Runoff and Erosion after the Oakland Firestorm

Expectations and Observations

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EXPECTATIONS: AFTER THE FIRESTORM

In fewer than 10 hours on October 20, 1991, hot dry winds blowing from the Central Valley reignited a backyard fire that had been smoldering since the day before and swept flames across the Oakland and Berkeley hills, killing 25 people and destroying 2,903 dwellings (Photo 1, Figure 1). The fire spread so quickly, even crossing an eight lane freeway, that only the cool, moist evening air gave the army of firefighters an opportunity to seize control of the fire and eventually extinguish it.

Immediately after the Oakland fire (officially named the Tunnel Fire) was contained, intense media coverage began drawing parallels with southern California fires, and focusing on the possibility of winter rains producing catastrophic landsliding in the 1,800 acres (728 hectares) of burned urban and wildlands. Steep burned slopes, the identification of strong to moderate soil hydrophobicity (water repellency) in association with eucalyptus *(Eucalyptus globulus)* and Monterey pine *(Pinus radiata)* (D.W. *Howell, Soil conservation* Service, Arcade Office, written communication, 1991), and the U.S. Department of Agriculture's Soil Conservation Service's (SCS's) classification of local wildland soils as extremely erodible (Welch, 1981), heightened the anticipation of problems for land managers immediately after the fire. Such concerns may seem, at first, obvious and justified on the basis of the "fire-flood" sequence observed in southern California, and popularized by John McPhee (1989) in his book *The Control of Nature*. Indeed, our perceptions of the effects of fire on landscape tend to be driven by the events that produce the most vivid memories.

An interagency emergency response task force was formed after the Oakland firestorm to identify erosional and rehabilitation problem areas. Based on the task force's recommendations, the City of Oakland applied erosion and sediment control measures (developed primarily for construction and mine reclamation sites) to the bulk of the burn within its jurisdiction, half of which could be considered wildlands. The response was swift, well coordinated, and complete.

