watersheds or in prescribing solutions is limited by a lack of information in environments different from where previous studies were conducted. The fact that few studies have documented fire effects in coastal Redwood/Douglas-fir forests that have vegetated zones that include fire-dependent species, such as chaparral and knobcone pine, supports the need to identify conditions that likely increase risk in the central part of the California Coastal Ranges.

3.2 Lockheed Fire

The Lockheed Fire began on the evening of August 12, 2009 in upper Bettencourt, tributary to Scotts Creek, near the ridgeline between upper Scotts Creek and Mill Creek. Warm temperatures, low humidity (RAWS stations BNDC1 at the top of Ben Lomond Mountain at the eastern edge of the watershed recorded single digit humidity before dawn on August 13), and high winds from the north quickly spread south the fire through the knobcone pine and chaparral vegetation, and the fire had reached High Hill on the north side of Little Creek by 10:00 p.m.. The wind driven fire appears to have spread rapidly across the east/west trending drainages in the ridgeline chaparral vegetation, and then burned more moderately down into the canyons. Suppression activities included extensive aerial support and significant ground-based resources went into holding the fire at the shaded fuel break along Warnella Road on the ridgeline between the Scotts Creek and San Vicente Creek watersheds. Fire suppression activities in Little Creek were limited to a handline on the eastern edge of the fire in the lower main channel, mop up activities, and regrading of existing firelines/roads on the ridgelines for access.

By the time the fire reached full containment about 10 days later, 3164 hectares (7,819 acres) were burned across a predominately forested landscape. Although burn severity varied; severities were mostly moderate to high to very high throughout the burn area. Ninety-two percent of the Little Creek 528 hectare (1,306 acre) watershed burned and over 40 percent had a high to very

high burn severity. The burn severity condition is likely the combined effect of a forest that had not experienced wildfire since the Pine Mountain Fire in 1948, an area that was experiencing two below average rain years, and extreme fire weather conditions. The burned landscape exhibits a mosaic of burn conditions that is evident by the amount of tree crown consumed, fire scars on the trunks, and also important is that nearly 100 percent of the shrub and ground vegetation was consumed by fire. The heat at the ground layer was extreme and soil burn conditions were extreme nearly everywhere in the burned upland portions of the Little Creek watershed. These conditions raised questions about how this landscape would recover following this disturbance, and how the landscape would respond to rain seasons immediately following the fire.

3.2.1 Fire Impacts

A fire burn severity map (Figure 3-1) was produced by Cal Poly in cooperation with CAL FIRE for the Lockheed Fire Post Fire Risk Assessment. USFS BARC (Burn Area Reflectance Classification) data were used and compared to aerial photos and ground observations to develop thresholds for low, medium, high, and extreme burn severity. These ratings are primarily related to impacts to vegetation and are not a direct proxy for impacts to soils from the fire (Hudak et al. 2007). Low severity areas still had some ground cover, low vegetation, and duff intact. In moderate areas, duff and low vegetation were consumed, but the tree canopy was still intact. In high burn areas the duff and understory was consumed and the tree canopy was scorched but the needles remained on the trees. In severe burn areas the canopy was completely consumed by the fire. With respect to the entire burn area, 92 percent of the Little Creek watershed burned in the fire. 11 percent burned at extreme severity, 31 percent at high severity, 53 percent at moderate severity, and five percent at low severity. Except for two tributaries that drain the north side of Little Creek along the mainstem, almost all areas adjacent to channels burned at moderate or low severity.

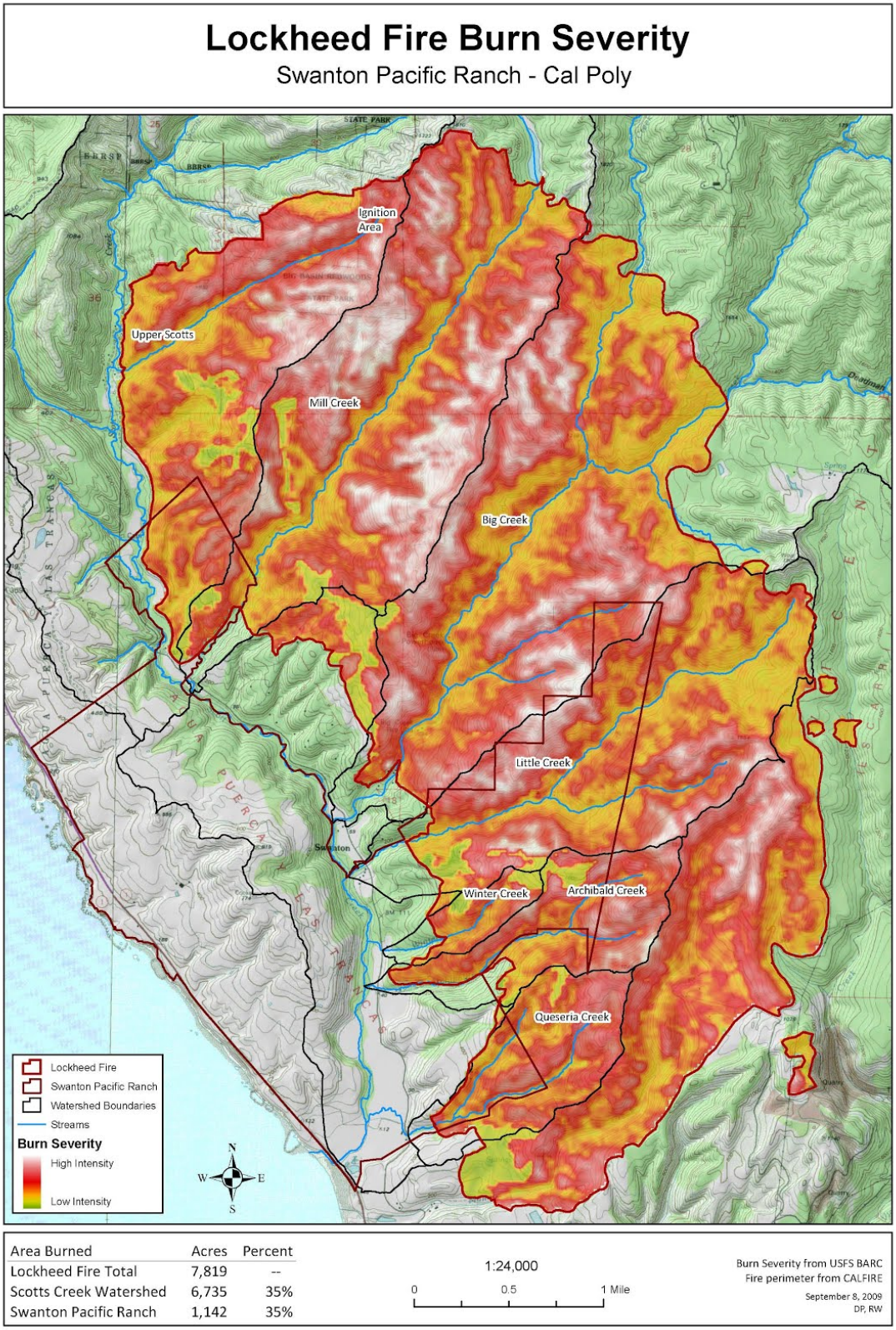


Figure 3-1. Burn severity map of the Lockheed Fire. (CAL FIRE, Big Creek Lumber Co., Cal Poly 2009).

3.2.2 Salvage Activities

Salvage logging by helicopter was performed in the Little Creek watershed on Cal Poly property during the spring of 2010. This harvest focused on the most intensely-burned areas primarily in the South Fork and along the upper Mainstem. The upper watershed, formally owned by the CEMEX Corporation, was logged by helicopter, cable-yarding, and ground-based logging methods in the summer of 2010. The silviculture and logging techniques used in the salvage operations were similar to the single tree selection logging used in other harvests in the watershed. Because of the timing and location of operations, it is difficult or impossible to separate potential impacts from the salvage logging operations in some of the data discussed in the study from those that may have been solely a fire effect.

3.3 Little Creek Post-Fire Study Initiatives

The effects of wildfire on watershed characteristics and function are a major concern, yet these effects remain poorly understood at the watershed scale, mainly because data have rarely been collected both before and after wildfires.[1] The Little Creek watershed offers one of these rare instances where a significant level of pre-fire monitoring data exists prior to a wildfire. The Little Creek watershed serves as Cal Poly's school forest and includes the long-term Little Creek Study. At the time of the fire, the study was in the in the eighth year of a pre- and post-harvest monitoring study to document the effectiveness of California's Forest Practice Rules in preventing increases in suspended sediment export. The study had measured hydraulic geometry and channel conditions for eight years. The fire that halted the pre-and post-harvest study provided the opportunity of having the benefit of an extensive pre-fire calibration period that allowed post-fire evaluations to begin immediately.

Immediately following the fire, steps were taken to capture as many opportunities to observe or study post-fire watershed response as it relates to change in physical condition and hydrologic processes. As with most similar incidents, the immediate focus was with public safety concerns, including the susceptibility of the watershed to experience accelerated surface erosion, debris flows, and debris torrents. From the scientific perspective, limitations were quickly realized due to the short time before the beginning of the rain season, staffing limitations, and funding. Meetings were held with agency representatives from CAL FIRE and the California Geological Survey, along with researchers from Oregon State University to locate possible sites for observing erosional processes. Some effort was placed on establishing sites for monitoring, while other opportunities were presented following the first rain storms.

Research opportunities were undertaken to help improve our understanding about fire-induced changes to watershed processes across the managed landscape found in the central part of the Coast Ranges. Key questions identified to drive the study included: (1) has the post-fire erosional and hydrologic response changed as a direct result of the fire, (2) has suspended sediment export

[1] Examples of previously documented pre and post-wildfire watershed studies include Rice et al., 1965 (San Dimas Experimental Forest) and Woodsmith et al. 2007 (Entiat Experimental Forest).

increased as a direct result of the fire, and (3) have channels in the watershed undergone change as a direct result of the fire? The research team sought to understand any change in the context of historic and catastrophic mass wasting and change to channel system? An additional goal initially was to understand watershed and channel change in the context of post-fire salvage logging. Although hillslope, channel, and water quality changes were evaluated within the Little Creek watershed following salvage logging, the lack of adequate pre-harvest monitoring for the salvage harvest presented a significant challenge regarding the ability to measure an effect.

Prior to the first significant rainstorm on October 13, 2009, a plot study was established to observe surface erosion from one-square meter plots on an intensely-burned hillslope that exhibited high soil burn severities. Widespread dry soil moisture conditions were observed following this first storm that produced rainfall amounts in Little Creek from four to seven inches and up to ten inches in the upper Scotts Creek. At that time through a collaborative effort with Oregon State University, sites were identified for rainfall simulations to investigate the effect of the fire on soil hydrologic properties. Sites were also identified for investigating soil water repellency. Additionally, monitoring work initiated for the pre- and post-harvest study to document suspended sediment export, channel morphologic change, and near-stream sediment sources were also continued. Lastly, an opportunity to better understand mortality of red alder along the riparian zone of Little Creek was initiated two years after the fire when red alder were observed dying at an accelerated rate.

Each of these investigations are described in more detail in sections 3.6 - 3.10.

3.4 Rainfall Summary

The first two winters following the Lockheed Fire were wetter than average (Figure 1-4.). The first significant rain after the fire came as an unseasonably strong October 13-14, 2009 storm. This storm brought 5-8 inches of rain to the Little Creek watershed and 11 inches to the Ben Lomond Mountain gage in the upper Scotts Creek watershed. Most of this rain fell in a 14-hour period from noon on the 13th to 2 a.m. on the 14th. Even though this storm brought a relatively high amount of precipitation for a 14 hour period, rainfall rates were consistently moderate and steady. At the LD rain gage, maximum hourly intensity was 0.7 in/hr and maximum 15 minute intensity was 1.12 in/hr. With dry antecedent moisture conditions, hydrologic response to this storm was relatively minor, even on the recently burned watershed. In Little Creek, a few small debris flows occurred in tributaries that had extensive severe fire intensity. If rainfall on January 18, 2010 had not ended after the high-intensity storm burst, it is likely more significant hydrologic and geomorphic impacts would have occurred. And likewise, had this storm occurred when antecedent moisture conditions were high, more significant hydrologic and geomorphic impacts would have occurred, including possible flooding in lower Scotts Creek. Greater discussion and rainfall data for the October 2009 storm are available at:

http://www.cnrfc.noaa.gov/storm_summaries/oct2009storm.php

Another notable storm of the 2009-2010 season occurred on January 18, 2010 (Figure 3-2). This was the second storm in a rainy week with five days of back to back frontal passages that produced 1-2 inches of precipitation followed by 6-12 hours of light showers or dry weather. The storm on the January 18th started with light to moderate rain (1.20 inches over approximately 8 hours) and cumulated with an intense thunderstorm as the front passed that dropped 0.6 inches between 10:00 and 10:15 a.m. before precipitation abruptly stopped and no rain fell until early the next morning. This short-duration high intensity rain (2 min: 4.5 in/hr; 5 min; 3.6 in/hr, 10 min; 3.18 in/hr, 15 min; 2.54 in/hr at the LD gage) triggered small debris flows in several small tributaries in Little Creek and rapid stage rises and turbid sediment-laden water in the main channels. The intense rainfall also initiated localized rilling on slopes on the north side of Little Creek Road (see discussion in next section).

The most significant storm since rainfall monitoring began in 1997 occurred on February 2-3, 1998, more than ten years prior to the Lockheed Fire. This storm produced lower rainfall intensities, yet also caused significant flooding, widespread landsliding, and some additional channel-derived debris flows. Rainfall intensities estimated from data of the Landing rain gage were: 2 min: 2.7 in/hr; 5 min: 2.4 in/hr; 10 min: 2.16 in/hr; 15 min: 2.08 in/hr. This storm totaled over 6 inches of rain during an already wet winter with antecedent moisture conditions approaching complete saturation.

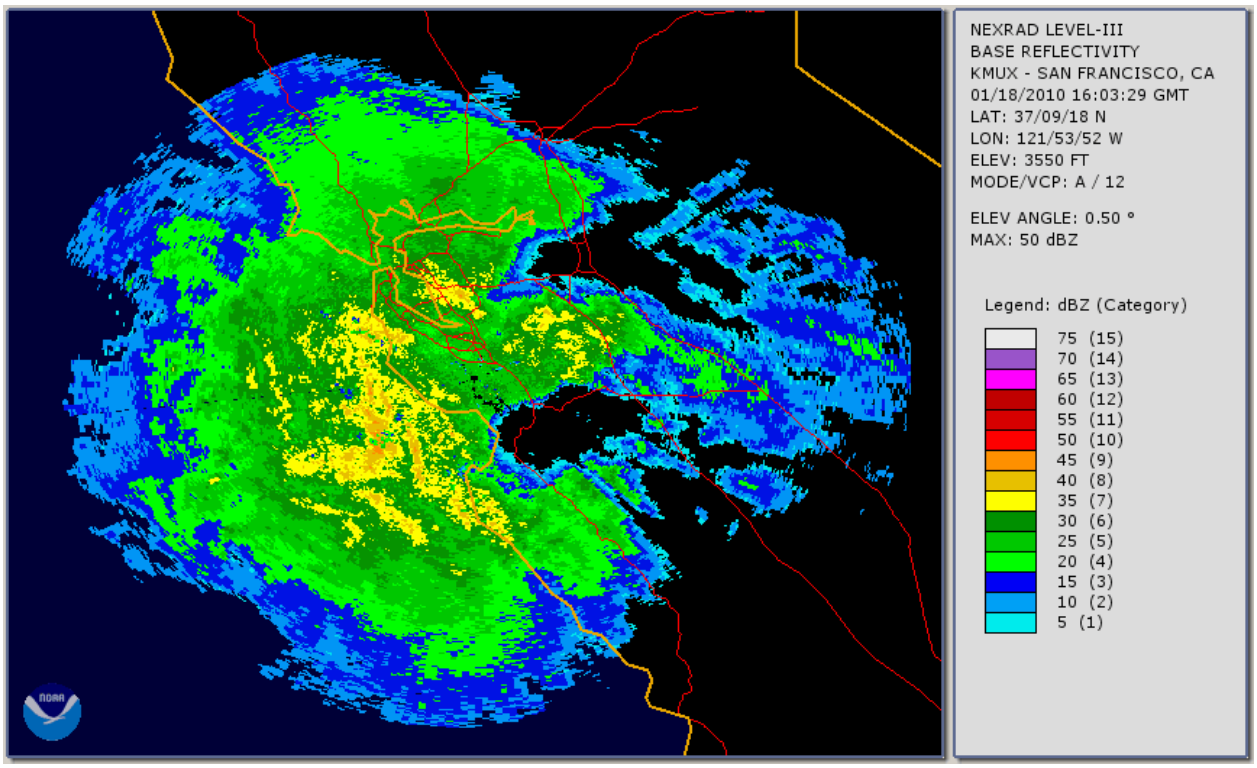


Figure 3-2. Radar from the January 18, 2010 storm event showing small embedded cells that produced extreme orographically-enhanced rainfall intensities.

3.5 Hillslope Evaluations

3.5.1 Lion's Flat Hillslope Erosion Evaluation

Hillslope-derived erosion is common after a wildfire due to lack of ground cover, loss of shrub and overstory canopy interception, reduced soil infiltration due to soil sealing, and production of hydrophobic conditions (Benavides-Solorio and MacDonald 2005; Ice et al. 2004; Larsen et al. 2009). One square meter plots were constructed in attempt to measure the amount of hillslope erosion in different slope classes. Plots were installed at Lions Flat, which is an area on the north facing slope of the South Fork of Little Creek. This area is located in a pocket of high burn severity in a transition zone of redwood to oak woodland. Plots were built using three beveled one meter wooden boards, with the downslope end containing a collection basin made from silt fence (Figures 3-3 and 3-4). The first nine plots were installed immediately before the first storm event on October 13th. An additional three plots were constructed in December 2009. Slope classes were 0-54%, 55-74%, 75%+, with the steepest slope being 102%. Hillslope plot basins were emptied during breaks between major storm events. Any organic matter in sediment basins was removed by hand and sediment was dried and weighed in the laboratory.

Figure 3-3. Lion's Flat erosion plot site.

Figure 3-4. Lion's Flat erosion plot showing trough designed to capture surface eroded material.

At the time of installation, there was no live ground vegetation present within the plot boundaries. Rock fragments and leaf litter were present, but were not measured when the plots were installed. Throughout the storm season leaf litter increased due to wind and rain removing dead foliage from overstory trees. Live vegetation also began to grow with moist soils during the fall and winter period and with warmer spring temperatures. Percent ground cover consisting of rock fragments greater than 1.3 cm (0.5 in), live vegetation and/or leaf litter, and bare soil were measured using a grid for each site following the last significant storm event of the first over-wintering period on March 11, 2010.

Results from Lion's Flat Hillslope

The hillslope erosion plots installed on the steepest slope class had the highest average erosion rate (Table 3-1). The plots located on the lowest slope class had the second highest average erosion rate. Percent bare soil correlated to erosion rate, with the highest percent bare soil plots having the highest erosion rates (Figures 3-5 and 3-6). Similarly, plots with the lowest erosion rates had the highest percent vegetation. The vegetative cover was predominantly newly-accumulated litter from needle fall within a month after the fire. The most significant observation

is that leaf or needle fall prior to the erosion-producing rainfall events provided protection capable of reducing surface erosion. Rock fragments did not have clear influence on erosion rate, although it was suspected they offered some level of surface erosion protection from moderate-intensity storms. Erosion rates are largely a function of slope gradient, but other soil physical properties also play a significant role (e.g., soil texture, permeability, coarse fragments, depth to restrictive layer).

Table 3-1. Summary of erosion rates for the measures periods October-March and January-March

	October to March (Plots 1-9)		January to March (Plots 1-12)	
Slope Class (%)	Average erosion rate (g/m^2)	Average erosion rate (tons/acre)	Average erosion rate (g/m^2)	Average erosion rate (tons/acre)
0-54	590.9	2.64	194.9	0.87
55-74	318.9	1.42	310.8	1.39
75+	1016.7	4.54	515.9	2.30
Bare soil (%)				
0-39	284.2	1.27	101.2	0.45
40-59	431.1	1.92	318.8	1.42
60+	1088.0	4.85	564.6	2.52

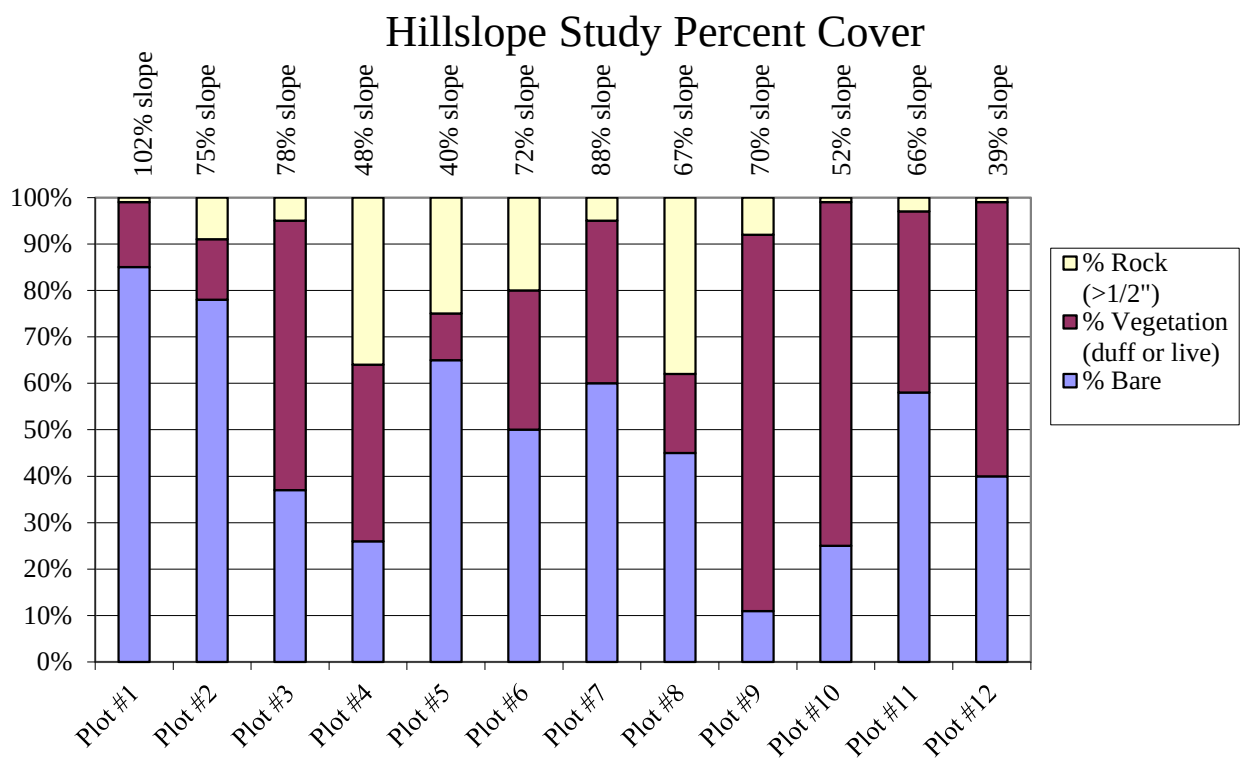


Figure 3-5. Percent cover for all Lion's Flat study plots.

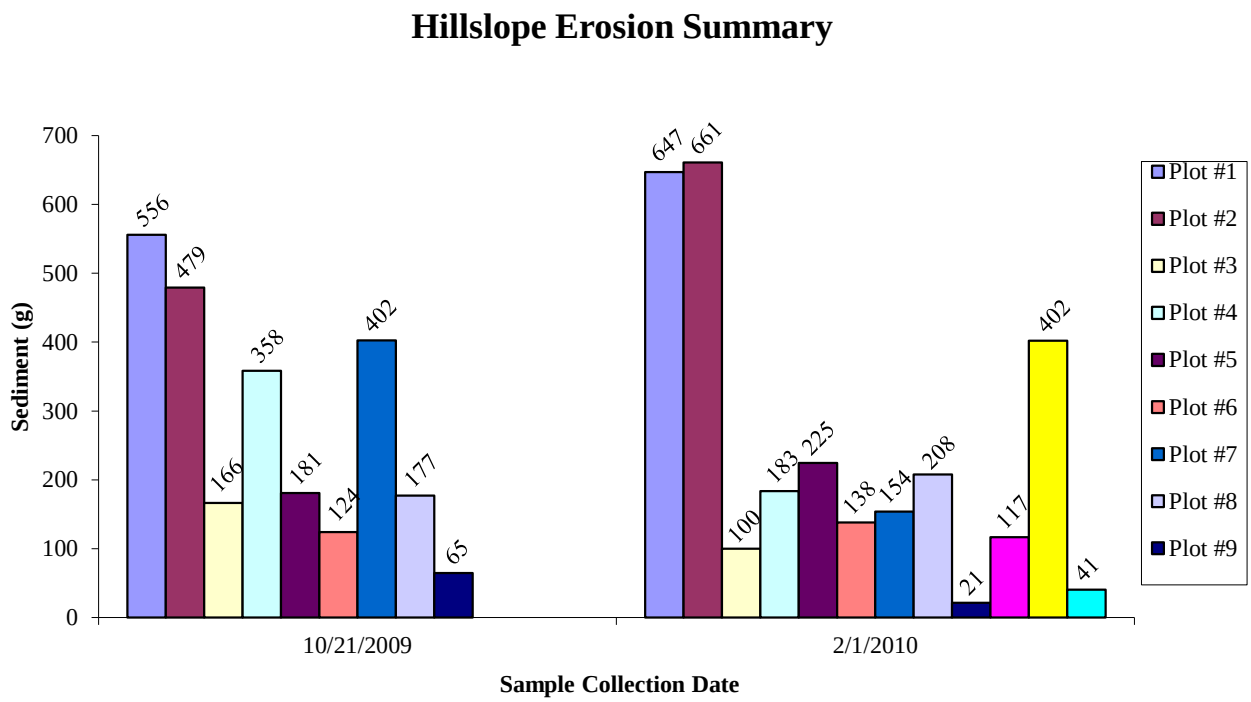


Figure 3-6. Eroded sediment (g) measured on October 21, 2009 and February 1, 2010, encompassing the two most significant storm events of the first rain season.

3.5.2 Debris Flows

The initial 6-inch storm on October 13, 2009 produced little in terms of surface erosion in the Little Creek watershed. There were several smaller channel-derived or swale-derived debris flows likely initiated by the efficient delivery of near-surface runoff to swales or tributary channels resulting in capacity flows in debris accumulated channels (Figures 3-7, 3-8, and 3-9). There was a debris flow in the R8 tributary and some small colluvial ravel type deposits on the Little Creek haul road.[2]

The January 18th storm initiated debris flows in several tributaries (R7, R8, and R9.5 and a very small one in a tributary to the South Fork that blocked a small culvert). There were more debris flows that produced significantly higher volumes of sediment than those observed after the October storm.

[2] Many of the tributaries are named after the Little Creek road crossing ID in the Swanton Pacific Ranch NTMP.

Figure 3-7. Left: Ravel deposit on Little Creek Road after the October 2009 storm. Right: A fluid debris flow deposit on road after January 18, 2010 storm.

Figure 3-8. Left: Debris flow fan at the confluence of R7 tributary and Little Creek after the January 18, 2010 storm. The Little Creek channel is visible at bottom right. Right: Small debris flow in R9.5 tributary after the January 18th storm. The extent of scour is evident on the left edge of channel. A deposit in the depression behind railroad fill is visible at top right.

Figure 3-9. Debris flow deposits on Little Creek Road from the R8 tributary.

Sediment Fence Observations

Hillslope erosion rates were also documented by installing sediment fences at various sites in Little Creek watershed. Using a technique described by Robichaud and Brown (2002), three sediment fences were installed in small swales at forested sites with varying slopes and moderate burn severity. The two other sites were located near hillslope erosion plots for comparison of erosion rates. These sediment fences were installed in December 2009. Two sediment fences were installed in February 2010 in swales downslope from an area with a large network of rill erosion. Sediment fences were inspected following storm events to identify if any sediment accumulation occurred. The sediment accumulations were cleaned out at the end of the storm season, and dried and weighed in the lab. The observations were sporadic and data inconclusive, hence these data are not presented here.

3.5.3 Rillslope Study

The second significant storm of the season on January 18th caused substantial rilling on approximately three acres of hillslope on the north side of Little Creek. The rilling was attributed to a very intense short duration burst of rainfall. A Cal Poly senior project was undertaken to measure the rills to estimate erosion rates, with three plots established on the rilled hillslope (referred to as the rillslope study) (Figure 3-10).

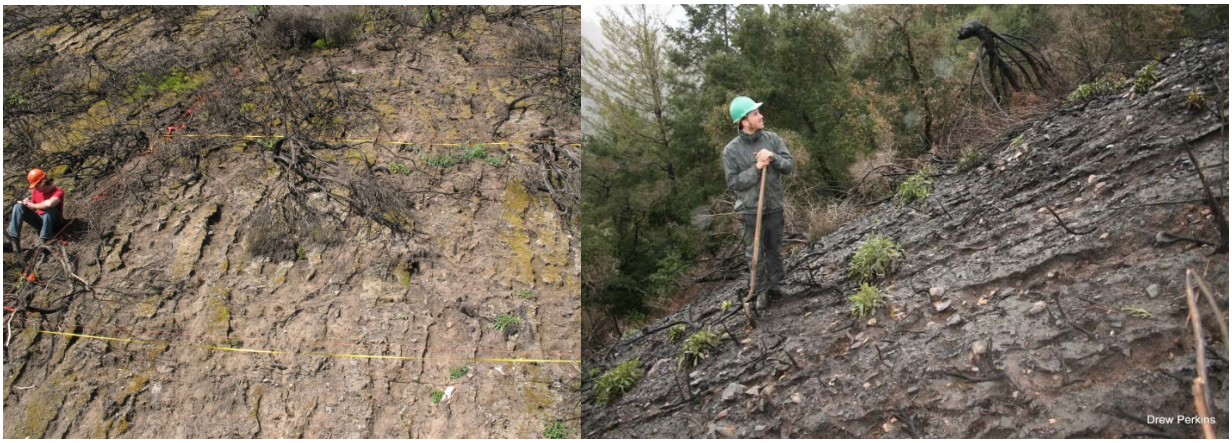


Figure 3-10. Rill erosion plots located in the Little Creek watershed, Swanton Pacific Ranch.

Three 10 m² representative plots were established on the hillslope and rill depth and width were measured along 10 transects within the plot using a ruler and cloth tape. The X/Y database was imported into ArcGIS to calculate cross-sectional areas and eroded area. Although the precision of this method is recognized to be low, the amount of sediment eroded from the hillslope was substantial and supported by the estimate of 3.68 x 105 kg/ha (164 tons/acre). The maximum five minute rainfall intensity experienced during this storm was estimated to be 3.6 inches/hr at a nearby rain gage (see rainfall data presented earlier). Niebrugge (2012) investigated the factors that contributed to rilling on these hillslopes compared to other areas in the watershed that had similar levels of fire impact, cover, slope, and soils. The factors identified were high clay content, greater slope length, and lower infiltration rates. This rilling was substantial and there was evidence that some of the sediment from this site was delivered to Little Creek. Much of the debris flow sediment from this hillslope and several other areas nearby were deposited on road surfaces below with limited delivery (estimated less than 10% of total volume) to stream channels. It is also important to note that surface rilling was only observed on approximately 0.3% of the watershed area.

