Modelling Runoff and Erosion Effects of Wildland Fires

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ABSTRACT

Millions of dollars are spent annually in California on erosion control measures after wildland fires despite the lack of quantitative evidence that such measures are needed or beneficial. Application of grass seeding and other measures after a fire are often justified on the basis of a perceived concern about the risk of debris and mud flows endangering property and lives. While the effectiveness of such measures can be seriously questioned, the risk may nonetheless be significant. We have conducted a two year study to test and expand a recently developed physically-based model for predicting the spatial pattern of landslide potential. This model can be applied at any time and serve as part of planning document to prepare for the effects of fire. The model uses digital elevation data and is based on simple assumptions about runoff and slope stability mechanisms; in it's simplest form the model is parameter free and easily calibrated

We first tested the model in the Oakland firestorm area. Here high resolution digital elevation data were available and 78 landslide scars had been mapped in a 12.12 km^2 area. A simple ratio of effective precipitation rate to the ability of the soil to transmit the water is calculated from the model for the condition of instability. The smaller the ratio, the higher the potential instability. As we have found elsewhere, there is threshold value which delineates all observed scars in the Oakland hill . During the study, the Highway 41 fire occurred in the San Luis Obispo area, consuming 196 km^2 of landslide prone topography. Aerial photographs were taken, and a detailed survey using global positioning techniques was accomplished to guide the construction of a detailed digital elevation model of the site. This past winter after the fire was one of the wettest of record and a total of 467 shallow landslides were mapped, with 82% occurring in the unburned areas and most of the landslides in the burned area occurring where the

grass seeding was most effective. Once we obtain the digital data we will use the landslide model to test various hypotheses for this unexpected, but important result.

Key words: fire effects, landslides, erosion

TABLE OF CONTENTS

LIST OF FIGURES

STATEMENT OF THE PROBLEM

In California, the annual cycle of dry summers, summer and fall wildland fires and winter storms is widely believed to lead to a heightened erosion hazard which requires aggressive intervention by resource agencies to prevent the loss of life and property, the loss of soil, and destruction of downstream habitat. Without doubt, in some parts of California fire-induced erosion is a significant problem. Where the combination of steep lands and naturally high erosion rates, combined with growing urbanization into debris flow prone territory, there exists the potential for disaster (e.g. Rice, 1982; Wells, 1987; Barro and Conard, 1991).

Millions of dollars are spent annually in California on erosion control measures after wildland fires despite the lack of quantitative evidence that such measures are beneficial. City, county, state and federal agencies are obliged to draft plans immediately after a fire for such work even though these agencies rarely have staff trained in erosion processes. In addition, they must implement these plans quickly because of concern about winter rains. Many in these agencies acknowledge that such measures seem unnecessary to them, but believe it is better to at least appear to be doing something. However, there is also the increasing realization that at least some of these measures may actually be detrimental. For example, ryegrass seeding may suppress native vegetation recovery (Krammes & Hill, 1963; Rice et al., 1969; Conrad, 1979; Barro & Conard, 1987; Taskey et al., 1989).

The most dramatic example of the rush to respond to an expected erosion hazard occurred after the Oakland-Berkeley fire of October 1991. While the fire was still being completely extinguished, intense media interest in this fire began to focus on the possibility of winter rains producing catastrophic landsliding and debris flows in the area. Various government agencies were quickly mobilized, and they followed a consulting firm's plan of using construction site erosion control measures of hydromulching, jute netting, hay bale construction, and silt fences. Eventually about 6 million dollars was spent (as compared to the roughly 6 million spent in 1987 and 1988 on the 700,000 acres of burned forested lands in all of California). The Soil Conservation Service alone spent over 2.5 million dollars on the Oakland hills burn.

The rehabilitation work in the Oakland hills has received wide attention, with various resource agencies conducting site visits to inspect the techniques used. After wildfires in 1993 in and around the communities of Laguna Beach, Altadena, and Malibu, several groups called for similar efforts to be mounted in their communities. Hence the rehabilitation effort in the Oakland Hills has become a sort of model for others. But was this work beneficial and should it be a model for others?

The widely-held view of the effects of fire comes largely from the well-documented work in the San Dimas Experimental Forest (e.g. Rice & Foggin, 1971; Rice, 1982; Wells, 1981,1987). There ravelling (gravity driven movement of non- cohesive sediments) during and immediately after the fire shed large amounts of sand and fine gravel into steep canyon bottoms. This sediment becomes mobilized as channel-initiated debris flows in the following winter rains. Accelerated runoff due in part to fire induced water repellency (hydrophobicity) and the delivery of sediment from rills to channels contributes to this cycle of fire and channel-initiated debris flows (Wells, 1981,1987; Barro and Conard, 1991). Wells (1987) and Keefer et al. (1986) proposed that these rills are actually formed by micro-debris flows rather than overland flow. There was a general concern that the Oakland hills might respond in the same fashion. However, despite repeated fires in the Berkeley and Oakland hills this century, no observations were available that suggested that the "fire-flood" cycle had any relevance here (Booker et al, 1993). Although the hillslopes are locally steep, the average slope and relief is much less than in San Dimas and local soils are more cohesive with less potential for ravelling.