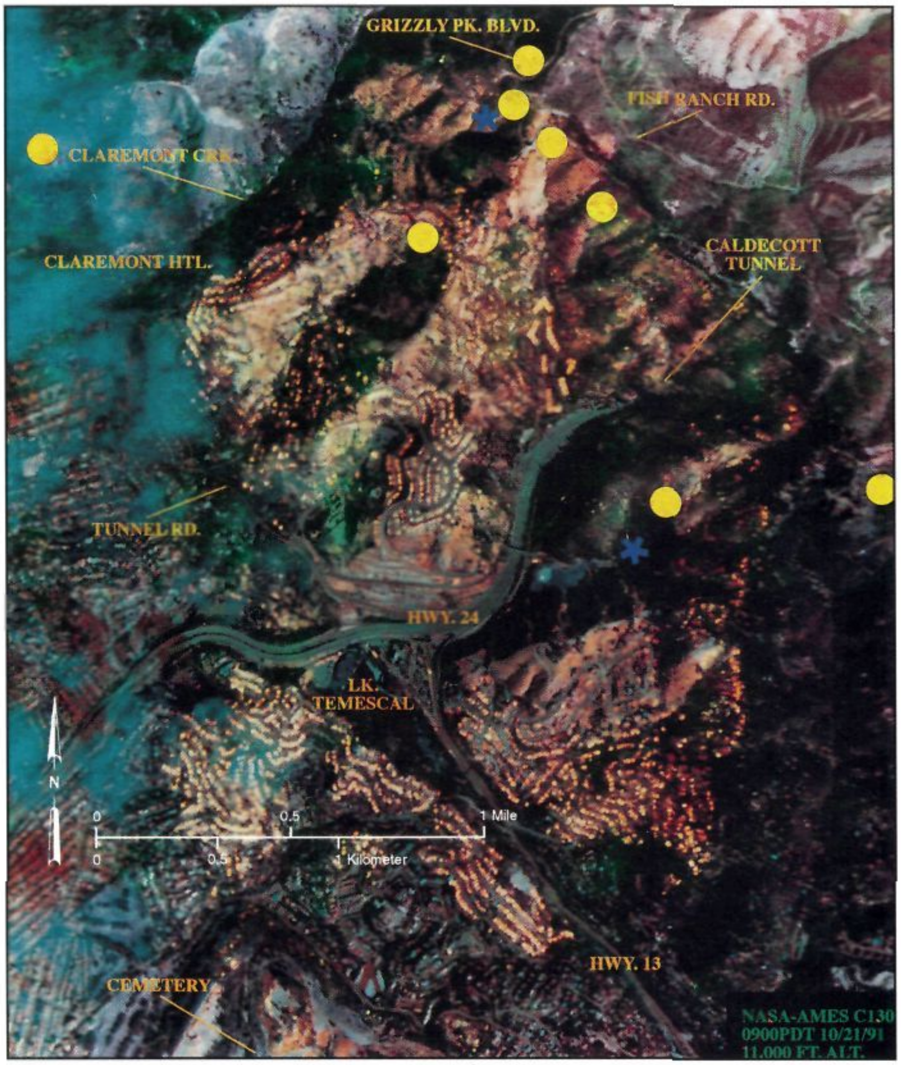

Photo 1. NASA-Ames air photo of the Oakland Firestorm area. Bright lights are burning foundations. The fire is bounded by Tunnel Road on the west, Claremont Creek on the north, and Grizzly Peak Boulevard on the east. The southern boundary is delineated by burning homes. Yellow dots designate runoff and erosion plot sites. Claremont Creek Regional Park and North Oakland Sports Center straw bale sites are marked by blue "stars."

Although media and public agency concerns focused on catastrophic landsliding resulting from winter rains, and protection of downstream water bodies, almost the entire erosion control effort was directed at preventing surface loss of soil and at temporary control of sediment in streams. The cost approached $5 million, making it the

Figure 1. San Francisco Bay Area. Orange rectangle approximates area in Photo 1.

most expensive post-fire erosion control project in California's history.

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 the highly flammable wildlands of California, the potential for such fire is increasing. The Berkeley Fire of 1923, which swept down toward San Francisco Bay on a similar day of hot dry winds from the Central Valley, destroyed 584 homes and served as a warning. More recently, the Santa Barbara Paint Fire in 1990, which burned 4,900 acres (1,980 hectares) and destroyed 641 homes, and Santa Barbara's 1977 Sycamore Fire, which burned 804 acres (325 hectares) and destroyed 234 homes, illustrate the risk of living at this interface. While much discussion and planning is underway to provide better fire response and reduce the risk of catastrophic fire, little has been done to assess the need and effectiveness of costly post-burn temporary erosion-control measures. This problem is not, of course, limited to the urban/wildland interface. California has extensive forest fires, such as the one that burned 600,000 acres (242,915 hectares) in 1987.

The issue of accelerated erosion affecting downstream resources is raised following each fire. There is a growing trend toward intervention, of implementing engineering solutions to control natural processes. Although state and federal laws require immediate post-fire erosion control efforts to be developed on public lands, there is a growing debate about the need and effectiveness of such commonly used measures as grass seeding and temporary straw bale check dams like those used after the Oakland fire. In fact, some evidence suggests that grass seeding can be counterproductive (Krammes and Hill, 1963; Rice and others, 1969; Rice and Foggin, 1971; Conrad, 1979; Gautier, 1983; Nadkarni and Odion, 1986; Barro and Conard, 1987; Miles and others, 1989; Taskey and others, 1989; Conard and others, 1991; Libby and Rodrigues, 1992; Booker and others, 1992).

We present an analysis of expectations, and observations of the runoff and erosional response to the Oakland firestorm as modified by erosion control measures. Our goal is not to second-guess the measures taken under emergency conditions, but rather to offer observations and recommendations that could prove useful in deciding appropriate responses to inevitable fires. Our fundamental point is that erosional response to fire varies greatly in a recognizable way based on factors such as geology, topography, climate, and land use. Costly temporary erosion control measures in some cases of wildland fire appear unnecessary and may even be counterproductive.