3.5.4 Rainfall Simulation Evaluation

Introduction

One significant observation made following the October event was the widespread dryness below the initial near-surface layer of the mostly consumed O and A horizons. This was observed by screeding away ash and the top one inch layer of soil, revealing mostly non-wetted soil horizons below with the exception of some occurrence of wetness via preferential pathways, such as root voids. The dryness combined with general lack of surface erosion evidence (sheet or rill erosion) led to hypothesizing that significant near-surface runoff was occurring without generating hillslope erosion. It was thought that rainfall simulations could explore the near-surface runoff phenomenon and quantify the volume of runoff produced in this shallow zone of the disturbed hillslope.

Approach

Thirteen rainfall simulations sites were established throughout the Scott Creek watershed following the Lockheed Fire. Simulation sites (Figure 3-11) represent variations in burn severity, soil parent material, vegetation types, percent slope, and accessibility. Sites were located in four burn severity classifications: non-burned, low, moderate, and high. Soil parent materials are granite, mudstone, and a mixture of mudstone and sandstone. Vegetation types are redwood dominant, knobcone pine/manzanita, and tanoak. Simulations were conducted annually over the summers and early fall from 2009 to 2013. Permanent plots were not established during the setup of this project, therefore a new plot was constructed at each site location every year.

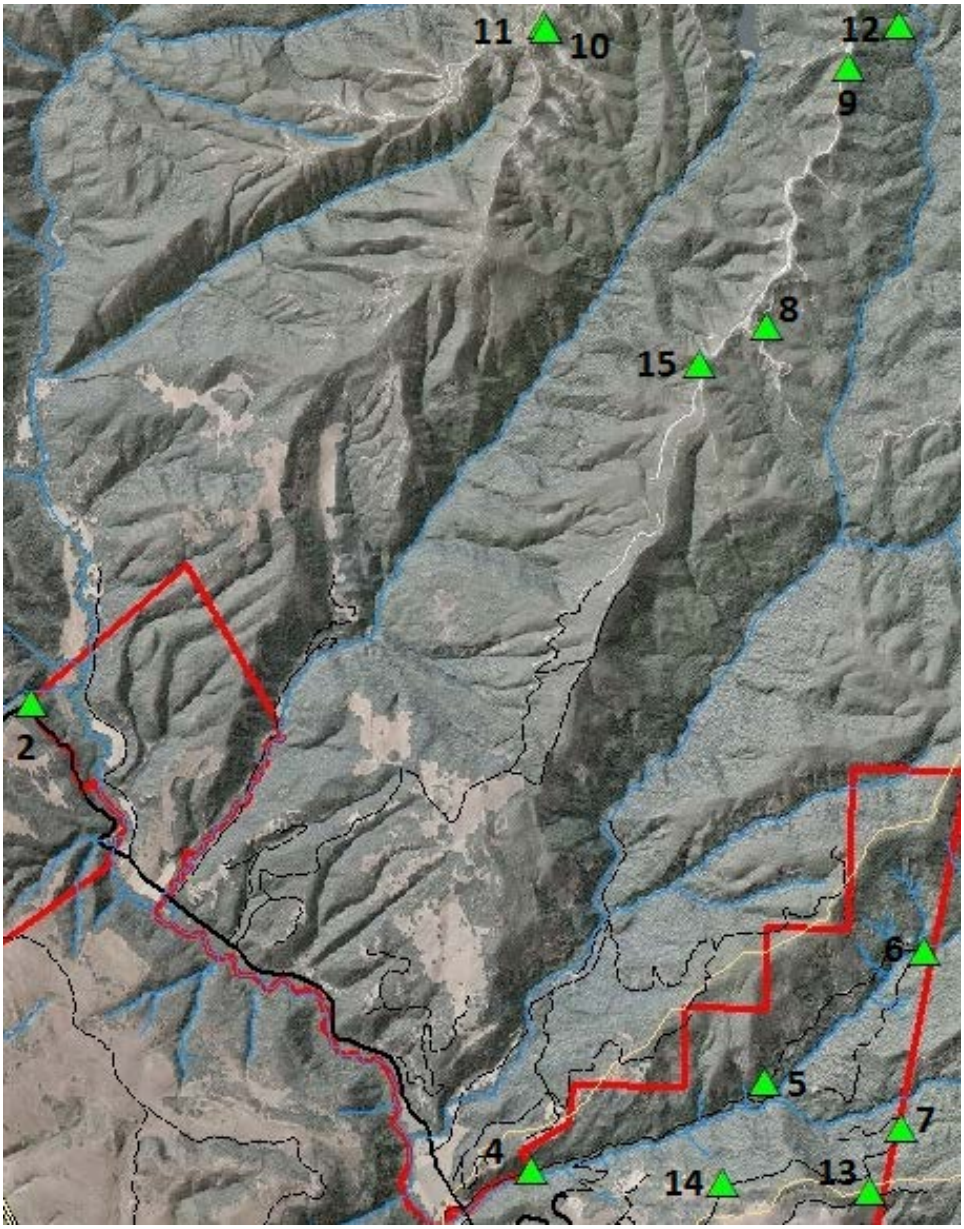


Figure 3-11. Site locations for rainfall simulations in Little Creek and Scotts Creek watershed.

A portable rainfall simulator with an oscillating sprinkler head that sprayed a rainfall rate of 5.08 centimeters per hour was placed over a one x one meter plot. Near-surface runoff was caught in a trough and funneled into a five gallon bucket where the depth of the bucket was measured every two minutes. The depth readings were placed into an Excel spreadsheet, where the total runoff volume and runoff rate was calculated. The infiltration rate was found indirectly by taking the difference between the rainfall rate and runoff rate. The runoff ratio, referred to as the hydrologic response, was calculated by finding the ratio of total runoff (L) to total rainfall (L).

Statistical analysis was performed by Jack Lewis, former (retired) statistician for the USDA Forest Service, Pacific Southwest Research Station, using mixed-effects modeling in the program R. Mixed-effects modeling was utilized in order to decipher whether or not there was a statistically-significant difference in the hydrologic processes (infiltration rate and hydrologic response) between burned and non-burned sites from 2009-2013. Parameters within mixed-effect models are categorized as either "fixed" or "random" effects. In the case of rainfall simulations, fixed effects are those variables that will influence infiltration rates and hydrologic responses, therefore, fixed effects are time, burn severity, and the interaction between burn severity and time. The interaction term is used to identify whether a significant change over time can be attributed to the burn severity or fire. The random effect is site number, since sites were randomly assigned a number. As a note, transformations were applied to the data in order to get a better fit during portions of the analysis.

Additionally, the four burn severity classifications were simplified into dichotomous burn contrasts: "hot burn versus all others" and "unburned versus all others;" "hot burn versus all others" lumps none, low, and moderate burn severities into the "other" category and high severity is classified as "hot." This dichotomy allows for testing a maximum fire effect, assuming higher burn severities translate to higher near-surface runoff amounts. The second classification, "unburned versus all others," lumps low, moderate and high burn severities into the "Others" category while non-burned sites are classified as "unburned." This burn dichotomy allows for testing whether or not a fire effect could be detected.

Rainfall simulation data

Infiltration rates ($\frac{\mathrm{L}}{\mathrm{min}}$) are shown for each burn severity classification as a function of time (days) (Figure 3-12). Sites are color coded and divided by burn severity classifications. Strong increasing trends in infiltration at the high burn severity sites and one unburned site from 2009 to 2010 are visible. The remaining unburned, low, and moderate sites exhibit an increase in infiltration over time as well, but are weaker from 2009 to 2010. There is a peak in infiltration in 2012 that is followed by a decline in 2013 at most of the sites.

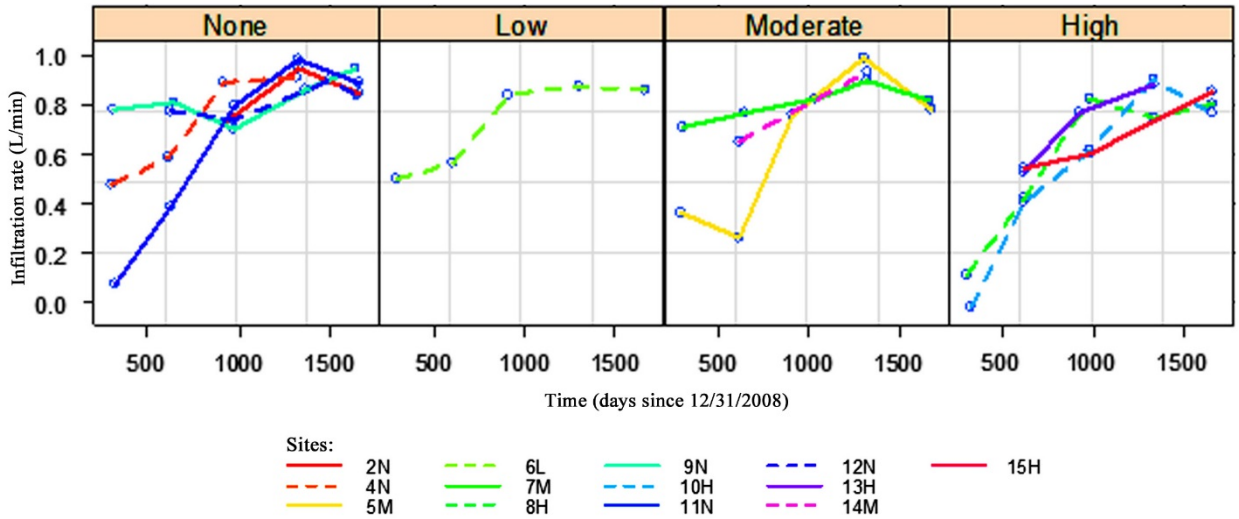


Figure 3-12. Infiltration rates (L/min) of different burn severity classes as a function of time (days since December 31st, 2008).

Hydrologic responses are shown for each burn severity classification as a function of time (days) (Figure 3-13). A strong, decreasing trend is evident at high severity sites from 2009 to 2010 as a result of high runoff volumes at site 8-Boyer and site 10-Scotts/Mill. Oddly enough, however, there is a strong decreasing trend from 2009 to 2010 at site 11-Scotts/Mill which is an unburned site. Field notes following the simulation at site 11-Scotts/Mill indicated natural soil water repellency was suspected.

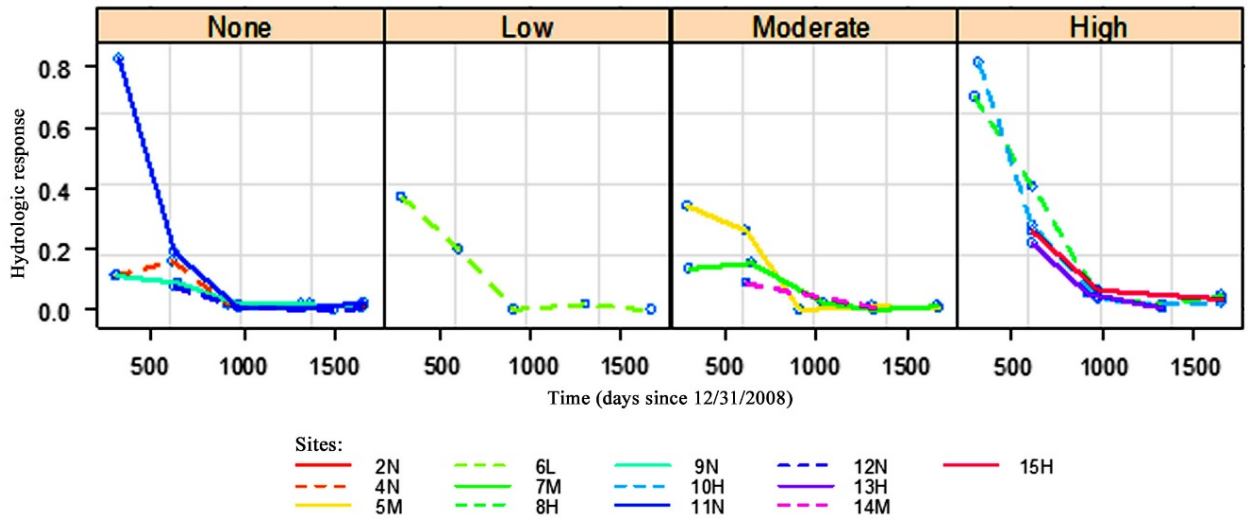


Figure 3-13. Hydrologic response of different burn severity classifications as a function of time (days since December 31st, 2008).

Rainfall simulation results

With infiltration rate as the response, time was a highly significant predictor ($p=0.0052$), however, burn severity ($p=0.32$) and the interaction between burn severity and time ($p=0.72$) were not. With the square root of runoff ratio as the response, time was significant but burn severity ($p=0.2288$) and the interaction between burn severity and time ($p=0.4610$) were not. These results suggest that the fire did not have a statistically-significant impact on soil hydrologic processes within the fire during the years following the Lockheed Fire.

Statistical analysis for the "Hot versus all others" burn dichotomy showed that time was highly significant predictor ($p<0.0001$) for infiltration rates, but burn severity ($p=0.95$) and the interaction between burn severity and time ($p=0.208$) were not significant predictors for infiltration rates. With square root of runoff ratio as the response for this model, time was a highly significant predictor ($p<0.0001$), burn severity was slightly significant ($p=0.023$) but the interaction between burn severity and time ($p=0.123$) was not significant.

Statistical analysis for the "Unburned versus all others" burn dichotomy showed that time was a highly significant predictor ($p<0.0001$) for infiltration rates while burn severity ($p=0.419$), and the interaction between burn severity and time ($p=0.596$), were not significant predictors. Regarding the square root of the hydrologic response as the response variable, time was a highly significant predictor ($p<0.0001$) while burn severity ($p=0.164$), and the interaction between burn severity and time ($p=0.211$), were not significant predictors.

Rainfall simulation discussion

Trends were present in the graphical displays, showing that infiltration rates and hydrologic responses changed over time regardless of the burn severity classification. This suggests that burn severity did not strongly influence the response variables over the five-year testing period.

Statistical analysis showed that time was a highly-significant predictor for infiltration rates and the hydrologic response, indicating that there was a statistically-significant difference in the average infiltration rate and hydrologic response among years. This is reasonable given that the unburned sites contained similar time trends as the burned sites. Burn severity was not a statistically-significant predictor for infiltration rates or hydrologic responses. This implies that burned sites are not different than unburned sites in regards to infiltration rates and hydrologic responses thus suggesting no fire effect. Similarly, the interaction between burn severity and time is not a significant predictor implying that the statistically-significant change in infiltration rates and hydrologic response among years cannot be attributed to the fire.

While the thirteen sites were representative of variations in burn severity classifications, soil types, and vegetation types, this study found that the number of classifications within each of these variables should be minimized. For instance, sites should be established in areas that have the same vegetation type and same soil type. This would allow for better comparisons among burned and non-burned sites as opposed to making comparisons between two innately different soils types associated with either the soil parent material or vegetation type. As well, multiple simulations should be conducted each year within a site in order to better account for the

variability within a site. Conducting simulations in this manner would likely have improved the ability to discern which sites had experienced fire-induced changes to the hydrologic properties in the near surface, as well as, distinguish sites with fire-induced effects from sites that have apparent high natural soil water repellency or high infiltration rates.

3.5.5 Mini-Disk Infiltrometer and Water Drop Penetration Time Tests

Approach

Twenty-three Mini-disk Infiltrometer (MDI) sites were established in October 2009 at a variety of locations within the Little Creek watershed (Figure 3-14) with the goal of assessing post-fire soil infiltration and water repellency throughout the entire watershed. In conjunction with MDI field tests, water drop penetration time (WDPT) tests were performed alongside the MDI tests as an alternative method for evaluating soil water repellency. MDI tests were conducted annually over the summer months from 2009 to 2013. The WDPT tests were conducted annually over the summer months from 2010 to 2013.

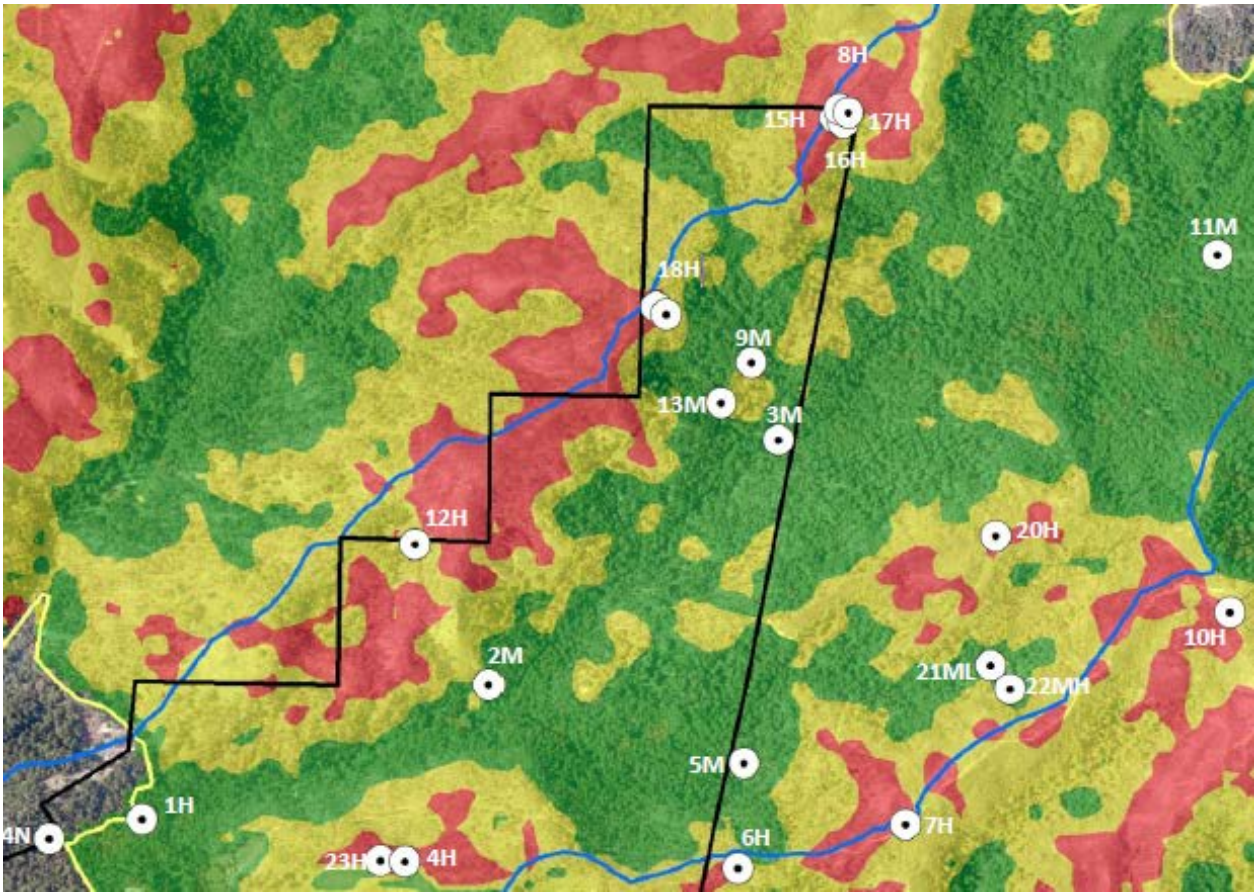


Figure 3-14. Site locations for the 23 MDI and WDPT tests.

Site locations represent variations in soil burn severity, percent slope, aspect, and slope position. One 30.48 meter transect was laid out adjacent to the contour of the landscape at each site location. The MDI and WDPT tests were performed every 6.096 meters (five positions total) along each transect. Furthermore, MDI tests were replicated three times at 1 and 3 centimeter depths at each position along the transect, while the WDPT tests were replicated three times at 1, 2 and 3 centimeter depths. A trowel was used to cut a platform for the tests at the correct depths and a ruler was used to ensure the platform was the correct depth. Duff was brushed aside so that depth measurements were taken from the mineral soil surface.

MDI tests were conducted by placing the infiltrometer on the soil surface for thirty-seconds. After thirty seconds was complete, the infiltrometer was lifted from the soil and the total volume of water that left the device and infiltrated into the soil was recorded. For WDPT tests, a single drop of water was placed on the soil surface and the time it took the drop of water to infiltrate was recorded.

Mixed effects modeling in the program R was used to display and analyze MDI and WDPT datasets. There are five soil burn severity classifications that were not equally represented among the 23 sites, therefore, burn severity classifications were simplified into two classes “Hot” and “Cool.” Hot incorporates hot, moderate-hot, and moderate, while Cool incorporates moderate-low and none.

MDI Data

Mean infiltration volumes are shown by year and simplified burn classification as a function of time (years) (Figure 3-15). This graph shows that mean infiltration volume does not appear to be related to depth as a result of trend lines that are neither strongly increasing nor decreasing.

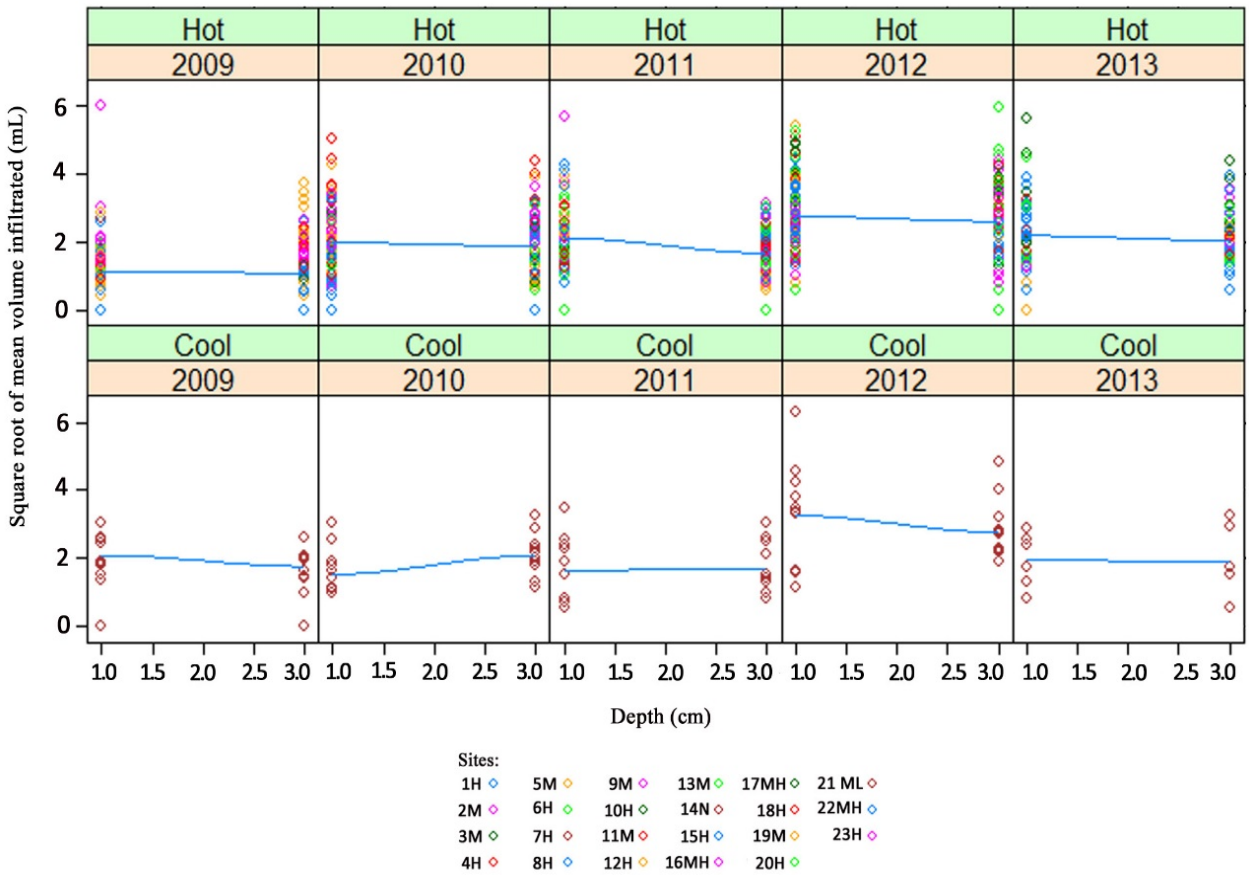


Figure 3-15. MDI mean volume infiltrated (mL) as a function of depth (cm) for each year and simplified burn severity classification. For the simplified burn classes, "Hot" incorporates burn severity classes M, MH, and H. "Cool" incorporates N and ML. Volumes have been transformed for this display using square roots. Curves are fitted by loess (degree = 1, span = 1).

Annual mean infiltration volumes are displayed by depth and simplified burn severity classification as a function of time (years) (Figure 3-16). The trend lines show maximum infiltration volumes occur in 2012 regardless of depth or burn severity classification.

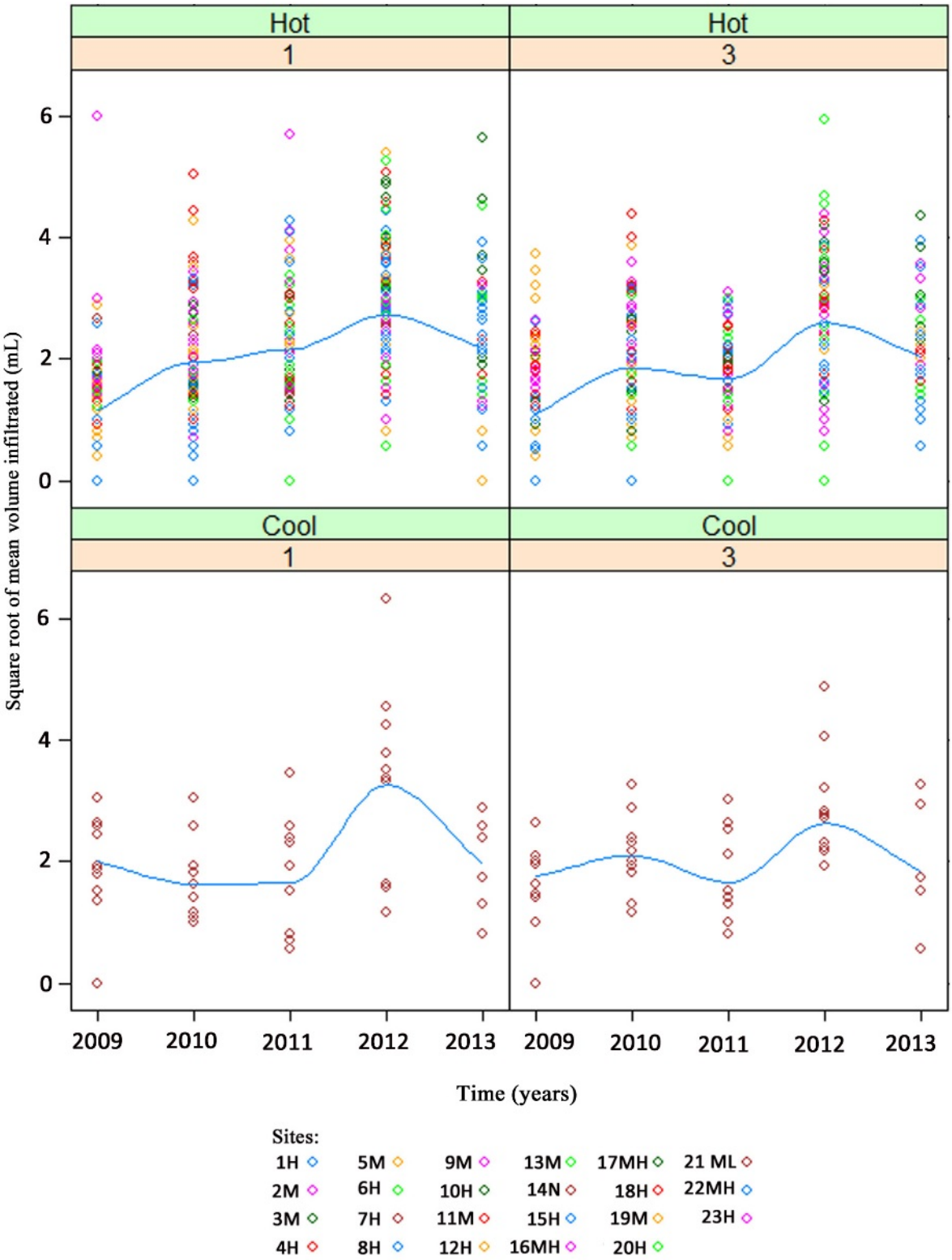


Figure 3-16. MDI mean infiltration volume (mL) as a function of time (years) for each depth (cm) and simplified burn classification. For simplified burn classes, "Hot" incorporates burn severity classes M, MH, and H. "Cool" incorporates N and ML. Volumes have been transformed for this display using square roots. Curves are fitted by loess (degree = 1, span = 0.5).

Mixed-effects models

In the mixed effects model, day number, burn severity, depth and the interaction between burn severity and day number were specified as fixed effects. Site number was specified as a random effect. A log transformation was used on the dataset in order to gain a better fit.

The log-transformed model for the mean infiltration volume showed that day number ($p=0.044$), burn severity ($p=0.0017$), depth ($p=0.004$), and its interaction between day number and burn severity ($p<0.0001$) were all significant. This model explains 50% of the variation in the logarithm of MDI volume. The coefficient is negative for depth, suggesting infiltration is reduced at greater depths. The interaction between burn severity and depth was not found to be significant ($p=0.17$).

WDPT data

WDPT data is displayed on a square root scale to aid the visualization of trends (Figure 3-17). There appears to be greater/higher infiltration times in 2010 for the hot simplified burn class. Penetration times seem unrelated to depth. There is only one penetration time greater than 100 seconds in the cool simplified burn class while there are many in the hot burn class.

