Post-Fire Near-Surface Runoff From Small-Scale Rainfall Simulations, Santa Cruz Mountains

Author:
Michael Founds
Senior Project Advisor:
Dr. Brent Hallock

Natural Resources Management and Environmental Sciences Department
California Polytechnic State University
San Luis Obispo CA
2011

APPROVAL PAGE

Title: Post-Fire Near-Surface Runoff From Small-Scale Rainfall Simulations, Santa Cruz Mountains

Author: Michael Founds

Date Submitted: 10/31/2011

Dr. Brent Hallock____ ____________________________
Senior Project Advisor **Signature**

Dr. Douglas Pirrto____ ____________________________
Department Chair **Signature**

ABSTRACT

The influence of environmental variables on the runoff response to a fire is poorly understood. Small-scale rainfall simulation was used to study the factors impacting near-surface runoff following the Lockheed Fire, which occurred on August 12, 2009. A variable speed rainfall simulator was used to rain on 15 different test plots at an average rate of $50mmh^{-1}$. Variables of burn severity, time following the fire, soil parent material, vegetation type, and presence of a duff layer were all analyzed using the ratio of runoff to rainfall. The difference in-between burned sites and similar control sites were 19±6%. Only sites with a high burn severity had a significantly different runoff than the control sites (p=.027). The sites burned at high severity had runoff to rainfall ratios that decreased an average of 39% between the original simulation three months after the fire and the second simulation ten months later. The knobcone pine and manzanita vegetation grouping, which also corresponded to a mudstone soil parent material, produced both the highest average runoff to rainfall ratios (52%) and had the highest variability after a fire. A confidence interval showed anywhere between -12% and 63% increase in runoff to rainfall ratio of the knobcone pine and manzanita vegetation grouping after a fire compared to 2% to 27% for redwood and Douglas fir dominated vegetation. Very high runoff rates following a fire were correlated to near surface water movement almost exclusively along the top 2 cm of mineral soil. The trends observed within this data should help to support and guide further research on post-fire runoff.

ACKNOWLEGEMENTS

I would like to thank Dr. Brian Dietterick for initiating this study and providing it with funding and resources through Swanton Pacific Ranch. I would also like to thank him for help and advice reviewing my paper. The funding for the project was provided through the study, Post-Fire Change Detection of Selected Water Quality and Watershed Characteristics following the 2009 Lockheed Fire, and was funded through the California Agricultural Research Initiative.

Cal Poly graduate students Drew Perkins and Drew Loganbill were responsible for collecting most of the data and they have been extremely helpful in answering the many questions that I had, and reviewing my paper. Drew Perkins also set up the excel analysis tool to make the calculations possible. Dr. Hallock was also very accommodating in agreeing to be my senior project advisor and giving me the flexibility and guidance to carry out this project.

I should also thank my parents for always supporting me through school. They have always supported my choices and for that I am very grateful.

TABLE OF CONTENTS

FIGURES

TABLES

APPENDICES

SUPPORT PHOTOS

INTRODUCTION

Wildfires frequently occur in California causing drastic changes in the landscape and significant economic costs. Over the last decade, the amount of money spent on post-fire rehabilitation has increased due to the threats of debris flows and floods in proximity to human population (Robichaud PR et al., 2000). Suppression efforts on the Lockheed fire cost the state 30 million dollars (Cal Fire, Lockheed Fire Post Fire Risk Assessment. accessed January 4, 2010. http//www.Santacruzcountyfire.com). High severity wildfires are especially dangerous because of their ability to impact runoff and cause erosion. Changes in soil productivity, watershed response, downstream sedimentation, and threats to human life can also be effects of high severity fires (Robichaud PR et al., 2000). Following the Lockheed fire, there was concern of hyperconcentrated floods, debris torrents, and debris flows due to an increase in runoff (Cal Fire, Lockheed Fire Post Fire Risk Assessment. accessed December 11, 2010. http//www.Santacruzcountyfire.com). These recommendations were made by Cal Fire and assorted experts; despite this, the actual response of the watershed to a fire was not well understood. After the first rain year following the Lockheed Fire, which included a number of significant storms, there was a surprising lack of large debris flows and flooding. This showed a need for a better understanding of how fire impacts runoff in this environment. Although a great amount of research is carried out on the effect of fire on vegetation and soil, nothing has been published that focuses on specific soils and vegetation groups in the Santa Cruz Mountains. Furthermore, not very much research has been completed on the impact of fire on coastal redwood forests in California.

It is essential that the effects of wildfires are known in order to design effective post-fire rehabilitation treatments (Benavides-Solorio J et al., 2001). The severity of a fire is often used for hydrologic modeling to develop a "runoff response" map following a fire (Parsons A, 2003). Despite this, there is not a great deal of consensus between studies on the degree that each variable plays into the response of a watershed to fire. Some of the key factors influencing post-fire runoff are percent cover, hydrophobicity, soil sealing, and amount of ash. Forested areas such as the sites where the simulations were conducted normally have high infiltration rates, lack of overland flow, and low erosion rates (DeBano LF, 1981). All of the simulations were carried out in forested areas that, prior to the burn, would have been protected by a duff layer. The loss of the protective litter layer and soil sealing has been found to cause the change from subsurface to overland flow (DeBano LF, 2000). An experiment in the Colorado Front Range attributed 81% of the variability in sediment yields to percent ground cover (Benavides-Solorio J et al., 2001). Surface cover has also been shown to inhibit soil sealing (Larsen IJ et al., 2009). Soil sealing is where a dense (.1-1mm) soil layer is developed at the mineral soil surface that has a hydrologic conductivity substantially lower than underlying soil (Larsen IJ et al., 2009). A study by Larsen and MacDonald found that ash can sometimes prevent soil sealing thus reducing post fire runoff and sediment yields (Larsen IJ, et al., 2009). Water repellency or hydrophobicity can naturally occur in a soil due to partial decomposition of certain plant types being mixed in with the mineral soil; this water repellent layer can be strengthened by a fire (DeBano LF, 1981).

The variables of slope and geology, which remain relatively constant over longer time scales also impact runoff (Swanson FJ et al., 1998). The higher the slope, the less critical shear stress is needed to initiate movement of sediment. However, in burned slopes the shear stress was found to be independent of soil type (Moody JA et al., 2005). Other variables influencing runoff intensity of each rain storm, the duration of rain storms, the shear stress associated with runoff, actual contributing area of runoff causing erosion, and sediment availability (Swanson FJ et al., 1998).

The overall goal of this study was to examine how burn severity, soil type, dominant vegetation, time after the fire, and presence of a duff layer influence the runoff response to a fire in the previously unstudied Santa Cruz Mountains. Measurements of runoff onto a $1m^2$ plot were measured to demonstrate what variables are the most important in determining the amount of near surface runoff. Increases in soil water repellency and near surface runoff were expected following the wildfire. Information gained from this study will demonstrate how fire interacts with soil to change the runoff response to a rainstorm in this environment.

METHODS

Study Sites:

The rainfall simulations were performed at Swanton Pacific Ranch and Lockheed Martin property. Both properties lie in the Scotts Creek watershed in Santa Cruz, California (Figure 1). One site lies within the Gazo's Creek Watershed which is very similar to Scotts Creek Watershed. The Lockheed Fire started on August 12, 2009. A total of 7,819 acres were burned before the fire was contained on August 23, 2009 (Cal Fire, Lockheed Fire Post Fire Risk Assessment. accessed December 13, 2010. http//www.Santacruzcountyfire.com). The majority of the fire occurred in the Scotts Creek watershed. The mean annual temperature of Santa Cruz County is 12°C to 14°C and the annual precipitation ranges between 70-165 centimeters per year. The Scotts Creek watershed is composed of 70% coniferous trees and 23% shrubs. The dominant types of vegetation represented are redwood (Sequoia sempervirens) and Douglas-fir (*Pseudotsuga menzieii*), knobcone pine (*Pinus attenuata*), manzanita (*Arctostaphylos*), and tan oak (*Lithocarpus densiflora)* (NOAA, Scotts Creek Watershed. Accessed December 12,2010. http//www.swr.noaa.gov). Redwood and Douglas fir represented 35% and 25% of the Lockheed fire respectively. 86% of the very high severity fire occurred within the chaparral which is dominated by Knobcone pine and Manzanita (Cal Fire, Lockheed Fire Post Fire Risk Assessment. accessed December 13, 2010. http//www.Santacruzcountyfire.com). The geology of this area consists of three main rock types. The basement rock is composed of the Paleozoic to Mesozoic quartz diorite and Schist (Clark JC, 1981). This is overlain by a thin layer of Santa Margarita Sandstone. The Tertiary Santa Cruz Mudstone, a medium to thick bedded laminated silicious mudstone, overlays the Santa Margarita Sandstone (Clark JC, 1981). Soil types include the Ben Lomend Catalli-Sur Complex, Santa Luica Shaly Clay loam, and the Maymen Rock Complex (Bowman RH et al., 1980). 90% of the soil found in the burn severity were mapped as having a moderate infiltration rate (.6-2.0 in/hr) or moderately rapid to rapid infiltration rate (2.0-6.0 in/hr) (Cal Fire, Lockheed Fire Post Fire Risk Assessment. accessed December 11, 2010. http//www.Santacruzcountyfire.com).