THE SOUTHERN CALIFORNIA MODEL

The erosional response of burned lands to winter storms in canyon lands in southern California has been well documented (Barro and Conard, 1991; Rice, 1982; Wells, 1981, 1987), and has commonly been referred to as the "fire-flood" sequence. Immediately after a fire, and in some cases during the fire, as organic debris dams are incinerated, debris and coarse sediments flow downslope into channels, washes, and gullies accentuating a process called "dry ravel" (Anderson and others, 1959; Wells, 1981; Rice, 1982). The process of dry ravel is most closely associated with very steep slopes underlain by granitic rocks or coarse-grained sandstones in areas that are tectonically active and undergoing rapid uplift resulting in background erosion rates as high as 0.06 to 0.09 inches (1.4 to 2.3 mm) per year (Wells, 1986; Scott and Williams, 1978). In parts of southern California, the process of dry ravel, independent of fire, accounts for half of all hillside erosion (Anderson and others, 1959; Krammes, 1965; Rice, 1974; Howard, 1982). Ongoing studies in the California chaparral wildlands demonstrate that dry ravel and, to a lesser extent, the formation of extensive rill networks account for most of the increased sediment production following a fire (Wells, 1986).

Fires can also vaporize organic compounds within the burning vegetation. The vapor moves through the soil to a depth where it will condense, forming a water repellent layer, or hydrophobic soil (DeBano, 1981; Savage, 1974). This water repellency is strongest in coarse soils (DeBano, 1981), and can produce increased runoff and sediment loading through the development of an extensive rill network (Wells, 1986) (Figure 2). The increased flow to channels during periods of intense rainfall can mobilize sediment and debris stored in the channel, as a debris flow, or what was originally thought of as a debris flood, hence the term "fire-flood" sequence. However, work done by Florsheim and others (1991), following the 1985 Wheeler Fire near Santa Barbara, suggests that normal fluvial transport of these sediments is more likely. According to Florsheim and others (1991), moderate storm events that could mobilize sediments are far more likely to occur than the large magnitude, high intensity storm events that would generate large destructive debris flows. More recently, the 14,900 cubic yards (11,400 m^3) of sediments deposited in debris basins following the 1990 Santa Barbara Paint Fire were also a result of normal fluvial transport of ravel derived sediments, rather than debris flow (David Valentine, U.C. Santa Barbara, oral communication, 1993).

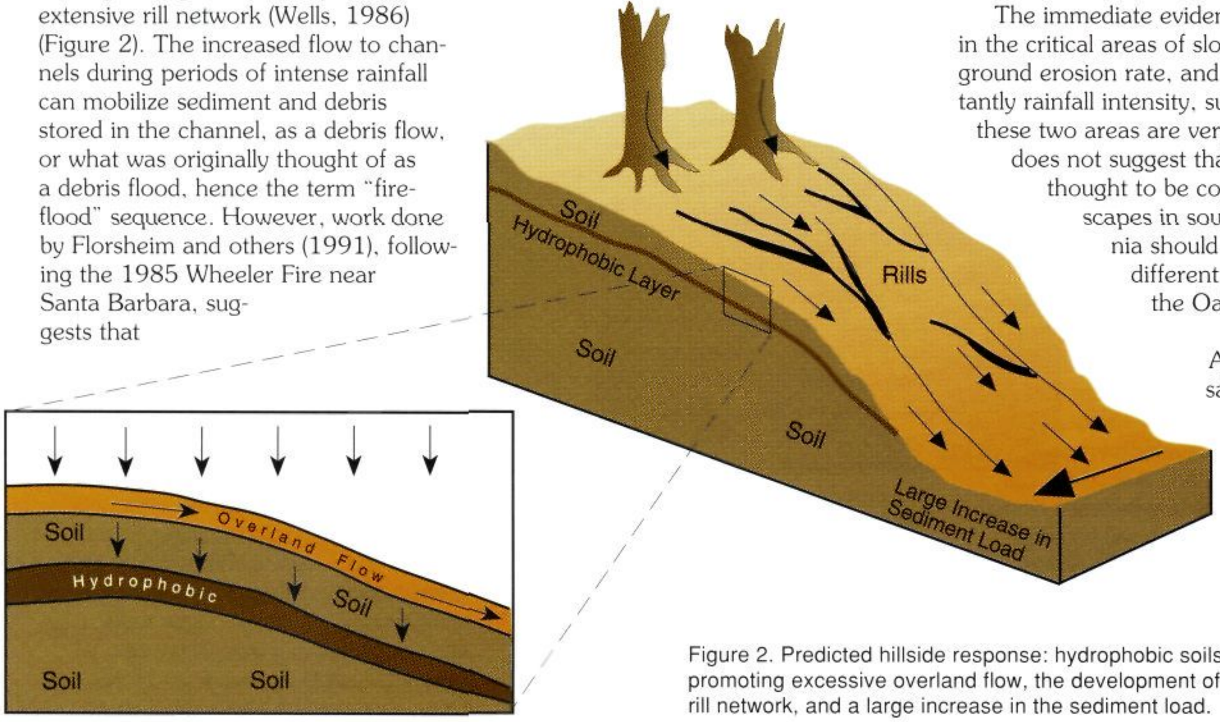

Figure 2. Predicted hillside response: hydrophobic soils promoting excessive overland flow, the development of a rill network, and a large increase in the sediment load.