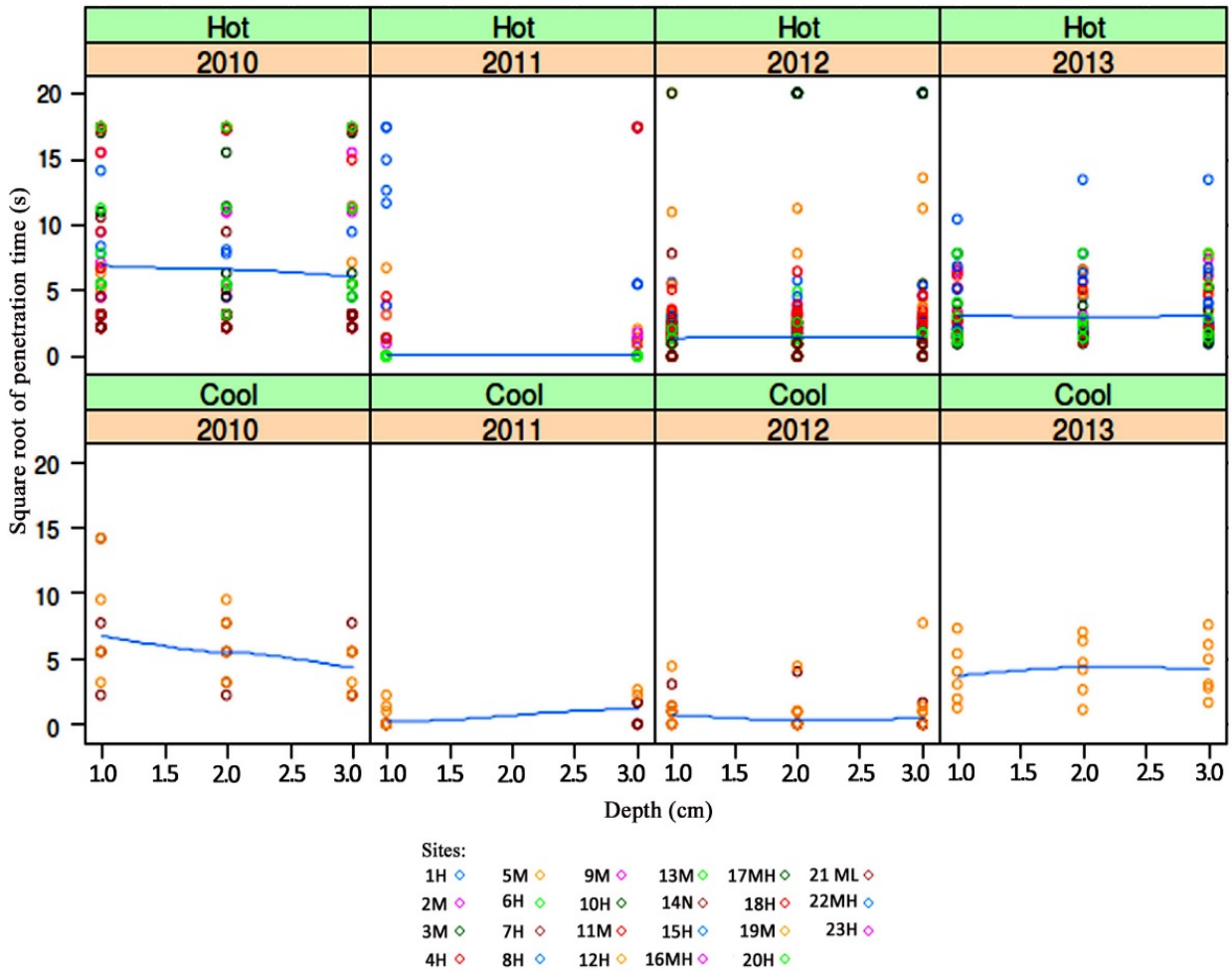


Figure 3-17. Square root of water drop penetration times (s) as a function of depth for each year and simplified burn classification. "Hot" incorporates burn severity classes M, MH, and H. "Cool" incorporates N and ML. Curves are fitted by loess (degree = 1, span = 1).

Penetration times in seconds are shown (Figure 3-18) as a function of year at 1, 2, and 3 cm depths for the simplified burn classes. The penetration times have been transformed using square roots to display trends. Once more greatest penetration times are shown in 2010 for both modified burn severity classes. "Hot" burns have longer penetration times regardless of depth.

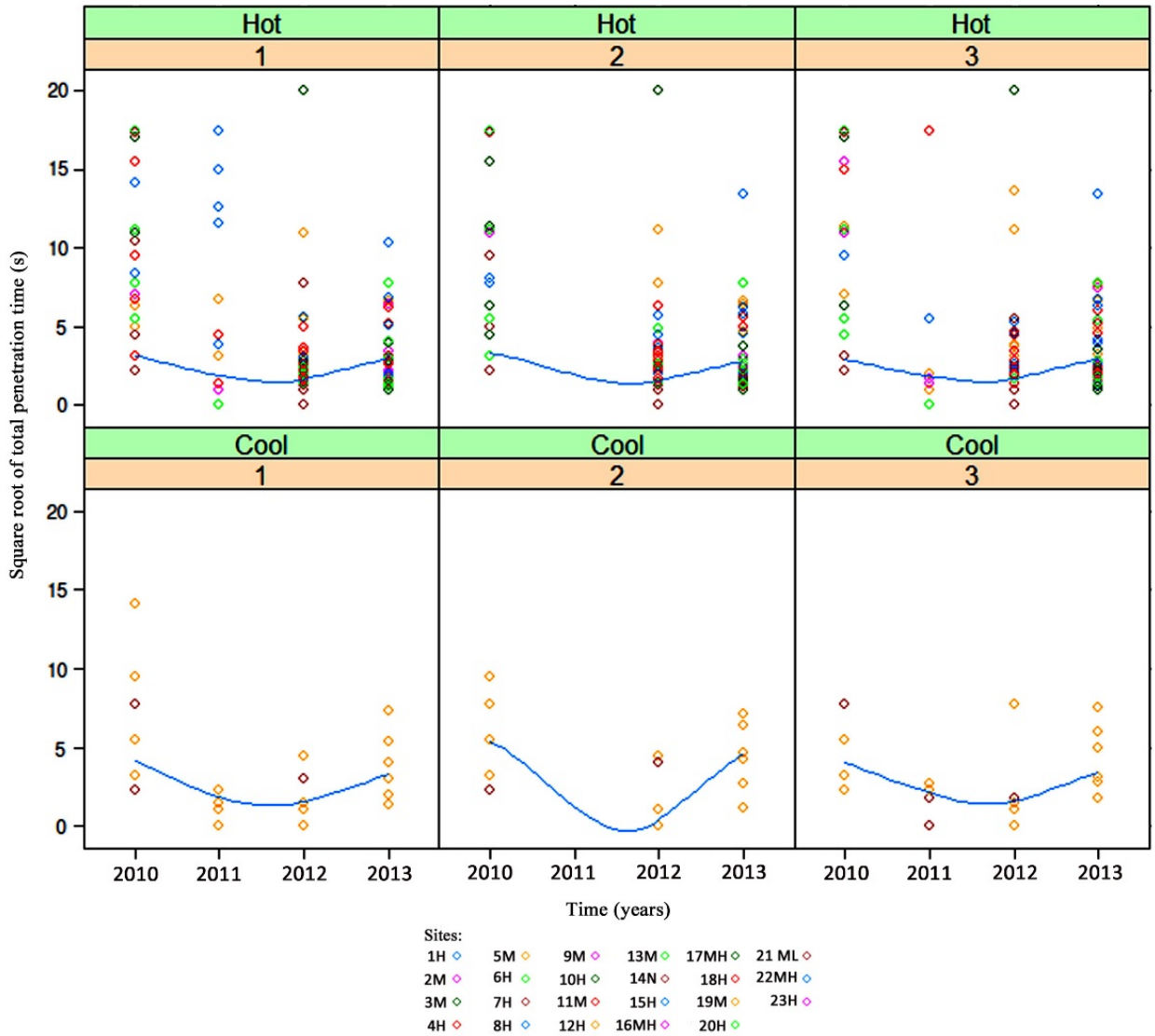


Figure 3-18. Square root of water drop penetration times (s) a function of time (years) for each depth (cm) and simplified burn classification. For simplified burn classes, "Hot" incorporates burn severity classes M, MH, and H. "Cool" incorporates N and ML. Penetration time has been transformed for this display using square roots. Curves are fitted by loess (degree = 1, span = 1).

Mixed-effects models

In the mixed-effects model, the response analyzed is continuous water drop times. Day number since 12/31/2008, burn severity and the interaction between burn severity and day number were specified as fixed effects. Random effects specified were site number and transect position.

A logarithmic transformation was applied to the data in order to get a better fit. The logarithm transformation improved the residual distribution but did not entirely normalize it. In this model, day number appeared to be highly significant ($p<0.0001$). However, burn severity ($p=0.185$) and its interaction with day number ($p=0.144$) were not significant.

MDI and WPPT Discussion and Conclusion

MDI tests showed that there was a statistically-significant difference in infiltration volumes between the burned and unburned sites, thereby supporting a fire effect on the hydrologic response of soils within the Little Creek watershed. Conversely, the WDPT tests showed that there is no significant difference in penetration times between burned and unburned sites even though these WDPT tests were conducted alongside the infiltrometer tests.

The difference in findings between the MDI and WDPT tests can be attributed to a variety of reasons. First, and perhaps most importantly, 2009 WDPT data is missing from the analysis because of a clerical error. Although there is debate on the strength and persistence of fire-induced hydrophobicity, experiments carried out in upper Michigan and coniferous forests in Montana found water repellency had disappeared within 1 year after burning (Reeder and Jurgensen 1979; DeByle 1973.) Thus, not having the 2009 WDPT data may have limited our ability to detect a significant change in post-fire infiltration.

Additionally, there was less consistency in the data collection for the WDPT tests. The methodology specified that there be three replications at 1, 2, and 3 cm depths at five positions along each transect. However, that did not necessarily get carried out at every site. In 2011, the 2 cm depth was not tested for unknown reasons. The absence of the 2009 data combined with the varied number of replications at each depth for the WDPT tests may be a contributing factor to explain why this test did not show a fire-induced effect.

Although the MDI showed significant changes in the soil hydrologic response, there was only one unburned site out of 23 sites total to compare with the burned sites. Furthermore, data were not collected from the unburned site in 2013 because of safety concerns with a wasp nest at the site. Had this non-burn site been tested, there is potential that these data could have bolstered the WDPT dataset and potentially contributed to a significant finding between the burn and unburned sites.

Conclusion for all post-fire soil hydrologic analyses

Rainfall simulations, Mini-disk Infiltrometer and water drop penetration time tests were employed to test whether there was a fire-induced effect on the hydrologic processes, including infiltration and runoff, following the 2009 Lockheed Fire. Rainfall simulations and water drop penetration time tests detected a significant change in infiltration rates, the hydrologic response and penetration times over time, however, simulations and water drop tests did not detect a significant difference in the rate of change between burned versus unburned sites. Alternatively, significant changes between the burned and unburned sites were detected using the Mini-disk infiltrometer, thereby suggesting that the significant change in infiltration volumes over time can be attributed to the Lockheed Fire.

It is challenging to have perfectly controlled experiments in a natural, field setting. Evaluating the post-fire effects within the Scotts Creek watershed using rainfall simulations, Mini-disk infiltrometer measurements, and water drop penetration time tests has provided meaningful results regarding post-fire effects on soil hydrologic processes, information on the limitations of

each method, and recommendations to be generated for future researchers who choose to use these methods.

Future work pertaining to near-surface hydrology in the Scotts Creek should aim to better understand the trends over time that were seen at nearly all sites for each test by conducting multiple simulations at a site per year, conducting testing at a subwatershed scale, and maintaining a balanced dataset by having equal amounts of the variable and subcategories represented in the datasets. A key part to understanding the influence of fire on soils lies within the physical characteristics of the sites including vegetation communities, soils, geology, antecedent moisture content, and duff depth, which, independent of fire, highly influence infiltration and runoff.

3.6 Channel Evaluation

Six geomorphic study reaches were established in 2002 along Little Creek. These study reaches were established to evaluate channel conditions before, during, and after a selective harvest of redwood in the Little Creek watershed in 2008. However, the implementation of these specified reaches has proven to be beneficial for a variety of post-fire monitoring projects.

The reach locations were chosen primarily based on ease of access, however they were also located in areas where channel change was identified after the 1997-1998 winter flood events (Figure 3-19). Reach gradients range from 0.02 to 0.05. Three reaches are on the mainstem (A, B, and C), two are on the North Fork (D and E), and one is on the South Fork (F).

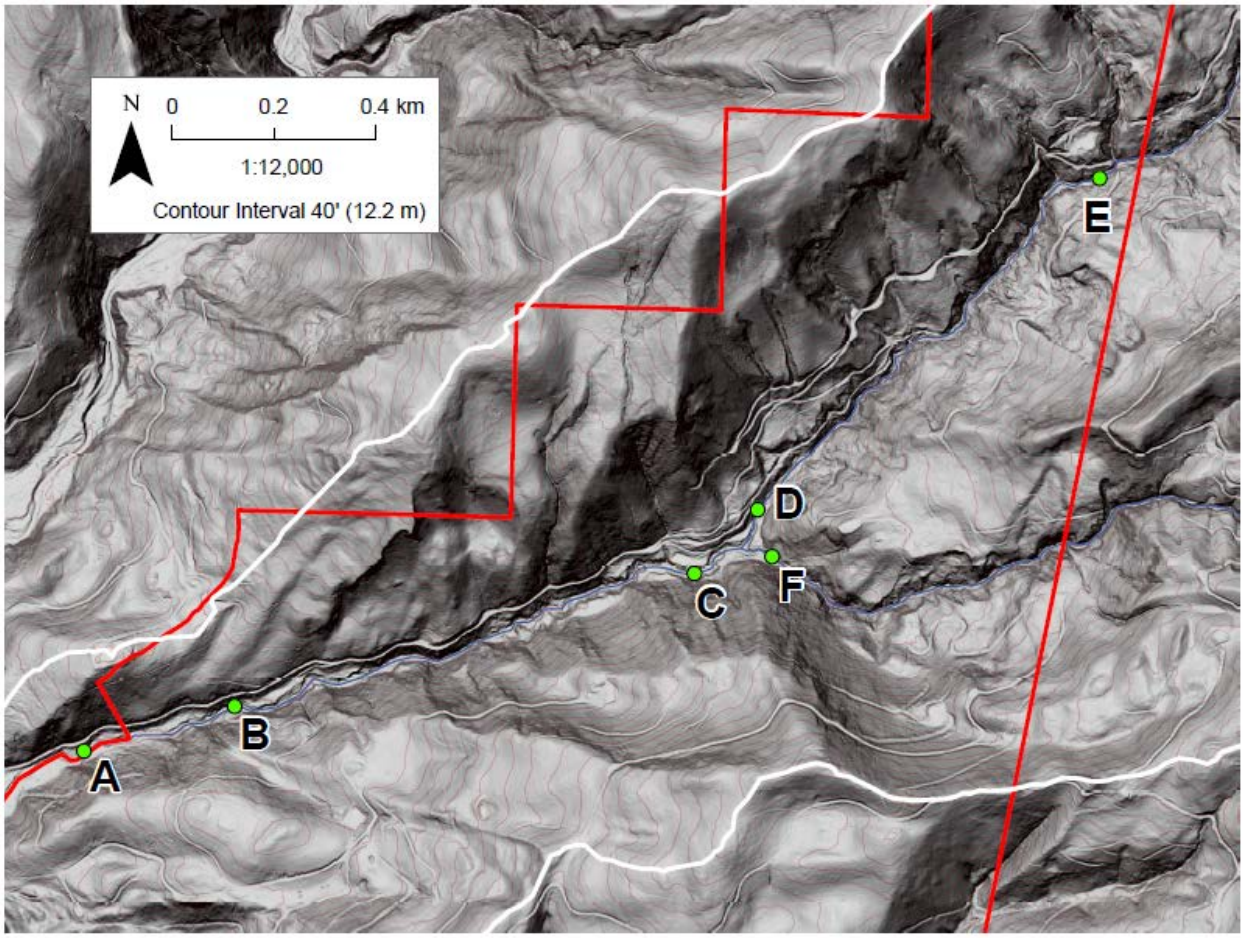


Figure 3-19. Map of Little Creek watershed showing study reaches. Red line is the Swanton Pacific Ranch property boundary.

Each study reach is approximately 100 meters long and contains 10 permanent monumented cross section locations identified with rebar and several permanent two inch diameter pipe bench marks. The pipe bench marks and rebar endpoints were tied into a professional survey of the Little Creek haul road and have been used to compare LiDAR derived channel features to ground surveys (White 2010, Dietterick 2012). Cross sections are surveyed with a tape and automatic level and a longitudinal profile through the reach is surveyed with a total station. The study reaches were surveyed annually each summer.

3.6.1 Post-Fire Change in Cross-Sectional Profiles

Channel surveys between 2002 and 2008 were analyzed in a master's thesis project (Perkins 2012). Channel changes during this time were relatively minor, and were mostly within the range of survey variability. A few areas within the survey area did experience small but measurable changes during the study period; these changes were typically associated with introduction or modification of coarse woody debris within the stream channel.

A similar analysis methodology was applied to data collected from 2009 to 2013 and results are summarized below. A database and spreadsheet were developed to plot and analyze changes in cross section characteristics. Thalweg elevation, cross-sectional area below a field identified bankfull stage, and mean bed elevation (bankfull area/bankfull width) were calculated for each cross section, and annual and cumulative changes were calculated.

Cross-sectional profile data

Plotted below are several of the 60 cross sections that are surveyed annually. It would be impractical to include all of them in the report, and the ones shown are representative of observations seen during the study period.

Reach A is in the mainstem of Little Creek and is the lowest gradient study reach and has a riffle/pool morphology. The upper part of this reach is relatively stable (Figure 3-20), while the lower part has experienced changes over the study period (Figure 3-21). Overall, the reach experienced a slight degradational trend since the fire.

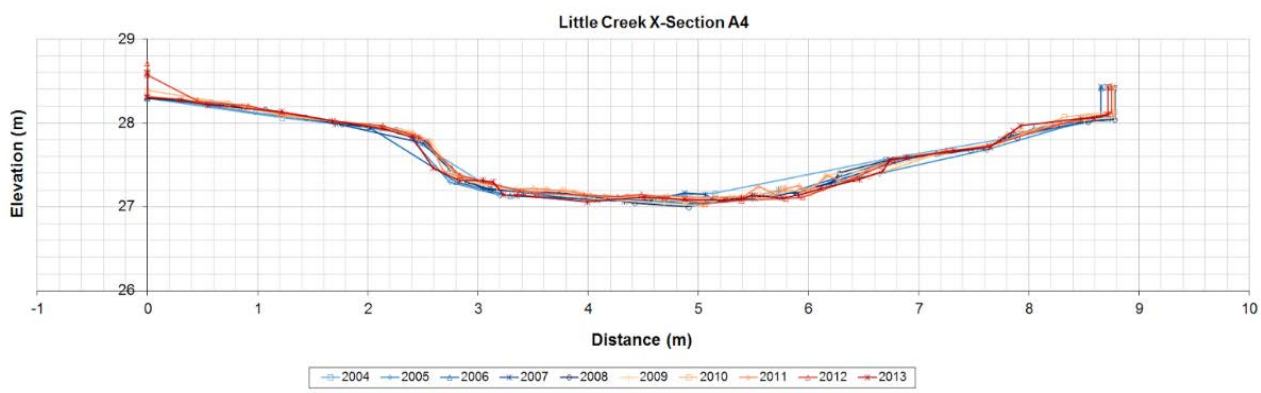


Figure 3-20. Annual cross-sectional profiles for A4.

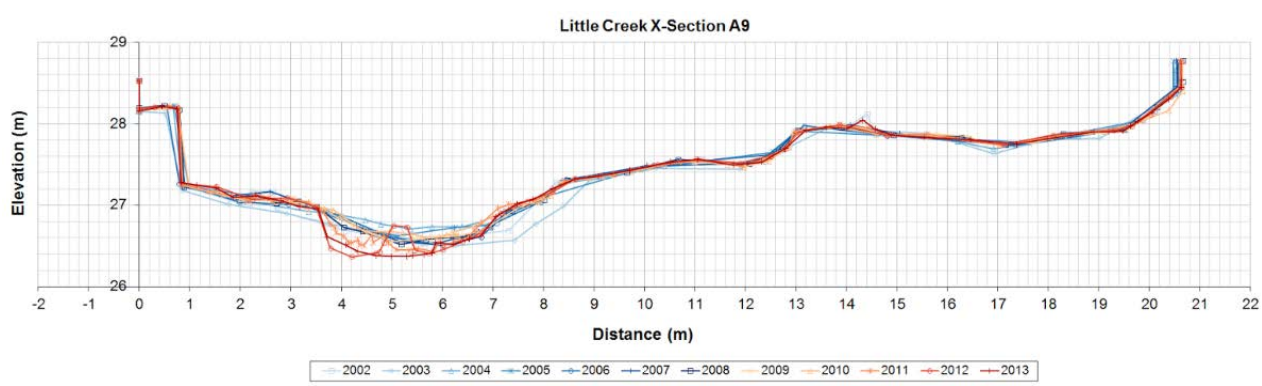


Figure 3-21. Annual cross-sectional profiles for A9.

Reach B is located in the mainstem and has a slightly higher gradient than Reach A, and a plane bed morphology with few pools. B4 is representative of a section of stream where accumulation and shifts of woody debris caused small changes in the channel year to year as flow shifted around a small wood accumulation downstream of the cross-sectional profile (Figure 3-22).

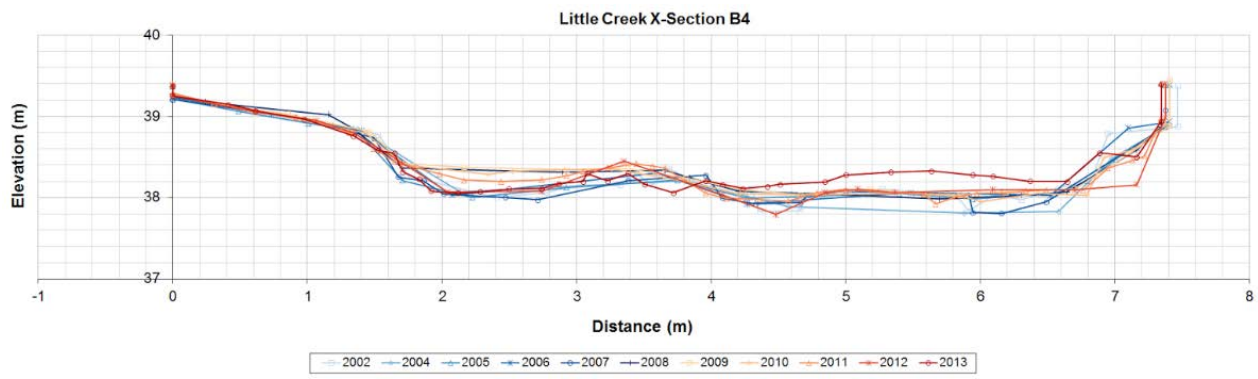


Figure 3-22. Annual cross-sectional profiles for B4.

Reach C is in the mainstem just below the confluence of the North and South Forks of Little Creek. Changes in this reach have been dominated by changes in a log/boulder jam in the middle of the reach between the two sets of cross-sectional profiles (Figures 3-23, 3-24, and 3-25). A log partially embedded in the channel provided a well-defined step, however this log shifted in the 2006 winter and caused scour to propagate upstream. This is very evident in the longitudinal profile discussed in 3.6.2. The shift of the log also caused reorganization and changes in the channel below the jam.

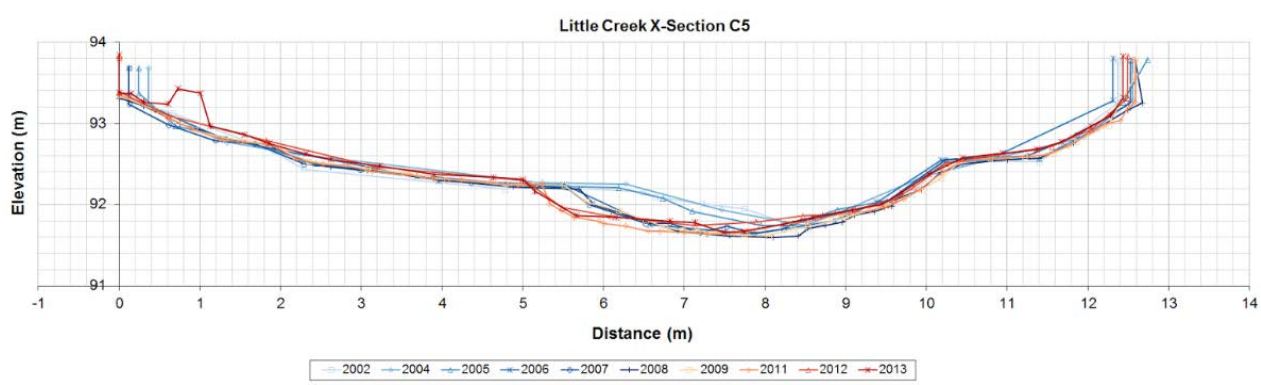


Figure 3-23. Annual cross-sectional profiles for C5.

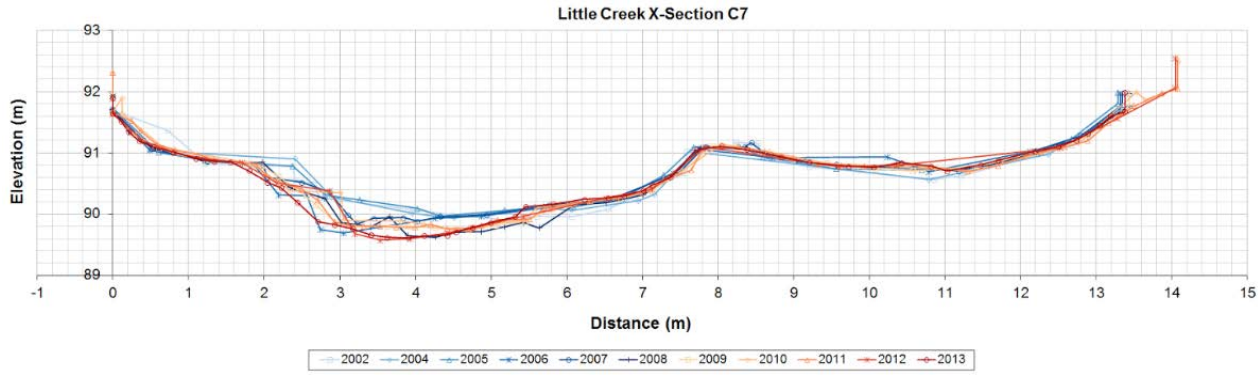


Figure 3-24. Annual cross-sectional profiles for C7.

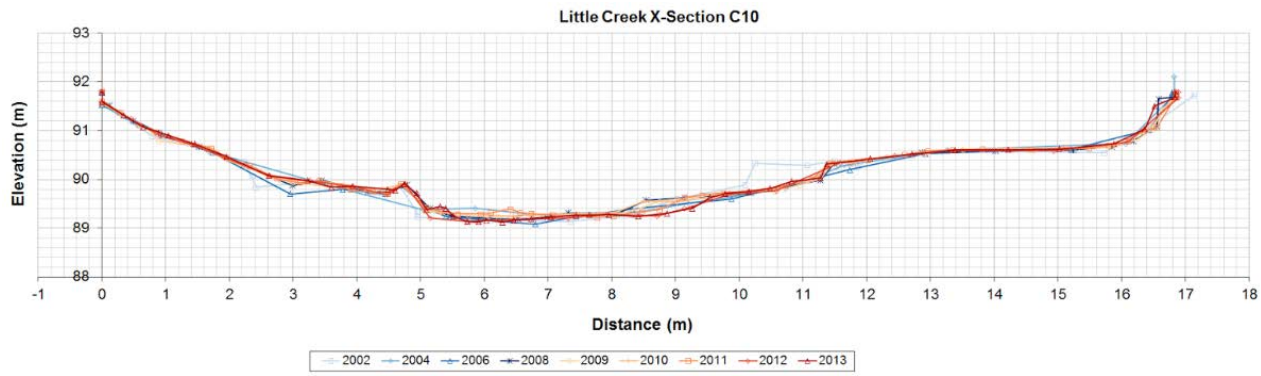


Figure 3-25. Annual cross-sectional profiles for C10.

Reach D is located at the lower end of the North Fork of Little Creek just upstream of the flume. This reach has been relatively stable during the study period except for profile D1 which aggraded in the years after the fire (Figure 3-26). Notice little to no change in cross section D2 immediately downstream (Figure 3-27) and similarly, no change was observed at D8 (Figure 3-28). Looking at the longitudinal profile, it appears the riffle at the tail of the pool upstream of D1 grew which caused this aggradation.

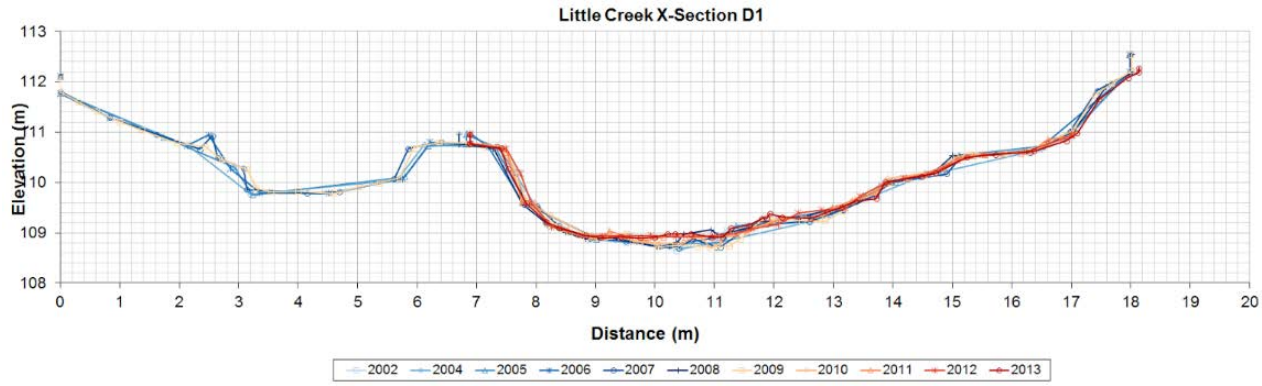


Figure 3-26. Annual cross-sectional profiles for D1.

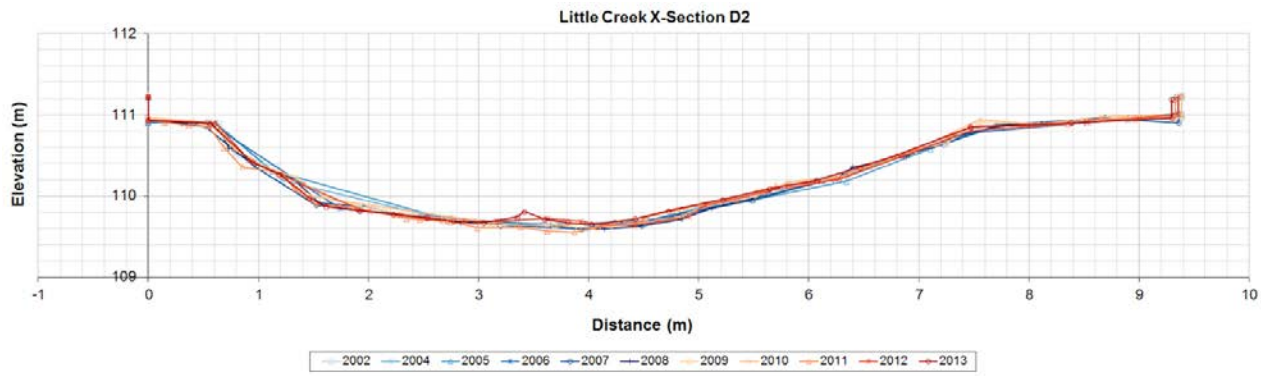


Figure 3-27. Annual cross-sectional profiles for D2.

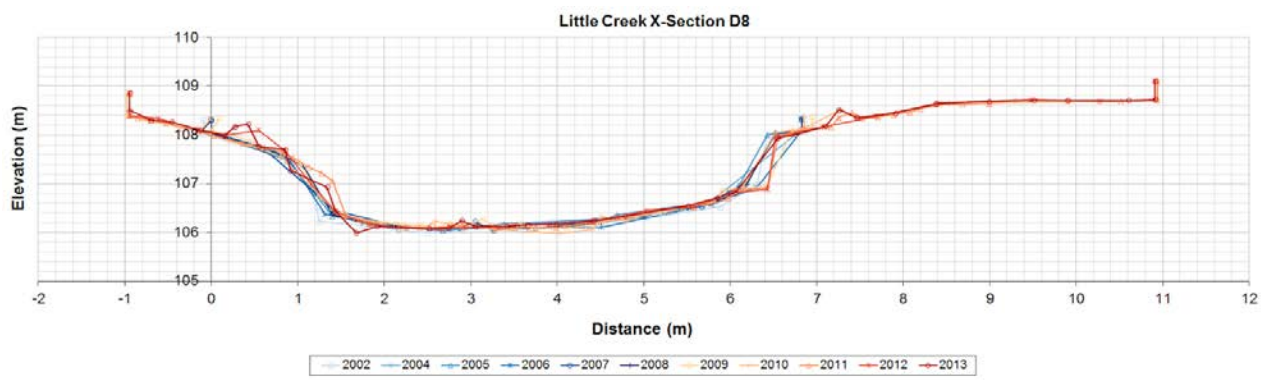


Figure 3-28. Annual cross-sectional profiles for D8.