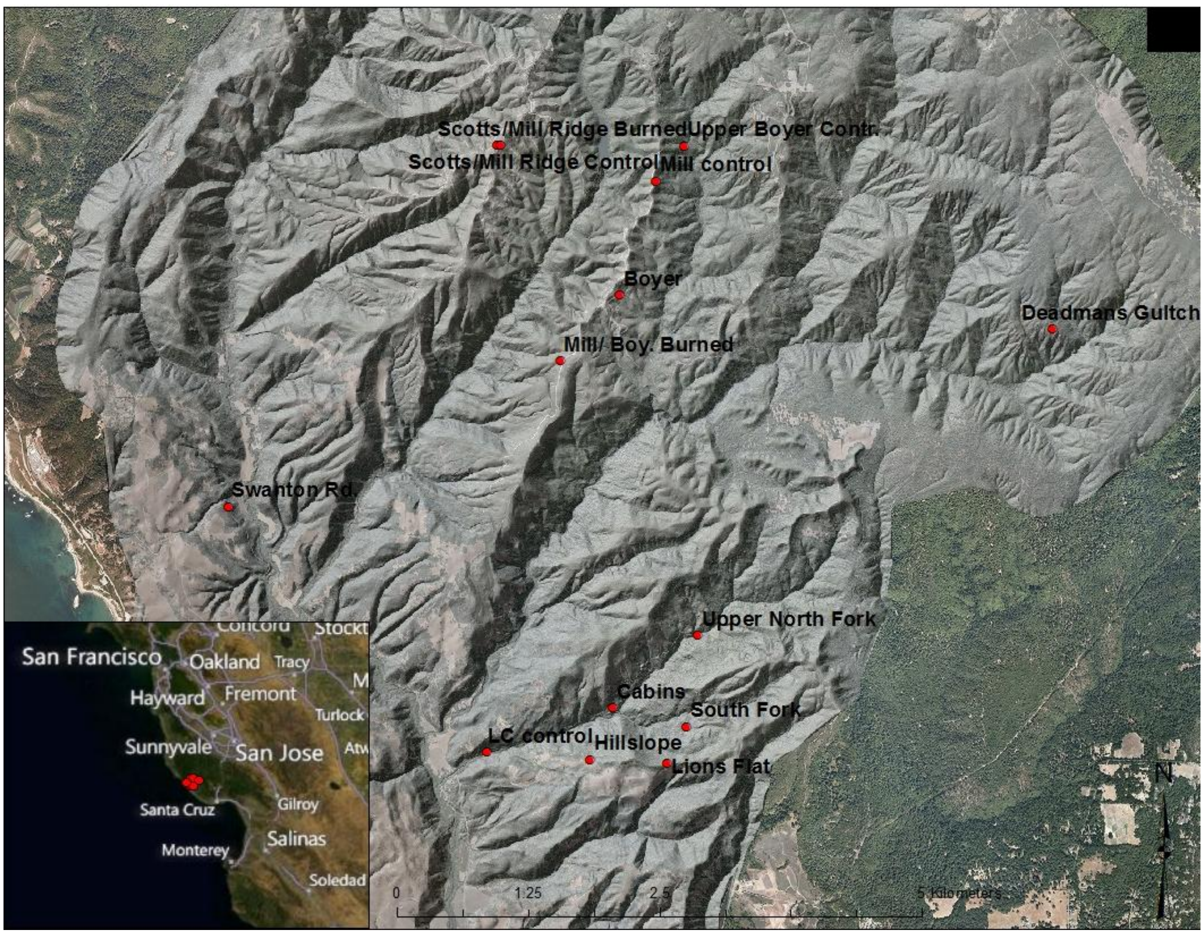


Figure 1: Location of rainfall simulation sites

Experimental Design:

There are fifteen rainfall simulator sites studied in this report representing varying soil parent material, percent slope, dominant vegetation, and burn severity. (Table 1)

Table 1: Soil Parent Material, Slope, Dominant Vegetation, and Burn Severity

Site number	Site Name	Case	Soil Parent Material	% Slope	Dominant veg.	Burn Severity
1	Deadman's Gultch Ridge	9/20/2010	Granitic	35	Oak/Madr./Manz.	None
2	Swanton Rd.	9/29/2010	MS	56	RW/DF	None
3	Gazo's Creek Watershed	10/13/2010	SS	45	Oak/Madr./Manz.	None
4	L.C Control	10/28/2009	MS	70	RW/DF	None
4	L.C Control	9/8/2010	MS	88	RW/DF	None
5	Cabins	10/29/2009	MS/SS	61	RW/DF	Moderate
5	Cabins	9/15/2010	MS/SS	65	RW/DF	Moderate
6	Upper North Fork	10/30/2009	Granitic	50	RW/TO	Low
6	Upper North Fork	2/9/2010	Granitic	47	RW/TO	Low
7	South Fork	11/2/2009	MS	54	RW/TO	Moderate
7	South Fork	9/7/2010	MS	48	RW/TO	Moderate
8	Boyer	11/4/2009	MS	60	KP/Manz.	High
8	Boyer	9/10/2010	MS	47	KP/Manz.	High
9	Mill Control	11/4/2009	MS/SS	55	KP/Manz.	None
9	Mill Control	9/10/2010	MS/SS	60	KP/Manz.	None
10	Scotts/Mill Ridge Burned	11/18/2009	MS	40	KP/Manz.	High
10	Scotts/Mill Ridge Burned	9/13/2010	MS	45	KP/Manz.	High
11	Scotts/Mill Ridge Control	11/19/2009	MS	30	KP/Manz.	None
11	Scotts/Mill Ridge Control	9/13/2010	MS	40	KP/Manz.	None
12	Upper Boyer Contr.	9/14/2010	Granitic	38	Oak/Madr./Manz.	None
13	Lions Flat	9/15/2010	MS	65	RW/TO	High
14	Hillslope Erosion Study	9/8/2010	MS	72	RW/DF	Moderate
15	Mill/ Boy. Burned	9/14/2010	MS	38	KP/Manz.	High

At each site the variables or percent slope, aspect, percent cover, and soil texture were measured. Percent slope was measured with a clinometer. Aspect was measured using a compass oriented in the downslope direction. Percent cover was judged by looking only inside of the 1m^2 plots. In some of the 2009 simulations percent cover had to be estimated based on photographic records. The surface cover was broken up into four categories: leaf litter, live vegetation, bare soil, and rock cover. (Table 2) Some of the 2009 sites do not have all of this information. Leaf litter was interpreted as any dead organic matter covering the site including leaves, sticks and pinecones. The soil was textured in the field to compare the relative percentages of sand, silt, and clay.