WILL THE "FIRE-FLOOD" SEQUENCE OCCUR IN THE OAKLAND HILLS?

Although at least 14 wildfires have occurred in the East Bay Hills since 1923, no written record or field evidence of catastrophic erosional response to fire has been found. If we approach the problems of hazard and risk assessment without any knowledge of fire history and post-fire erosional response in the East Bay Hills, how could we assess the likelihood of possible catastrophic response to the October 20, 1991 Oakland fire?

We could start by looking for similarities in landscape between southern California and the Oakland Hills that suggest a debris flow/"fire-flood" response could be possible (Table 1).

The immediate evidence, especially in the critical areas of slope, soils, background erosion rate, and most importantly rainfall intensity, suggests that these two areas are very different. It does not suggest that processes thought to be common to landscapes in southern California should apply to a very different landscape in the Oakland Hills.

A reconnaissance of the Oakland Hills burn area on

Table 1. Watershed Parameters for Southern California and the Oakland Hills.

PARAMETER	COASTAL SOUTHERN CALIFORNIA "FIRE-FLOOD" WATERSHEDS	OAKLAND HILLS FIRE AREA WATERSHEDS
Max. Relief	9,184 feet (2,800 m)	1,100 feet (335 m)
Slope	Ave: 65%; Max: >100% (Wells, 1981)	Ave: 35%; Max: 90%
Watershed area	1 km^2 - 13 km^2 (0.6 - 7.8 square miles) (Wells, 1981; Taylor, 1983)	<1.2 square miles 1(2 km^2)
Soils	coarse (granitic, sandy) soils, shallow, no soil profile development (Wells, 1981)	loams, shallow, moderate to well developed profiles (Welch, 1981)
Background erosion rate	1.4 - 2.3 mm/year (0.06 - 0.09 inch per year) (Wells, 1981; Scott and Williams, 1978)	0.08 mm/year (0.003 inch/year) (Reneau, 1988)
Rainfall intensity	25 mm/hr (1 inch/hr) 2-10-year return interval (Phil Holland, Santa Barbara County Flood Control district, oral communication, 1993)	25 mm/hr (1 inch/hr) 100-year return interval (Rantz, 1971)

October 22, 1991, immediately after the fire, and again on October 25, 1991, after the first storm of the season, showed little evidence of natural rilling except from road runoff. Significant piles of ravel at the bases of slopes or in the channels were not evident.

At a weather station 3 miles (5 km) south of the fire area, rain for the October 25 storm was reported as 75 mm (2.96 inches) during 13 hours (a 10-year return interval [Rantz, 1971]) with maximum intensities of 30 mm per hour (1.2 inches/hour) for a 6-minute interval. A station 1.2 miles (2 km) north of the fire area reported 34 mm (1.34 inches) (a 2-year return interval [Rantz, 1971]) during 13 hours of rainfall and maximum intensities of 7 mm (0.28 inches) per hour for a 7-minute interval. Raveling and rill development are usually initiated early on, and if they are not evident after the first significant storm, the likelihood that they will develop decreases as the winter progresses (Wells, 1986).

The 1985 Lexington Fire burned 13,800 acres (5,585 hectares) about 6 miles (10 km) south of San Jose. Although this fire is closer geographically to Oakland, geomorphology and climate are still very different. Runoff from early winter storms developed a rill network in the poorly consolidated highly fractured shales and interbeded sandstones. Most of these rills developed during storms between October and December 1985, after about 12 inches (300 mm) of cumulative rainfall. This is about 30 percent of the mean annual rainfall for the area (30 to 48 inches [760 to 1,220 mm] depending on elevation) (Rantz, 1971). Few rills developed after December, despite an additional 51 inches (1,300 mm) of rain in early 1986 (Keefer and others, 1986).