Reach E is located on the North Fork just below the property line. This reach has the steepest gradient and substrate is dominated by cobble and boulder sized particles. This reach had some changes associated with a small wood accumulation and reorganization of flow around boulders (Figures 3-29, 3-30, and 3-31).

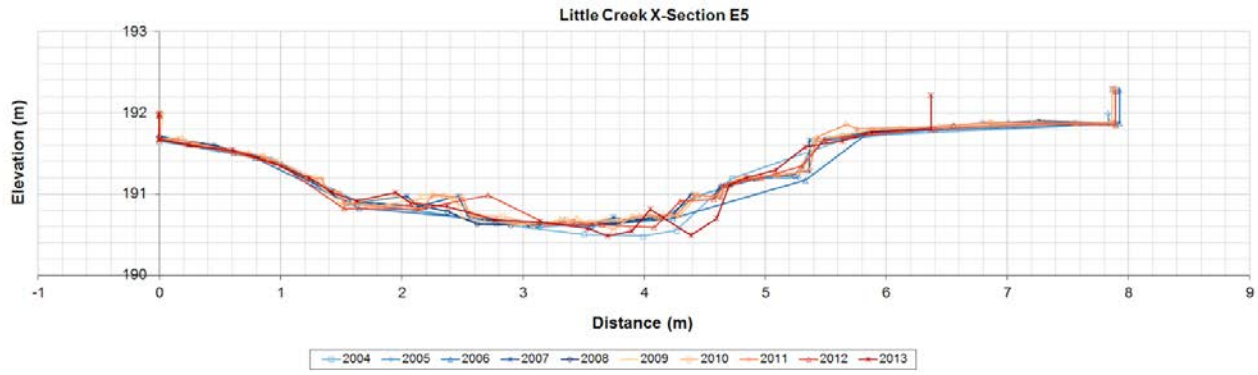


Figure 3-29. Annual cross-sectional profiles for E5.

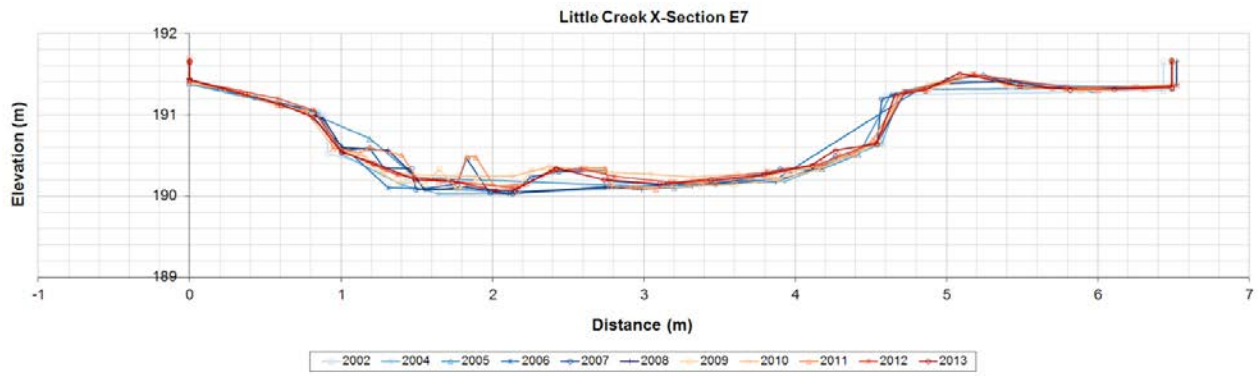


Figure 3-30. Annual cross-sectional profiles for E7.

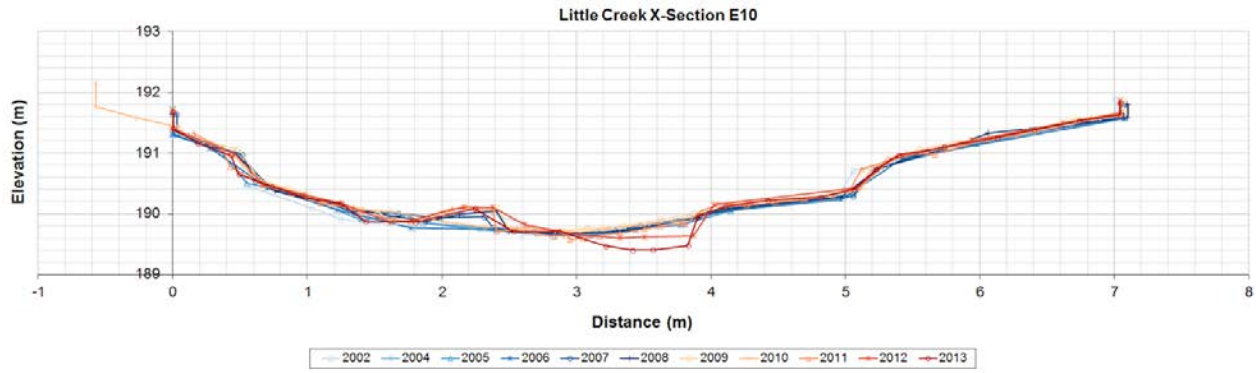


Figure 3-31. Annual cross-sectional profiles for E10.

Reach F is located near the base of the South Fork of Little Creek. This reach generally experienced aggradation before the fire and downcutting following the fire. F2 experienced little observable change (Figure 3-32) while F3 aggraded before the fire (Figure 3-33) and F4 has degraded after the fire (Figure 3-34). The response was highly variable among the cross sections, and again many of the changes were influenced by small woody debris accumulations. Note that the left bank of cross section F4 is along the base of the steep hillslope that received dry ravel after the fire.

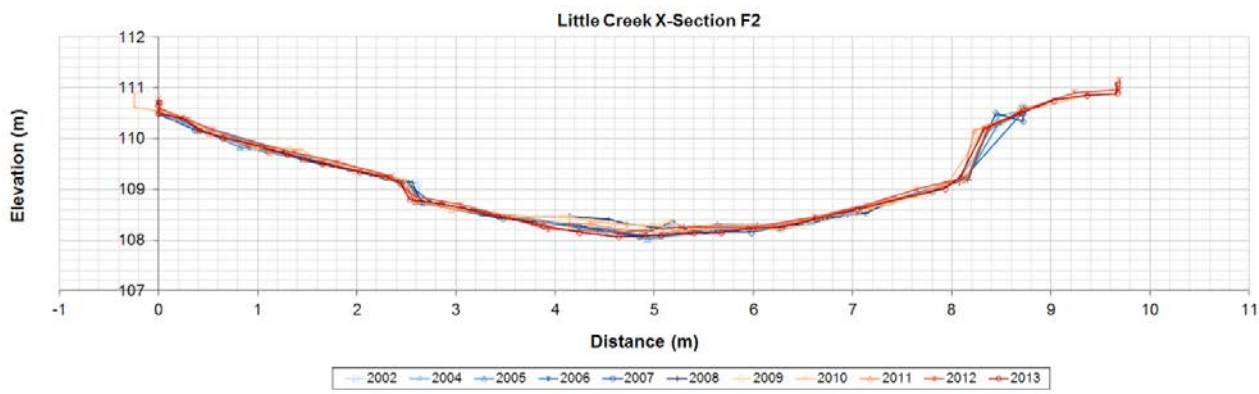


Figure 3-32. Annual cross-sectional profiles for F2.

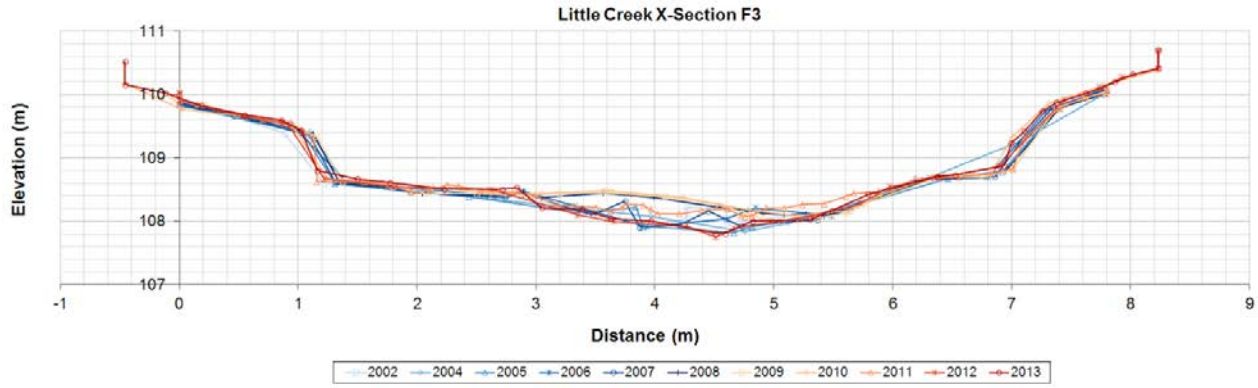


Figure 3-33. Annual cross-sectional profiles for F3.

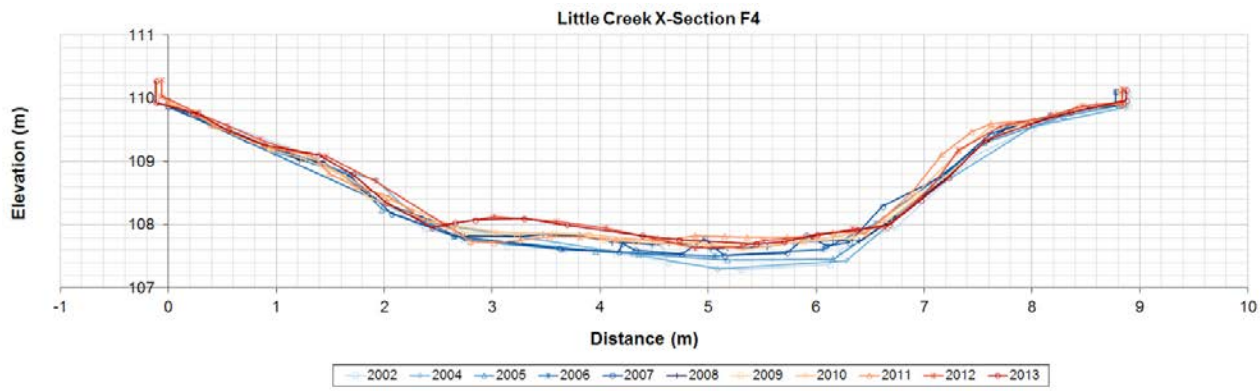


Figure 3-34. Annual cross-sectional profiles for F4.

Boxplot comparisons

Boxplots can be used to visualize if change occurred between cross sections before versus after the fire (Figures 3-35, 3-36, and 3-37). The boxplots show interquartile range, median, and mean for changes observed in each reach over time. The boxplots allow us to assess reach wide trends which can be more difficult to determine from plots of the individual cross sections as shown below. The plots for Reach C, located immediately below the confluence of the North and South Forks, suggest that it has experienced significant change (degraded) and the plots show that Reach F has experienced notable aggradation. It is important to note, however, that the degradation trend at Reach C and the aggradation at Reach F were evident prior to the fire as well as after the fire, suggesting no indication of a fire effect.

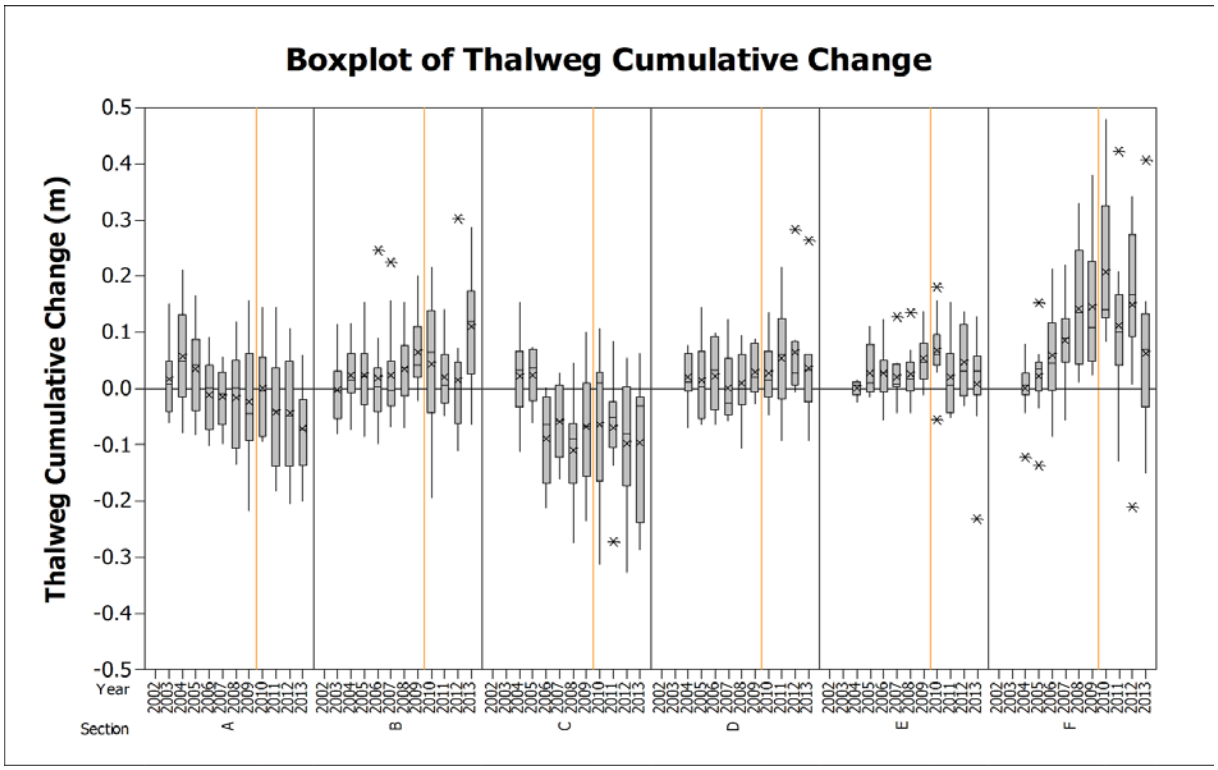


Figure 3-35. Boxplot of thalweg cumulative elevation change by reach. Timing of the Lockheed Fire is shown with the orange lines.

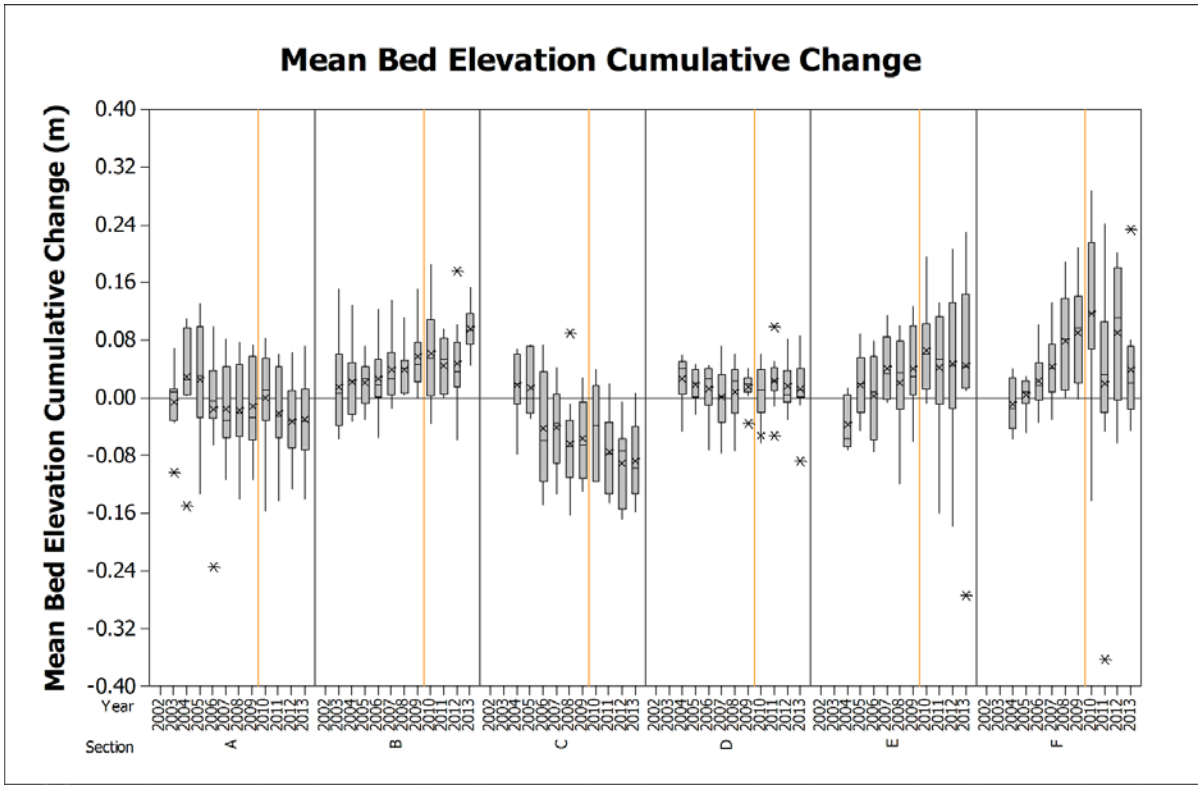


Figure 3-36. Boxplot of mean bed elevation cumulative elevation change by reach. Timing of the Lockheed Fire is shown with the orange lines.

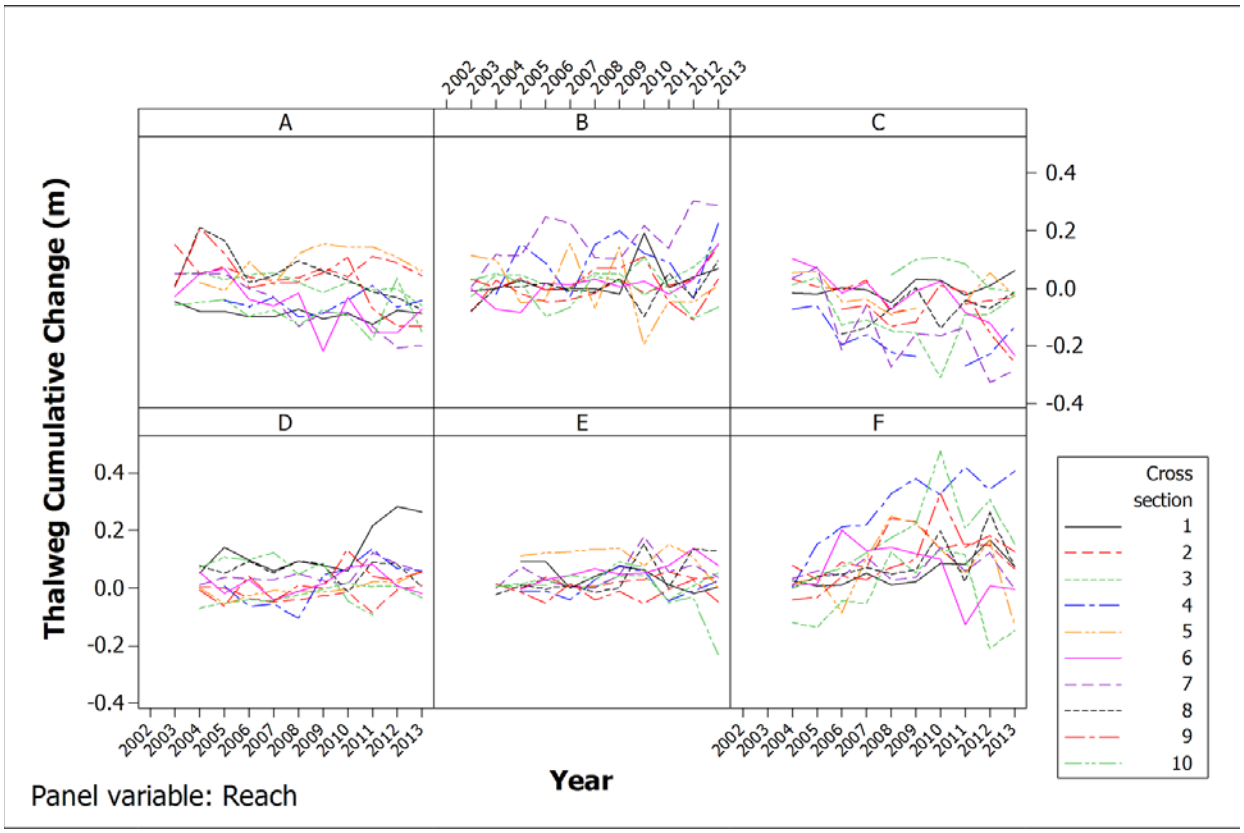


Figure 3-37. Thalweg cumulative change in meters by reach.

Estimated error of measurement for the cross section metrics was estimated in Perkins (2012) as ±-0.04 m for elevation and 0.4m² for cross-sectional area measurements. Changes under this magnitude could likely be attributed to error and may not even reflect changes in the channel. Additionally, in many cross sections, soil creep, falling trees, and other factors caused displacement of endpoint benchmarks. We tried to correct for this movement as much as possible in the quality control process, however this movement could be causing apparent changes in elevation or cross-sectional area.

Generally, changes in the study reaches were small during the study period compared to changes throughout this system in 1998, and those expected to have occurred during other years with large flood events, such as 1982 and 1955. Individual cross sections showed significant changes in some cases; however, those changes averaged over the reach were minor in the context of channel changes during large and extreme flow years. Therefore, collectively the changes documented during the study are considered minor.

Data from USGS gaging station No. 11160500, San Lorenzo River at Big Trees were used to put the flow record for Little Creek in a longer term perspective. The San Lorenzo River data confirm that no large flood events occurred during the study period (Figure 3-38). The return period for annual peak flows on the San Lorenzo River ranged from 1.1 to 5.6 years during this period (Table 3-2). Peak flows on Little Creek (Table 3-7) experienced higher variability with

respect to bankfull flow (estimated at 25 cfs). Assuming 25 cfs is a reasonable approximation, then a close to bankfull flow was experienced five of the 11 years on Little Creek. The channel changes experienced are also brought into perspective by considering that three logging entries and one salvage operation occurred during the entire study period. The fire disturbance was expected to yield the largest impact in terms of sediment delivery to streams, yet no obvious changes to channel morphology in the study reaches, as identified in the cross-sectional surveys, could be attributed to the fire. The lack of large stressing storms during the study period, evident through the analysis of flow records from the San Lorenzo River at Big Trees (described above), is expected to have strongly influenced this outcome.

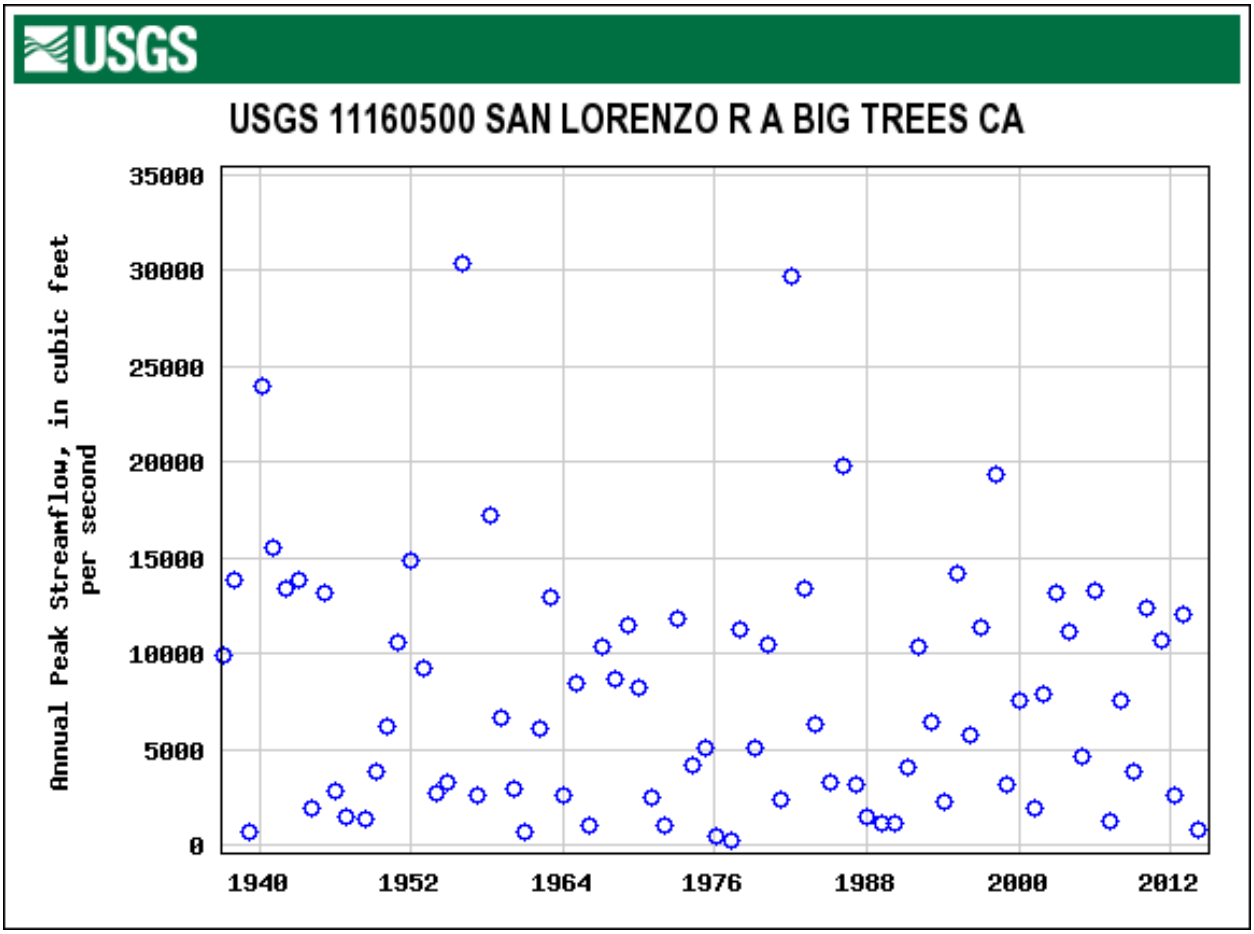


Figure 3-38. Plot of annual peak flows for the San Lorenzo River at Big Trees station, located approximately seven miles from Little Creek. Note the lack of large flood events from 2001 to 2013.

Table 3-2. Probability and return periods during the study period for USGS 11160500 San Lorenzo River at Big Trees. Return intervals were calculated with the USGS PeakFQ program (Ver. 7.1).

Water Year	Peakflow (cfs)	Probability	Return Interval
2002	7880	0.4430	2.3
2003	13200	0.1899	5.3
2004	11200	0.3038	3.3
2005	4620	0.5823	1.7
2006	13300	0.1772	5.6
2007	1210	0.8734	1.1
2008	7570	0.4557	2.2
2009	3820	0.6329	1.6
2010	12400	0.2278	4.4
2011	10700	0.3165	3.2
2012	2660	0.7342	1.4

3.6.2 Post-Fire Change in Longitudinal Profiles

Longitudinal profile data were collected annually with a total station. Because of small changes in thalweg location and surveyor interpretation of the stream channel, channel lengths between identical features are not consistent year-to-year. To allow meaningful comparison of repeated surveys, the profiles were shifted and stretched/shrunk so that the distances where the plane of the cross-section profiles is crossed are consistent year to year (matched up to the 2002 survey). For example, in the A reach, all longitudinal profiles were adjusted so the location where the longitudinal profile crosses the plane of cross section 10 is at 29.39m, cross section 9 at 34.75m, cross section 8 at 38.73m, and so on. This allows visual comparison of similar features.

Longitudinal profile data

Reach A is the lowest gradient reach (Figure 3-39). The biggest changes occurred in the lower half where flow around several large boulders readily reorganized the channel bed as debris accumulated and moved around. The channel in the early surveys was likely aggraded behind one of these accumulations, and when this accumulation disappeared the channel downcut. The upper part of the A reach has been relatively stable.

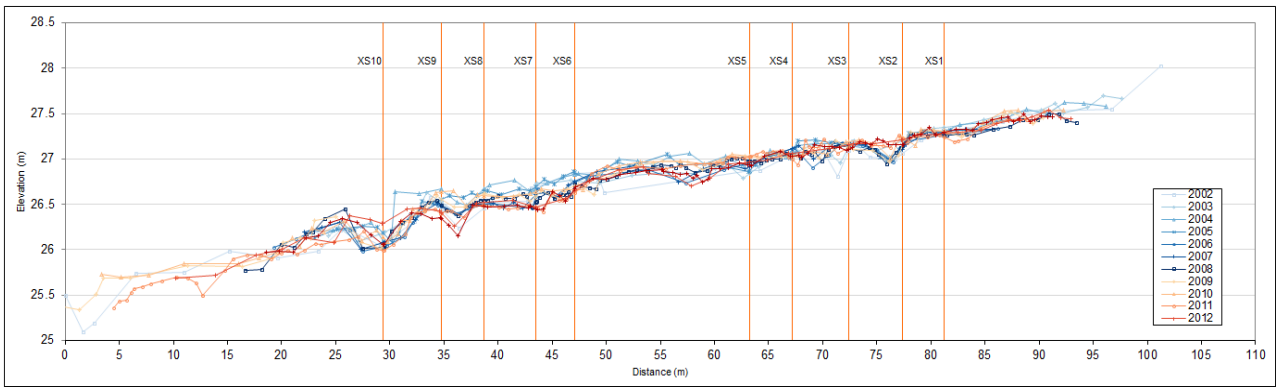


Figure 3-39. Annual longitudinal profiles of Reach A.

Reach B has the fewest pools of all the reaches (Figure 3-40). Again, most of the changes were associated with the formation of small debris jams which caused aggradation and/or reorganization of the bed. The reach was generally stable during the study period.

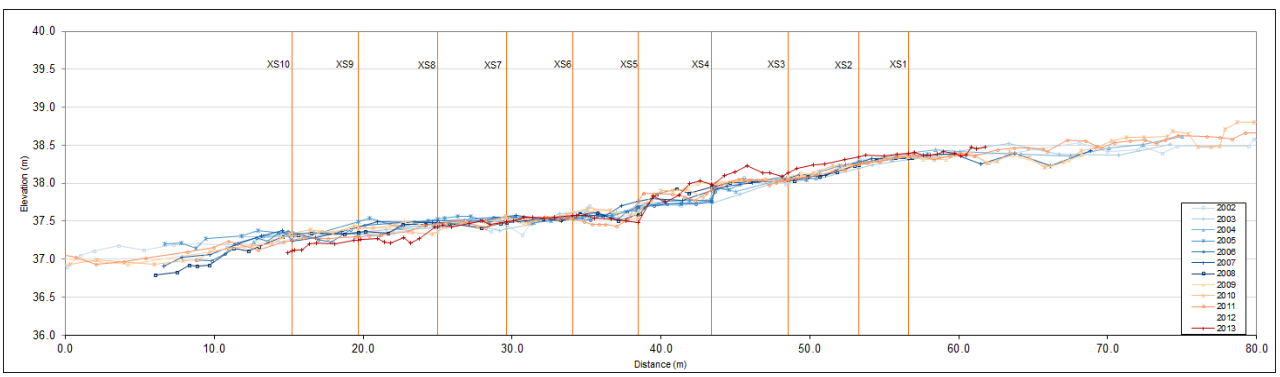


Figure 3-40. Annual longitudinal profiles of Reach B.

