Executive Summary

Landscape and Management Response to Wildfires in California

by

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Burned Watersheds Erosion Study
CDF No. 8CA38629

June, 1998

Abstract

The mechanisms controlling runoff and erosion after wildland fires and the effectiveness and necessity of post-fire erosion control measures were explored at 6 sites in California over a 4 year period. Observations from field monitoring of runoff and erosion in burned watersheds following wildfires between 1993 and 1996, coupled with results from sprinkler experiments following the Oakland fire suggests that runoff mechanisms and erosion process are tied to soil texture. Fine-textured soils, which tend to have some cohesive strength, develop a shallow hydrophobicity after a fire, which leads to Horton overland flow production during rainstorms. Bare, coarse textured soils are typically cohesionless, and the fire-induced hydrophobic layer is usually many centimeters below the surface. This layer forces infiltrating rainwater to perch and generate a shallow subsurface flow. Horton overland flow from upslope areas of lower infiltration can overwhelm the through flow capacity of this layer and cause the formation of saturation overland flow. This flow may generate downslope propagating rills in the coarse textured soils through a sequential process of localized entrainment, lateral displacement and deposition of sediment as small ridges, dictated by local perturbations in slope and heterogeneity of infiltration. Field tests using a shear vane revealed that a threshold value of strength of 0.1 kg cm^{-2} differentiated rilled from unrilled soils after winter runoff in burned wildland areas. After a fire, overland flow quickly became detachment-limited, and then flushed steeper low order channels of accumulated sediment.

A review of nearly a century of debris basin data for the San Gabriel Mountains revealed that the greater the proportion of the watershed area with slopes greater than 35 degrees, the higher sediment yields. Sediment yields from the San Gabriel Mountains were not dominated by fire events, but rather by major storm events.

Erosion control following wildfires was generally ineffective. Applied grass seeds germinated after first rainfalls had already caused most of the erosion, and generally failed to reach sufficient cover to be beneficial. Furthermore, landslides appear to be less common on bare hydrophobic soils than on soils with successful germination or on unburned grassy areas. The use of temporary channel structures to trap and store sediment proved to be ineffective because their design typically could not handle the high flows generated from burned watersheds.

Rather than continue to use erosion hazard reduction methods that have proven to be ineffective, the State should use modeling and field observations to delineate potential high sediment producing areas, and the paths of debris flows and torrents. Such hazard maps could then be used as a tool for risk reduction in fire prone areas.

Introduction

Urban growth and fire suppression have led to a high potential for destructive fires at the urban wildland interface. With the continued expansion of urban lands into highly flammable wildlands of California, the potential for such fires is increasing. Between 1919 and 1996, a total of almost 8.6 million acres of California have burned with the loss of 224 lives and 11,653 buildings, which illustrates the risk of living at this interface. For the last 46 years, while the acreage burned has remained fairly constant, there has been a rapidly increasing loss of structures and resulting dollar damage due to urban encroachment into fire prone wildlands (Figure 1). This trend of increasing losses over time due to fire also represents the increasing risk and potential loss and damage by post fire erosion as urban growth abuts and spreads into the steep canyon lands of the California Coastal Ranges. Although many useful studies have been done of runoff and erosion following fires there remains a lack of knowledge and corresponding tools for identifying which landscapes will produce the biggest response to fire. Therefore, erosion control measures tend to be used relatively blindly to reduce erosion hazard.

Coupled with the increasing risk of erosional hazards is the ongoing controversy regarding erosion control mitigation. Erosion control practices following wildfires has evolved from early attempts to control runoff and erosion by contour trenching entire hillslopes to the less invasive practice of seeding burn areas. Recently, erosion control practices developed to mitigate construction site erosion has been offered as a complement to seeding. Seeding programs however, have been regarded as have questionable success by many researchers, while temporary measures developed for construction sites have received relatively little study.