Another major fire-induced erosion mechanism, and one that still poses a great danger to downstream structures and people, is debris flows. An effective cause of this fire-related landsliding, would be the reduction of vegetative root strength. The concern is real: in 1982 storms produced thousands of debris flows in the Bay area, killing at least 4 people and damaging many homes (Cannon & Ellen, 1988), (these debris flows, however, were not associated with burned areas). One very obvious feature of the post-fire landscape were the numerous landslide scars. Most are relatively shallow slope failures that occurred during periods of sufficiently intense rain, typically after a build up of antecedent soil moisture (Cannon & Ellen , 1988). The intent of seeding, hydromulching, netting, hay bales and silt fences is to try to prevent the buildup of overland flow and the rilling and gullying of the ground surface. These measures enhance infiltration. However, encouraging infiltration is the least desirable thing to do when concern is the generation of debris flows from hillslopes. It has even been argued by some (Morton, 1989) that burned slopes may be less susceptible to landsliding where they produce significant overland flow due to shallow water repellency (as could occur after a fire) and permit less pore pressure buildup (channels draining burned areas may still receive ravel debris and generate channel-initiated debris flows). Thus it could be argued, that in landslide prone areas any erosion mitigation effort such as those undertaken in the Oakland hills that increases total infiltration, and subsequently soil moisture, can only increase the potential for landsliding.

In light of the fact that there is a relatively poor understanding of post fire hazard assessment, we feel there is a need for a fundamental study of the problem of landscape response to fire that can provide a rational approach to management decisions about erosion control. Observations regarding erosional response to fires or erosion control techniques in one part of California should not be blindly applied to all fire areas. Defensible procedures for quickly deciding appropriate response to individual wildland fires are needed.

RESEARCH OBJECTIVES

With the advent of cheap computing, we see that virtually all resource agencies are acquiring digital information about landscapes. Reasonably high resolution digital elevation data can provide for the first time an opportunity to combine process-based analyses with spatially varying resources conditions to quantify possible landscape response to landuse and fire. We anticipate a time when resource agencies will have digital information of their lands that can be continually updated and can be used especially in the emergency following a fire to dictate appropriate response.

The purpose here is to start with generally the most serious problem of fire-induced erosion: debris flow initiation. We focused on testing a simple, process-based model for predicting debris flow source areas using digital elevation data from the Oakland hills and if opportunity availed itself, at least one other fire area. The proposal as originally envisioned would provide the seed for stronger interaction with resource agencies and for development of a general study of the problem. In August of 1994, the Highway 41 fire in San Luis Obispo County which burned 19,648 hectares (48,551 acres) provided that opportunity. With additional funding from the California Department of Forestry a broader study is being undertaken that involves extensive field study to develop an empirical base for predicting landscape response to fire, with field experiments to test hypotheses and expansion of the modeling effort to include ravelling and rilling potential.

An initial form of the model had already received some initial testing in a study area near San Francisco (Dietrich et. al, 1992, 1993) and in recently clear-cut areas in Oregon and Washington (Montgomery and Dietrich, 1994). In general our approach was to keep the model as parameter free and a simple as possible and to add other effects, such as those just mentioned, as demanded by failure of the model to perform adequately. We did not intend to develop a highly-tuned parameter-rich model that gives the illusion of very high local accuracy.

Of particular interest is the interpretation of the inevitable differences between the landslide map and our predicted pattern of instability, especially given the urban setting. We feel this will be an important test of the model in a landuse application. If the model proves reasonably useful, then it ultimately could be used both in planning and perhaps as part of the landslide warning system developed by the United States Geological Survey (Keefer et al.,1987). For example, when a hazard warning is issued, our model could delineate those specific areas of a city that are the most susceptible to debris flows.

METHODS AND RESULTS

Debris Flow and Landslide Mapping - Oakland

Following the Oakland fire in October, 1991, the landscape offered a clear view of the numerous landslide and debris flow scars that had formed during previous wet years. The city of Oakland felt that despite the preventative measures applied immediately following the fire, the potential for further erosion and landslide activation was significant. It was believed by the city of Oakland and their consultants that the landslide potential was greatest in areas exhibiting either: previous instability; steep slopes; or on hillslopes and channels that could receive uncontrolled runoff. The City requested that a detailed topographic map of the fire area be developed and that all debris flow and landslide locations which consisted of not only observed scars but also inferred potential failure sites within the fire area (7.28 km^2) be mapped.