Reach C experienced the most drastic changes during the study period (Figure 3-41). A large log that created a step and deep pool in the channel at 55m shifted during the 2005-2006 winter which allowed water to scour underneath it. The channel subsequently downcut and widened upstream up to XS2. Changes were also observed below this debris jam and are likely related to rerouted flow paths and energy dissipation patterns associated with the change in the log step.

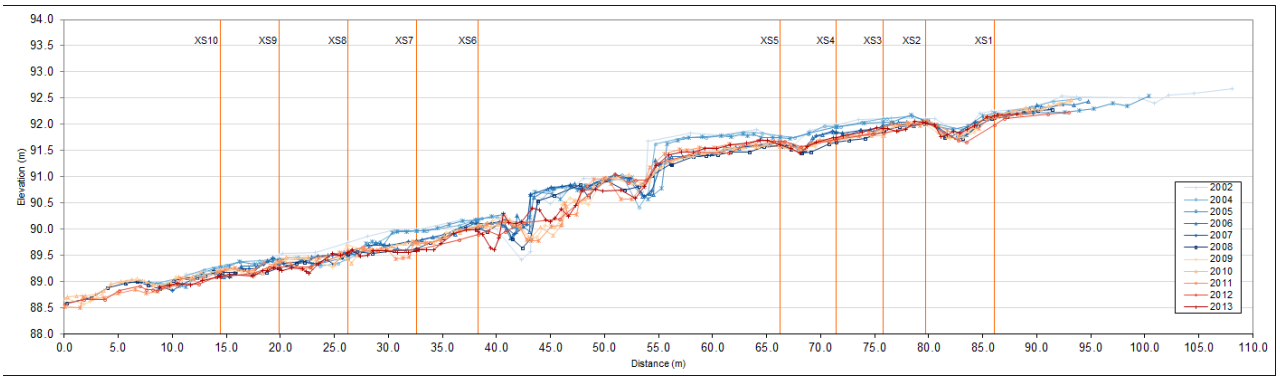


Figure 3-41. Annual longitudinal profiles of Reach C.

Reach D was the most stable reach during the study period (Figure 3-42). The reach is split into two clusters above and below a 1998 landslide deposit of rootwads, boulders, etc. Some changes occurred in the debris jam, however some of this variability may also be due to the difficulty of surveying through the log jam associated with the 1998 landslide.

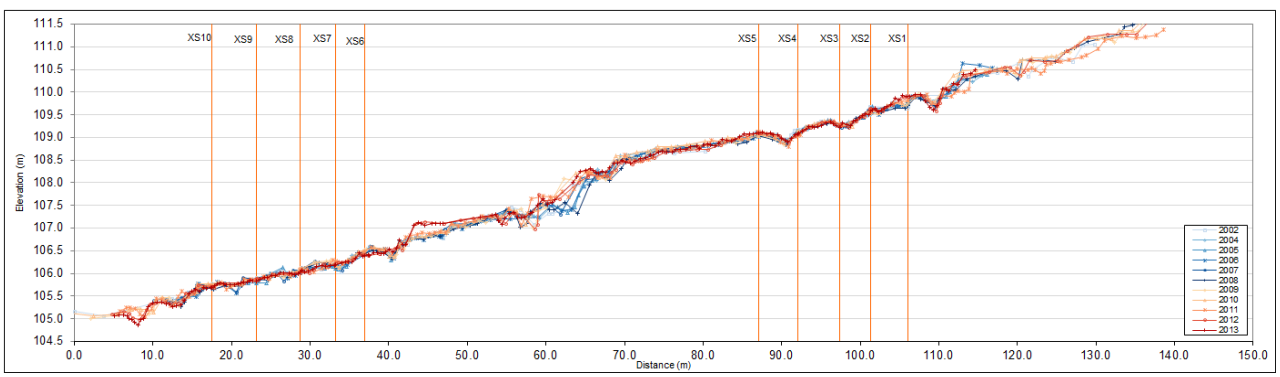


Figure 3-42. Annual longitudinal profiles of Reach D.

Reach E is the steepest study reach and the morphology is dominated by boulders (Figure 3-43). This reach was also relatively stable during the study period but did have more year to year variability primarily associated with small debris accumulations (for example at 35 meters).

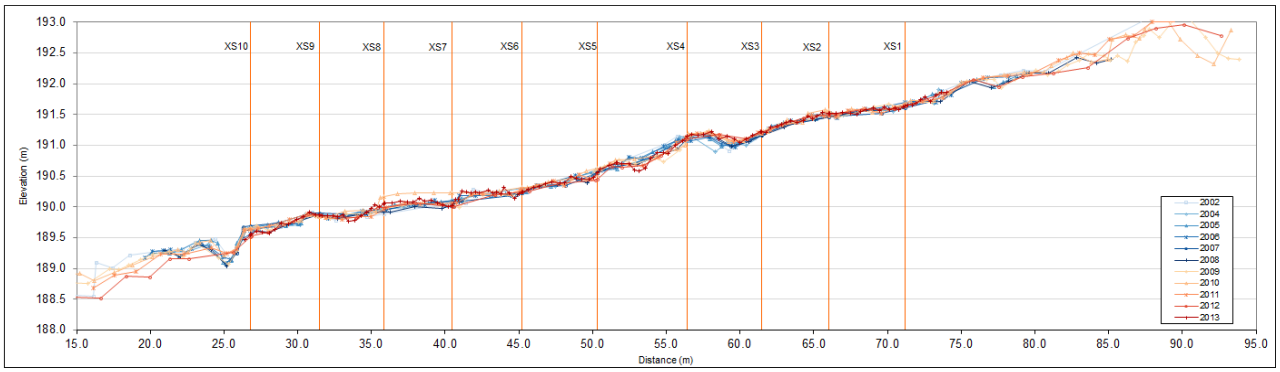


Figure 3-43. Annual longitudinal profiles of Reach E.

Reach F also had changes during the study period, again primarily associated with small debris jam creation and reorganization (Figure 3-44). The reach experienced an aggradation trend before the fire and has degraded after the fire. Much of the degradation signal is associated with the loss of the debris created step and pool at 65m in 2012.

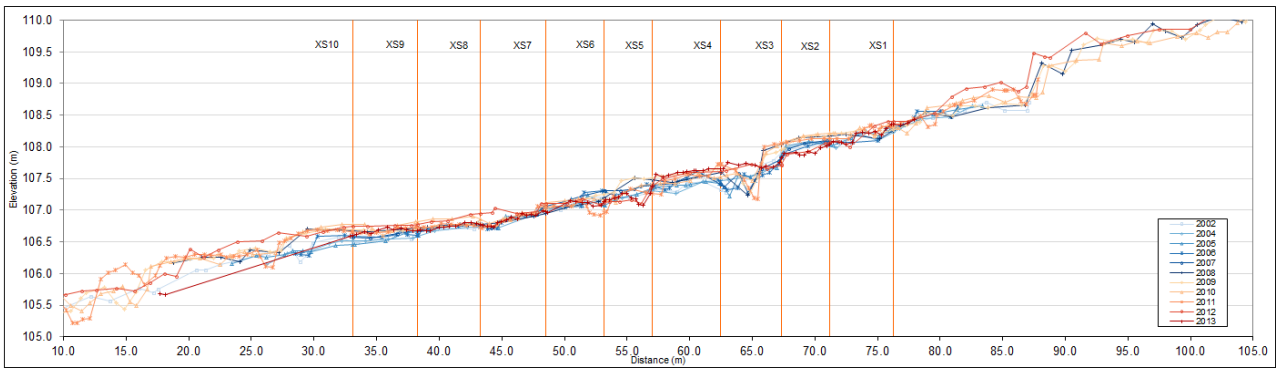


Figure 3-44. Annual longitudinal profiles of Reach F.

Vertical variability in thalweg profile has been identified as a geomorphic characteristic that is reduced by inputs of sediment or other stream disturbance (e.g., large woody debris removal) (Madej 2001; Lisle 1995; Bartley and Rutherfurd 2005). To calculate profile variability, a least squares best fit line is applied to the profile data and the residuals calculated. Changes in the standard deviation of the residuals are interpreted as a change in variability of the thalweg profile. To weight each section of stream equally, the thalweg profile needs to be interpolated at a constant interval. Custom formulas and an MS Excel™ spreadsheet were used to reinterpolate each longitudinal prole at 0.305 m (1 ft) intervals. This interval was chosen because it could accurately represent small-scale features like steps and would also likely sample the deepest portion of pools. Thalweg profile variability was analyzed using a subset of the longitudinal profile data that included only the portion of the reach that had been surveyed in all years. A function was fit to each profile using the General Linear Model routine in Minitab and residuals

were calculated and stored. For some profiles a linear fit did not match the larger scale trend of the profile and the residual plots showed large scale curvature. For these profiles a second and/or third order polynomial term was added to the model so only smaller-scale variability (i.e., filling of pools) would influence standard deviation calculations. Figure 3-45 shows the standard deviation of the fitted residuals over time for each of the six reaches.

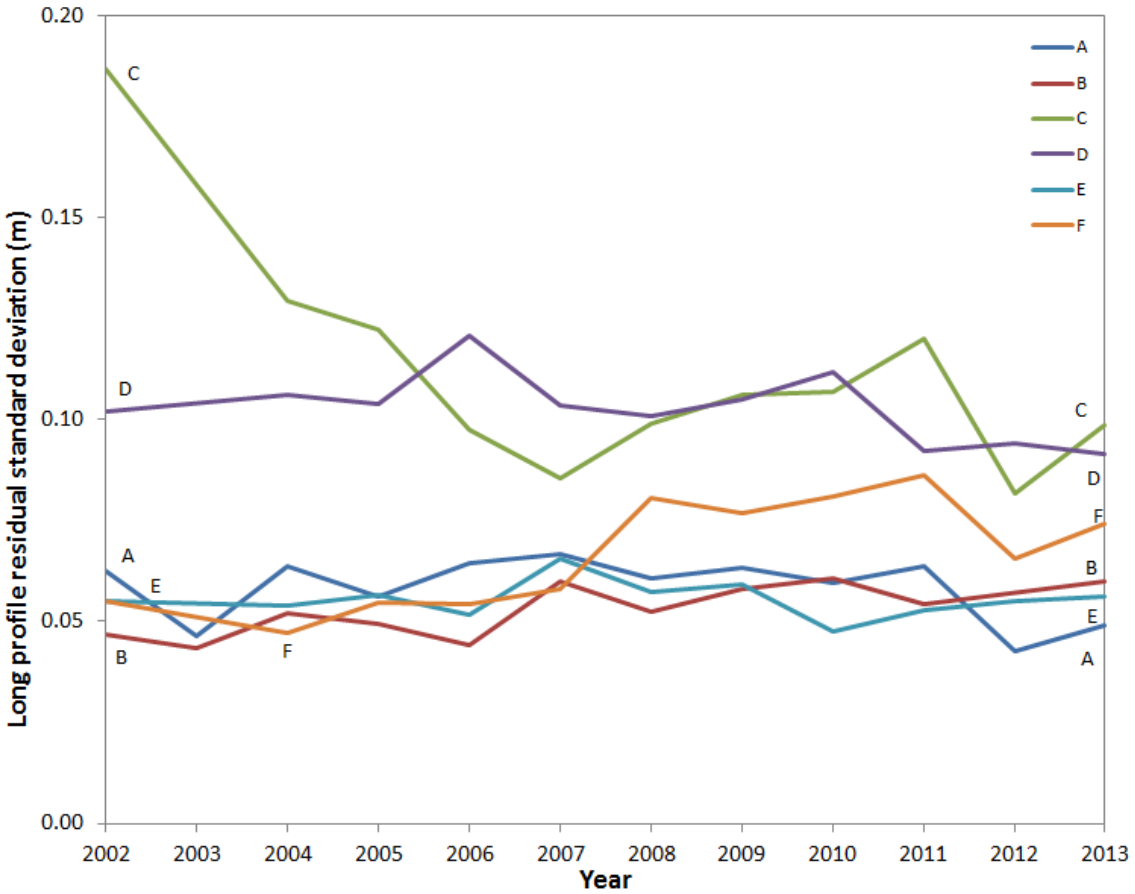


Figure 3-45. Standard deviation of longitudinal profile residuals calculated from a least squared fit.

Changes in fitted residual standard deviation did not change substantially after the fire and changes are similar to the magnitude of changes observed before the fire. This indicates that there were no major changes in the variability of the bed surface caused by sediment input from the fire.

As in the analysis of residuals of a function fit to a longitudinal profile, it is possible to evaluate statistical variation in the residual depths along the profile. The residual depths were calculated for each point in the re-interpolated longitudinal profile. Areas outside pools have a residual depth of zero. Variability is displayed in the plots for each reach from year to year for the entire period of the study (Figure 3-46) with no clear indication that significant change occurred either

as a result of the fire or timber harvest. These graphs show a slight decrease in pool depth and variability in the 2010 survey and an increase in depth and variability in 2011, especially in the C and F reaches. However, the magnitude of these changes is within the range of variability observed before the fire, and it appears that the fire did not have a significant effect on pool depth and volume in the study reaches.

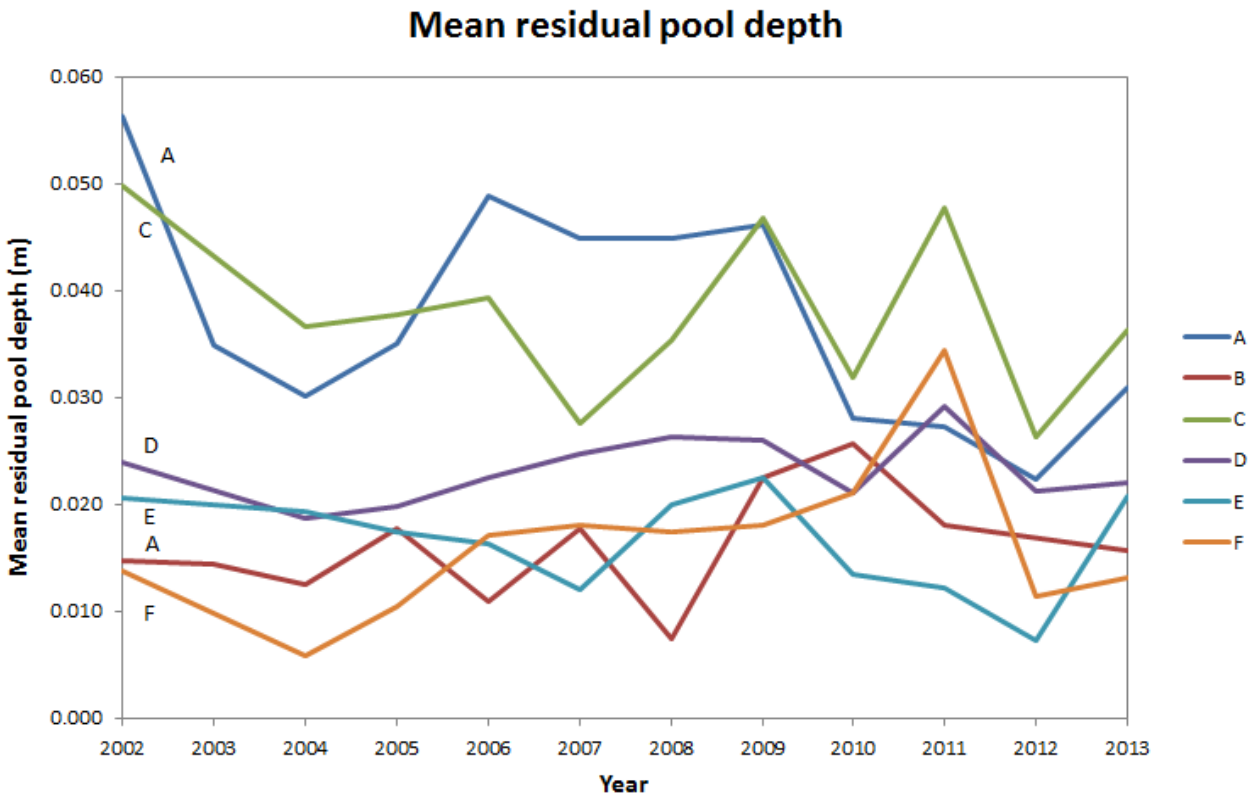


Figure 3-46. Mean residual pool depth of cross-sections A-F.

Additional analysis of mean, standard deviation, and third quartile value (25% of the reach has a residual depth greater than the Q3 value) of pool depth in the re-interpolated longitudinal profile could also indicate changes in pool filling and bed variability that may result from increased sediment inputs. Again, changes observed after the fire (and timber harvest) are well within the magnitude of change observed during the calibration period (Figures 3-47 and 3-48).

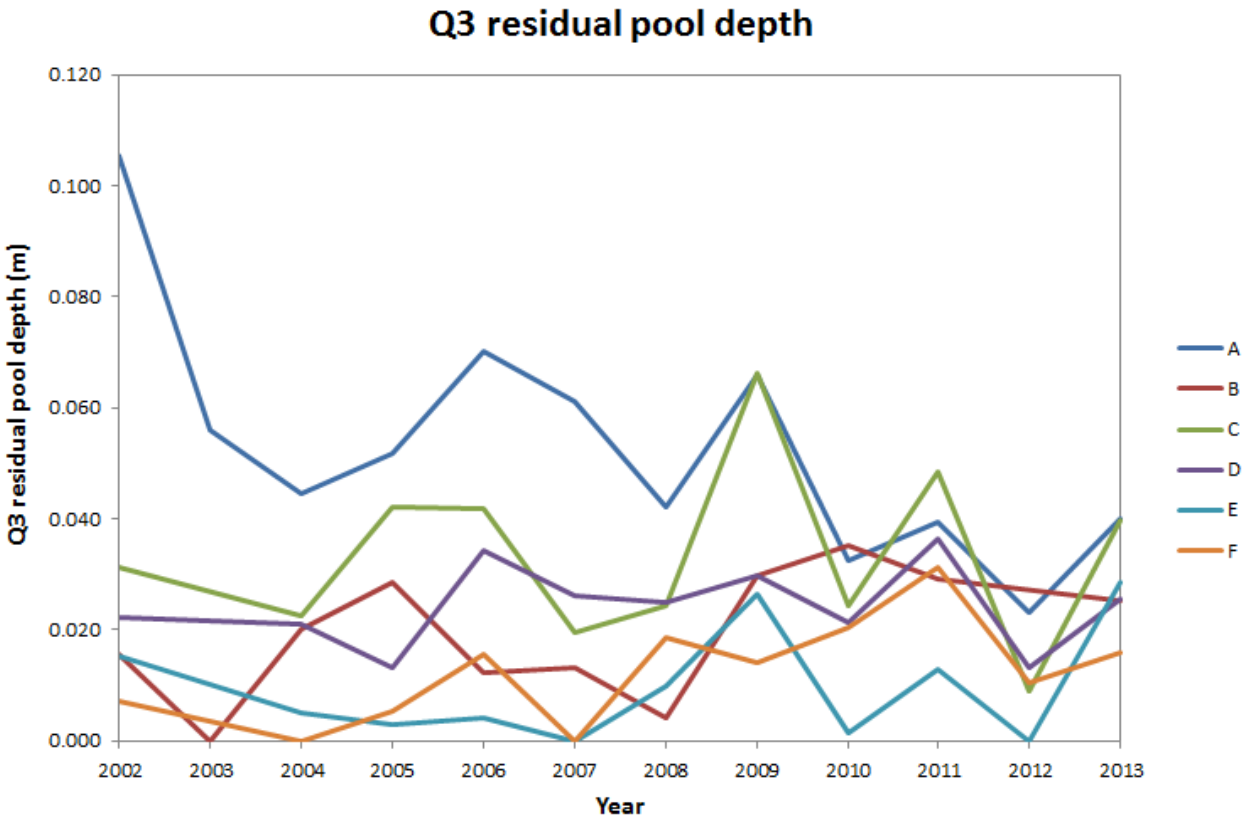


Figure 3-47. Third quantile residual pool depth of cross-section A-F.

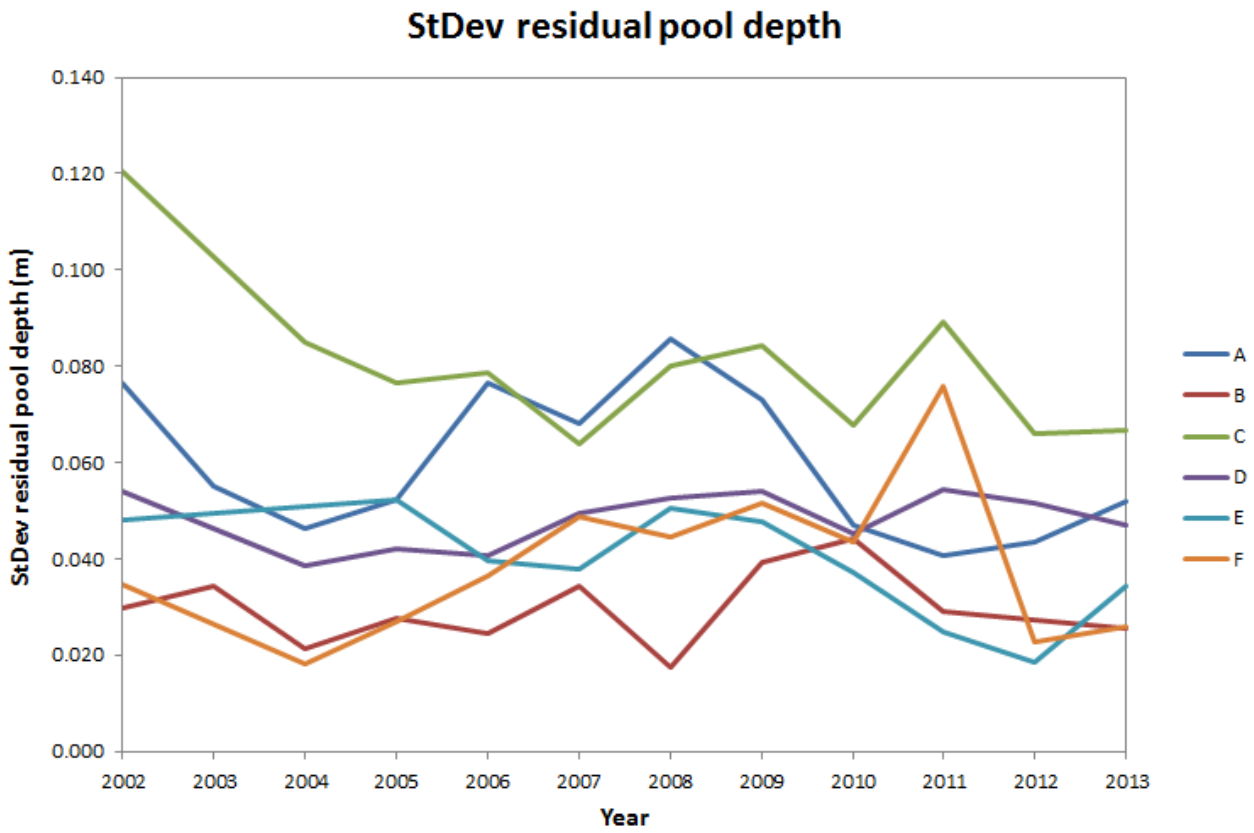


Figure 3-48. Standard deviation of residual pool depth for cross-sections A-F.

Another way to visually compare residual pool depths between years in each reach is to graph them using an empirical cumulative distribution function (Figure 3-49). This graph shows the percentage of each reach with a residual depth less than the value on the x-axis. The y-intercept is the percentage of the reach that is not in pools (residual depth = 0) and the upper x-intercept is the depth of the deepest point in the reach. These graphs show how residual depths vary over the entire reach through time. This graph could indicate whether an increase in the mean residual pool depth resulted from pools getting longer or pools getting deeper. A shift of a line downward and to the right indicates an increase in quantity and depth of pools in the reach. A shift upward and to the left indicates a loss of pool quantity and depth.

These plots demonstrate the high level of variability between years in some reaches. Reach A and Reach E appear to have generally lost pool depth and volume after the fire while Reach B, C, and D were relatively similar to pre-fire conditions. Reach F developed some larger pools but these disappeared in 2012 and 2013. None of the reaches appear to be significantly different after the fire and post-fire are generally within variability observed before the fire.

Channel geometry discussion and conclusion

There were no significant changes in channel geometry, including measures such as pool filling, in the study reaches after the fire. However, even though the study reaches were selected based

on areas likely to experience change, they are a small percentage of the total channel and may not be representative (the reaches represent approximately 10 percent of the Mainstem, five percent of the North Fork and three percent of the South Fork). However, anecdotal evidence indicates that significant changes to channel geometry did not occur even in areas more directly impacted by the fire like junctions with tributaries that experienced debris flows.

The largest changes observed were degradation in the F reach since the fire and loss of pool volume in reaches A and E in 2010-2012, with some recovery observed in the 2013 survey. Generally, post-fire observations are within the range of variability observed before the fire.

The morphology of the channel type in the study areas (transport reaches in Montgomery and Buffington classification) is generally stable and less sensitive to sediment/flow regime changes than other channel morphologies. See discussion in Ch. 6 in Perkins (2012) for further information.

Prior to the fire, most channel changes were associated with input and modification of woody debris (both small and large). There were no significant fire related LWD inputs in the study reaches, but fire influenced LWD loading (tree throw during/after fire from root loss and mortality) has been observed in several places along Little Creek and may continue to impact LWD loading in future years with increased alder mortality along the channel.

Major channel changes were observed after the 1997-1998 winter floods both in the study reach locations and the length of the channel. The fire likely had some impact on channel morphology, but changes are small in comparison relative to changes observed after the last large flood events which had the energy to reorganize channel forcing features and associated LWD and sediment inputs from widespread streamside mass wasting. During the study period, the return period on Little Creek was likely near or less to the five-year event based on the flow frequency analysis at the gage at San Lorenzo at Big Trees.

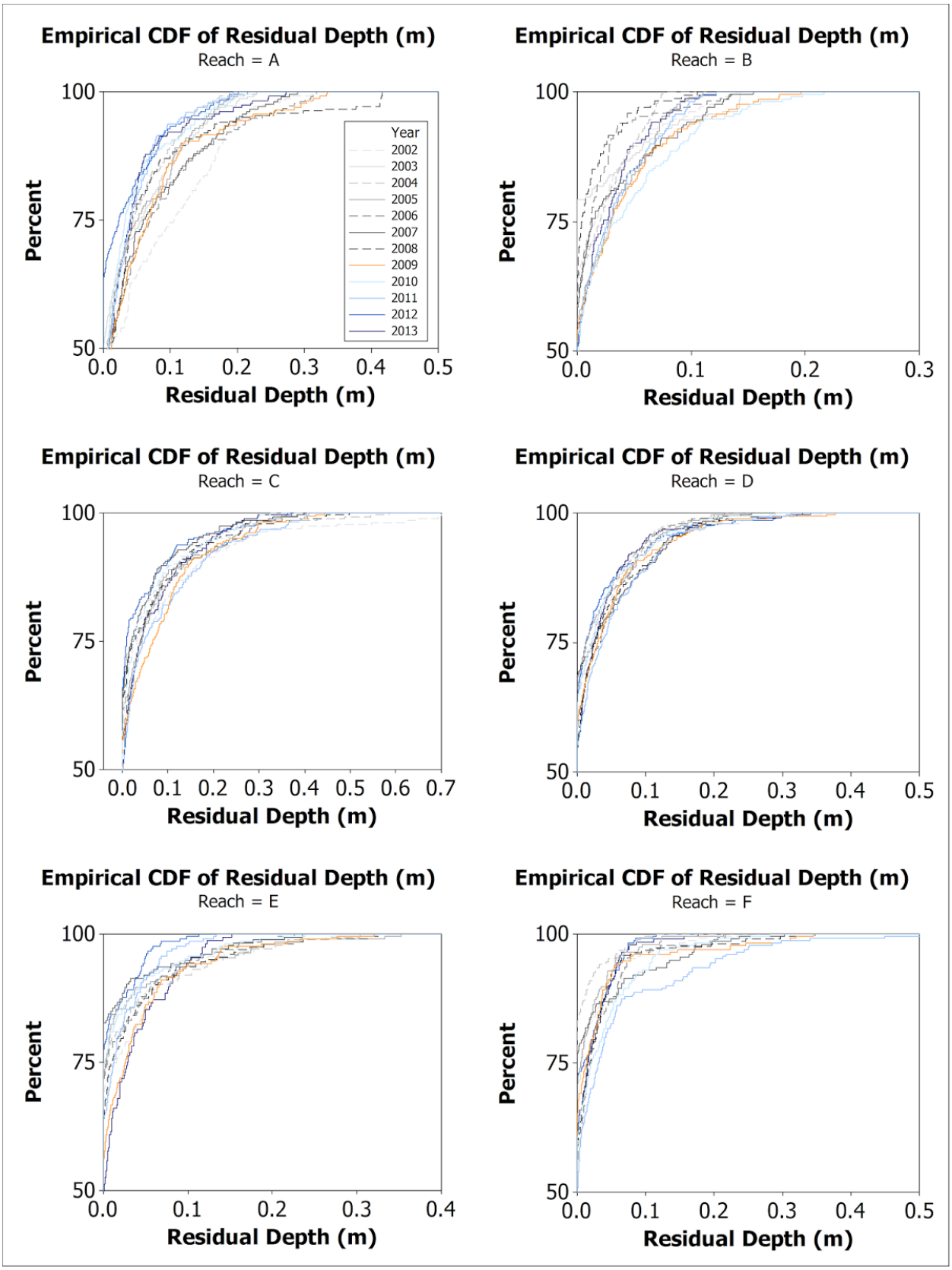


Figure 3-49. Empirical cumulative distribution function (CDF) of the residual pool depth for cross-sections A-F.

3.6.3 Pebble Counts

Introduction and methodology

Previous studies have found that watershed responses to wildland fire are highly variable. The complex secondary effects of wildland fire on in-stream sedimentation and channel substrate composition may be attributed to the interaction of multiple highly variable hydrologic and environmental factors, including fire severity and size, residual ground cover and infiltration rates, topography, channel gradient, and geologic substrate (Benevides-Solorio and MacDonald 2001; DeBano 2000; Minshall et al. 1997; Minshall et al. 1998). Responses also vary through time and throughout a stream network (Minshall et al. 1998). The Lockheed Fire created an opportunity to analyze the effects of the aforementioned characteristics on post-fire watershed characteristics across space and time. This portion of the study, conducted by Kromshroeder (2009) and by Boerman (2010) were Cal Poly senior projects focused on the response of channel substrate particle size distribution.

Pebble count methods

Four tributaries of the Scotts Creek watershed were sampled in this study: Little Creek, Scotts Creek, Mill Creek, Big Creek. Subwatershed catchment area varies from 523.2 ha to 2900.8 ha for Little Creek and Big Creek subwatersheds respectively, while average channel gradient ranges from less than 1% in the lower reaches of Scotts Creek to 8.4% in Little Creek. The geologic substrate of all subwatersheds is composed of Quartz Diorite and Mudstone in varying proportions, with Lower Scotts Creek dominated by Mudstone and Big Creek by Quartz Diorite (Brab et al. 1997).