Table 2: Surface cover of rainfall Simulation sites

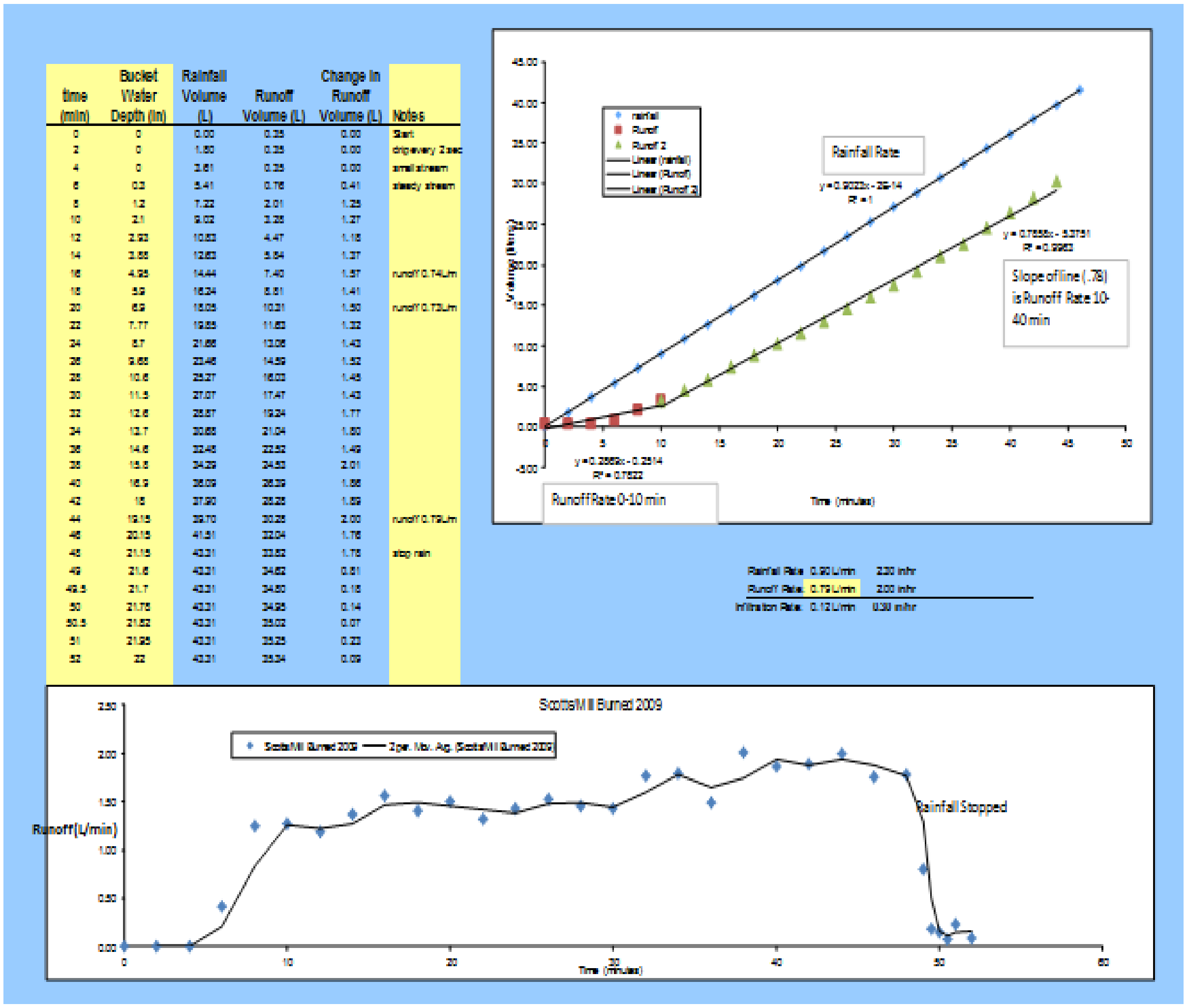
Site number	Site Name	Months After Fire	% Rock Cover	% Leaf Litter	% Live Veg.	%bare soil	Presence of Duff Layer >5cm
1	Deadman's Gultch Ridge	13	0	97	3	0	N
2	Swanton Rd.	13	0	95	5	0	Y
3	Gazo's Creek Watershed	13	0	100	0	0	Y
4	L.C Control	2	0	75	25	0	Y
4	L.C Control	13	0	55	45	0	Y
5	Cabins	2	10	50			N
5	Cabins	13	0	35	60	5	N
6	Upper North Fork	2	0	65	0	35	N
6	Upper North Fork	13	0	95	3	2	N
7	South Fork	3					N
7	South Fork	13	0	93	5	2	N
8	Boyer	3					N
8	Boyer	13	95	0	0	5	N
9	Mill Control	3	10	82	3	5	Y
9	Mill Control	13	3	95	2	0	Y
10	Scotts/Mill Ridge Burned	3					N
10	Scotts/Mill Ridge Burned	13	59	10	30	4	N
11	Scotts/Mill Ridge Control	3					N
11	Scotts/Mill Ridge Control	13	0	100	0	0	N
12	Upper Boyer Contr.	13	0	100	0	0	N
13	Lions Flat	13	3	87	10	0	N
14	Hillslope Erosion Study	13	0	15	65	20	N
15	Mill/ Boy. Burned	13	75	10	5	10	N

The parent material of the soil, dominant vegetation, and burn severity were all recorded at the site. Soil parent material was categorized a MS (mudstone), MS/SS (mudstone and sandstone colluvium), Granitic, and SS (sandstone). The vegetation was classified into four main groups in order to represent the different areas covered in the study. These are RW/DF (Redwood and Douglas fir), RW/TO (Redwood and Tan oak), KP/Manz. (Knobcone pine and manzanita), and Oak/Madr./Manz. (oak, madrone, and manzanita: a mix of chaparral and woodland plants). The RW/DF grouping is found in the lowest parts of the watershed often very near the creeks. The RW/TO is found above this area as the dominant vegetation shifts from Redwood to chaparral communities. The Knobcone pine and Manzanita cover the uppermost ridges of the watershed. The burn severity was grouped into four groups (High, Moderate, Low, and None). (Appendix 1) They were judged based using criteria and definitions used by the USDA Forest Service's Burned Area Emergency Rehabilitation (BAER) teams. It is important to note the difference between burn intensity and burn severity. Intensity has to do with the amount of heat produced during the fire while severity specifically pertains to the effects on soils, vegetation, and long-term health of the ecosystem (Parsons A, 2003). The criteria used to classify the severity of the fire are outlined in Parsons A (2003), and is included as Appendix 1. 14% of the Lockheed fire burned at very high severity, 37% at high severity, 43% at moderate severity, and 6% at low severity (Cal Fire, Lockheed Fire Post Fire Risk Assessment. accessed December 13, 2010. http//www.Santacruzcountyfire.com).

A modified Perdue University rainfall simulator was used in each simulation. The simulator was made by the USDA Forest Service and has been previously used in studies looking at erosion on forest roads (Marbet E, 2003). The simulator produces rain through a nozzle that rotates back and forth over a fixed opening. Intensity can be adjusted by changing the amount of time that the nozzle spends directed toward the opening. The simulator stands on three fiberglass legs 3m above the plot. Each site was prepared by creating a $1m^2$ plot around the soil. The plot is metal and the sides and top were fitted into the soil to approximately 3cm of depth. The upslope part of the plot was protected from additional runoff entering the site by a sheet of plastic. The side of the profile facing downhill was cut down to a depth of approximately 7cm to allow primarily the capture of surface movement of water. A catchment box with a metal sheet was then attached to this profile so that all surface runoff would be captured. The top of the catchment box was protected by a wooden panel angled downslope in order to ensure that the rain only falls onto the $1m^2$ plot. (Support Photo 1) The runoff ran from a catchment box to a tube emptying into a bucket of known volume. In order to calibrate the simulator, a $1m^2$ metal catchment box was placed over the plot. (Support Photo 2) The simulator was then run until the necessary rainfall rates were achieved. Each site was calibrated to approximately a 50mm h^{-1} rainfall event. The sites were rained on about 40 minutes or until the runoff rate was very consistent. Depth measurements were taken from the bucket every 2 minutes. After the simulation, the plot was screed off to find exactly where the water had infiltrated into the soil.

Analysis:

The bucket depth and rainfall rates were entered into Microsoft Excel 2007. The bucket depth was then converted to a volume of runoff using the formula [(0.009712*(Bucket Water Depth^2)+(1.377*Bucket Water Depth)]. The rainfall rate was adjusted to the slope of the plot using the formula: [((Average of Runoff Rates measured directly)*0.12)/25.4)*(1/(COS(ATAN(%slope/100))]. For each site a graph was made of total runoff (liters) vs. time (min). The independent variable of time was on the x axis and the dependent variable of runoff was placed on the y axis. The slope of this line was consistent on almost every graph after 10 minutes. For that reason runoff rates were calculated when the as runoff was beginning between 0 and 10 minutes, and when the rate was consistent between 10 and 40 minutes. Runoff rates were found by determining the slope line created by the graph of runoff in liters compared to time (Figure 2).



time (min)	Bucket Water Depth (in)	Rainfall Volume (L)	Runoff Volume (L)	Change in Runoff Volume (L)	Notes
0	0	0.00	0.35	0.00	Start
2	0	1.80	0.35	0.00	drip every 2 sec
4	0	3.61	0.35	0.00	small stream
6	0.2	5.41	0.76	0.41	steady stream
8	1.2	7.22	2.01	1.25	
10	2.1	9.02	3.28	1.27	
12	2.93	10.83	4.47	1.18	
14	3.88	12.63	5.84	1.37	
16	4.95	14.44	7.40	1.57	runoff 0.74L/m
18	5.9	16.24	8.81	1.41	
20	6.9	18.05	10.31	1.50	runoff 0.73L/m
22	7.77	19.85	11.63	1.32	
24	8.7	21.66	13.06	1.43	
26	9.68	23.46	14.59	1.52	
28	10.6	25.27	16.03	1.45	
30	11.5	27.07	17.47	1.43	
32	12.6	28.87	19.24	1.77	
34	13.7	30.68	21.04	1.80	
36	14.6	32.48	22.52	1.49	
38	15.8	34.29	24.53	2.01	
40	16.9	36.09	26.39	1.86	
42	18	37.90	28.28	1.89	
44	19.15	39.70	30.28	2.00	runoff 0.79L/m
46	20.15	41.51	32.04	1.76	
48	21.15	43.31	33.82	1.78	stop rain
49	21.6	43.31	34.62	0.81	
49.5	21.7	43.31	34.80	0.18	
50	21.75	43.31	34.95	0.14	
50.5	21.82	43.31	35.02	0.07	
51	21.95	43.31	35.25	0.23	
52	22	43.31	35.34	0.09	

Figure 2: Example of how runoff data and graph where runoff and rainfall rates were calculated. Slopes of lines on graph are the Rainfall Rate (top), Runoff Rate 10-40 min (right), and Runoff Rate 0-10 min (left).