The base map topography was developed by Hammon, Jenson, Wallen & Associates of Oakland, using automated contouring methods. Terrain data was photogrammetically measured from air photos (scale of 1:12,000) flown by Pacific Aerial surveys of Oakland, on October 23, 1991. Photogrammetric points were not measured at a regular interval as is terrain data for USGS topographic maps, but at irregular intervals consisting of data strings made up of break lines and math points. Break lines were hard lines such as roads and walls, and soft lines such as ridge lines, breaks in slope and other geomorphic features. Math points were identifiable ground points on overlapping air photos which were surveyed to local bench marks by the city of Oakland to provide the necessary aerotriangulation needed to develop the map and future DEMs. Horizontal and vertical control was established by the city of Oakland based on the California coordinate system NAD 1927 and NGVD 1929. The completed set of terrain data consisted of 58,189 x,y,z points covering an area of 12.12 square kilometers. Arcinfo v.10 was used to develop the topographic map on which consultants for the city of Oakland mapped all debris flow and landslide features. It was the raw data set of 58,189 x,y,z coordinates that we received from the city of Oakland for our modelling runs.

Potential failure locations and actual debris flow and landslide features were identified using air photos and ground surveys done from a car. There was some debate as to the accuracy of this mapping effort. Features were not always accurately located and in some cases were incorrectly identified. Several locations were mapped as having both debris flow features and deep seated landslide features. However, this mapping effort was significantly better than anything that had previously existed for this area.

Debris Fow and Landslide Mapping - San Luis Obispo (Hwy 41 Fire)

In August of 1994, an arson fire in San Luis Obispo County raced across the landscape burning a total 19,648 hectares (48,551 acres) and 87 structures, at a pace that sometimes approached 2,800 hectares per hour (7,000 acres/hr). The burn area included 7,269 ha (37%) of state and federal lands and 12,378 ha of private property (63%). A joint state and federal task force assessed the fire area and recommended a series of treatments (Madden, 1994).

Of the twenty watersheds impacted by the fire, only two watersheds experienced a 100% burn; Tassajara Creek and Margarita Creek. Tassajara Creek is an approximately 12 km^2 watershed which drains into Santa Margarita Creek basin which flows into the Salinas River. Most of the structural damage that occurred during the burn took place in this watershed, where over twenty homes were lost and ten homes survived the fire (at this time most of the destroyed homes have been rebuilt). Seventy-three percent of the basin burned with high intensity, eighteen percent moderate intensity and nine percent was a low intensity burn. The watershed consists of a varied geology (shales, sandstones, landslide alluvium, and Franciscan mélange), steep slopes (30 to 50 degree slopes are common), and was rated by the multi agency task force as having the greatest potential risk to life and property by debris flows and mud flows of all the watersheds in the burn area. Estimated sediment yields for this watershed were approximately 8,000 m^3/km^2 a 1600% increase in sediment yield from the pre-fire condition (Madden, 1994).

This basin was chosen as a study area, because of the relatively easy access to the upper watershed area, the uniformly steep slopes, the variety of geology, and the relative lack of urban impact (roads) in the upper watershed area and the predicted debris flow and mud flow hazard. Most importantly, the east fork of Tassajara Creek and a tributary creek are impounded behind dams, which allowed for an accurate assesment of sediment production. Additionally the open landscape made it an ideal site for a GPS survey to obtain the necessary accuracy for a useful digital elevation model.

In April, 1995, the entire Tassajara Creek watershed was flown at a scale of 1:6000, with the intent of producing a high precision digital elevation map of the upper watershed area of approximately 6 km^2. A series of 37 stations were surveyed during the spring, using a differential Global Positioning System (GPS) of three receivers which should allow for a 0.5 meter vertical and horizontal accuracy over the entire upper watershed (figure 1). Station location and datum analysis is currently ongoing at Lawrence Berkeley laboratory, after which the generation of the DEM and mapping will be done by us at the United States Forest Service office in San Francisco. We will carry on this analysis despite the completion of this grant. This is possible in part, because of the "seed" effect this initial work provided that enabled us to develop a more extensive project with the California Department of Forestry and Fire Protection.

The winter of 1994 proved to be one of the wettest on record in San Luis Obispo County. Rainfall for the winter was close to being double the normal rainfall. Over 1,100 mm of rainfall was measured in the Tassajara Creek Watershed at two stations. Despite the fact that all