In Little Creek, pebble counts were conducted at the six permanent channel morphology reaches between the upper most and lower most cross sections. Survey reaches for Upper and Lower Scotts Creek (sites 7 and 8), Mill Creek (site 9), and Big Creek (site 10) were determined on a site-specific basis with consideration of channel morphological characteristics. The survey reach at each site included one full meander wavelength of the channel in a location considered representative of the variability in substrate and flow characteristics.

Pebble count field data collection

Pebble count surveys were conducted to assess changes in channel substrate composition at each study site. Surveys included 10 transects along the survey reach identified for each site. Transects were located in either pools or riffles in proportions representative of the pool to riffle ratio singular to each survey reach. Each transect extended across the bankfull width. The bankfull width was divided by 10 in order to determine the appropriate distance between each of the ten sampling events. During sampling, the surveyors averted their gaze while reaching straight into the stream at their toe, collecting the first substrate particle touched by their index finger.

This process was repeated at even intervals across transects, resulting in the collection of 10 particles per transect, for 100 particles total across the entire survey reach. The size class

representative of the median diameter of each particle was recorded for further analysis (Potyondy and Helvey 1994).

Fall surveys were completed at all 10 sites from October 17th to October 25th, 2009 following the first precipitation event of the winter which occurred on October 10th. Site 1 was re-measured immediately after initial measurement to determine the prevalence of sampling error. Surveys were repeated in the spring from April 3rd to April 4th, 2010 following the majority of winter precipitation events. Additional surveys were completed at sites 1-6 on April 21, 2012, while surveys were complete at site 7-10 on May 13, 2013.

Pebble count data analysis

The focus of the data analysis is to distinguish whether there is a change in substrate size in subsequent years following the burn. Cumulative particle size class distribution and particle size histogram graphs were produced comparing the fall 2009, spring 2010 and spring 2012 surveys at each site (Kromshroeder 2010; Boerman 2012). The particle diameters representing 16%, 50% and 84% of all surveyed particles (d16, d50, and d84) were identified for each site for all spring and fall surveys (Table 3-3). The percent change in sand, gravel, and cobble between the spring 2010 and spring 2012 surveys was calculated and can be seen in Boerman (2012). Correlations between particle size and contributing area, reach gradient, and percent burned at high severity were determined by calculating the R^2 value for fall 2009, spring 2010, and spring 2012 surveys.

Pebble count results

Table 3-3 shows that there was a varying degree of increase in particle diameters throughout all survey sites. When comparing the fall 2009 to the spring 2010 survey data, no consistent trend in channel substrate composition was identified across all the reaches surveyed in the Scotts Creek watershed. Five sites (1, 2, 6, 7, and 10) exhibited a general trend toward coarser channel substrate composition after winter precipitation. Alternatively, three sites (3, 5 and 9) exhibited a general trend toward finer channel substrate, while two sites (4 and 8) experienced a highly complex response to various environmental factors affecting substrate composition.

Significant trends became evident between the spring 2010 and spring 2012. There was a marked increase in coarse substrate across all sample sites three years following the fire. This increase in coarse substrate was likely due to introduced fresh coarse substrate to the stream that became distributed further throughout the system by Spring 2012. Attempts to observe trends by correlating D16, D50, and D96 to burn severity, channel gradient, and contributing area were unsuccessful. Yet, the trend toward coarser gravels was unmistakable at all sites. The trend toward coarse gravels typical for the six sites in Little Creek is shown in the cumulative particle size distribution plots (Figure 3-50).

Table 3-3. Change in particle diameters for survey reaches. Site 1 = Lower Mainstem Little Creek, Site 2 = Middle Mainstem Little Creek, Site 3 = Upper Mainstem Little Creek, Site 4 = South Fork Little Creek, Site 5 = Lower North Fork Little Creek, Site 6 = Upper North Fork Little Creek, Site 7 = Lower Scotts Creek, Site 8 = Upper Scotts Creek, Site 9 = Mill Creek, and Site 10 = Big Creek.

	site 1			Site 2			Site 3			Site 4			Site 5		
	d16	d50	d84	d16	d50	d84	d16	d50	d84	d16	d50	d84	d16	d50	d84
Fall 2009	0.20	3.80	78.30	0.10	4.50	48.00	0.30	10.50	87.50	0.10	9.40	62.80	0.50	10.10	91.00
Spring 2010	0.10	11.00	82.00	0.30	13.00	78.10	0.30	6.80	56.20	0.30	7.40	64.00	0.30	7.00	56.80
Spring 2012	8.80	27.30	73.50	1.00	27.00	77.50	5.30	36.00	114.10	7.60	57.20	209.10	6.10	44.70	222.60
% change															
09-10	-42%	193%	5%	239%	188%	63%	7%	-35%	-35%	150%	-22%	2%	-45%	-30%	-27%
10-12	8700%	148%	10%	233	108%	-1%	1667%	429%	103%	2433%	673%	227%	193%	539%	239%

	site 6			Site 7			Site 8			Site 9			Site 10		
	d16	d50	d84	d16	d50	d84	d16	d50	d84	d16	d50	d84	d16	d50	d84
Fall 2009	0.10	1.00	120.00	0.20	7.10	44.00	0.30	6.00	51.50	0.60	16.00	54.00	1.40	37.50	134.00
Spring 2010	0.20	3.40	162.40	0.60	21.00	54.20	0.60	7.50	42.20	0.10	0.20	16.00	1.90	69.90	154.50
Spring 2012	6.30	58.20	285.40	3.50	26.40	61.60	6.10	44.00	101.40	11.60	62.20	116.00	6.50	84.30	145.60
% change															
09-10	91%	242%	35%	215%	198%	23%	83%	24%	-18%	-86%	-99%	-70%	42%	86%	15%
10-12	3050%	1612%	76%	483%	26%	14%	917%	487%	140%	11500%	31000%	628%	242%	21%	-6%

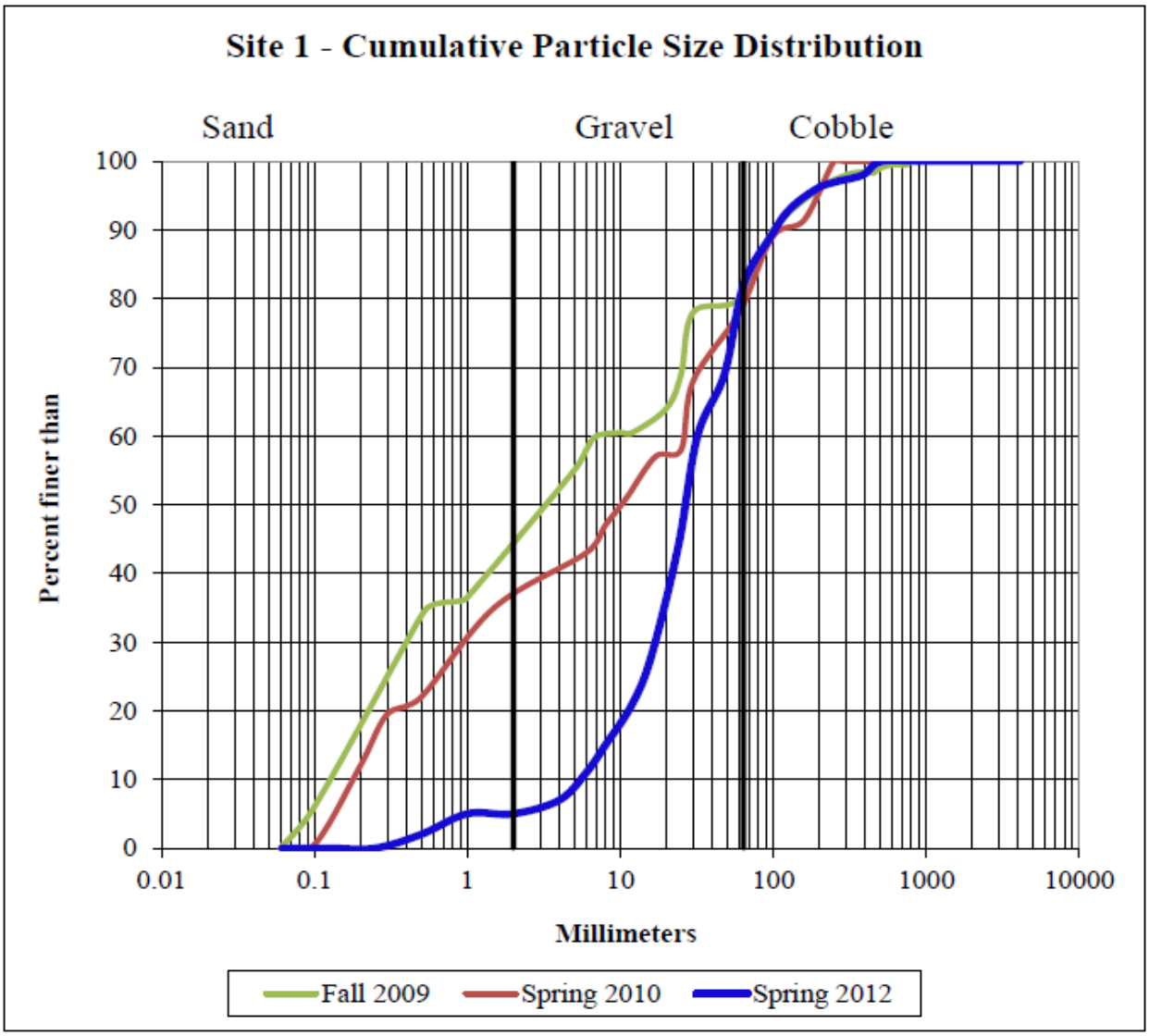


Figure 3-50. Cumulative particle size distribution for the lower Mainstem (Site 1).

3.7 Riparian Corridor Evaluation

3.7.1 Alder Mortality Evaluation

Introduction

Riparian zones are highly heterogeneous, biologically diverse and function as the transitional zone between aquatic and terrestrial ecosystems (Naiman et al. 2003). Fire in riparian zones does not occur often, but is influential in shaping vegetation dynamics and structure. Red alder seldom come into contact with fire given the nature of riparian habitat. Little Creek contains several age

classes of red alder but the dominant stand of this tree species readily colonized the stream corridor following the catastrophic debris torrent in 1955. The vegetation within the riparian corridor was consumed and transported downstream leaving mineral soil for the red alder to colonize.

Within four hours, the Lockheed Fire spanned the upper Little Creek watershed, encompassing the ridgelines and back burning into the riparian corridor. By the end of the third day, most all of the riparian zone of Little Creek had burned in a mosaic pattern with some portions of the litter layer being lightly charred while other portions were entirely consumed and soil surface was devoid of any litter or down woody material.

Immediately after the fire, an initial assessment of the riparian corridor along Little Creek produced only minor signs of red alder damage (B. Dietterick pers. comm.). Standing red alder in Little Creek produced leafy crowns in the spring of 2010, approximately seven months after the Lockheed Fire. During the second spring after the fire (2011), significant numbers of red alder began exhibiting signs of stress and mortality. The unanticipated second-year mortality prompted further investigation. Establishing a record of post-fire effects to overstory vegetation in the Little Creek riparian zone will create a baseline for future studies relating to riparian vegetation succession and the hydrologic function of Little Creek.

Using population and mortality data to estimate the volume of red alder large woody debris (LWD) associated with the Lockheed Fire will allow for temporal analysis of LWD input in Little Creek and also establish baseline conditions for future studies. Information relating to the effects of fire on red alder will be beneficial to resource managers working in riparian areas in North America (Theobald 2014).

Approach

An observational study was performed utilizing field data and personal accounts of the 2009 Lockheed Fire in order to describe how the fire influenced red alder mortality and the riparian zone of Little Creek. Four red alder field surveys were conducted from August 2011 to November 2013 from the confluence of Scotts Creek and Little Creek to the North and South Fork confluence of Little Creek (Figure 3-51). Red alder height and diameter at breast height (DBH) data were used to estimate volume of red alder LWD recruited into the Little Creek channel following the fire.

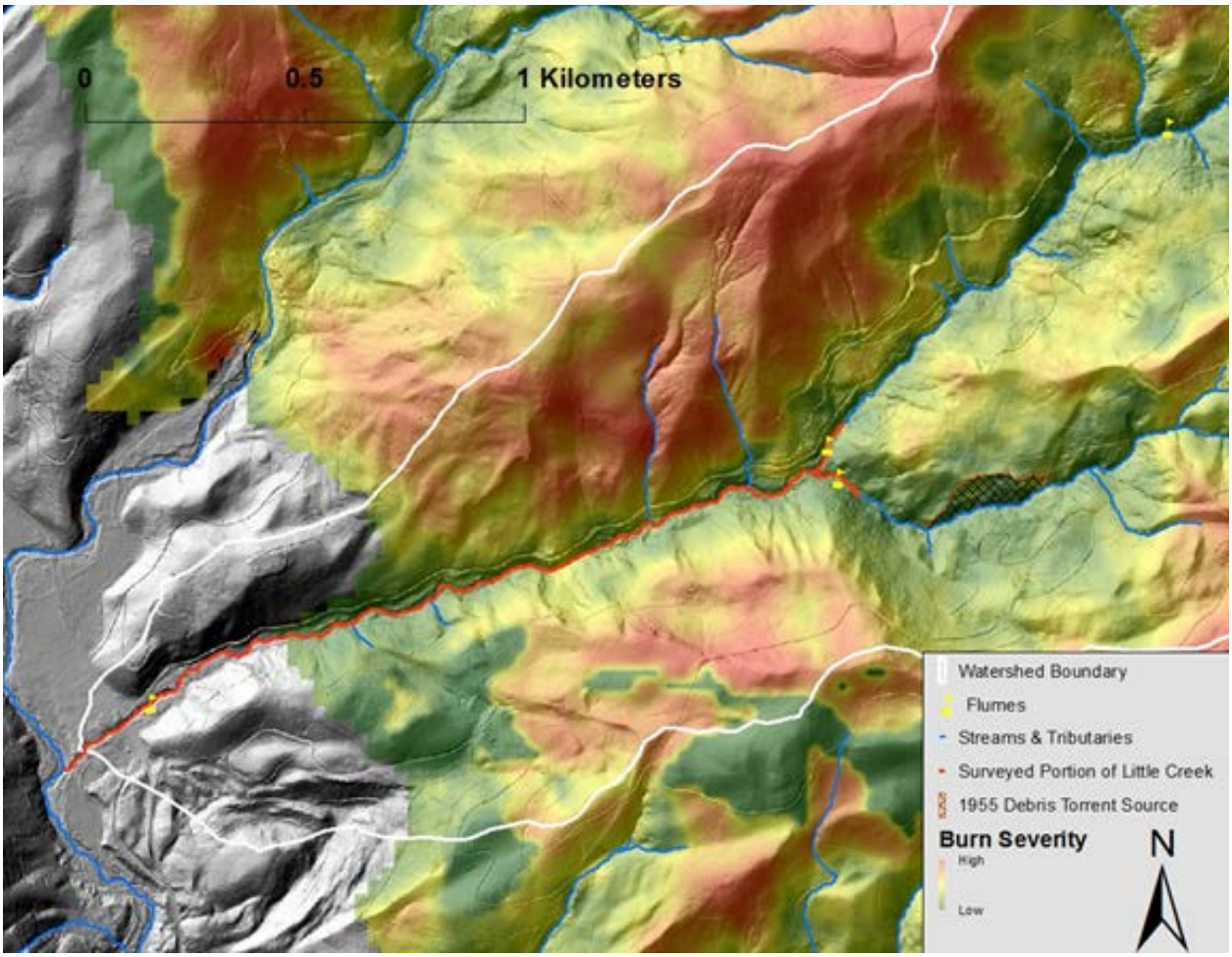


Figure 3-51. Riparian study area within the Little Creek watershed and Lockheed Fire burn severity layer.

A total of four surveys were conducted over 66 study reaches (30.48 meters per reach) from the confluence of Little Creek and Scotts Creek to the confluence of the North and South Forks of Little Creek, with the goal of gathering a variety data from the both live and dead trees. Data collection included the total number of red alder in each reach as well as the status of trees (i.e., live or dead). Notes and photographs relating to fire severity, vegetation dynamics, and geomorphic features were also collected.

The first two surveys (August, 2011 and June 2012) set out to count the mortality along Little Creek. Mortality data included a mortality classification and diameter at breast height. The third survey (May 2013) was conducted with the objective of improving the accuracy of previously collected GPS points using rebar monuments, and to further investigate fire severity. The fourth survey was conducted in order to collect the tree height using a laser range finder and DBH data using a DBH tape of 30 dominant and co-dominant red alders.

Mean values of DBH and height for red alder experiencing mortality following the fire were then applied to Smalian's formula in order to generate an estimate of volume in cubic meters.

$$V = \frac{A_1 + A_2}{2} \bullet L$$

Where: V is the volume of the log in cubic meters

A_1 is the area of the small end of the log in square meters

A_2 is the area of the large end of the log in square meters

L is the length of the log in meters

Smalian's formula is a basic log scaling formula applied to log sections that have been bucked into shorter lengths with minimum taper. Smalian's formula will generally overestimate the volume of a standing tree because a standing tree significantly tapers from the base to the apex. However, Smalian's formula was used for this study in order to provide a consistent and efficient comparison to the LWD volume calculated in 2010. LWD volumes in this study are rough estimations.

The following assumptions were made in this study regarding LWD volume: (1) red alder experiencing mortality after the fire have relatively the same DBH and height, (2) red alder diameter becomes less than 7.62 cm (3 in) approximately five feet from the apex of the tree,[3] (3) all red alder experiencing mortality following the fire will topple within the flood prone area of Little Creek, (4) DBH and three inches will be used in calculating A1 and A2 in Smalian's formula, and (5) the stump and root wad associated with each red alder will also contribute to LWD, but a rough estimation of LWD volume is desired.

Several attempts were made to age trees within each diameter class in order to perform age versus DBH regression. Using this regression equation paired with the timing of the 1955 debris torrent generated satisfactory estimates of age for alder in this study.

Alder mortality results

Mortality. Five hundred eighty red alder were observed in the 2.02 km reach of Little Creek surveyed. Reaches 0-20 were located within the non-burn zone. Reaches 21-66 were within the burn-zone. The burn zone was determined based on scorch marks of upland vegetation visible from the stream channel. Low severity is defined by scorch marks on upland vegetation less than 3 meters (10 ft), but no evidence of the fire reaching the stream channel. Medium severity is defined by scorch marks of upland vegetation greater than 3 meters (10 ft) and evidence of the fire reaching the stream channel. A box-plot of the proportion of dead red alder versus in or out

[3] Therefore, subtracting five feet from the average red alder height value produces a reasonable estimate of length in Smalian's formula.

of the burn zone illustrates a larger proportion of dead red alder within the burn zone (Figure 3-52).

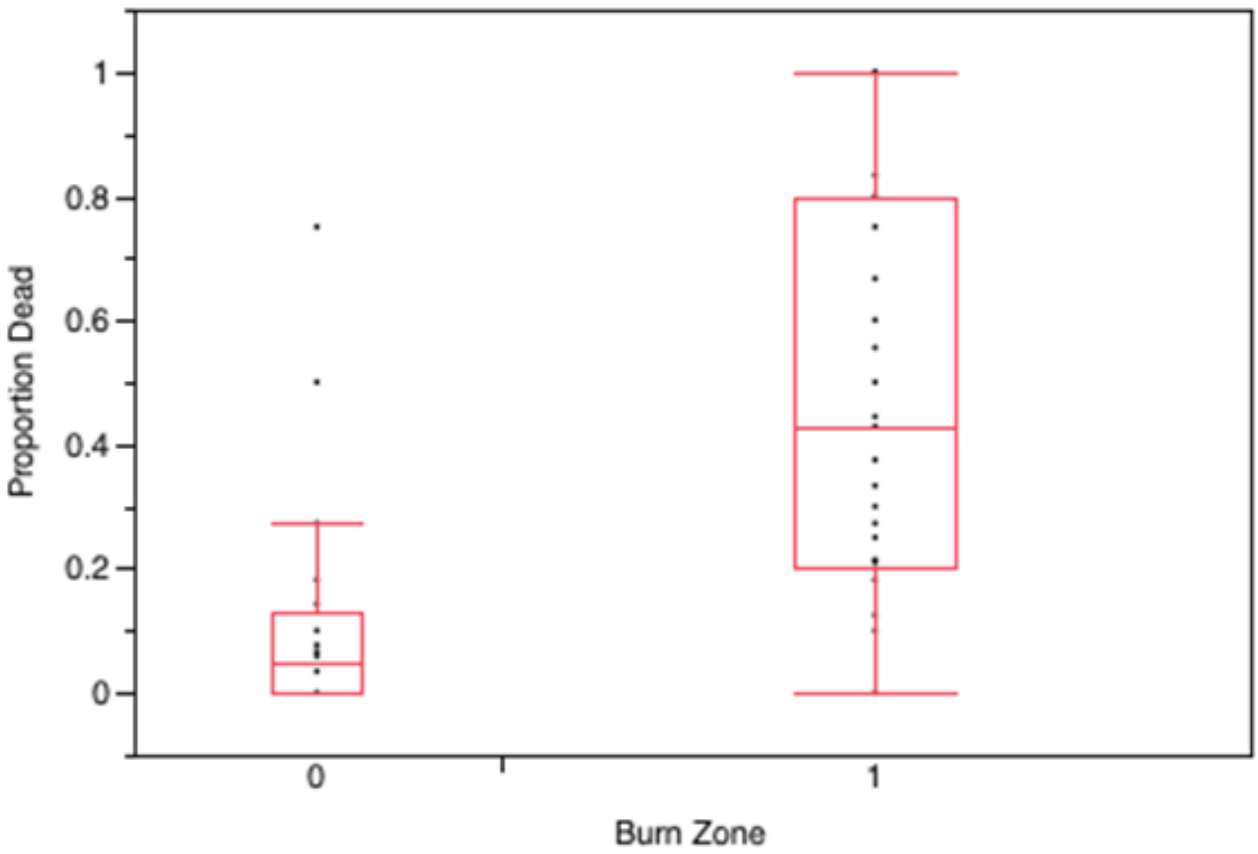


Figure 3-52. Box-plot of proportion of red alder vs. burn zone. The non-burn zone and burn zone are coded as 0 and 1, respectively.

Table 3-4 shows the mean proportion of dead red alder within the non-burn zone and burn zone are 0.11 and 0.45. Dead red alder within the non-burn zone could be explained by windthrow or other causes associated with weathering and the fact that the alders were approaching senescence.

Table 3-4. Proportion of dead red alder in and out of the burn zone

	Non-burn zone	Burn zone
Mean	0.11	0.45
Std Dev	0.19	0.34
Std Err Mean	0.04	0.05
Upper 95% Mean	0.20	0.56
Lower 95% Mean	0.02	0.34
Sample Size	20	42

The proportion of dead red alder versus live red alder on a reach-by-reach basis are shown graphically along with the longitudinal profile of the channel for perspective (Figure 3-53). White and black bars represent live and dead red alder respectively. Total bar height represents total red alder population within each reach. The black line represents a longitudinal profile of Little Creek derived in GIS from a 2011 LiDAR based digital elevation model (DEM).

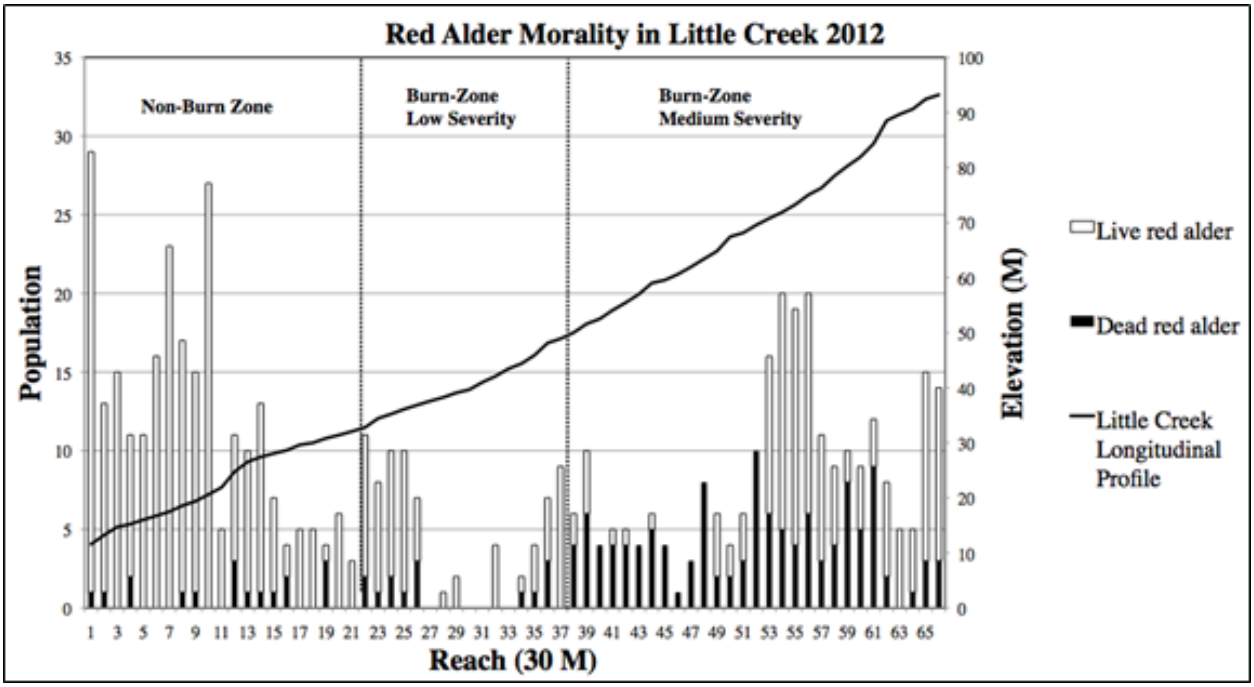


Figure 3-53. Red alder mortality in Little Creek.

Table 3-5 summarizes the observed live and dead red alder associated with burn severity. Of the 250 red alder in the non-burn zone, 7% were dead. Of the 75 red alder in the low severity burn zone, 18% were dead. Of the 264 red alder in the medium severity burn zone, 46% were dead. However, not all mortalities can be considered a direct result of the fire.

DBH and Age. Diameter at breast height was collected on 128 of the surveyed trees during the first survey and 29 trees during the fourth survey. The distribution of dead red alder for different diameter classes is shown graphically in Figure 3-54. Mean DBH of all dead alders from the two survey periods, was 44 cm (17 in) and 36 cm (14.5 in), respectively. Mean DBH of dead red alder in Little Creek was 45.79 cm (18.0 in). The two outliers with a DBH greater than 70 cm can be explained by an error made in data collection. Both outliers are two trees growing together that were measured as one tree during the first survey.

Table 3-5. Summary table of red alder population and mortality in Little Creek

	Non-burn zone	Burn-zone low severity	Burn-zone medium severity	Total
Reaches	1-20	21-37	37-66	66
Live	224	61	141	426
Dead	17	14	123	154

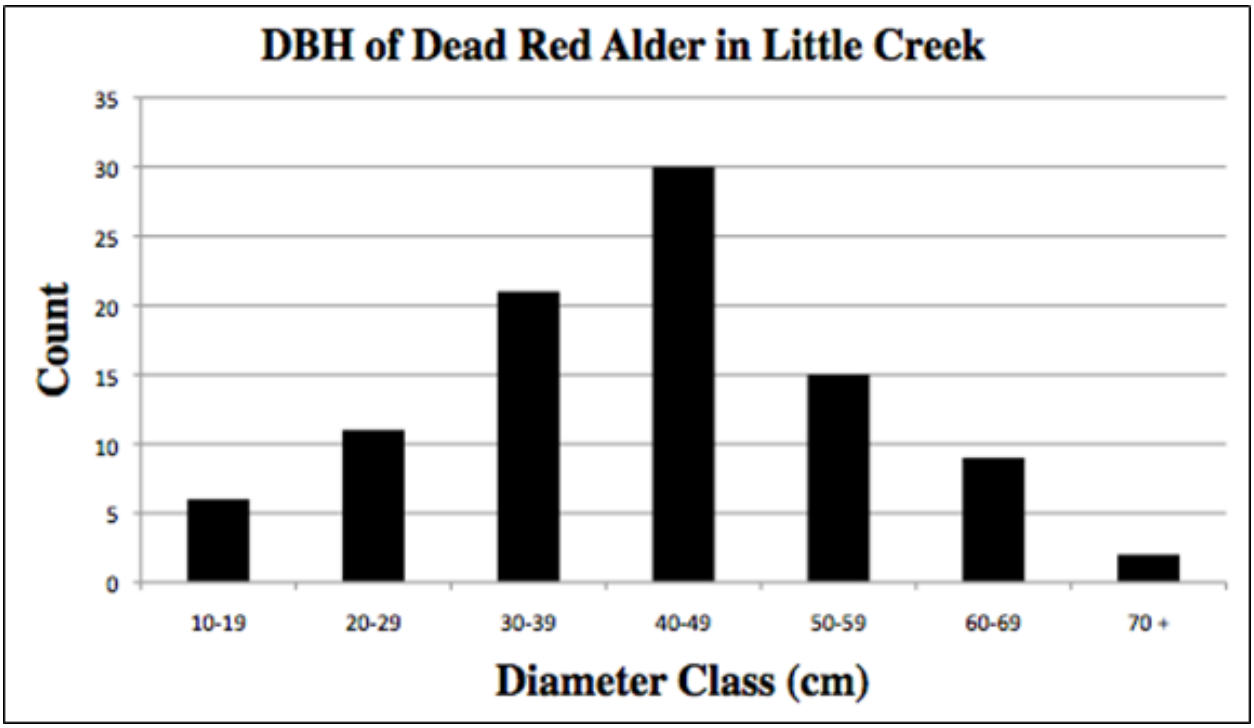


Figure 3-54. DBH of dead red alder in Little Creek. (Hardy 2012).

Thirteen red alder were aged using an increment borer at breast height (1.37 m or 4.5 ft). A regression of age and DBH produced an R-squared value of 0.76 (Figure 3-55). With 95% confidence, the mean age of dead red alder in Little Creek with a DBH of 45.69 cm (17.98 in) is between 29 to 38 years old. However, the sample size was only 13 out of 580, and large variation exists within each DBH class, so the regression equation should not be used if precise estimations are desired.