Approach

In order to develop and understanding of what controls the post-fire runoff and erosion of landscapes and to evaluate the effectiveness of various erosion control methods on California landscapes, a multi year study was undertaken. The broad based study consisted of: 1) a literature review; 2) analysis of long term erosion data for the San Gabriel Mountains and Verdugo Hills, collected by the Los Angeles county Department of Public Works; 3) observation and monitoring of a total of 8 fire areas; and 4) the development of a process-based conceptual model. A separate study was devoted to exploring the use of digital terrain models to delineate sediment hazards. Initial hypotheses proposed during monitoring and sprinkler experiments following the Oakland fire area were further developed during this research project. Fire areas chosen for observation and monitoring (Figure 2), consisted of 4 fire areas in Southern California: Laguna Beach (1993, Big Bend Fire); Malibu (1993, Old Topanga Fire); Altadena (1993, Kinneloa Fire); and Malibu (1996, Calabasas Fire). Additionally, a fire area in the Central Coastal area, San Luis Obispo (1994, Highway 41 Fire), and a fire area in Northern California, Pt Reyes National Seashore (1995, Mt Vision Fire) were also visited. Although not part of this study, fire areas in Idaho (1994, Rabbit Creek Fire), and Australia (1994, Sydney Fires) were visited as they provided additional information about post fire processes for different landscapes. At each burn area, the focus was on noting: 1) channel condition and response; 2) the presence of and the availability of sediment on hillslopes; 3) the potential for fire induced surface runoff; 4) the style and sequence of erosion; 5) the role of rilling in delivering water and sediment to channels; and finally, 6) the performance of erosion control measures.

Summary of Literature Review

A review of the literature on sediment yields following wildfires reveals a highly variable landscape response. Seasonal timing, intensity of burns, and the effects of rainfall, geology, slope, and vegetation on landscape response can result in order of magnitude variation in sediment yields. Post-fire erosion studies where rilling, sheetwash, and rain splash are the primary processes, equivalent soil losses ranged between 0.05 mm and 6.1 mm the first year after a fire. Estimated soil loss by raveling for unburned watersheds ranged from 0.03 to 0.4 mm, while such loss for burned watersheds ranged from 0.3 to 17 mm. Fluvial erosion, which in many cases consisted of a debris torrent response (fire-flood sequence), resulted in sediment yields of 10 to 118 mm or 100 to 1180 tons ha^{-1} for a single event following a fire. Unburned catchments within the San Gabriel Mountains however, have been known to purge considerable amounts of sediment in response to high intensity rainfall events in wet years. In 1969, following severe rainfall intensities, several catchments debauched enough sediment to produce equivalent soil losses as high as 13 to 30 mm.

The general conclusion that emerges from research throughout fire prone landscapes is that following fires there is an increase in river discharge, but more significantly, an increase in peak discharge and sediment load may be anticipated. The post-fire erosional environment is dominated by a sequence of events that typically unfolds in the first storms following the fire. If ravel occurs it is most active during and shortly after the fire. The first significant rains, even short duration ones, if they are sufficiently intense will produce overland flow and the generation of a rill network. Discharge of rill runoff and sediment leads to sedimentation of ravel deposits lying in steep canyon bottoms and possibly their subsequent mobilization as mass flow. Mud flows that initiate in channels we refer to as debris torrents to distinguish them from hillslope initiated landslides, which mobilize as debris flows. A common pattern has been an initial flush of sediment, usually in the first major runoff producing rainstorm event, followed by declining levels of soil loss with the landscape tending to return to what may be called the background erosion rate after several years. This recovery period may vary pending on the type of environment (vegetation, soils, geology, geomorphology) represented by the burn area. In terms of landscape response, burned and disturbed (ground surface has been mechanically disrupted) sites are more prone to accelerated erosion than are burned but otherwise undisturbed areas. Disturbed sites may be in the form of roads, bulldozed firebreaks, logging haul roads and skid tracks, walking trails or areas of reconstruction in urban-wildland interface areas. There appears to be a distinction in post-fire processes between areas where overland flow is rare or absent and the vegetation is killed (i.e. Northwest conifer forests) and in areas where vegetation is fire adaptive, hydrophobicity results in significant overland flow runoff. In the former, the primary source of post-fire sedimentation is shallow landslides associated with reduced root strength whereas in the latter, sedimentation is dominated by erosion by overland flow and the mobilization of stored sediment in steep tributary channels as debris torrents.