RESULTS

Site Characteristics:

The first rainfall simulations began on October 28, 2009 following the Lockheed Fire, which occurred in mid-August 2009. Eight simulations were completed where data was collected. During the first simulations, all the burned sites had no remaining vegetation or leaf litter. In September and October of 2010 simulations were carried out on the same sites along with six additional sites. By this point in time some of the vegetation, particularly on the sites within the redwood and Doug Fir vegetation groupings had begun to regrow. (Table 2) The process of setting up the rainfall simulator along with post-rainfall analysis disturbed the sites. Simulations from 2010 had to be moved a few meters to find a suitable area. The plots had percent slope ranging from 35 to 88 with a mean slope of 53%. Variation in slope wan not found to have any effect on runoff. (Appendix 2) The total number of simulations carried out at different severity burns were the following: two at high severity in both 2009 and 2010 with two additional sites high severity sited added in 2010, two at moderate severity in 2009 and 2010 with one additional site in 2010, one low severity site in both 2009 and 2010, and ten control sites. All high severity sites were in located in the mudstone parent material which was found at higher elevations within the watershed. All moderate and low severity dominated by the RW/DF or RW/To vegetation grouping. The high severity burns occurred in the Knobcone Pine and Manzanita vegetation type with one exception in site 13 Lions Flat.

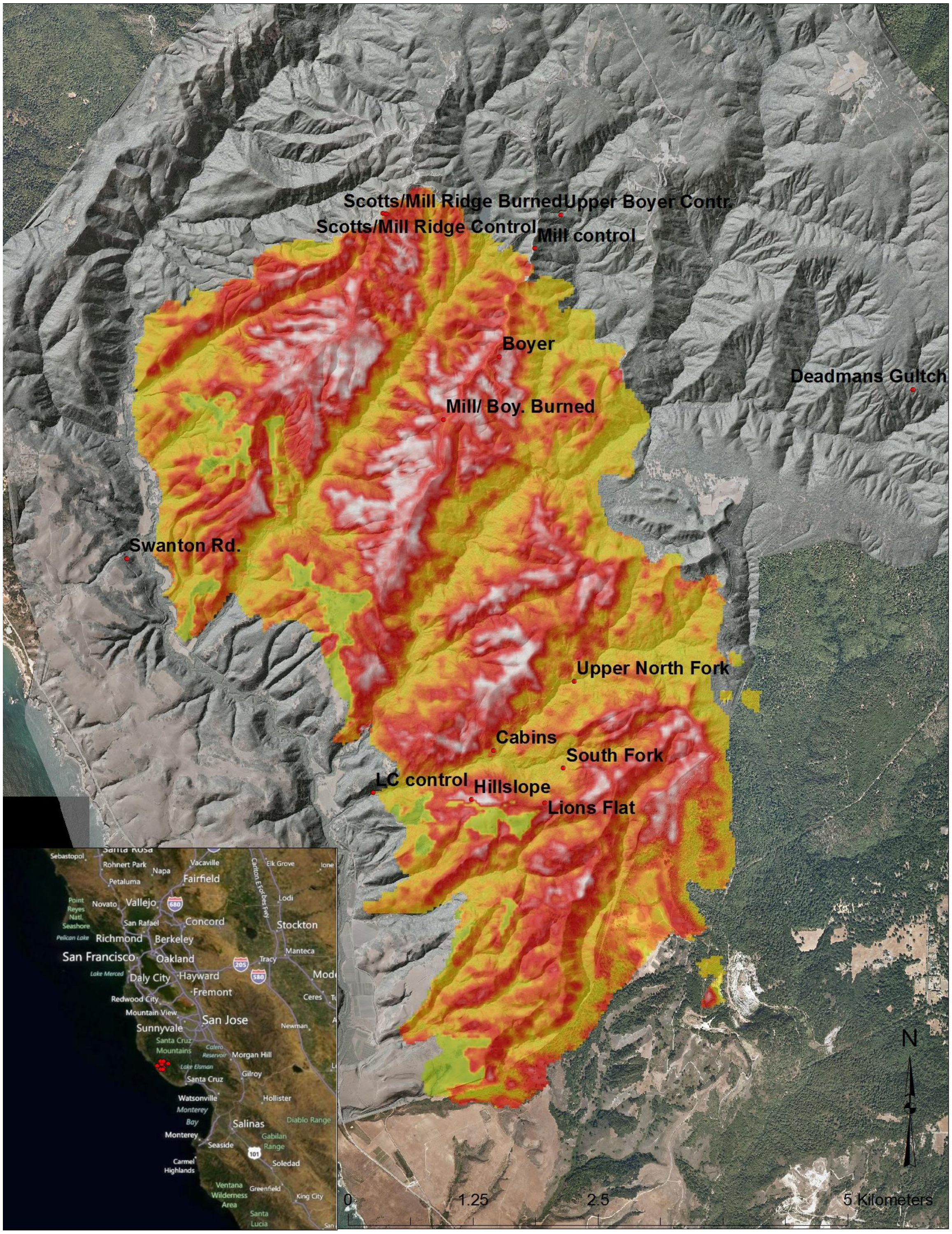


Figure 3: Map of fire by burn severity. Values range from white (very high) to green (low).

Data:

The measurement of runoff was the water that traveled through the near surface. Near surface was determined by the depth that the catchment box was placed into the soil. This was usually about 7cm. Runoff was statistically analyzed using the runoff to rainfall ratio to allow incorporation of changes in rainfall rates along with runoff rates. This approach has been used in similar studies (Benavides-Solorio, 2001). The runoff to rainfall ratios used in graphs and analysis are from 10-40 minutes after the runoff rate had stabilized. In the first ten minutes of rainfall, the runoff ratio's ranged from 0% to 57% with a mean of 12%. (Table 3) The runoff to rainfall ratios between 10 and 40 minutes ranged from 5% to 88% with a mean of 33% and a standard deviation of 22%. (Figure 4) Between 10 and 40 minutes most plots had reached consistent runoff rates shown by R^2 values above 99%. (Figure 2) The runoff-to-rainfall ratios of five variables were analyzed to determine what impact they had on near surface runoff. These are burn severity, soil parent material, vegetation, time following the fire, and presence of a duff layer.

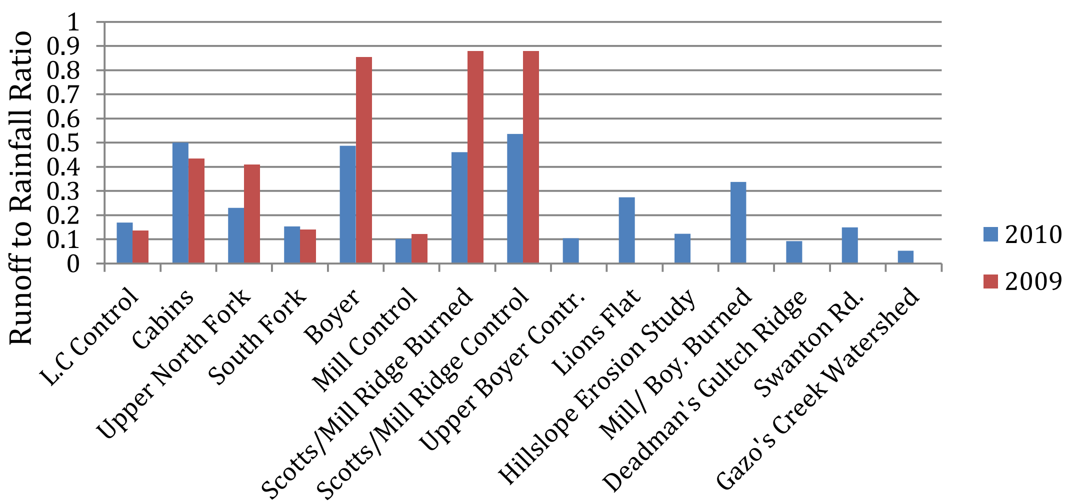


Figure 4: Runoff to Rainfall Ratio of All Sites

Table 3: Rainfall, Runoff, Infiltration, Runoff to Rainfall Ratios

Time Following Fire	Site Name	Months After Fire	Rainfall Rate (L/m)	Runoff Rate 10 40min (L/m)	Runoff Rate 0 10 (L/m)	Infiltration Rate 10 40 (L/m)	Runoff Ratio 10 40min	Runoff Ratio 0 10min
1	Deadman's Gultch Ridge	13	0.76	0.07	0.07	0.69	0.09	0.09
2	Swanton Rd.	13	0.80	0.12	0.13	0.68	0.15	0.16
3	Gazo's Creek Watershed	13	0.75	0.04	0.00	0.71	0.05	0.00
4	L.C Control	2	0.96	0.13	0.04	0.82	0.14	0.04
4	L.C Control	13	0.71	0.12	0.10	0.59	0.17	0.14
5	Cabins	2	0.74	0.32	0.00	0.42	0.43	0.00
5	Cabins	13	0.56	0.28	0.04	0.28	0.50	0.07
6	Upper North Fork	2	0.88	0.36	0.16	0.51	0.41	0.18
6	Upper North Fork	13	0.74	0.17	0.05	0.57	0.23	0.07
7	South Fork	3	0.79	0.11	0.03	0.68	0.14	0.04
7	South Fork	13	0.91	0.14	0.10	0.77	0.15	0.11
8	Boyer	3	0.88	0.75	0.37	0.14	0.85	0.42
8	Boyer	13	0.82	0.40	0.11	0.42	0.49	0.14
9	Mill Control	3	0.90	0.11	0.04	0.78	0.12	0.05
9	Mill Control	13	0.79	0.08	0.06	0.71	0.10	0.07
10	Scotts/Mill Ridge Burned	3	0.90	0.79	0.28	0.12	0.88	0.31
10	Scotts/Mill Ridge Burned	13	0.76	0.35	0.03	0.41	0.46	0.04
11	Scotts/Mill Ridge Control	3	0.90	0.79	0.51	0.11	0.88	0.57
11	Scotts/Mill Ridge Control	13	0.84	0.45	0.14	0.39	0.54	0.17
12	Upper Boyer Contr.	13	0.86	0.09	0.02	0.77	0.10	0.02
13	Lions Flat	13	0.73	0.20	0.06	0.53	0.27	0.08
14	Hillslope Erosion Study	13	0.73	0.09	0.03	0.65	0.12	0.04
15	Mill/ Boy. Burned	13	0.86	0.29	0.00	0.56	0.34	0.00

Paired Sites:

Each burned site was matched with the most similar control site. The average difference between the runoff ratio of burned sites and their similar controls was 19% ± 06%. (Table 4) The difference in runoff to rainfall ratios allowed paired t-test to be carried out. A confidence interval of 95% was established for all burned sites in the two years following the fire showing that the runoff to rainfall ratio from simulations will increase between 5% and 32%.