The total rainfall of 63 inches (1,600 mm) is about 300 percent of normal for the Oakland Hills area (22 inches or 560 mm per year). Despite the large amount of runoff, burned slopes yielded little sediment. In fact, the response was contrary to the popular notion of how a burned landscape should respond following a fire; there was no evidence of a "fire-flood" response, or of significant landsliding (Keefer, and others).

ESTIMATION OF EROSION POTENTIAL

Slope response similar to the southern California "fire-flood" sequence outlined in Figure 2 was predicted because of the identification of hydrophobic soils in the Oakland Hills fire area* and the belief that rainfall intensities of 2 inches (50 mm) per hour for as long as 3 hours (>100-year storm) were possible for the Oakland fire area (U.S. Department of Agriculture, Soil Conservation Service video of post-fire conditions, October 24, 1991). Water repellency was evaluated by the SCS using the standard water drop test. The time required for a large drop of water to soak into the soil determines its class of hydrophobicity.* Of the six wildland sites tested, five showed evidence of hydrophobicity. Hydrophobicity was most pronounced in intensely burned eucalyptus groves, with slight to strong hydrophobicity evident in burnt stands of Monterey pine. Subsequent tests show these two vegetation types to be relatively equal in hydrophobic development beneath healthy (unburned) stands.

As a result of an anticipated increase in runoff and erosion, an estimate of possible soil loss for the Oakland Hills was 75 cubic yards per acre (142 m^3/hectare) (unpublished Interagency Task Force soil erosion treatment meeting notes, October 24, 1991). Conversely, geologists from the U.S. Geological Survey (USGS) and the California Department of Conservation's Division of Mines and Geology (DMG) (Tom Spittler, oral communication) felt water repellent soils were discontinuous and there was not a serious erosion hazard in the firestorm area (see Spittler, this issue).

MITIGATION EFFORTS AFTER THE FIRESTORM

As a result of potential erosion estimates, 1,800 acres (720 hectares) of the burn area were initially seeded by air (29 pounds per acre or 32 kg/hectare) on October 23 and 24, 1991. The seed mixture consisted of six species, three of which are not natives: California soft chess *(Bromus mollis)*, Hykon rose clover *(Trifolium hirtum)*, and Zorro annual fescue *(Festuca megalura)*. The three native species are Berkeley blue wildrye *(Elymus glaucus)*, California poppy *(Eschscholzia californica)*, and native blue lupin *(Lupinus ssp.)* (Libby and Rodrigues, 1992). The first storm of the season was on October 25, 1991. The burn area was reseeded as part of a hydromulch application during November and December, 1991. Hydromulch was applied to more than 500 acres (200 hectares) of burned wildlands.** Each acre received 29 pounds (13 kg) of seed, 1,000 pounds (455 kg) of paper mulch, 500 pounds (227 kg) of wood fiber, and 110 gallons (416 l) of acrylic copolymer glue, at a cost of approximately $1,750 per acre ($4,325/hectare) (International Erosion Control Association, 1992).

In addition, 1,700 straw bale check dams were placed in gullies, channels, hollows, and landslide features in an attempt to moderate channel flow and hillside overland flow. Roadside areas were treated with seed, straw mulch and the copolymer glue (International Erosion Control Association, 1992). Over 35 acres (14 hectares) of steep hillsides overlooking buildings that survived the fire were treated with straw, fiber, and monofilament erosion blankets, and additional roadside areas were treated with straw mulch (International Erosion Control Association, 1992). It is important to note that these treatments have only one purpose: to prevent the surface loss of soil by overland flow, not mitigate the larger effects of landslides.

Additional engineered features such as concrete and steel debris racks and silt fences were installed, but these features were designed to mitigate erosion, not prevent it. Two small drainage basins of 12 acres (5 hectares) or fewer were extensively engineered. Slopes were laid back, all remaining vegetation was removed, and the incised channels were filled with soil and then resurfaced, one with monofilament erosion mats.

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*D.W. Howell, Soil Conservation Service, written communication, 1991.

**The number of acres treated with hydromulch is an extrapolation derived from total quantities of products (Woodward Clyde Consultants Inc., 1992, video about erosion control response), and the recipe for hydromulch used in the Oakland fire response (International Erosion Control Association, 1992).