Literature pertaining to erosion control consisted primarily of papers on seeding burned hillslopes following wildfires. Other temporary erosion control methods such as temporary check dams and hydromulching typically have not been monitored in a wildland environment and were thus not covered in the literature. To be effective in mitigating runoff and erosion, seeded grasses needed to provide substantial cover following a fire. Several papers established a minimum 30% cover by grasses as necessary to mitigate erosion for light intensity rainstorm events with higher percentages of cover needed to mitigate the effects of greater rainfall intensities. Cover less than 30% tended not to be effective in reducing peak overland flow. A review and compilation of percent cover data for 67 fire areas throughout California (CDF annual fire reports, 1956-1972) revealed that less than 20% of seeded wildfire areas generated at least 30% cover the first year after a fire (Figure 3). During the second year, less than 30% of seeded fire areas generated at least 30% cover. Generally, most of the papers reviewed during this study questioned the success and need for seeding fire areas. Additionally, this study found no evidence in the literature that seeding burned hillslopes reduced erosion by any significant amount.

Summary of Field Study Results

1. Rapid decline in sediment yield following first effective rainfalls
    a. In Oakland (Figure 4), declining sediment yield was measured for 5 erosion plots over a four month period following the fire in 1991.
    b. Rill networks which evolved in Highway 41, Old Topanga, and Big Bend fire areas during initial rainfall events did not appreciably increase their density over time. Rather, soil loss due to *in-situ* incision occurred at a rate slower than rill initiation.
    c. Within the Highway 41 fire area, alluvial fans deposited during early rainfall events, incised following continued rainfall.
    d. Monitored channel cross sections for the Highway 41, Old Topanga, and Big Bend Fires exhibited a similar sequence of channel aggradation early in the wet season followed by the middle and end of the season incision.

2. Controls on Runoff and Erosion
    a. The depth on hydrophobicity dictates the magnitude of overland flow following a fire, and the hydrophobic layer can be locally patchy. Figure 5 illustrates findings from our monitoring and sprinkler experiments in the Oakland Hills. The sites (labeled with letters and numbers) are arranged such that from left to right hydrophobicity ranges from absent to progressively shallower in the soil. In the modest rainfall intensities following the Oakland Fire only the areas with the lowest infiltration capacity and shallowest hydrophobicity produced significant overland flow. For light rains, all the water infiltrates and travels as subsurface flow off the hillslope. With increasing rainfall intensity, those sites with

well developed shallow hydrophobic horizons will generate a very shallow subsurface flow, and, with sufficient rainfall duration, overland flow will develop. In the case of coarse soils, the overland flow is essentially a very shallow saturation overland flow rather than Horton overland flow (Dunne, 1978), while, in finer textured soils, very shallow hydrophobicity coupled with lower infiltration capacities promotes Horton overland flow. The hydrophobic layer plays a dual role: it perches infiltrating water and thereby forces the development of overland flow, and it builds up a zone of elevated pore pressure that can drive flow into preferential flow paths. This model suggests that those processes that control hydrophobicity and the development of preferential flow paths are most crucial in determining the amount of surface runoff generated at a site.

b. The shear strength of surface soils can be used to predict the runoff potential of burned hillslopes. Coarse textured soils typically have low values of shear strength. If hydrophobicity is present it will be found at some shallow depth within the horizon of non-cohesive sediments, or at the boundary between loose surface soils and underlying cohesive soils. The overlying wettable horizon of non-cohesive soils acts as a storage element for soil water, in which a shallow subsurface flow may form and reduces the potential for overland flow. Soils with high shear strength values (typically finer textured) will have a hydrophobic layer at the soil surface and under appropriate conditions of rainfall intensity will generate overland flow very quickly. Figure 6, describes the relationship between shear strength, hydrophobicity, and their effect on runoff generation for experimental plots in the Oakland Hills. Figure 5, shows the relationship between overland flow, through flow, and the thickness of the wettable horizon for the experimental plots. These observations taken together suggest a general model for runoff generation.

c. Shear strength measurements (using an inexpensive, commercially available, handheld shearing device) of rilled and unrilled soils at 5 fire areas reveals a threshold of about 0.1 kg cm^{-2} between rilled and unrilled soils (Figure 7a). Tests at three sites following the Calabasas fire suggest that shear strength can successfully predict erosion potential (Figure 7b). Shear strength tests following the Mt. Vision fire however, were less conclusive due to low intensity rainfall events and extensive bioturbation (Figure 7c). Here only one site with extensive hydrophobicity and low shear soils rilled extensively.