Table 4: Comparison of each burned site (shaded in blue) matched with a similar control site (not shaded). Sites with data for two years appear with the data from 2009 above data from 2010.

Site number	Site Name	Runoff to Rainfall Ratio 10 40	Burned Site	Control	**Difference**
10	Scotts/Mill Ridge Burned	0.88	0.88	0.88	0.00
11	Scotts/Mill Ridge Control	0.88			
10	Scotts/Mill Ridge Burned	0.46	0.46	0.54	-0.08
11	Scotts/Mill Ridge Control	0.54			
8	Boyer	0.85	0.85	0.12	0.73
9	Mill Control	0.12			
8	Boyer	0.49	0.49	0.10	0.39
9	Mill Control	0.10			
15	Mill/ Boy. Burned	0.34	0.34	0.10	0.24
9	Mill Control	0.10			
5	Cabins	0.43	0.43	0.14	0.29
4	L.C Control	0.14			
5	Cabins	0.50	0.50	0.17	0.33
4	L.C Control	0.17			
6	Upper North Fork	0.41	0.41	0.09	0.32
1	Deadman's Gultch Ridge	0.09			
6	Upper North Fork	0.23	0.23	0.09	0.14
1	Deadman's Gultch Ridge	0.09			
13	Lions Flat	0.27	0.27	0.15	0.12
2	Swanton Rd.	0.15			
14	Hillslope Erosion Study	0.12	0.12	0.15	-0.03
2	Swanton Rd.	0.15			
7	South Fork	0.14	0.14	0.14	0.00
4	L.C Control	0.14			
7	South Fork	0.15	0.15	0.17	-0.02
4	L.C Control	0.17			

Soil Parent Material:

The difference between every burned site and its paired control was found for each soil parent material. Mudstone (MS) derived parent materials had a mean difference in runoff to rainfall ratio of .15 ±.09, Mudstone and Sandstone Colluvium (MS/SS) had a difference of .26±.02, and Granitic soils had a difference of .23±.09. A 95% confidence interval showed an increase in runoff to rainfall ratio following a fire of .05 to .35 for Mudstone, .17 to .34 for Mudstone and Sandstone Colluvium, and -.16 to .62 for granitic soils.

An analysis comparing the mean runoff to rainfall ratio of soil parent materials to control sites with the same parent material showed significant trends. The difference between burned and unburned sites in the granitic parent material returned a p value of .066 which is was not statistically different from normal results. No significant difference was found between burned and unburned sites within the mudstone parent material (p=.44). For the MS/SS parent material a significant result was found (p=.004).

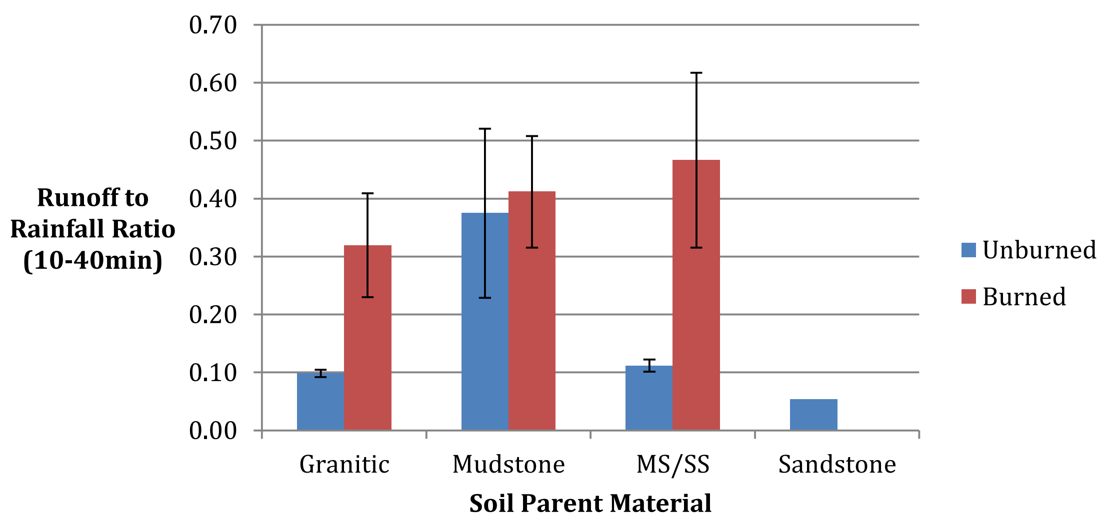


Figure 5: Mean Runoff to Rainfall Ratio of burned and control sites for each soil parent material. The black bars show the standard error.

Burn Severity:

The mean difference between the burned sites and controls were .23±.12 for high burn severity, .11±.08 for moderate burn severity, and .23±.06 for low burn severity. A 95% confidence interval was created that the runoff to rainfall would increase between .06 and .53 for high burn severity, -.09 to .32 for moderate burn severity and .47 to -.01 for low burn severity.

A comparison was done between the mean runoff to rainfall ratio of each different severity fire and the mean of the unburned controls. The only significant difference was found between the high-severity and unburned sites (p=.027). No difference was found between the low and moderate severity sites (p=.43, .31). (Figure 5) Figure 8 also shows higher runoff to rainfall ratios for sites that were burned at high severity.

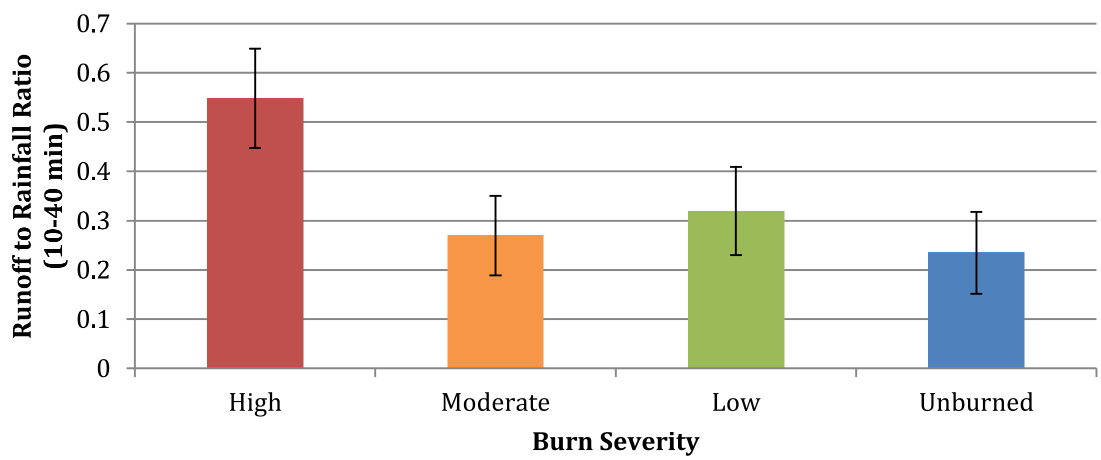


Figure 6: Comparison of burn severity and runoff to rainfall ratio

Vegetation:

The average difference between burned sites paired with their similar controls in the Knobcone Pine and Manzanita vegetation grouping was .26±.15 compared to .14±.05 in the Redwood, Douglas Fir, and Tan Oak vegetation grouping. A paired t-test established a 95% confidence interval that following a fire the runoff to rainfall ratio will increase between -.12 and .63 in the Knobcone Pine and Manzanita dominated forests as opposed to a between .02 and .27 for Redwood, Douglas Fir, and Tan Oak vegetation groupings.

The average runoff to rainfall ratios of each vegetation category were also compared to controls of the same category. (Figure 7) Of the four vegetation types, the Knobcone Pine and Manzanita had the highest average runoff rate .52 compared to .28 for Redwood and Douglas fir, .24 for Redwood and Tan oak, and .08 for Oak Madrone and Manzanita. However, they were not significantly different from the unburned control sites (p=.20). The Redwood and Douglas fir vegetation categories appeared to have much more difference between their burned and unburned runoff to rainfall ratios, but their statistical variation was not significant (p=.14).