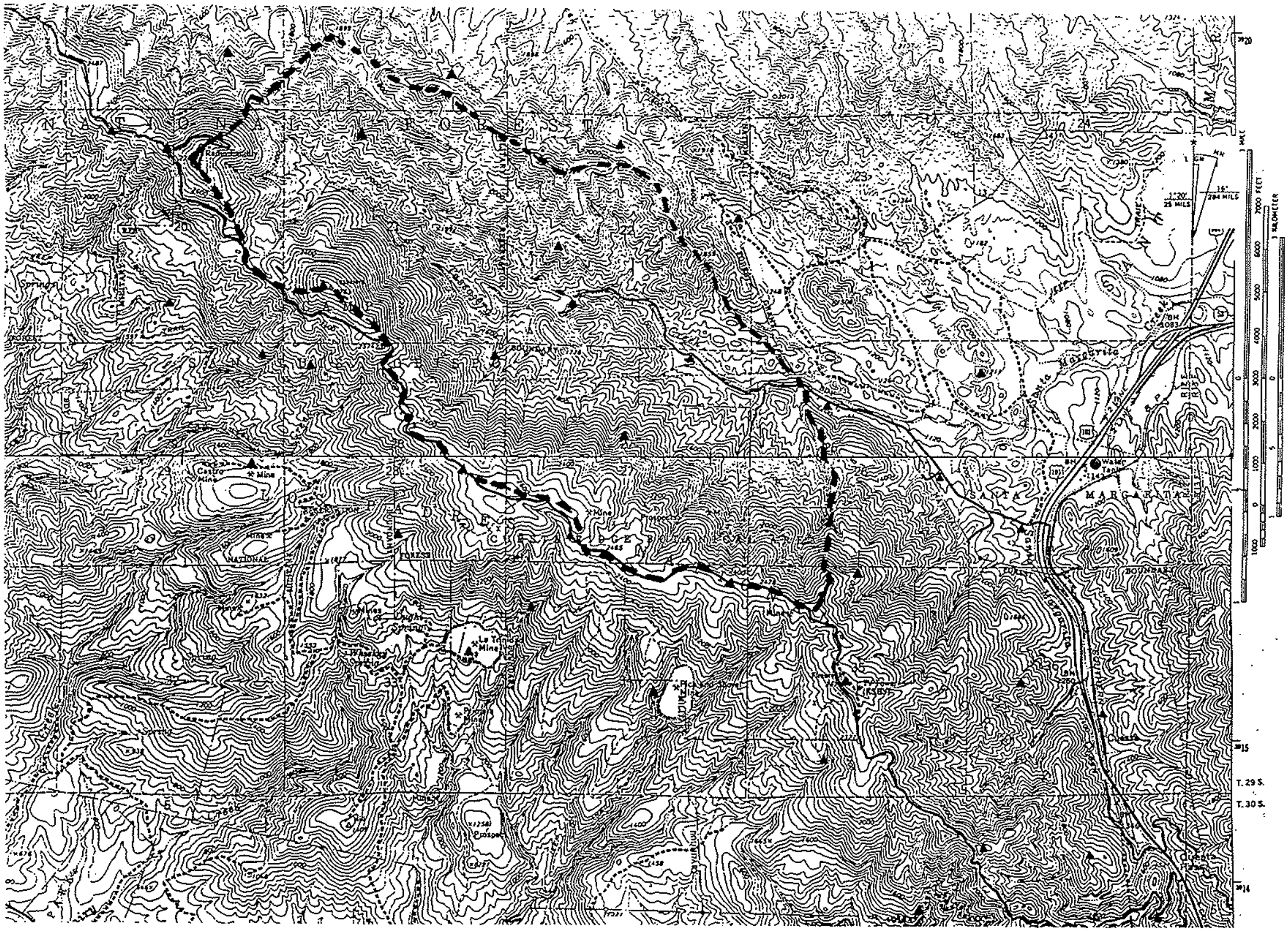


Figure 1. Tassajara Creek watershed, Highway 41 fire area, San Luis Obispo County. Triangles denote survey monuments.

hypothetical conditions (hydrophobic soils, steep slopes, intense rainfall, and lots of loose material) for a fire-flood sequence of debris flows and mud flows existed, only a few small events occurred early in the winter after only 25 mm of rainfall had occurred. Field observations confirmed that the initial response of sediment loading to channels was mostly from ravel, which overall was rather light. With the early rains, a rill network was established, and it was this ravel and rill sediment that was the source of the few early mud flows. Subsequent rainfall events maintained the rill network, by progressively deepening the rills without increasing rill network density despite the greater rainfall intensities and size of rainfall events during the rest of the winter. After the initial pulse of sediment into channels, the erosional response was dominated by increased overland flow. This increased overland flow scoured channels to bedrock, and undermined channel side slopes. Following heavy rainfall events in March, there was an increased incidence of landsliding and debris flow occurrence in San Luis Obispo County. To our surprise, of the 467 shallow landslides that were mapped, 82% of them were found on unburned hillslopes and of the remaining 85 found in the burned area, 66% were on slopes where grass seeding had been most effective. Burned hillslopes that remained barren throughout the winter shed only about 6% of all the landslides. This raises the possibility that aerial seeding by grasses may increase the chance of shallow landsliding.

Application of the Digital-Terrain-Based Shallow Landslide Model

Debris and mud flows after a fire may originate either as a hillslope failure, as a failure of sediment that has accumulated in steep channels, or as sediment loading of runoff waters that carry sediment from hillslopes and picks up more sediment in the channel, eventually becoming a viscous slurry. Clearly the channel network defines the runout path for such flows once they enter the channel or if they originate there, and simply preventing road crossings, housing infringement and the like on channels would reduce the post-fire hazard. The more difficult task is to identify sites of highest potential for failure on hillslopes. We proposed testing the model developed by Dietrich et al. (1992, 1993) and widely applied by Montgomery and Dietrich (1994) in grass and forested landscapes of the coastal Pacific mountains to areas where there is a perceived or documented post-fire landslides erosion hazard. The model uses a cohesionless, infinite slope stability analysis in which the pore pressure is calculated from a steady state subsurface runoff model. The model is thoroughly presented in these papers, and in all these papers we relied on the use of TOPOG, a digital terrain model that uses contours and flow lines to generate cells in which calculations are performed. While this digital terrain model has been useful, it is limited to small basins and requires considerable user skill to employ. We have since : 1) developed a simple, grid-based version of our basic cohesionless slope stability model, and 2) explored the significance of changing root strength in a similar model that relies on predicted patterns of soil depth. This new model is described in Dietrich et al. (1995). Soil depth is first predicted based on a simple balance of soil production and diffusive transport that operates for an extended time period. Then using the calculated soil depth, and estimates of apparent cohesion due to vegetation and variation in soil and bedrock conductivity with depth, we can estimate in a similar fashion to the simpler cohesionless model, the spatial distribution of relative potential hillslope instability.