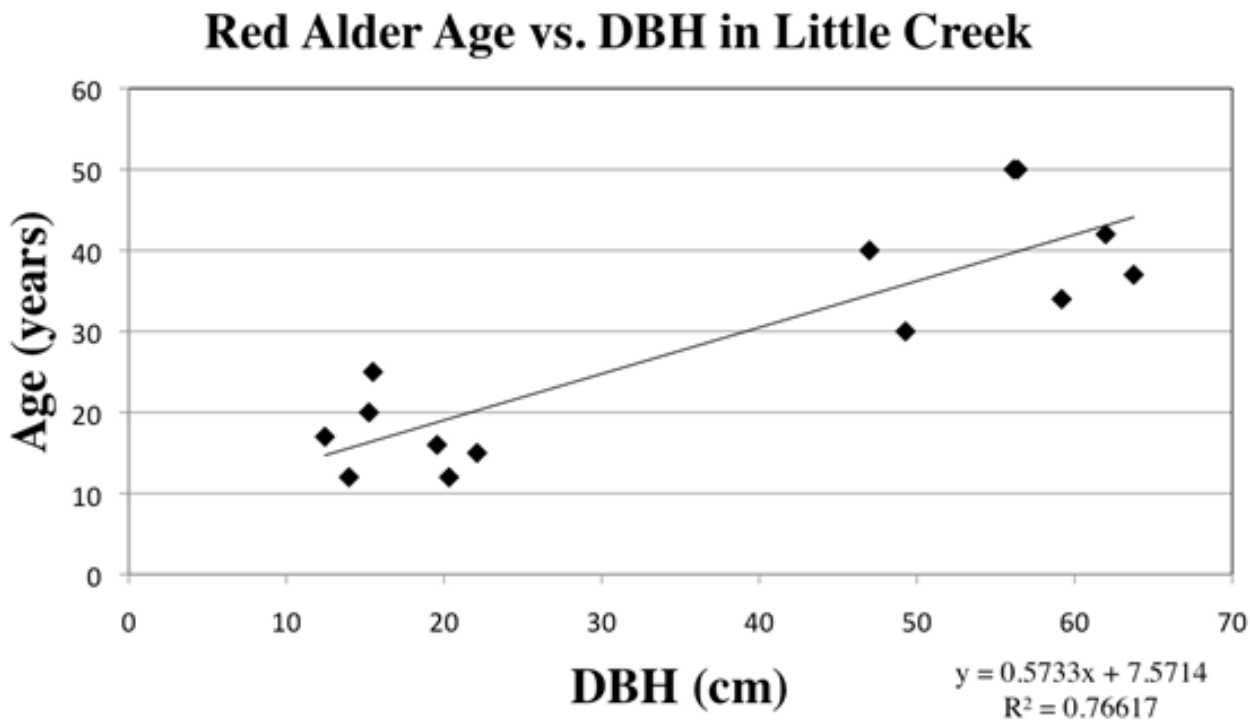


Figure 3-55. Red alder age vs. DBH.

DBH and Height. The height of 29 red alder representing each dominant and co-dominant population within individual reaches was collected using a laser range finder during the fourth survey. The distribution of height classes is shown graphically in Figure 3-56. Tree heights were collected starting at the Main Stem flume (Reach 12, Swanton Rd.) and ending at the confluence of the North and South Forks (Reach 66). Height was not collected on many of the dominant stands of red alder above Reach 38 because most had toppled since the fire.

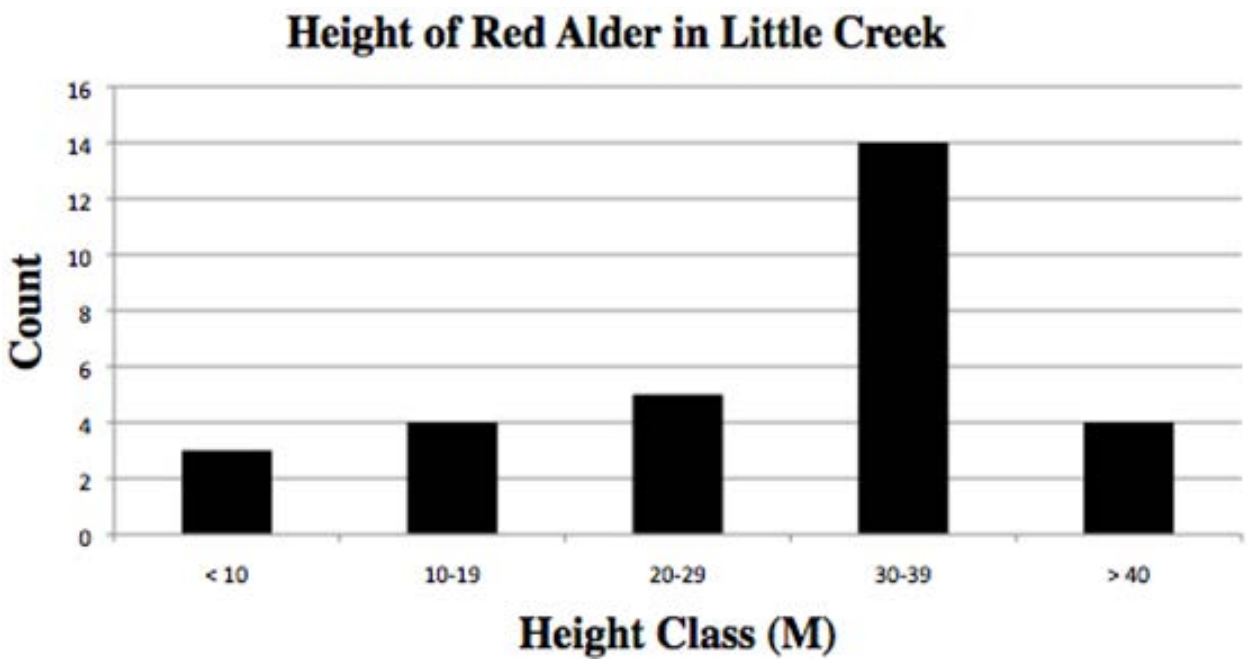


Figure 3-56. Heights of red alder in Little Creek.

The maximum height observed was 40.8 meters (134 ft). The shortest age class of red alder measured was 6 meters (20 ft) and had a DBH of 5.08 cm (2 in). Mean height of the dominant stand of red alder was 33.7 meters (110.8 ft). Mean height of the younger age class of red alder was 10 m (34 ft). The youngest age classes of red alder were not measured (i.e., red alder sprouting after the fire). A regression of red alder heights and DBH produced an R-square value of 0.62 (Figure 3-57).

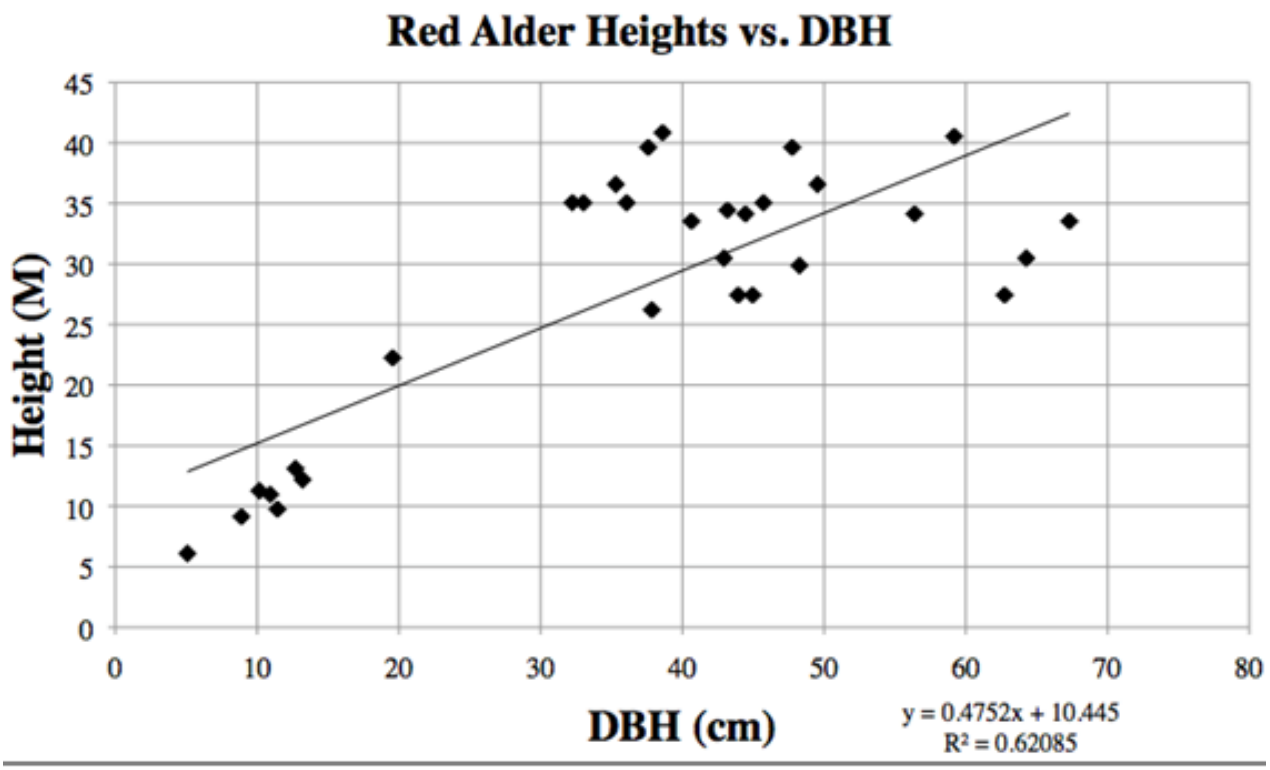


Figure 3-57. Red alder heights (M) and DBH (cm) collected during survey four (2013).

The average red alder experiencing mortality following the Lockheed Fire had a DBH of 45.69 cm (17.99 in) and a height of approximately 33.5 m (110 ft). Using 45.69 for A_1, 7.62 for A_2, and 32 m for length in Smalian's formula produces a volume of 2.69 m^3 (95.21 cft) per red alder. Given the assumptions listed in the methodology section, a total of 362.42 m^3 (12,798.70 cft) of red alder LWD is associated with the Lockheed Fire, an increase of approximately 245% from the (Smith 2010) LWD survey (Table 3-6). The dead red alder volume, available for LWD recruitment, is shown graphically for each reach and each burn severity (including no burn) (Figure 3-58).

Table 3-6. Summary table of red alder LWD 2010 vs. 2013

	Non-burn zone	Burn-zone low severity	Burn-zone medium severity	Total
2010 Total volume of red alder LWD in effective and potential Zone (Smith 2010) (m^3)	26.26	44.05	77.57	147.88
2013 Estimated total volume of red alder LWD contributed since 2010 (m^3)	40.00	32.95	289.46	362.42

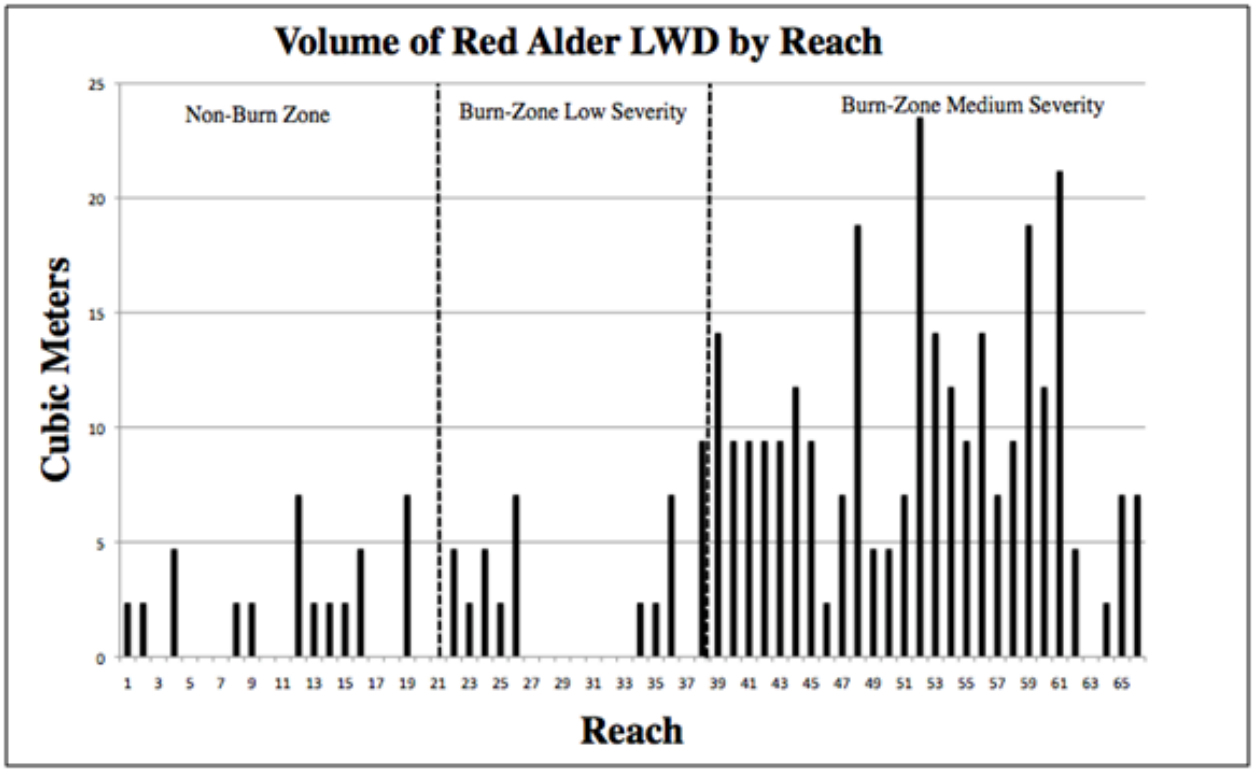


Figure 3-58. Estimated volume of red alder LWD in Little Creek.

Alder mortality logistic regression

Logistic regression in the statistics package JMP Pro 10 was utilized in order to predict red alder mortality. The predictor variables burn zone (in/out), reach (1-66), reach^2, reach*burn zone, and reach^2*burn zone were tested for significance. Burn zone was designated as reaches 21-66 and

coded as a 0 or 1. Reaches 37-50 had the highest burn severity based on field notes and photographs and also lowest probability of surviving based on this model depicting probability of being alive for each reach (Figure 3-58).

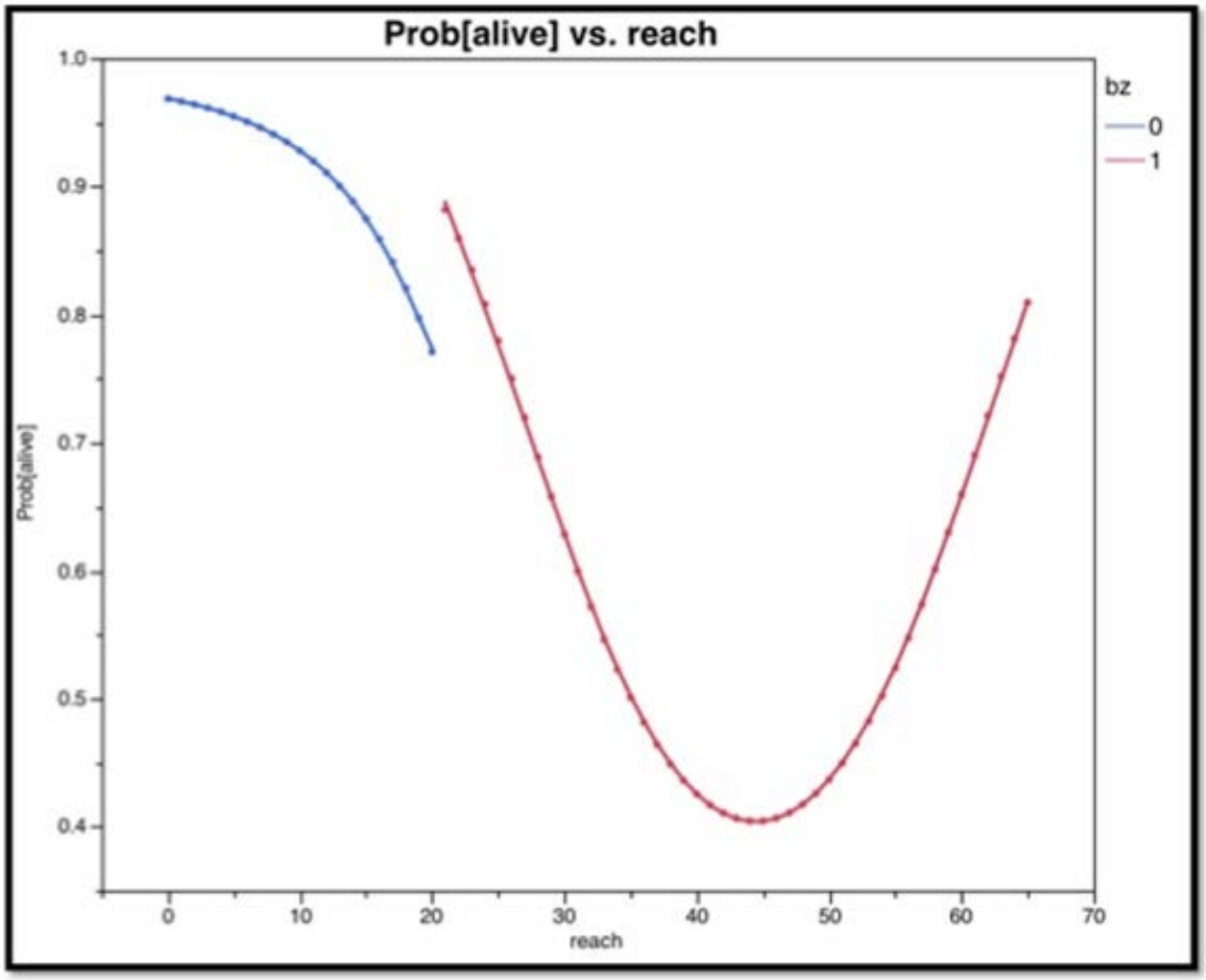


Figure 3-59. Probability of being alive vs. reach. Blue signifies non-burn zone, red signifies burn-zone.

According to the logistic regression performed, red alder in the burn zone were 9.7 times more likely to be categorized as dead than trees located in the non-burn zone. However, this is an overly simplified model of the many ecosystem processes at work leading to red alder mortality. This model only shows two variables associated with red alder mortality, not direct causation. Some other factors not accounted for in the model could also explain the accelerated rate of red alder mortality within the burn zone.

Alder mortality discussion

During the first spring after the fire (2010), the red alder canopy produced leaves, but the distribution of energy was likely disrupted due to damaged cambium associated with fire. Phloem, which carries nutrients throughout vascular plants, may have been significantly stressed from heat generated by the fire. Energy was being produced in the canopy, but not distributed down to the root system. Without proper distribution of nutrients, red alder were no longer able to sustain normal biological processes. The fire may have essentially girdled red alder, eventually resulting in mortality. This likely best explains why red alder in Little Creek first appeared to have survived the Lockheed Fire, but then experienced second-year mortality.

Not all red alder experiencing mortality after the fire had fire scars directly on the bole of the tree. Damaged cambium may explain some red alder mortality, but another possibility could be damaged root systems. The fire burned on the ground over several days and was smoldering in the riparian zone of Little Creek. Where water is readily available, red alder have relatively shallow root systems, and fire burning on the ground may have burned red alder roots. Burned root systems would almost certainly result in mortality.

With 95% confidence, the mean age of dead red alder in Little Creek with a DBH of 45.69 cm is between 29 to 38 years old. However, using time since the 1955 debris torrent to predict the age of the dominant stand of red alder produces a value closer to 54 years old at the time of the fire. The maximum life span of red alder is approximately 100 years, with the average red alder reaching maturity at 60-70 years old (Worthington et al. 1962). Mature red alder do not respond as well to disturbance as younger red alder according to Harrington (1984), and the fire may have been enough to push the dominant stand of red alder into a terminal condition.

Alder mortality conclusion

A positive association was identified between the burn zone and red alder mortality in Little Creek evident by the proportion of dead red alder within the burn zone and low probability of survival associated with the burn zone. This suggests mortality was fire induced, however, this observational data does not prove causation and other factors such as pathogens could also play a role in red alder mortality.

Changes in the Little Creek stream channel from 2002-2012 have been relatively small, but typically associated with the introduction of LWD (Perkins 2012). Since the fire, increased red alder mortality has occurred and will continue to dramatically increase the recruitment of LWD. The volume of red alder LWD in Little Creek has increased approximately 245% since a LWD survey conducted in 2010. Red alder large wood, however, has a short live span and degrades rapidly compared to Coast Redwood or other conifers.

Red alder population and mortality data provides a baseline for understanding the influence of the Lockheed Fire on red alder mortality and the Little Creek riparian zone. This information is an important contribution to the exploratory phase of research related to red alder in the Little Creek watershed.

3.8 Watershed Evaluations

3.8.1 Suspended Sediment Yield and Hydrologic Evaluation

Introduction

One of the initial analyses to be explored was to assess the first-year post-fire impacts on suspended export and to understand if sediment sources changed as a direct result of the fire. The study objectives undertaken by Loganbill (2011) to address these topics included:

- Evaluate changes in suspended sediment concentration, event sediment load, and event stormflow occurring the first year post-fire at three stream monitoring stations.
- Assess changes in sediment sources and determine the factors contributing the most influence on sediment production.

Three monitoring stations along Little Creek were utilized for the post-fire streamflow, turbidity, and suspended sediment concentration analysis. The three monitoring stations utilized for this portion of the project were Upper North Fork (UNF), North Fork (NF), and South Fork (SF). UNF and SF served as the control stations, whereas the North Fork station was located in the experimental harvest section of the watershed. Seven years of data were collected from each of these stations prior to logging in 2008; one year of data were collected post-harvest before the fire in August 2009; and four years of post-fire data were collected from 2010-2013. One year of post-harvest analysis was conducted prior to the fire in August of 2009 (see Chapter 2).

Streamflow Instrumentation and Methodology

Each monitoring station included a rated-section flume with multiple instruments to record stage. The primary instrument used to measure and record stage was the ISCO® 4230 Bubbler Flow Meter, which records stream stage at 15 minute intervals. Secondary stage recording equipment included a Wescor® water level sensor (pressure transducer), Belfort® FW-1 stage recorder, and Telog® data recorder with a Druck® pressure transducer. Additionally, a staff plate for manual stage readings was installed on an inside wall of the flumes. Rating curves were developed for each station for converting stage measurements to discharge.

Streamflow Data and Analysis

Peak flows are typically higher following wildfire in forested watersheds (Moody and Martin 2001; Helvey 1980). However in the four years post-fire in the Little Creek watershed, increases in annual peak flows were not observed (Table 3-7). Stormflow volume was also calculated for each event at each monitoring site (see Appendix--Water Quality). During the post-fire period (2010-2013), annual stormflow volumes, with the exception of 2011, were less than the maximum annual stormflow volume observed during the pre-fire period at all locations (Table 3-8).

Table 3-7. Annual peak flow in cubic feet per second for the North Fork, South Fork, and Upper North Fork monitoring stations. The red line indicates when the fire occurred.

	Annual Peak flow (cfs)		
Water Year	NF	SF	UNF
2003	18	2	25
2004	48	9	35
2005	19	7	29
2006	32	14	34
2007	14	5	18
2008	36	14	35
2009	15	5	16
2010	13	7	19
2011	26	13	24
2012	19	12	33
2013	15	15	34

Table 3-8. Empirical frequency data for the North Fork monitoring station using Weibull plotting formula (n+1)/m, where n = total record and m = rank

Water Year	Ranked Discharge	Occurrence Frequency
2004	48.0	0.0833
2007	31.0	0.1667
2011	26.0	0.2500
2006	24.0	0.3333
2008	23.0	0.4167
2005	19.0	0.5000
2012	19.0	0.5833
2003	18.0	0.6667
2009	15.0	0.7500
2013	15.0	0.8333
2010	13.0	0.9167

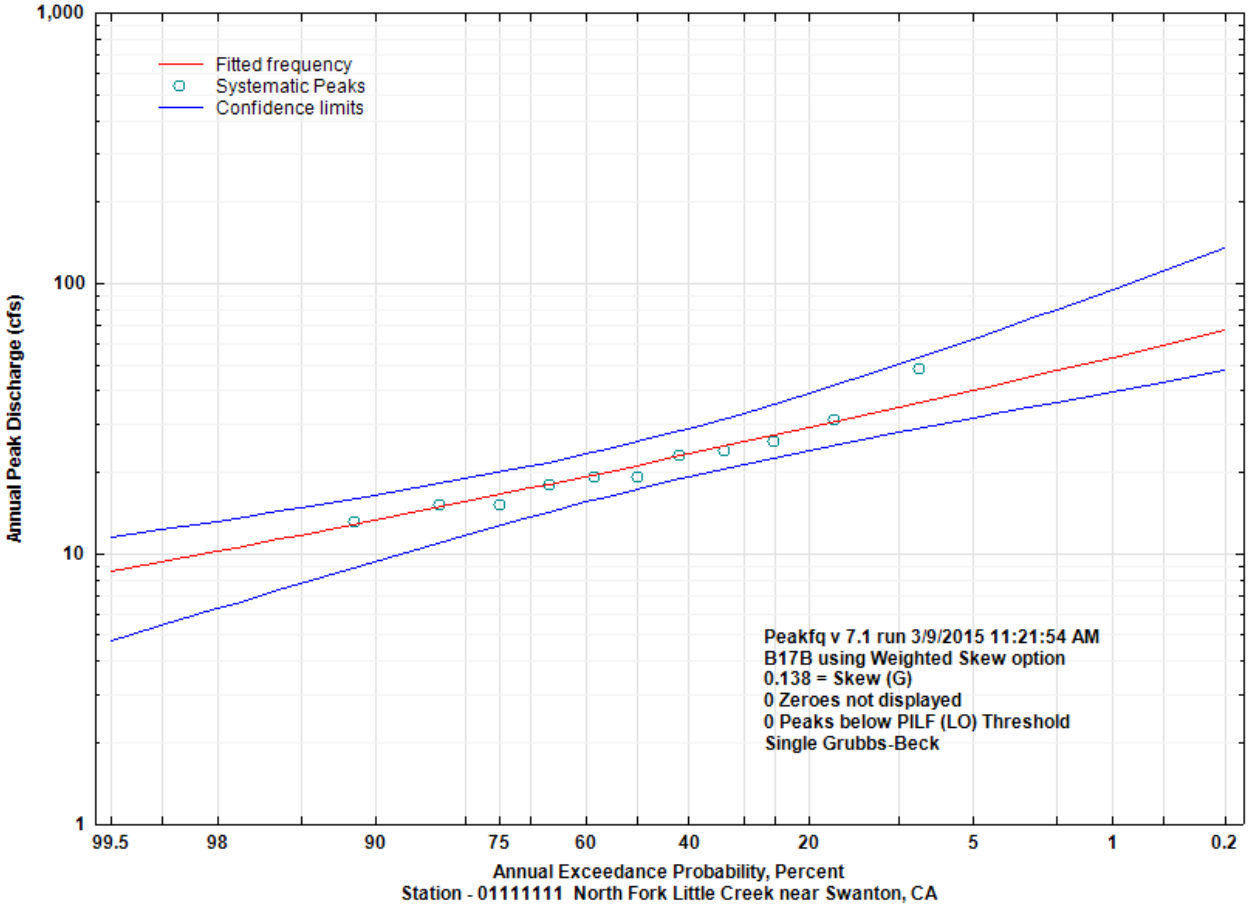


Figure 3-60. Exceedance probability for the North Fork Little Creek monitoring station.

For the first year post-fire, event stormflow volume was used as a response variable and event basin precipitation volume, 28-day previous rain (measure of antecedent soil moisture at beginning of storm), and fire were used as predictor variables (Loganbill 2013). The results of the regression analysis for the NF and UNF showed that 28-day previous rain and basin precipitation volume had a significant influence on stormflow volume and fire had a significant negative influence to this relationship. SF also showed that 28-day previous rain and basin precipitation volume had significant influence on stormflow volume, but fire was not significant (Loganbill 2013), suggesting the effect of the fire did not influence the storm flow volume response.

Turbidity and SSC instrumentation and methodology

Post-fire event based water quality sampling was conducted annually for water years 2009 to 2013. ISCO automated samplers were utilized to collect hourly water samples at the UNF, NF, and SF monitoring stations along Little Creek. The samplers were programmed to pump 350 mL samples on the hour continuously through each storm event. Samples were pumped through 3/8 inch PVC tubing situated on a swinging metal boom suspended in the active stream channel, such that the intake was maintained in the upper half of the water column to prevent pumping of

bedload. Samplers contain 24 one-liter bottles which were replaced every 24 hour time period by field technicians.

Water samples were transported from the field to an on-site laboratory and processed for turbidity and SSC. Turbidity measurements were made by agitating the sample and pouring a portion of the sample into a HACH® Sample Cell vial that was analyzed in a HACH® 2100AN turbidimeter.

SSC analysis methods were adopted for the project following consultation with personnel at the USFS Pacific Southwest Research Station Redwood Sciences Laboratory in Arcata, the USGS Water Laboratory in Marina, and other researchers. These methods were modified from ASTM D3977-97, Standard Test Methods for Determining Sediment Concentration in Water Samples, to follow procedures established by the Redwood Sciences Laboratory.

Due to the time-demanding nature of the sampling process, protocols were established to minimize the number of samples run for SSC. A modified version of the turbidity threshold sampling (TTS) protocols used in the Caspar Creek Watershed Study and elsewhere was implemented using turbidity as a predictor of SSC (Lewis 1996). Turbidity was measured for all samples and based on this sampling scheme, it was generally determined that samples with turbidity values below 20 NTUs would not be processed to determine SSC.

Turbidity and SSC Data and Analysis

Suspended sediment and turbidity regression equations were developed for storm events for all post-fire storm events during 2010-2013 water years. When suspended sediment concentration was not available, turbidity was used to predict hourly suspended sediment concentration using regression equations. During storm events, total sediment loads were calculated using hourly suspended concentration and corresponding instantaneous flow (Gaedeke 2006).

Annual sediment load was variable at all sites throughout the study (Figure 3-61). For the North and South Fork stations, post-fire annual sediment loads were within the range of observed annual sediment loads before the fire. The greatest annual sediment load occurred pre-fire for both North and South Fork stations. The relationship at Upper North Fork is less clear due to missing sediment load data during pre-fire storm events. For most water years in the study period, it was observed that the majority of the annual sediment load was produced during a single storm event (Table 3-9). The sediment contribution from a single event compared to the annual sediment load ranged from 29-96 percent, with an average of 64 percent.

Table 3-9. Percent of annual sediment load contributed by one storm. The red line indicates when the fire occurred.