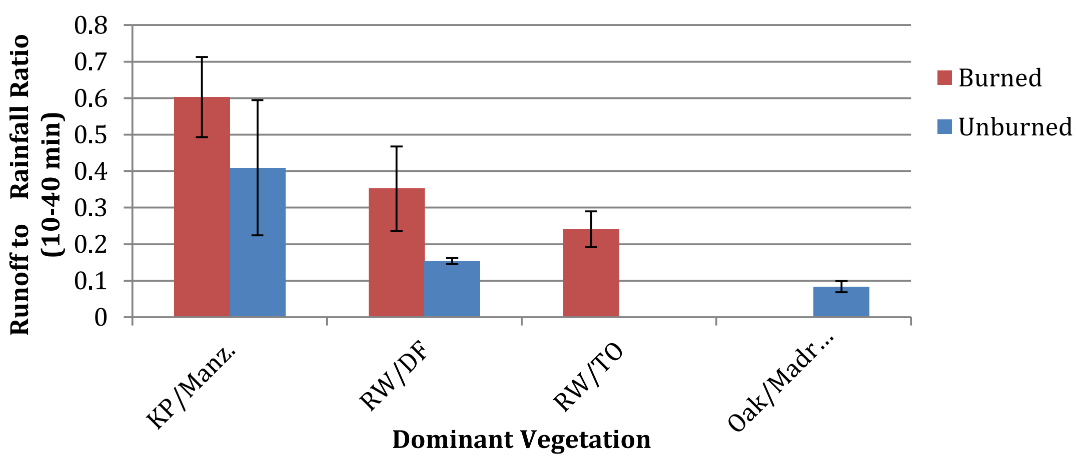


Figure 7: Comparison of mean runoff to rainfall ration of burned and control sites for each vegetation grouping.

Time:

Hydrographs were made comparing how each site's runoff rate changed over time. The runoff rate of each site is characterized by a relatively flat plateau after approximately 10 minutes. (Figure 8,9,10,11) There were differences in the rising limbs of hydrographs. The high severity burns in 2009 (Scotts/Mill ridge and Boyer) both showed a steep spike as runoff rates rose quickly. The same sites rose less drastically and to a lower level in 2010. (Figure 8) Their runoff to rainfall ratio decreased an average of .39 between the two simulations. This trend was most visible with high burn severity sights.

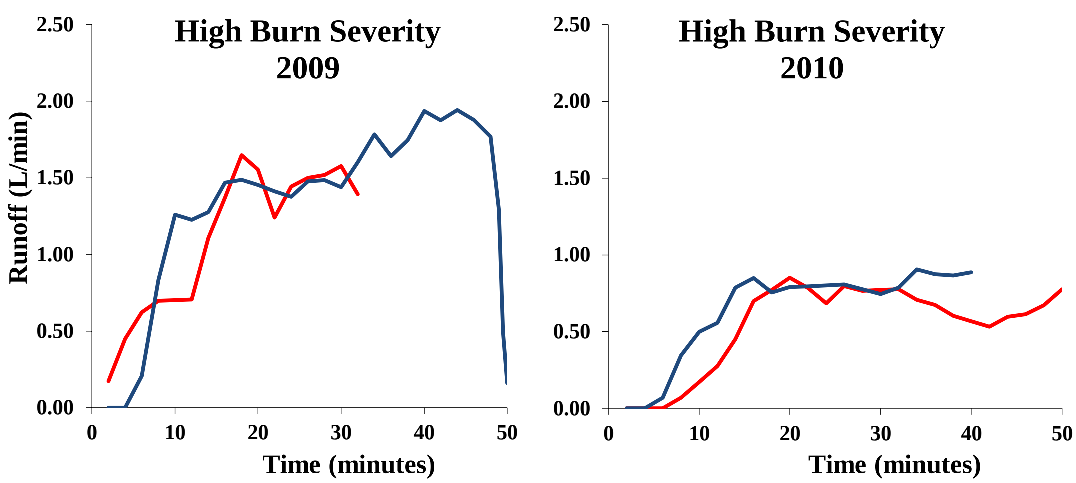


Figure 8: Rainfall simulation on High Burn Severity Plots. Boyer (red) and Scotts/Mill ridge (blue).

The moderate and low severity sites did not appear to have a large change in runoff between 2009 and 2010. This also seems to be the case for the low severity sights. The controls from 2009 had some very high runoff rates. The control sites from 2010 had much more normalized data. (Figure 11)

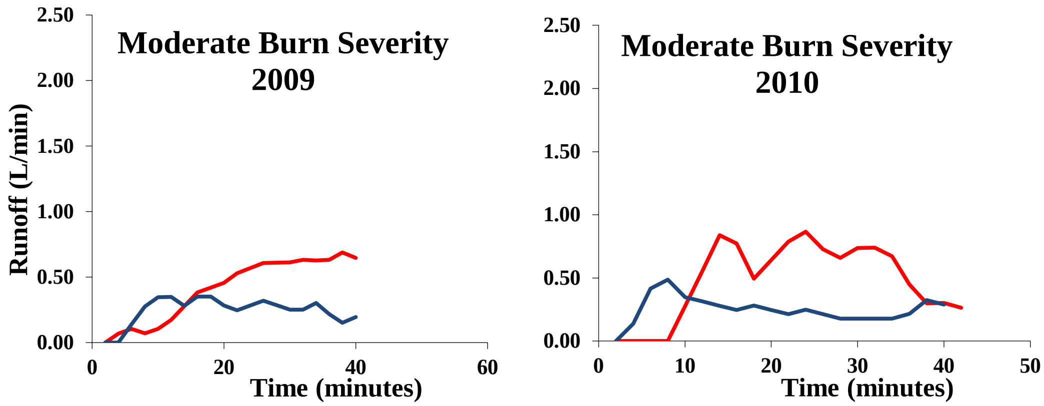


Figure 9: Rainfall simulation on Moderate Burn Severity Plots. Cabins (red) and Southfork (blue).

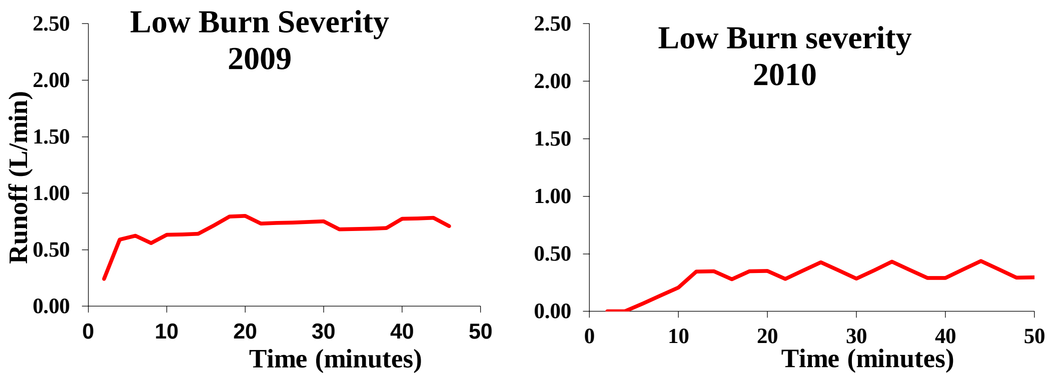


Figure 10: Rainfall simulation on Low Burn Severity Plots. Upper North Fork.

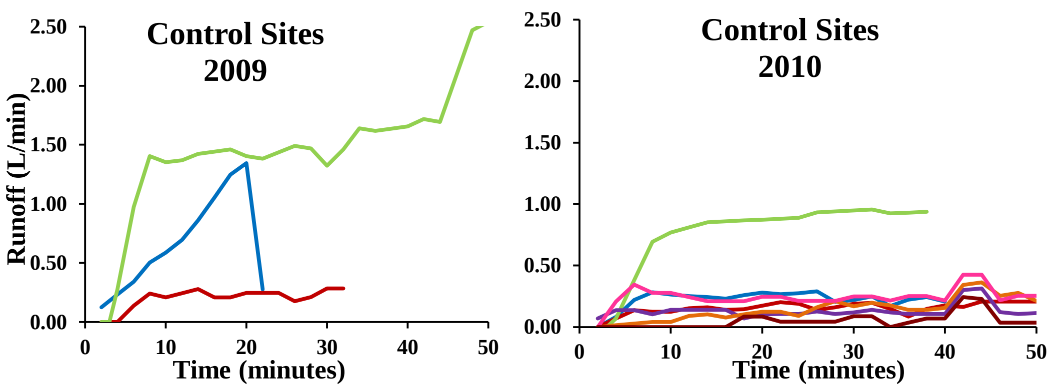


Figure 11: Rainfall Simulation on control plots. Little Creek Control (blue), Scotts/Mill Ridge Control (green), Upper Boyer Control (orange), Mill control (red), Deadmans Gultch (purple), Swanton Road (pink).