The model has been applied to the Oakland hills firestorm area in order to compare predicted patterns of instability with the map of shallow landsliding. None of the mapped landslide features, however, resulted from the fire. Nonetheless, as noted below the performance of the model is excellent. Once the digital elevation data have been generated for the San Luis Obispo burn area is complete we will be apply the model to this area. The model will be very useful in establishing the similarity based on topography alone of the potential for slope instability in the burned and unburned areas.

Figure 2, shows the mapped landslide features in the Oakland hills firestorm area. The mapping was done for the city of Oakland by its consultants. A total of 78 features in the 7.28 km^2 fire area were identified.

Figures 3 and 4, show the predicted relative potential for landsliding in the Oakland hills. We used parameters set from field estimates in Marin County and previously published (Dietrich et al., 1995). Hazard potential is based on the predicted ratio of effective precipitation (q) to soil transmissivity (T). Where this ratio is low, we infer relatively little precipitation is necessary to initiate instability, and such areas are ranked as having high potential instability. This ratio has the units of 1/meters and because it is always small we use the logarithm of the ratio and have found that mapping in 0.3 units effectively distinguishes the spatial pattern of instability. In Figures 3 and 4, the legend values are for the log(q/T) with high negative values meaning low potential stability and highest hazard. Sites labeled as too steep are places estimated to fail even when the ground is dry, and places too gentle will not fail if the ground is saturated and water is running over the surface. Inspection of Figures 3 and 4, reveals that areas of greatest instability are associated with steep convergent slopes (valleys) draining large areas. The effect of adding only minor apparent cohesion of 1000 Nt/m^2 (figure 3) is to reduce the area of potential instability. The shift from this value to a value of zero (figure 4) may happen after a fire on a grass and low-density