d. We propose a conceptual model linking runoff production and erosion to shear strength and rainfall intensities. Figures 8a and 8b, summarizes the processes, linkages, and controls that lead to the different responses to the fires reported on in this study. The flow diagrams represent two primary attributes: hydrologic and erosional processes (in the rectangular boxes) and the factors that determine general kinds of response (in the diamond boxes). Shear strength is a surrogate for two parameters: the infiltration capacity; and erodability. Based on limited experimental data and field observations, it is suggested that loose, cohesionless (low shear strength) soils will produce deeper hydrophobic barriers which in turn means a greater tendency for subsurface flow, but also a greater susceptibility to erosion by overland flow and instability to rilling. In contrast, high strength soils will tend to be finer textured, forcing hydrophobicity closer to the surface and therefore favoring Horton overland flow and sheetwash without rilling. Figure 8, specifically emphasizes the apparent importance of upslope Horton overland flow washing across downslope, low strength materials in the formation of rills. Under periods of intense rainfall, rill/gully flow and/or extensive Horton overland flow can generate sufficient runoff to mobilize debris stored in the channel transporting it from the watershed. Debris can consist of ravel, shallow landslide deposits, alluvial sediments, and bank failures. These debris torrents may threaten lives, homes and other downstream resources.

3. Sediment yield in the San Gabriel Mountains and Verdugo Hills
   a. Mean sediment yield data for 108 debris basins varied by an order of magnitude for similar sized watersheds (Figure 9). Mean annual erosion rates varied between 1 mm and 10 mm a year, a rate comparable to measured uplift rates for the San Gabriel Mountains.
   b. On average, sediment yield increased with increasing proportion of the watershed in slopes greater than 35° (Figure 10). The average yield for debris basins with a greater than twenty year record varied from about 1 mm yr^{-1} when no slopes are greater than 35° to 4 mm yr^{-1} when over 40% of the basin had slopes greater than 35°.
   c. Regressions of sediment yield with mean slope of watersheds revealed variable sediment yield for quartz diorite, granite, sedimentary, and watersheds with mixed bedrock (Figure 11). The data suggests that watersheds within areas of granitic bedrock tended to be the most sensitive to the effect of slope, whereas watersheds with sedimentary facies being the least sensitive.
   d. Sediment yield as a function of fire history was also highly variable. Those basins which have experienced the most fire (3 or more burns in 20 or more years) had the least variation in sediment production between sites (Figure 12). Some catchments with no recent fire history had sediment yields comparable to that of the most frequently burned sites, hence the overall steepness and higher erodability of the San Gabriels appears to dictate these higher sediment yields rather than the effects of periodic burns.

4. The effectiveness of erosion control measures
   a. Monitoring of temporary structures used to control sediment within the

channel system in 3 fire areas suggests that initially check dams have less than a 50% success ratio, with total failure by the second year. Monitoring suggests that temporary structures should not be used in catchments with drainage areas greater than 1 hectare (2.4 acres) as they are typically not designed to handle the higher flows experienced in wildland areas.

b. Straw bale and sand bag check dams failed for several reasons: piping under the structure; the absence of energy dissaptors resulting in dam faces being undermined by flow over the structure; and where spillways were inadequate for the higher discharges, channel banks were destabilized due to localized flow (Figure 13).

c. For the larger structures such as K-rails, pipe flow under the dam was the most likely cause of failure (Figure 14).

d. Debris fences (hog wire and silt netting) typically failed by piping or due to the lateral pressure of stored water behind the structure (Figure 15).

e. Failure of structures within the channel system resulted in increased downstream erosion.

f. Hydromulch applications in the Laguna Beach burn area were not warranted, as soil strength limited the erosion potential.

g. Hydromulch in the Kinneloa fire area did not prove effective in preventing rilling of hollow axes or shallow landsliding.

h. In the Highway 41 fire area and the Kinneloa fire area hydromulch was used along inboard and outboard edges of Forest Service right-of-ways. Overland flow generated upslope of treated areas rilled hydromulched soils of low shear strength as overland flow typically exceeded the shear strength of the mulch and soils.