Surface Cover:

The presence of a duff layers over the soil made a large difference in the amount of runoff. Sites without a substantial duff layer had an average runoff to rainfall ratio of .25±.06 compared to .12±.015 for sites that did have a duff layer greater than 5 cm. In these sites the duff layer was able to absorb the entire amount of rainfall without wetting the mineral surface of the soil. (Figure 12) In the sites with the higher runoff ratios, water almost exclusively traveled through the top 2 cm or mineral soil. The soil below this remained almost completely dry. Water was observed near exclusively in the top two centimeters in the following sights: Boyer 2009 2010, Scotts/Mill Ridge Burned and Control 2009 and 2010, Mill/Boyer Burned 2010. (Figure 14) In some sites water stayed for the most part in the top 2 cm of soil, but was still able to infiltrate through preferential near-surface flowpaths. This was observed at the Cabins and South Fork in 2010. (Figure 13)

DISCUSSION

Site Characteristics:

The sites were chosen to represent the wide variety of vegetation and soils found throughout the watershed. In order to analyze the data, sites had to be grouped. The soil parent material groupings were easy to determine, but the vegetation and burn severity were much more challenging. It was not always clear what vegetation existed at a site before it was burned. Evidence was used to make the best estimate of what vegetation was there before the fire. The burn severity was also somewhat subjective. The map of burn severity created by Cal Fire might have overestimated the severity of the fire in some areas. There are also high amounts of variation within a small spatial scale on each site. When sites are moved even just a few meters, significant changes in soil cover and slope were noticed. The number of simulations was not large enough to adequately represent many of the variations in soils and vegetation. Further studies of this type could help to establish what type of runoff rates should be expected for each vegetation and soils grouping.

Data:

The runoff data used for the statistics in this report is the near surface runoff to rainfall ratio between 10-40 minutes of rainfall. In order to better understand what the differences in runoff to rainfall rations signifies it is important to notice the different ways that this water traveled through the soil profile. After the rainfall each of the sites was excavated to see what pathway the water had taken through the soil. In the unburned forested soils with a large duff layer runoff would absorb the majority of the rainfall only allowing minimal amounts reaching the catchment area. Some of this water could have also been infiltrating deeper into the soil profile. This resulted in a very low runoff to rainfall ratio. In many of these sites, water did not even infiltrate to the mineral surface of the soil. (Figure 12)

Figure 12: Left: Little Creek Control 2010 Right: Mill Control 2010: water does not wet mineral surface of soil despite over 40 minutes of heavy rainfall.

When there was less of a surface cover, the water would infiltrate to a depth of a few centimeters. Some of the water would infiltrate deeper through permeable channels within the soil that had higher hydrologic conductivity. (Figure 14)

Figure 13: Left: Cabins 2010 Right: Hillslope Erosion Study 2010. Water mainly stays in top centimeter, but still able to infiltrate through preferential flowpaths.

In the sites burned at high severity that had high runoff to rainfall ratios, the water stayed exclusively in the top 2 cm of soil. (Figure 15) In some parts the water did not even penetrate below .5cm of the soil profile. (Appendix 5) This could either be a result of hydrophobic layers, soil sealing, or both. Once this thin layer is saturated, the water would quickly reach the catchment area giving these sites the highest initial runoff rates between 0-10 minutes.

Figure 14: Boyer 2010 water remains exclusively in top 1-2cm of soil. Soil below remains completely dry.

The runoff to rainfall ratios had a greater range than noted in other studies. A study in the Colorado Front range found runoff to rainfall ratios ranging between 28% and 79% with an average of 55%. (Benavides-Solorio, 2001) This study found runoff to rainfall ratios ranging from 5% to 88% with an average of 33%. The variability of the data in this study is likely due amount of variation in vegetation and soils over small spatial scales in the Scotts Creek Watershed.

The simulations were based on a rain event of about 50 mmh-1 for 40 minutes. This is a more intense rainfall event than was seen the entire winter following the fire. However, in a large storm, the total amount of rainfall in greater. The soils are likely to already be very wet, and water transport through the near surface is coming from upslope. A storm that rains over a few days is more likely to completely saturate the soil potentially causing overland flow. Despite this, all our simulations had very constant runoff rates between 10-40 minutes which would suggest that the soil profile was at some type of equilibrium of infiltration and runoff. Another important variable that was not studied in this project was the antecedent soil moisture. All soils have a certain amount of moisture in them that varies over seasons and throughout the day. It is difficult to determine the degree that the soil moisture prior to the simulation played in the runoff response.

Paired Sites:

The paired sites comparisons are based on the assumption that the two sites were similar enough regarding soil type and vegetation. The only difference should be that one site is burned. The closest approximations of what the burned site would have been most similar to were made, but it possible that sites were not actually that similar regarding their runoff rates. With the small amount of data, the paired t-test is generally one of the best ways to find significant results.

The paired t-test also uses the assumption that the data is normalized. In order for the data to have what is considered a normal distribution, generally 63% of the data must fall within one standard deviation and 95% must fall within two standard deviations. 88% of the data fell within one standard deviation. However, there were three outliers that had very high runoff to rainfall ratios which fell outside to two standard deviations.

Despite its uncertainties, the t-test was a valuable way to determine a level of confidence that a certain change in runoff would occur.

Soil parent material:

It can be very difficult to separate soil parent material from burn severity and vegetation. The structure of the watershed places the mudstone above the sandstone which lies on top of the granite stratigraphic layers. The higher ridges were burned at the highest severity which was always in a mudstone derived soil usually within the Knobcone Pine and Manzanita vegetation grouping. The areas of granitic soil parent material mainly burned at low severity. A separate watershed without these geologic and vegetation relationship would have to be tested in order to see if the type of soil parent material was playing a roll impacting runoff. In many of the control sites, the mineral layer of the soil was not even wetted due to a large duff layer. Therefore the vegetation would play the most important role in determining the runoff response to the fire. This would make it impossible for the soil to be directly impacting near surface water movement. On the other hand, some of the sites burned along the ridge exposed a great deal of the mudstone parent material. The simulations rained directly on the mudstone fragments which do not absorb water and likely played a big part in increasing runoff. It is likely that the highly fractured mudstone geologic structure would play a very significant role in impacting the amount of runoff.

The paired t-test confidence intervals can be misleading. Some of the results were significant due to their similarities even though there were very few sites. There was only one burned site in both the MS/SS and granitic soil. Despite the small sample size the MS/SS soil group was found to be significantly different than controls of the same soil type. The Cabins site responsible for this result did seem to have different infiltration pathways than mudstone sites of similar burn severities. (Figure 15) Further studies would need to be carried out to understand if the Ms/SS vegetation grouping was actually influencing near surface runoff and infiltration.

Burn Severity:

Only the soils burned at high severity were found to be statistically different than control sites. The runoff to rainfall ratio of moderate and low severity sites was surprisingly not very different than controls. All of the moderate and low severity sites were within the RW/DF or RW/TO vegetation category. This might suggest that low and moderate severity fires within a redwood forest area do not have a very large impact on near surface runoff following a rain event similar to the one mimicked by our study. The lack of data on burned sites makes it difficult to say this with any large degree of confidence.

Vegetation:

The KP/Manz. vegetation category had the highest runoff average runoff rates and increased by the largest amount compared to similar sites (.26±.15). This vegetation category is found on the higher ridges of the watershed which are always within the mudstone parent material. These sites were extremely variable in runoff to rainfall ratio with a 95% confidence interval of increasing runoff between -.12 and .63. Even the control sites had very different runoff rates in 2009 than they did in 2010. On the other hand, sites within the RW/DF and RW/TO had a 95% confidence interval that an increase between .02 and .27 would occur. These two vegetation types were extremely different from one another both burned and unburned. (Support photo 4, 5) An explanation for the extreme variability in the KP/Manz. is soil hydrophobicity. The Scotts/Mill control site had high levels of hydrophobicity in 2009. The same control site had a lower runoff rate in 2010 when no hydrophobicity was noted. Soil sealing could also be responsible for this result. However, to order to determine that were the case, a thin section would need to be taken of the soil. Further studies will need to be carried out to determine which of these two variables was playing the largest part in the observed results.

Time

The runoff to rainfall ratios in the sites burned at high severity decreased an average of 39% from 2009 to 2010. Low and moderate burn severity sites showed no major changes. If the soil was indeed impacted by soil sealing and hydrophobicity after the fire, this could mean that the soil is recovering. Many of the sites already had returned to high percentages of leaf litter and live vegetation by the second round of simulations in 2010. (Table 2) However, many sites burned at high severity in the Kp/Manz. Vegetation community still had bare soil with large mudstone rock fragments exposed. The runoff to rainfall ratio still decreased in the year following the fire with very limited new plant life and surface cover. It is very plausible that these soils could have lost its seal or hydrophobicity after the rainy season. Some of the controls also changed following between 2009 and 2010. A potential explanation of this trend in data is that the original simulations were carried out in November as opposed to September. Slight changes in leaf litter or vegetation could easily account for these differences.

Surface Cover

The surface cover of a soil has been shown to be one of the most important factors influencing surface runoff. After raining on many of the sites with a substantial duff layer, the mineral surface of the soil was completely dry. The duff layer both slows and absorbs the rainfall. The opposite is true for sites with a very exposed soil. The sites with the highest runoff rates had their surface litter burned away. The exposed rock and soil in these sites primarily only allowed for percolation into the top 2cm. It is not clear what exactly is causing this phenomenon, but it is correlated with combination of the mudstone soils, Kp/Manz. vegetation, and high burn severity. Runoff rates were much higher in these sites, but the soil may still have protection from extreme erosion. Large mudstone fragments are found covering a great amount of the burned soils. These fragments may be protecting the watershed from extreme amounts of erosion.