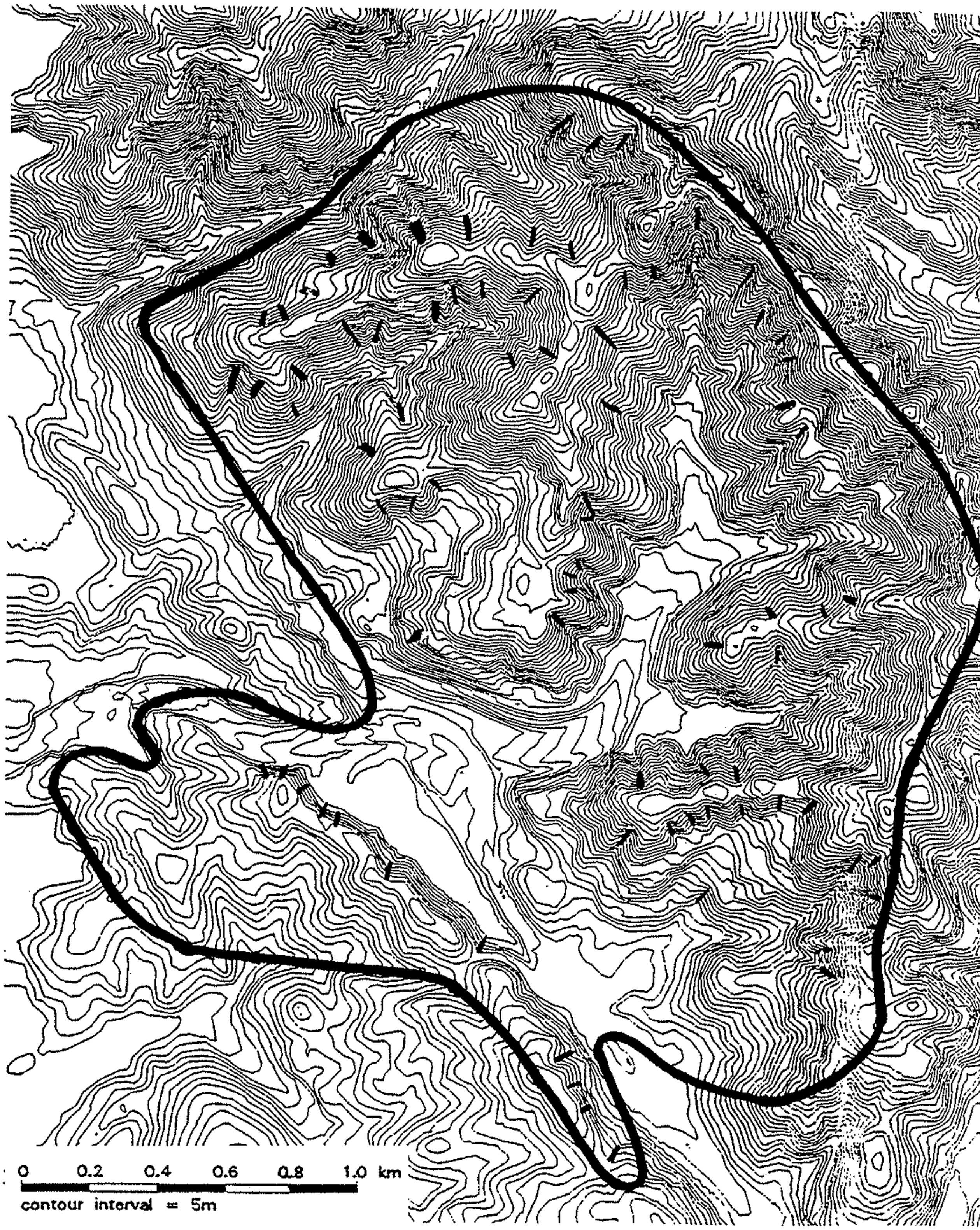


Figure 2. Shallow landslide features in the Oakland Firestorm area.

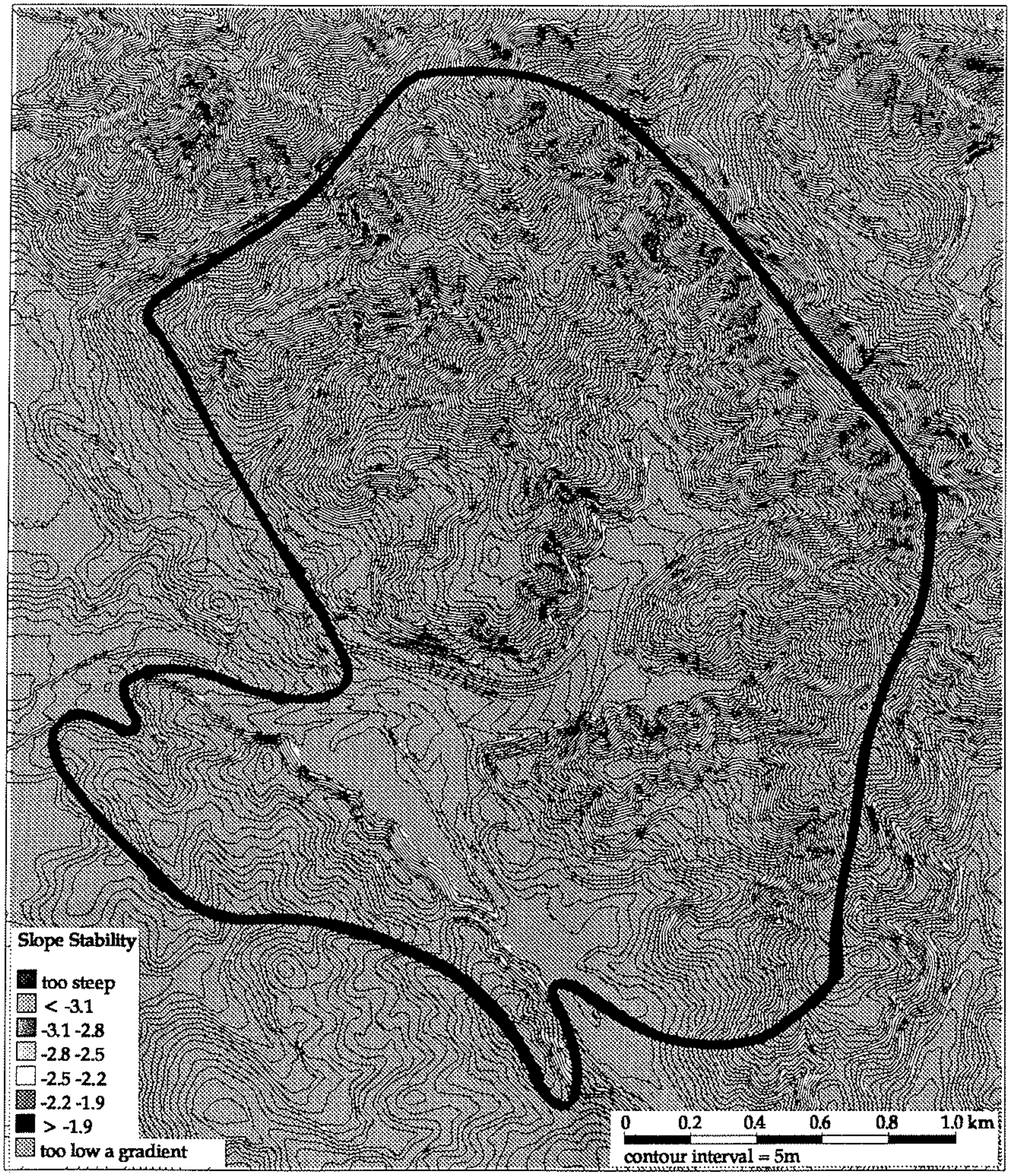


Figure 3. Map of shallow landslide potential in the Oakland Hills fire area, with apparent root cohesion of 1000 Nt/m^2.