i. Seeded grasses germinated after the peak erosional response for all seeded fire areas.

j. When germination did occur, it typically provided less than the 30% cover necessary to mitigate erosion potential. Of a total of 18 monitored sites in 4 fire areas, only one site was provided more than 30% cover, while the mean of the other 17 sites was 5%. Of the 6 sites monitored a second year, the mean cover provided by grasses was 42%.

k. Seeds are most likely to wash off of hillslopes where soil strength is high and hydrophobicity is present. Seeds in low shear soils will germinate in place, but are subject to early mortality if hydrophobicity is present and rainfall is intermittent, as overlying non-cohesive soils dry out quickly.

l. Observations following the fire and heavy rainfall after the Highway 41 Fire suggests that fire may *reduce* the propensity for hillslope landsliding and grass seeding -if successful- would *increase* the potential for landsliding.

m. We conclude that none of the temporary structures nor grass seeding proved effective in controlling erosion at any of the study sites. Such measures should be abandoned and other approaches taken.

Modeling Sediment Hazards

We propose to delineate debris flow and debris torrent (mudflow) hazards using three simple digital terrain models. To define the relative risk of mass flows being generated within channels, sweeping downstream, and presenting a threat to people and structures, we have coupled a model that estimates the relative potential for ravel activity across a landscape with a debris torrent runout model (based on a slope threshold for cessation of motion). The hypothesis is that landscapes that have a greater potential ravel activity are more likely to discharge significant quantities of granular materials into steep channels where it can subsequently be mobilized into debris torrents by high runoff events. The second model delineates channels in the digital terrain surface with a drainage area threshold and assumes that debris torrents travel downslope until they reach a slope that causes them to stop. We have used 66% for the threshold of ravel activity on hillslopes, 10,000 m2 for a drainage area threshold and 4% for the depositional slopes of debris torrents. The models have been run on 30 m U.S. Geological Survey digital data quadrangles in the San Luis Obispo and Los Angeles area. They successfully predicted the location of a debris torrent that destroyed a house near Malibu after the 1993 fire.

A second model, SHALSTAB, is used for delineating hillslope failures (as compared to failures that initiated within channels due to bulking up of ravel deposits). This model has been extensively tested and reviewed elsewhere. A copy of a review paper is included with this report. SHALSTAB is a coupled steady-state runoff, infinite-slope stability model that can be used on digital topographic surfaces. When coupled with the slope dependent runout model, the full hazard associated with hillslope failures can be delineated. The model correctly predicted as high hazard the location where 4 people were killed in 1998 in Laguna Beach.

We recommended that these models (or other models that perform similar functions) be used throughout the State by the California Department of Forestry and Fire Prevention to delineate potential hazards area. This would then focus efforts and resources of prevention and warning systems and away from ineffective post-fire emergency mitigation.

Recommendations

1. Temporary structures should not be used in channels where the drainage area is greater than 1 hectare (2.4 acres). If public agencies want to control sediment, structures designed and engineered for the higher flows anticipated for burned catchments should be used. Los Angeles County has successfully been using this approach for years.
2. Because seeding burned hillslopes does not cause post-fire erosion suppression, and could in fact increase the risks of landsliding and because temporary channel structures usually fail an alternative approach to mitigation the sediment hazard due to fires is needed. We propose that public agencies could take the following course of action:
    a. *Before* a wildland fire
        i. Use digital terrain mapping tools to delineate site specific locations on landscapes where if fire were to occur there

        would be significant risk to roads, structures, and lives due to debris torrents (mud flows). Field work could be done to refine and improve hazard mapping.

        ii. In concert with local agencies, develop a guide for homeowners and a community warning system to be used during storms.
        iii. Improve flow passage for undersized culverts and construct where necessary permanent control structures.
    b. *After* a wildland fire
        i. Perform field tests using a shear vane and maps of ravel accumulation in channels to gage site specific risks of runoff and erosion hazards.
        ii. Use weather forecasts and hazard maps to inform public of high risk locations and implement warning system.
3. Obtain high resolution topographic data in order to delineate more precisely and accurately the high hazard areas resulting from wildland fires. At the least, obtain digitized USGS 7.5' quadrangle data but preferably acquire higher resolution data from airborne laser altimetry.