Photo 2. Old landslide and debris flow scars shown by arrows (some associated with road runoff) are revealed following the loss of vegetative cover in the Oakland Hills fire. These slopes have been treated with a hydromulch application of seed, mulched paper, wood fiber, and acrylic copolymer glue.

SLOPE FAILURE AND FIRE

After the fire, the vegetation-free landscape offered a clear view of the numerous landslide scars that had formed during previous years (Photo 2). These landslides, mostly slides, slumps, and flows, contrast with the "fire-flood" debris flows that are generated in steep canyon bottoms in freshly deposited ravel. Most are relatively shallow slope failures that occur following increases in ground saturation. Shallow soil slides can develop into fast moving debris flows of saturated soil, whereas slumps and earth flows are typically slow moving. Debris flows are initiated during intense rainstorms under specific conditions of antecedent ground saturation, rainfall intensity, and storm duration (Cannon and Ellen, 1988). The landslides related to urbanization are commonly shallow slides along road cuts and fills, along gully walls that have been incised by concentrated road runoff, or where the gully incision has destabilized the slope above it.

One cause of fire-related landsliding is the reduction of vegetative root strength, which would not occur until several years after a fire. Soil pits dug after the fire typically showed roots deeper than about 3 inches (8 cm) below the surface to be strong and unburned. During the winter many species of pre-fire plants resprouted. The dominant brush species, coyote brush *(Bacharris pilularis)*, was able to crown sprout following the fire. Bluegum eucalyptus trees, introduced to the Oakland Hills in the early 1900s, are being cut down by homeowners and public agencies because many think they are responsible for the rapid spread of fire. The stumps are starting to resprout so it is not known how their root strength will be affected. Monterey pines, which were introduced at the same time, did not survive the fire, and their root deterioration will continue over several years.

In the event of a severe loss of root strength in fire-damaged plants, reseeding Oakland hillsides with grasses would not prevent landsliding. The shallow landslide features common to the Oakland Hills typically have failure planes below the rooting zone of grasses. We think that heavy densities of reseeded grasses would only increase infiltration, and therefore soil moisture.

LANDSLIDE MAPPING AND REBUILDING

Consultants contracted by the City of Oakland counted 184 scarps or other geomorphic features thought to be associated with landslides within the burn area, prompting city employees to map existing and potential failure sites. The consultants issued a draft report, in which the probability and consequence of a landslide failure were evaluated at each identified feature, and a relative measure of risk was calculated for each affected area in terms of the probability of significant damage to public or private properties. This report was used by the City of Oakland in the development of a management plan to revise build-ing permit policy in order to address these landslide risks. Although the mapping and assignment of hazard probability can be debated, the City of Oakland deserves credit for developing a planning tool of this kind. Even though development of the plan was facilitated by the exposure of the landscape by fire, this type of management plan is beneficial at any time, because of the chronic landslide hazard in the Oakland Hills.

BURN AREA OBSERVATIONS: MONITORING PROGRAM

To evaluate the effectiveness of the erosion control measures and to analyze how wildfires influence runoff and erosion processes in the Oakland Hills, we monitored winter runoff and erosion on several small erosion plots established in the upland areas of the burn. During the summer of 1992, the number of erosion plots was increased, and runoff and erosion were measured during several controlled artificial rainstorm experiments. Sprinkler experiments allowed a more detailed analysis of runoff and erosion mechanisms and provided a broader range of rainfall intensities than occurred in a normal winter (Meyer and McCune, 1958; Selby, 1970; Birk and others, 1979; Dunne and others, 1980; Imeson and others, 1992).

Given the emergency status and time constraints of the project, it was not possible to install and monitor a large network of observation points. Instead, we focused on collecting field data and understanding processes at representative sites. These observations were supplemented by extensive inspection of the burn area during storms.

Seven plots were established on slopes of 30 to 40 degrees for winter monitoring in four drainage basins in wildland areas of the Oakland Hills. Steeper than average slopes were selected because they are typical of slopes found in southern California, and because erosion will be greatest on these steeper slopes. Five plots were in the fire area, and two in an unburned canyon adjacent to the burn. Plots were established on soils from the two predominant parent materials, chert and sandstone (gravelly loam and loam soils), and on hydromulch-treated and untreated slopes. The pre-fire vegetation types for these plots were predominantly eucalyptus and Monterey pine, which are associated with the water repellent soils found in the fire area. Plots were approximately 15 feet (4.5 m) long by 5 feet (1.5 m) wide, with sheet metal boundaries. A covered trough at the downslope end trapped sediment and directed overland flow to a storage container (Photo 3). Seven additional plots were constructed on sites with similar conditions during the summer of 1992 for the simulated rainfall experiments.