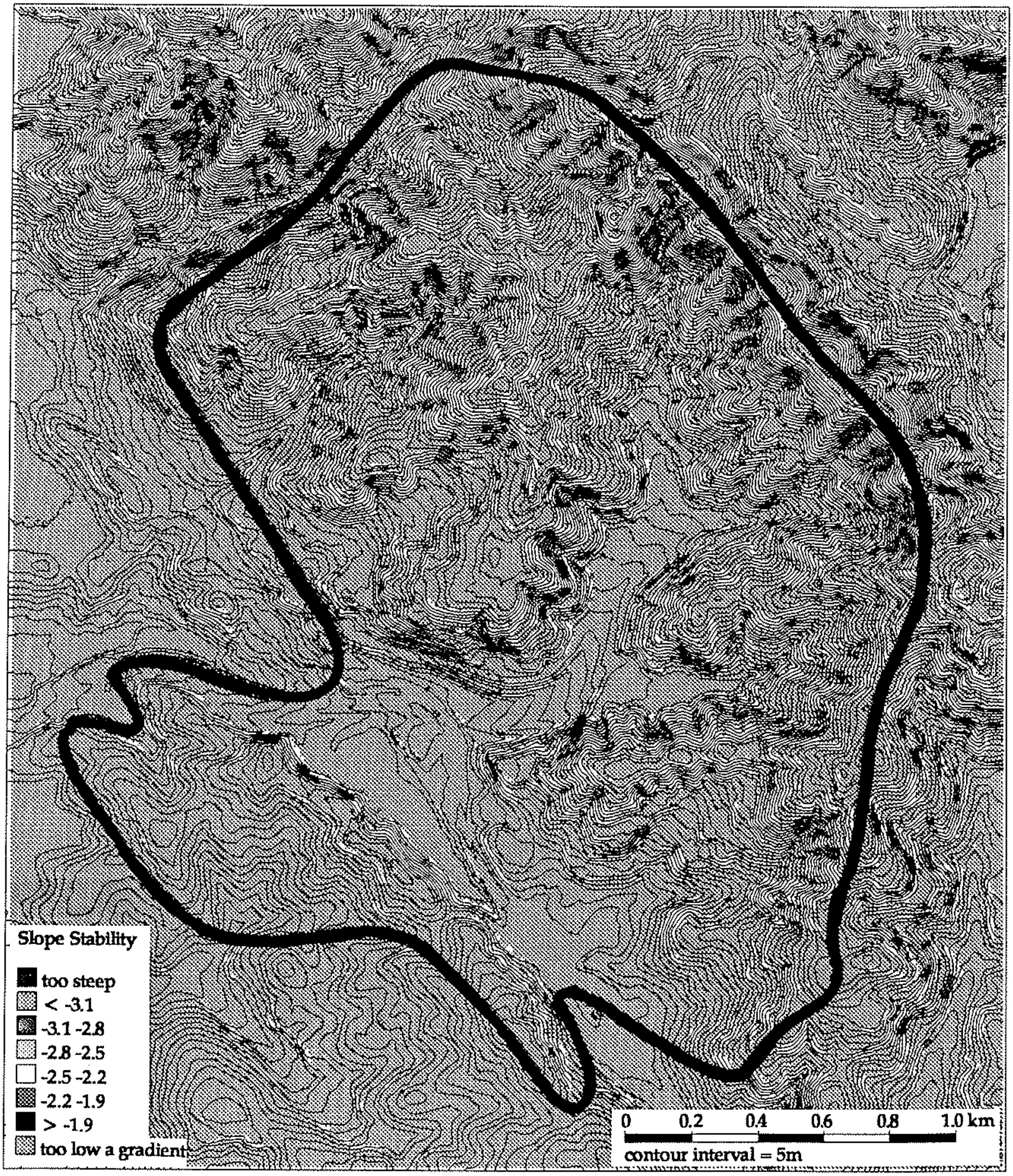


Figure 4. Map of shallow landslide potential in the Oakland Hills fire area, with apparent root cohesion of 0 Nt/m^2.

brush covered hillside, if the fire is hot enough.