	Percent of annual sediment load from one storm		
Water Year	NF	SF	UNF
2003	56	57	56
2004	63	62	64
2005	53	41	62
2006	29	42	78
2007	84	92	98
2008	64	78	77
2009	84	90	76
2010	31	34	48
2011	41	64	44
2012	58	66	74
2013	75	96	64

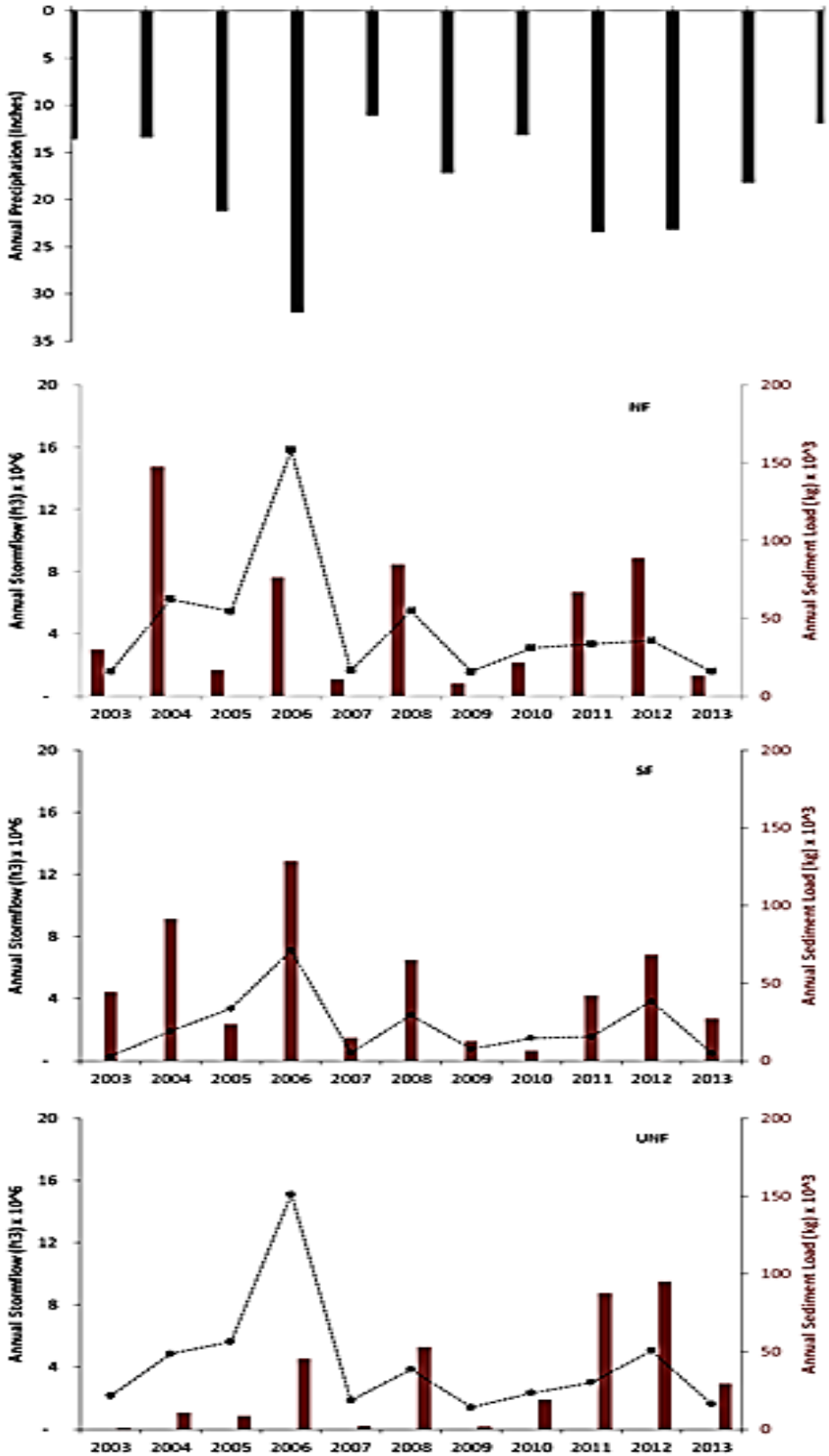


Figure 3-61. Annual stormflow (black dashed line) and annual sediment load (red bar) at the NF, SF, and UNF stations with annual precipitation (black bars) for the Little Creek watershed during water years 2003-2013.

Included in the analysis were changes in suspended sediment concentration, event sediment load, and event stormflow occurring the first year-post fire, water year 2010, at NF, SF, and UNF monitoring sites. Multiple stepwise regressions suggest EI30 (erosivity for 30-minute rainfall interval) and 28-day previous rainfall (measure of antecedent moisture conditions) were the variables that most consistently predicted the influence of fire on the event sediment load. This analysis resulted in a statistically-significant lower suspended sediment load for NF and SF versus EI30 and 28-day previous rainfall (Loganbill 2013).

Turbidity and SSC Discussion and Conclusion

In the first year post-fire, sediment response appeared largely related to high intensity-short duration rainfall events, and the event loads did not reflect large increases associated with the fire. Further statistical analysis is being conducted on sediment loads during later post-fire years. The first year post-fire secondary statistical analysis of event sediment loads do not suggest an effect of fire on event sediment loads at NF, SF, and UNF sites (Loganbill 2013).

The lack of significant fire-induced effect is best explained by soil hydrologic properties and storm characteristics during the first year following the fire. Although variability of soil water repellency was evident throughout the watershed, widespread hydrophobic conditions were observed, particularly in the burned chaparral areas along mid and upper slopes.

During storms exhibiting low to moderate rainfall intensities, total rainfall was significant. For example, the first significant storm of the season occurred in October 2009, with greater than 6 inches falling in 24 hours. The storm total at the Landing raingage near the centroid of the watershed was 5.05 inches and the maximum 10-minute rainfall intensity (I10) was 1.25 in/hr. In the upper Scotts Creek watershed where the storm rainfall was 10.55 inches the I10 was 1.62 in/hr (Figure 3-62). The most surprising observation for this storm that produced notable precipitation totals and moderate rainfall intensities was that observed rapid near-surface runoff did not trigger significant sheet or rill erosion. However, rapid concentrating flow in Class II and III headwater drainages resulted in at least three channel-derived debris flows occurring during the October storm. The connection of these debris flows to the receiving Class I stream was minimal due to trapping of sediment by the road system, which in many cases is located within the WLPZ. Additional channel scour was observed throughout the headwater streams and in some cases headwall swales.

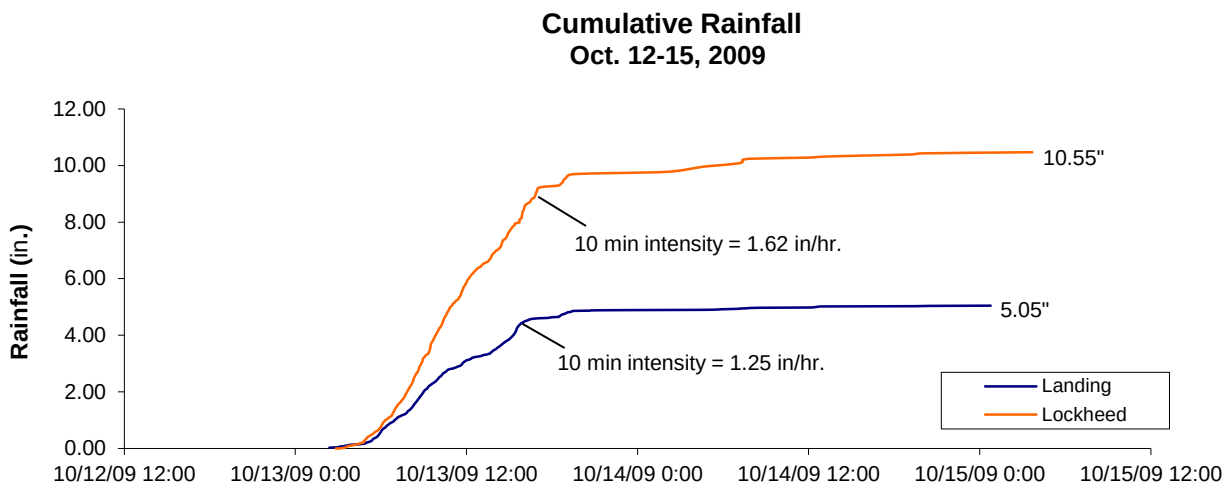


Figure 3-62. October 13-14, 2009 storm rainfall totals.

The next significant storm event on January 18-23rd (Figure 3-63) produced comparatively lower storm totals (6.32 in and 8.15 inches for the Landing and Lockheed raingages, respectively). This storm had four distinct rain periods. During the first six hours when approximately two inches fell, a brief downpour generated significantly greater rainfall intensities than those documented for the remainder of the storm event.

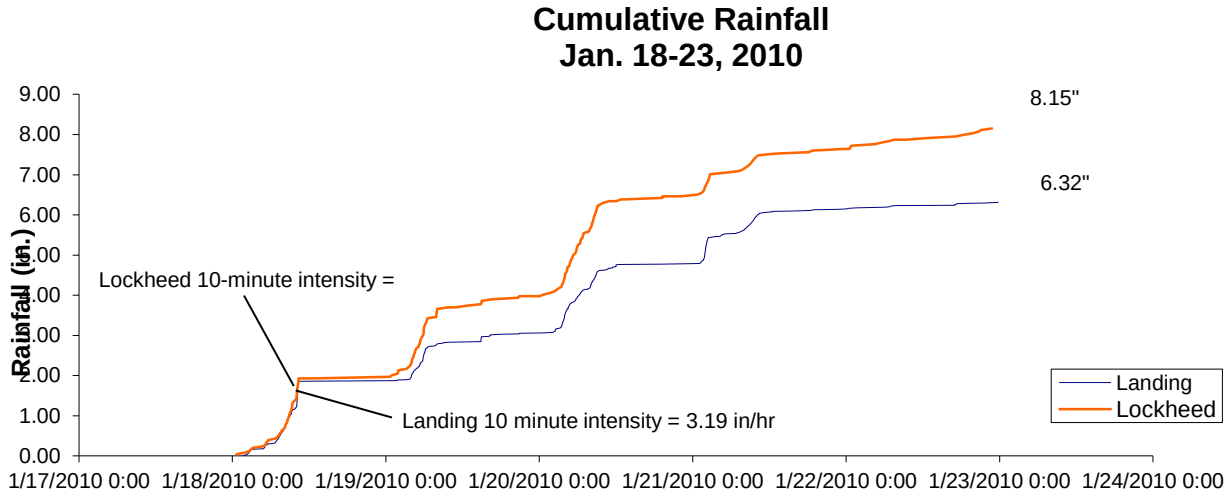


Figure 3-63. Cumulative rainfall plots at the Landing and Lockheed rain gages for the January 18-23 storm.
Lockheed 10 min. intensity

These observations and rainfall intensity data suggest an intensity threshold exists for short duration storm bursts where near-surface flow pathways in fire-disturbed soils are overwhelmed, breaking out onto the surface and likely initiating rilling. The rilling on hillsides then can become

concentrated into mudflows having significant travel distances downslope, increasing the likelihood of delivery to receiving stream channels or initiating channel-derived debris flows. In this study, rilling occurred almost exclusively on upper and mid slope positions supporting chaparral and knobcone pine vegetative communities on south-facing slopes. Areas forested in redwood and Douglas-fir immediately below on mid and lower slope positions did not experience rilling. A few limited exceptions exist on steep forested north-facing slopes. The evidence suggests the threshold for rilling initiation is I10 > 1.25 inches per hour and < 3.6 in/hr. This important observation informed the rainfall simulation study which led to the constant 2.0 in/hr rainfall intensity target. The results of that study improved our understanding of the ability for significant movement of lateral near-surface runoff to occur on soils with partial to extensive soil water repellency (fire-induced or naturally-occurring).

3.8.2 Near-Stream Sediment Source Surveys

Introduction and Methodology

Near-stream sediment source surveys (NSSSS) were instituted in 2002 with the objective to identify, quantify, and monitor sediment inputs to Little Creek from near-stream landslides and streambank erosion. The 2002 survey was conducted during the summer with the goal of identifying and quantifying the 1997-98 winter features. Approximately 66 inches of rainfall fell within the Little Creek watershed during the 1997-98 winter, compared to the annual average range of 30-45 in. The elevated rainfall amount during the 1997-1998 winter year, along with stormflow discharge with an estimated return interval of approximately 16 years (using the long term San Lorenzo River annual peak flow data), resulted in saturated soils that eroded into the channel via landsliding and bank failure. Additional surveys took place throughout the winter and summer months of 2006, 2009, 2010, 2011, 2012, and 2013.

For the purposes of this survey, Little Creek was divided into three segments in relation to the monitoring stations (Main Stem-MS, North Fork-NF, Upper North Fork-UNF). Each segment was further divided into 30.5 m (100 ft) reaches marked on the ground by tagged rebar and marked at eyeline with flagging above the flood prone area. Surveys were conducted by traversing up the stream channel recording: location of erosional feature, volume of feature, estimated volume contributing to the stream channel, feature type, and contribution factor. Approximately 64% of the main channel was surveyed starting at the confluence of Little Creek and Scotts Creek, continuing up the North Fork, and ending at the property line just above the UNF monitoring station.

Features with recent active erosion containing void volumes of 0.76 cubic meter (one cubic yard) and greater were recorded. Sediment sources identified in previous surveys or with volumes less than 0.76 m^3 were not recorded unless a potential for greater contribution existed or additional sediment contribution occurred. The location of features were identified by stretching a 30.5 m (100 ft) cloth tape up the stream channel and noting stream reach name (MS, NF, UNF), reach number, right or left bank, and length of feature, as indicated on cloth tape.

Features types were recorded by an acronym of the most common features encountered: eroded bank (EB), landslide (LS). The width, depth, and height of features were measured with tape measure or pocket rod to determine the volume of the feature. Since features were not normally uniform in volumetric shape, an estimate of the volume of sediment, along with consideration to the amount of sediment that directly contributed to stream channel, were noted. The contribution factor of either 'upslope' or 'fluvial' was recorded along with other notes that helped identify and describe the sediment source.

NSSSS Data

The first survey conducted in 2002 accounted for all near-stream sediment sources dating back to the 1997-98 storm season. Little Creek had an abundance of landslides and bank failures as a result of the abnormally high rainfall amount during the 1997-98 winter season that led to above average flow and flood stages. There were substantial volumes of sediment contributed to the channel as a result of this storm season.

A vast number of features were identified in the 2002 survey, as would be expected in the initial survey. There were 54 and 53 sediment sources greater than 0.76 m^3 (1 yd^3) on the Main Stem reach and North Fork reaches, respectively (Table 3-10). The 2002 survey resulted in the most features and the total calculated volume was more than an order of magnitude higher than recorded in the surveys that followed (Figure 3-64). The majority of the features identified were bank erosion from fluvial activity. Subsequent sediment surveys conducted in 2006, 2009, 2010, 2011, 2012, and 2013 found decreasing numbers of contributing features with smaller volumes of sediment delivery to Little Creek.

Table 3-10. Summary of near-stream sediment source surveys for each year

Year	Stream	# of Features	EB[1]/LS[2]	m^3	yd^3
2002	MS	54	45/9	5982.1	7822.4
2002	NF	53	35/18	6719.3	8788.6
2006	MS	20	18/2	181.5	237.5
2006	NF	29	19/0	201.2	263.1
2009	MS	16	9/5	78.7	103
2009	NF	3	3/0	9.9	13
2010	MS	11	7/2	38.2	50
2010	NF	8	7/1	11.7	15.2
2011	MS	15	11/4	121.5	158.9
2011	NF	8	7/11	6.1	8
2012	MS	11	9/2	96.8	126.6
2012	NF	3	1/0	25.1	32.9
2013	MS	1	0/1	4.4	5.8
2013	NF	3	0/3	154.3	201.8

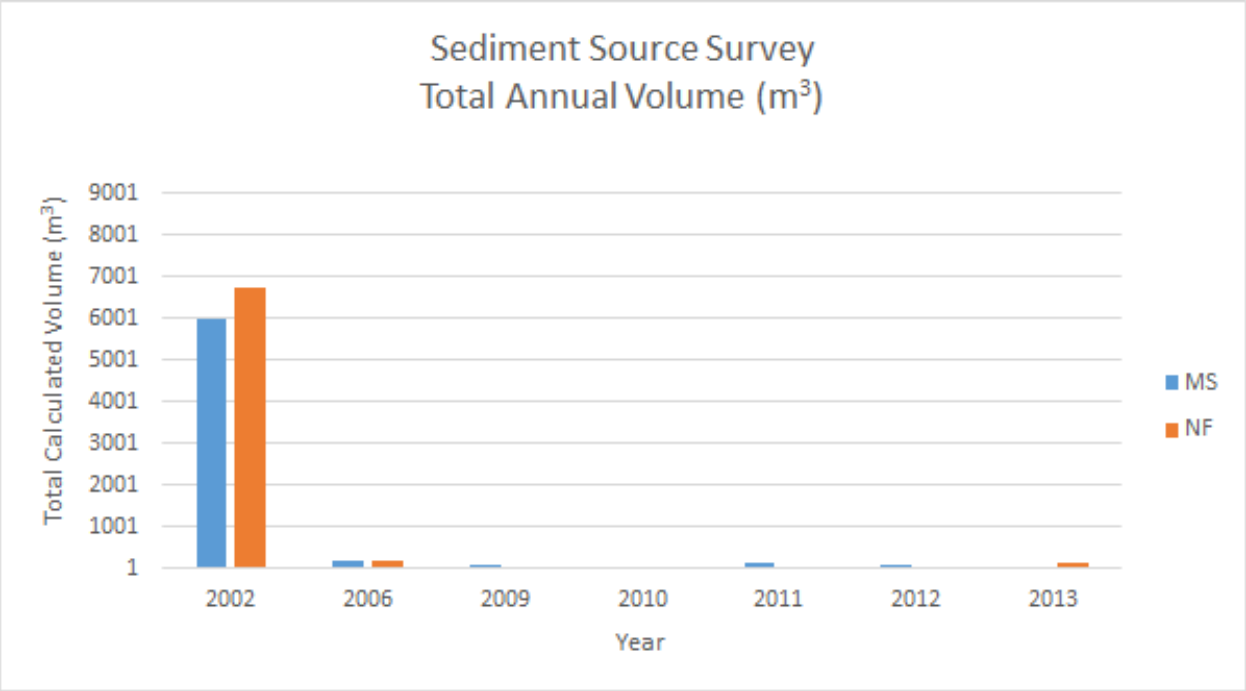


Figure 3-64. Annual total calculated volume for each near-stream sediment survey.

In 2010 two surveys were conducted, one mid-winter and one in June after all significant storm events had occurred. The 2010 sediment survey was the first survey following the wildfire; new sediment sources were identified that were induced by the fire such as upslope dry ravel and landslides from fallen trees. Eleven new sources were identified on the mainstem and eight features on the North Fork, with eroding banks being the dominant feature. Total calculated volume was half as much as was recorded in the 2009 survey on the mainstem and only slightly more than the 2009 survey on the North Fork.

Many of the previously recorded features from 2002 were noted as still contributing, but it was difficult to obtain high levels of accuracy when quantifying the change in volume of these features. It would have been beneficial to have erosion pins or other methods to record and quantify continuously eroding features.

NSSSS Discussion

The number of near-stream sediment sources continued the decreasing trend after the fire. The amount and volume of sediment sources decreased in the MS compared to 2009 survey, although the NF had more features and slightly higher volume than recorded in the 2009 survey. Eroded banks were the most common feature recorded. Fire-induced dry ravel accumulations, especially in inner gorge sections of the stream channel, and tree fall from fire contributed sediment to stream channel at relatively low volumes. It is important to recognize that even though the majority of the watershed experienced a wildfire that resulted in reduced vegetation and ground cover, the amount and volume of near-stream sediment sources remained relatively low. Compared to near-stream sediment inputs that occur during significant storm events like those

that occurred in 1998, it appears that both the smaller storms experienced since and the dry ravel and surface erosion after the fire contributed orders of magnitude less sediment to stream channels in the Little Creek watershed. This may explain the lack of significant changes in sediment loads the first year after the fire.

3.8.3 Post-Fire Suspended Sediment Export Using a Modeling Approach

The Lockheed Fire in 2009 burned at varied intensities throughout the Little Creek watershed, disrupting the ongoing paired watershed study. The fire eliminated the ability to use a paired treatment and control watershed approach. An alternative approach was developed to detect wildfire effects on stormflow volume, peakflow and sediment loads from Little Creek using hydrologic models and sediment runoff relationships. Modeled storm runoff from models calibrated to the pre-disturbance time periods were used as the control for the control/treatment evaluation. This approach is described in Surfleet, Skaugset, and Dietterick (2012).

The analysis of the effect of the fire on storm runoff, peakflows, and sediment load using hydrologic models was done for the first two winters following the Lockheed Fire (2010-2011). An alternative analysis was used to detect stormflow and sediment load changes due to the wildfire by comparing measured post-treatment stormflow and sediment load to simulated pre-disturbance responses predicted with the hydrologic models HBV-EC and DHSVM. High natural variability of stormflow and sediment measurements compounded with uncertainty associated with the hydrologic models and climate suggest only large changes can be detected. The fire and subsequent salvage harvest created an approximately 9-12 percent reduction in forest overstory canopy and 70-90 percent consumption of understory vegetation. No discernible change in slopes of regression lines were detected between pre-disturbance and post-fire stormflow volumes, peakflows, or sediment loads. No change was detected in stormflow volume, peakflow, or sediment loads comparing pre- and post-fire vegetation inputs to the DHSVM hydrologic model. The lack of detected change in streamflow to accelerate stream channel erosion combined with low to moderate fire severity adjacent to stream channels most likely were the reasons for no detected change to sediment loads post-fire (Surfleet et al. 2014).

Chapter 4. Conclusions

The Little Creek Study, which began in 2001 as a long-term watershed-scale study to evaluate change associated with selection timber harvesting, shifted abruptly in 2009 one year into the post-harvest phase of the study. One year of post-harvest data were collected and used as the basis to evaluate change in water yield and sediment, recognizing first-year effects are often the greatest. With the shift in study objectives after the Lockheed Fire, the eight years of pre-fire data as the baseline were used to evaluate changes due to the fire disturbance.

4.1 Pre- and Post-Harvest Evaluation

Paired and nested studies were used during the calibration period. The post-treatment evaluation focused only on the paired study after identifying unresolved flow control changes at the upstream station for the nested study. Analysis of three first year post-logging treatment storms found no evidence that any increase in suspended sediment export occurred due to those operations. It was also shown that no perceptible change occurred in stormflow volumes or annual peak flows, the agents most associated with increases in suspended sediment export from previous studies (Loganbill 2013). These three measures were all within the variability experienced from the population during the calibration period. The results were expected due to the small scale of the harvest (20 percent of area upstream of NF gaging station) and low intensity of the harvest (30 percent of the timber volume removed). The North Fork Little Creek harvest was typical of selection harvests used in Santa Cruz County, and supports observations that timber harvest with proper implementation of the California Forest Practice Rules can occur in steep environments with geologically-sensitive locales without adverse impact to stormflow volumes, peak flow, and suspended sediment export.

Further, change in channel geomorphic characteristics were minor and where change in longitudinal or cross-sectional profiles did occur it was associated with local additions of large wood or the evacuation of large wood from the area leading to adjustment in bed topography (Perkins 2012).

Attempts to characterize sediment sources were limited due to the precision and repeatability of measurements made using the Near Stream Sediment Source Survey (NSSSS). However, evident from the NSSSS data is that large forcing events, such as the 1998 flood, introduce near-stream sediment to the channel orders of magnitude greater than disturbance associated with timber harvest. The majority of sediment from bank erosion and all of the near-stream landslides occurred during the 1998 large discharge events, an event estimated as a 16-year return interval event using data from the USGS San Lorenzo at Big Trees gaging station.

4.2 Post-Fire Evaluation

The 1,300 acres of the Little Creek watershed burned during the Lockheed Fire experienced change in watershed processes as a direct result of the fire. There were storms during the first overwintering period, when the watershed was at greatest risk to surface erosion that led to small channel-derived debris flows and surface erosion on hillslopes that were virtually unprotected from raindrop impact and other surface erosional processes. Yet, the catastrophic response, expected by many resource professionals, did not occur during these first four years following the fire. Seeking to answer the question of why did erosion occur when and where it did, was equally important to the question associated with why was it not much worse. It was estimated that approximately 95 percent of the ground vegetation and litter layer was completely consumed, leaving behind an ash layer covering the bare mineral soil below. Observations made prior to the first rainfall of the 2010 water year demonstrated extreme erosion susceptibility with a high risk of dry ravel and delivery of ash to stream channels in inner gorge areas with side slopes often exceeding 75 percent. The reasons why the post-fire erosion impacts were minimal lie in the meteorological characteristics of the storms that occurred, low burn severities near riparian areas, and variability in the condition of soil hydrologic properties. Visual and field observations of soil hydrologic characteristics immediately following the fire suggested that measured changes in soil hydrologic properties would be evident and surface erosion would increase following the fire, particularly when short duration rainfall intensities exceeded 2.0 in/hr. Results suggest that soil hydrologic changes occurred in the study period, yet there was a lack of conclusive evidence that those changes were attributed to the fire.

The suspended sediment monitoring showed suspended sediment export decreased the first winter following wildfire. A change in hydrologic flow pathways suggested the watershed, more efficient in hydrologic response, was delivering sediment from distances further from receiving channels and from more localized source areas compared to typical pre-fire events.

Additional conclusions from this study include:

1. Soil hydrologic changes occurred on both burned and non-burned sites.
2. Red alder mortality was attributable to heat effects from during the fire, yet mortality was not evident until two years following the fire when buds for the following season were already produced.
3. A delayed effect was experienced in channel substrate change. Pebble counts revealed significant introduction of coarse gravels.
4. Hillslope erosion was reduced when significant leaf and needle drop occurred immediately following fire.
5. Suspended sediment export was shown to decrease the first year following the fire in the absence of larger peak flow events.
6. Rainfall simulations showed that rainfall rates of two inches per hour were disposed as near-surface runoff and deeper pathways of subsurface flow (lateral subsurface and deeper percolation).

7. Observed hillslope rilling suggests that a threshold likely greater than two inches per hour and less than 3.25 inches per hour on burned chaparral hillslopes is necessary to initiate surface erosion. This threshold is likely greater than 3.25 inches per hour on forested hillslopes, except on granitic soils.

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Appendix. Data Tables

Water quality data

WaterYear	EventStartDate	NF Event Stormflow (ft3)	SF Event Stormflow (ft3)	UNF Event Stormflow (ft3)	NF Event load (kg)	SF Event load (kg)	UNF Event load (kg)
2003	12/13/02 0:28	598212	91365	850098	11742	25337	212
2003	12/14/02 13:06	193849	53512	233086	1007		66
2003	12/16/02 0:49	638942	139106	866448	16633	18837	360
2003	12/19/02 11:04	72964		30502			
2003	12/28/02 11:51			174992			
2003	2/15/03 16:48	73503			369		
2004	11/8/03 17:49	51045	6487	40522	403	377	26
2004	12/20/03 11:10	276550	46188	252975	5179	3567	78
2004	12/24/03 2:06	273612	67972	371547	1754		35
2004	12/28/03 22:49	2576535	704836	2003825	93461	56554	6971
2004	1/1/04 2:09	2611865	786514	1868980	44697	30225	3761
2004	2/2/04 17:26	32264		27069	289	79	
2004	2/17/04 16:11	247714	62096	189294	1481	719	
2004	2/25/04 1:55	155057	250140	105312	384	195	
2005	10/19/04 1:13		29963	87155			
2005	12/6/04 22:17	43905	18435		117		11
2005	12/7/04 20:49	650895	210692	979230	8909	9568	1173
2005	12/26/04 9:16	448199	281600	453789	2834	2497	131
2005	12/29/04 18:54	466409	235753	789014	637		162
2005	1/6/05 22:58	1224242	846942	903109	3418	1554	1529
2005	2/17/05 15:44	159398	352174	391305	728		293
2005	3/21/05 12:58	2384029	1392641	1841807		9681	5386
2005	3/27/05 15:39	73668		202916	205	201	
2006	12/17/05 13:39	468748	216980	941410	4821	7283	249
2006	12/21/05 9:39	1170276	501984	1283079			3148
2006	12/25/05 5:52	312628	333696	407074	1116	922	92
2006	12/28/05 3:25						
2006	12/30/05 10:43	1417489	638505	1693022	11967	11619	1911
2006	1/1/06 7:50	3097649	1538692	3525798		54415	35263
2006	2/26/06 10:26	186075	14561	176467	394	365	
2006	3/3/06 1:01						
2006	3/5/06 17:32	1183902	831136	1147522		6192	2951
2006	3/13/06 22:03	63263	99956	33458	111	54	59
2006	3/20/06 8:02						
2006	3/24/06 16:44						
2006	3/27/06 13:36						
2006	3/29/06 1:33	1048043	459610	645659	3566	2497	515
2006	4/2/06 16:48	1471983	480361	1240133	11521	10318	
2006	4/3/06 7:51						
2006	4/4/06 3:20	2372288	984373	1614891	21856	15226	
2006	4/10/06 20:34	3034306	1029298	2395704	21091	19846	1148

WaterYear	EventStartDate	NF Event Stormflow (ft3)	SF Event Stormflow (ft3)	UNF Event Stormflow (ft3)	NF Event load (kg)	SF Event load (kg)	UNF Event load (kg)
2007	11/13/06 3:36	73382		56255	265	119	
2007	12/9/06 15:42	7644		12103	14	21	
2007	2/8/07 20:29	301564		386796	1306	1016	
2007	2/10/07 1:01	1238997	509318	1388714	9058	13684	2024
2007	2/21/07 22:40		4877	8438		4	13
2007	4/21/07 18:18	31013	10765	15560	98	33	25
2008	12/17/07 21:23	59013	15614	31295	267	87	32
2008	12/19/07 23:05	100736	26467	59157	793	437	137
2008	1/3/08 13:20	666214	219995	577772	11904	7824	775
2008	1/24/08 1:55	2475047	1421234	1985300	53874	50718	40478
2008	1/26/08 17:22	159004	268822	260392	335		455
2008	1/31/08 16:28	102336	49925	31321	299	146	63
2008	2/2/08 13:54	1893275	959890	914261	17151	5729	10958
2009	11/1/08 5:26	77850	16361	77036	490	359	66
2009	2/15/09 3:20	1033743	404073	949752	6792	11566	1358
2009	2/21/09 18:35	436355	329085	385599	842	938	374
2010	10/13/09 3:01	666944	132510	685128	5033	484	9238
2010	1/18/10 1:46	252782	106218	166151	6785	872	4580
2010	1/19/10 1:47	197531	87656	97856	406	71	145
2010	1/19/10 21:29	498862	252541	379389	2318	1741	1796
2010	1/21/10 1:10	533121	302536	499738	384	327	226
2010	2/4/10 15:11	167552	74369	69853	860	121	269
2010	2/6/10 0:53	285582	217962	185094	3725	2262	1893
2010	2/23/10 9:32	215979	229703	137110	1073	538	693
2010	2/26/10 12:57	52475		15280	106	0	24
2010	3/2/10 2:42	35910	7313	12345	132	10	28
2010	3/3/10 4:07	93875	56695	57276	613	153	459
2010	3/12/10 11:38	43503			84	0	0
2010	4/20/10 1:44	42266		28426	55	0	44
2011	10/23/10 21:00	137286	20164	77389	519	84	532
2011	11/7/10 9:00	19152	7002	28588	18	1	50
2011	11/20/10 19:00	37620	2254	41000	14		13
2011	12/17/10 16:00	108842	92441	216990	395	301	962
2011	12/18/10 15:00	448956	276095	603644	5305	11934	38643
2011	12/21/10 21:00	157658	88783	132653	211	109	128
2011	12/28/10 20:00	341816	291305	326164	27488	27053	23565
2011	1/2/11 10:00	92606	31885	140983		27	199
2011	3/2/11 6:00	24325	26240	64811	56		178
2011	3/19/11 18:00	223996	107381	286531	5550	1149	1971
2011	3/23/11 2:00	260413	101905	214506	1169	76	387
2011	3/24/11 10:00	947275	356591	408236	22291	651	12935
2011	3/26/11 6:00	446422	114250	274928	3832	643	6486
2011	6/4/11 2:00	90659	36911	214085		76	1555

Streamflow

WaterYear	EventStartDate	NF Event Stormflow (ft3)	SF Event Stormflow (ft3)	UNF Event Stormflow (ft3)	NF Event load (kg)	SF Event load (kg)	UNF Event load (kg)
2012	10/3/11 16:00	25704	4586	31781	29	1	30
2012	10/5/11 1:00	28721	133553	80579	304	458	1242
2012	11/19/11 23:00	13766	56790	30550	11		16
2012	1/20/12 16:00	59432	47423	210931	576	177	2358
2012	1/23/12 1:00	58032	49889	155603	55		113
2012	3/13/12 11:00	146426	12276	112835	82		98
2012	3/14/12 6:00	2244031	3063600	3500042	51769	44902	70524
2012	3/16/12 6:00	968512	478408	936418	35985	22631	21015
2013	11/17/12 1:00	36454	10145	47336	22	2	18
2013	11/30/12 4:00	734771	97567	488156	3193	183	4429
2013	12/1/12 21:00	497707	106351	441043		978	6089
2013	12/22/12 9:00	11797	3773	18871	8		
2013	12/23/12 7:00	285746	288482	635562	9699	26233	18813