CONCLUSION

Near-surface runoff following a wildfire is an extremely complicated process. This is demonstrated by both the amount of variables that may influence near-surface runoff, and the variability within the rainfall simulation data. On the watershed scale, comparison between similar sites in the 13 months following a fire we can be at least 95% confident that the runoff to rainfall ratio will increase somewhere between 5% and 32%. Only sites burned at high severity were found to be significantly different than control sites (p=.027). In all but one site, high burn severity was located in the Knobcone pine and Manzanita vegetation grouping on a rocky soil derived from mudstone. This combination of soil and vegetation grouping had the highest average runoff to rainfall ratios (.52) and were very hard to predict. A 95% confidence interval showed a post-fire increase in runoff to rainfall ratio of anywhere between -12% and 63%, compared to 2% to 27% for sites in with Redwood and Douglas fir as the dominant vegetation. The extremely high runoff rates were often associated with a change of near surface water movement to the top 2cm of soil. This phenomenon of a transition from deeper infiltration to movement of water only in the very near surface of the soil is possibly a result of hydrophobicity or soil sealing. There have been very few studies on forest soils in similar environments to Scotts Creek Watershed. This study's findings will help guide further research into more specific questions regarding near surface runoff in this environment.

REFERENCES

Benavides-Solorio J, MacDonald LH. (2001). Post-fire runoff and erosion from simulated rainfall on small plots. Hydrol. Processes 15, 2931-2952

Bowman RH, Estrads DC. (1980). Soil Survey of Santa cruz County, California, U.S. Department of Agriculture, Soil Conservation Service, retrieved from http://www.ca.nrcs.usda.gov/mlra02/stcruz/index.html, 150 p., 10 plates, map scale 1:24,000

Clark JC. (1981). Stratigraphy, Paleontology and Geology of the Central Santa Cruz Mountains, California coast Ranges: U.S. Geological Survey, Professional Paper 1168, 51 pages, map scale 1:24,000

DeBano LF. (1981). Water repellent soils: a state-of-the-art. Gen. Tech. Rep. PSW-46, Pacific Southwest Forest and Range Experiment Station, Forest Service, US Dept. Agriculture, Berkeley, CA 21.

DeBano LF. (2000). The role of fire and soil heating on water repellency in wildland environments: a review. Joural of Hydrology 231-232: 195-206.

Larsen IJ, MacDonald LH, Brown E, Rough D, Welsh MJ, Pietraszek JH, Libohova Z, Benavides-Solorio J, Schaffrath K. (2009). Causes of Post-Fire Runoff and Erosion: Water Repellency, Cover, or Soil Sealing? Soil Sci. Soc. Am. J. 73:1393-1407

Marbet E. (2003). Hydrology of Five Forest Roads in Oregon Coast Range. Oregon State University http://hdl.handle.net/1957/9569

Moody JA., Smith JD, Ragan BW. (2005). Critical shear stress for erosion of cohesive soils subjected to temperatures typical of wildfires, J. Geophys. Res., 110, F01004, doi:10.1029/2004JF000141.

Moody JA, Martin DA. (2009). Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. International Journal of Wildland Fire 18, 96–115.

Parsons. (2003). Burned area emergency rehabilitation (BAER) soil burn-severity definitions and mapping guidelines. RSAC-2003-RPT1, US Department of Agriculture Forest Service, Remote Sensing Applications Center, Salt Lake City, Utah (2003), 9 pp.

Robichaud PR, Beyers JL, Neary DG. (2000). Evaluating the effectiveness of postfire rehabilitation treatments. Gen. Tech, Rep. RMTS-GTR-63. U.S. For. Serv., Rocky Mountain Res. Stn., Fort Collins, CO

Scotts Creek Watershed. (2008) National Oceanic and Atmospheric Administration http://www.swr.noaa.gov/sr/Watershed%20Characterizations/Scott_Watershed_Stats_and_Maps.pdf

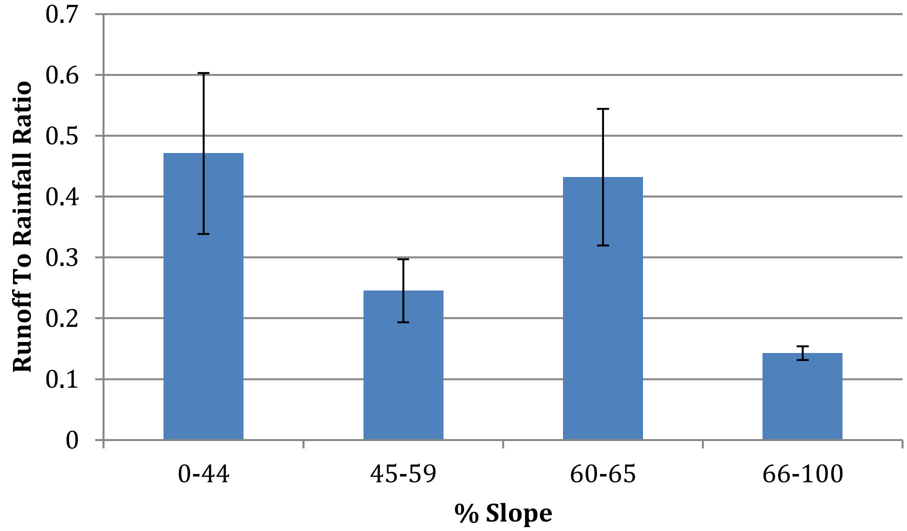
Swanson FJ, Johnson SL, Gregory SV , Acker SA (1998). Flood disturbance in a forested mountain watershed. Bioscience 48(9), 681–689.

APPENDICES

Soil Burn Severity Definitions and Mapping Guidelines April 22, 2003 **Table 1. BAER Soil Burn Severity Class Indicators.**

Soil Burn Severity Class	**Substrate - litter/duff**	**Vegetation - understory/shrubs/herbs**	***ANCILLARY FACTORS ONLY!*** *Highly variable and **NOT** key to determining soil burn severity; Very General Guide ONLY:* **Overstory – conifer/hardwoods**
Unburned	not burned	not burned	no fire-caused mortality; overview of canopy appears unchanged
Low	mineral soil unchanged; litter charred or partially consumed; upper duff layer charred; wood/leaf/needle structures charred but recognizable	foliage and smaller twigs (less than ¼ inch) scorched or partially consumed; grasses mostly consumed, black or gray ash; shrub stems intact, canopy scorched.	slight tree mortality possible but generally less than about 10%; overview of canopy may show individuals or small pockets of mortality (brown needles or black sticks)
Moderate	moderate soil heating, moderate ground char; soil structure intact; litter mostly charred but not ashed, however some areas of litter consumption may be found, leaving shallow ash; duff and wood partly consumed; wood/leaf structures may be recognizeable; burned roots and rhizomes usually still present; reduced permeability may be present over some of the area.	foliage, twigs and small stems (¼ to ¾ inch) consumed; shrub stems charred, root crowns intact, shrub canopy consumed.	tree mortality may be mixed and range widely; seedlings are usually consumed, large trees often killed but retain some fine twigs, brown needles or leaves (future mulch) and cones with light to moderate bark char; where tree cover had been dense, the area is usually not dominated by black sticks, but can be in some cases; specific characteristics of this class and percent tree mortality need to be defined for each fire as they can vary by ecosystem
High	High soil heating, deep ground char; litter and duff consumed leaving fine ash, often more than an inch or two deep and often gray or white; surface soil may be visibly altered, often blackened or reddish and usually lacking structure; all or most organic matter is removed; fine roots and rhizomes may be consumed; reduced permeability may be pronounced (strong and/or thick water repellant layer) over much of the area; large fuels completely consumed or nearly so.	all plant parts consumed, including fuels greater than ¾ inch, leaving some or no major stems/trunks of shrubs.	generally 80 to 100% tree mortality; saplings and large trees are dominantly black sticks with moderate to heavy bark char and no needles or leaves remaining. Individuals or small pockets of live trees may remain, but are not dominant in the delineation.

Appendix 1: Soil Burn Severity classifications (Parsons, 2003)



Appendix 2: Runoff to Rainfall Ratios shown in different slope classes. No correlation showing higher slopes contribute to higher runoff to

SUPPORT PHOTOS

Photo 1: Plot with protective top to prevent water from directly entering catchment area.

Photo 2: Calibration sheet covering plot.

Photo 3: Water remains in top .5 cm at Boyer 2010


Mill Control


Scotts/Mill Ridge Burned


Mill Control


Boyer


Mill Control


Scotts/Mill Ridge Burned

Photo 4-9: Comparison of Controls (Left) and Burned (Right) sites within the Knobcone Pine and Manzanita vegetation grouping 2010


Little Creek Control

South Fork


Deadmans Gultch

Lions Flat


Little Creek Control

Hillslope Erosion Study

Photo 10-15: Comparison of Controls (Left) and burnt (Right) sites within the RW/DF and RW/TO vegetation groupings 2010