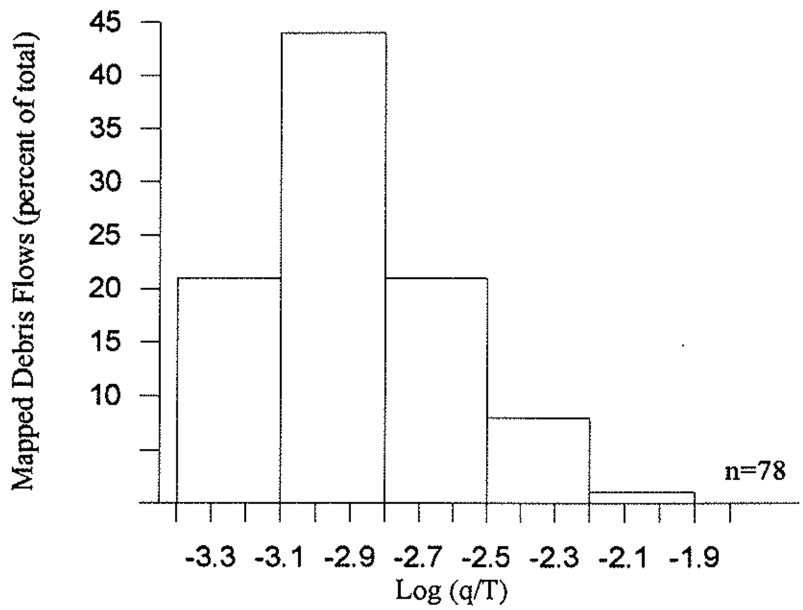
By overlaying mapped areas of instability on the predicted relative stability map, and assigning a log(q/T) value based on the least stable point (highest negative value), we have constructed a histogram of log(q/T) values of observed instability. Figure 5, shows results for the Oakland hills area. As we have found in every other case were we have tested this approach (5 sites in California, Oregon and Washington), all scars are found to occur at values smaller (larger negative numbers) than -2.2, and nearly all occur at values smaller than -2.5. As a practice elsewhere to make the slope stability model parameter free, we have fixed the angle of internal friction at forty five degrees and set cohesion equal to zero. If we had used forty five degrees rather than forty degrees for the cohesionless case (Figure 4) more of the landslides would occur at values greater than -2.5 (i.e. in the -2.5 to -2.2 category).

This result is very encouraging because it suggests that the simplest cohesionless model can be used in a parameter free mode. Calibration based on mapped landslides can be done, but so far areas falling the in log (q/T) value of -2.5 and smaller (i.e. -3.1 etc) can be assumed to be a highest risk.

The slope stability model can be applied in any year and need not wait for a fire to be used. Hence this model could be incorporated into land use planning. It is currently being used by Weyerhaeuser Company, Louisiana-Pacific, Plum Creek and the Bureau of Land Management as a guide in timber practices.

Once we complete the construction of our digital terrain model for the San Luis Obispo area we will be able to explore this model's application in explaining patterns of observed landsliding. The digital data and field observations should form the basis for developing a model

Hillslope Stability for the Oakland Hills - Apparent Cohesion: 1000 Nt/m^2



Hillslope Stability for the Oakland Hills - Apparent Cohesion: 0 Nt/m^2

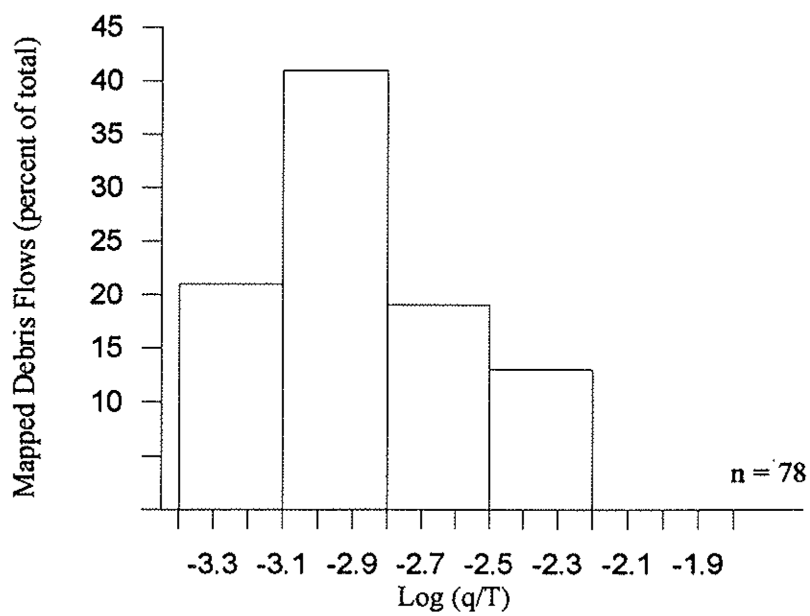


Figure 5. Minimum stability ratios (log q/T) for observed shallow landslide features in the Oakland Firestorm area. The larger the negative number, the smaller the rainfall amount needed to cause instability.

that not only delineates potential hillslope instability, but also areas prone to in-channel failures and places where runoff may accumulate sufficient sediment to change rheology to that of a mudflow.

SUMMARY

The application of the simple digital terrain model for slope stability hazard analysis in the Oakland hills firestorm area suggests that the model could be used to identify sites of greatest potential for slope instability. This application could be done well before a fire has occurred and be used to guide land use planning and hazard awareness programs. Documented pattern of shallow landsliding after the 1994 fire in the San Luis Obispo area raises serious questions about the value of grass seeding after a fire. It is possible that grass seeding increases the risk of landsliding. Once we have created our digital elevation model for this area we will explore this hypothesis more through modeling. Work is still needed in identifying those areas where mud flows originate from runoff into sediment laden steep channels.

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