Winter of 1991-92

Rainfall for each plot was monitored using rain gauges at each site. Rainfall intensity was monitored through the Alameda County Flood Control District's ALERT network, and reported in 1-mm- (0.04-inch-) per-minute increments. Two stations were used, one 1.2 miles (2 km) north of the burn area, and a new station established in the fire area. There were 14 storms between January and April, 1992, with none exceeding 0.5 inches (12 mm) of rain in an hour, or 2.25 inches (57 mm) in 24 hours (a storm event with approximately a 2-year return period). Total rainfall for the winter approximated the mean annual precipitation of 22 inches (559 mm).

As the winter progressed, it became clear that although there was significant evidence of hydrophobic soils throughout the burn area, overland flow and erosion on the natural undisturbed slopes were limited. Intermittent minor rilling developed at the base of some large bare eucalyptus trees as a result of concentrated stem flow onto exposed soils. This process did not continue once new eucalyptus growth dispersed the flow. Additional small rills developed downslope of game trails and exposed bedrock. Rills were observed in only two other areas: where concentrated road runoff was directed onto the hillsides, and where runoff from fire hoses had been concentrated. Existing natural rills were subsequently smoothed by rain splash, sheetwash, and animal activity.

Photo 3. A runoff and erosion plot. Runoff is funneled from the trough to 5-gallon plastic containers connected in series to store runoff and suspended sediment. The emergent vegetation is Indian Soap Plant *(Chloragalum pomeridianum)* and is not a result of the reseeding effort.

In the gravelly loam soils, near surface flow was predominantly confined to about a 0.8-inch- (2-cm-) thick wettable soil horizon above the hydrophobic layer. Within this wettable soil there was significant flow through the soil (through flow), a process also documented by DeBano (1968), Savage (1974), and Wells (1981). This wettable soil layer was a mixture of ash, gravel, and mineral soil. Direct precipitation on saturated areas of this wettable soil horizon produced a thin saturated overland flow. In the loam soils, through flow was observed only within ash layers, not within any soil horizon. When the mineral soil was exposed, the surface (0.2 inch or 5 mm) became saturated while the underlying soil remained drier. Rivulets of overland flow developed under conditions of intense rainfall. Continuous overland flow to channels did not occur. Instead, the numerous deep cracks and holes in the soil formed by pedogenic (soil-forming) and biologic processes diverted flow to greater depths. Similar processes were noted by Imeson and others (1992) while studying fire effects on infiltration and runoff on Mediterranean forest soils, and by Santa Barbara County Flood Control District engineers during two separate sprinkler experiments following the 1977 Sycamore Fire and the 1990 Paint Fire (Phil Holland, oral communication, 1993).

Maximum surface runoff as a percentage of rainfall for the gravelly loam soils was estimated to be no greater than 7 percent for the plot without hydromulch and 5 percent for the treated plot. Control plots in an unburned eucalyptus grove produced a maximum overland flow of 5 percent. The surface runoff for our two untreated plots on the loam soils was higher than that on the gravelly loam sites. Maximum runoff for the loam soils was 23 percent of total precipitation at the untreated sites but only 3 percent at the treated site. This higher value appears to be due to lower infiltration rates of the loam soils and less crack and hole diversion of runoff to deeper soil horizons (Table 2).

On the untreated plots, sediment loss as a result of overland flow was very low. If we take the total sediment collected from each untreated plot and divide it by the plot area, we get an equivalent

Table 2. Runoff for Seven Sites Following the Fire. January–April, 1992.

SITE	VEGETATION	SOIL TEXTURE	HYDRO-MULCHED	MEAN RUNOFF	MAX. RUNOFF
M1	Monterey pine and brush	loam	no	11.4%	23%
M2	Monterey pine and brush	loam	yes	1.4%	3%
VN1	eucalyptus	loam	no	13.8%	24%
GW1	eucalyptus	gravelly loam	yes	2.9%	5%
GW2	eucalyptus	gravelly loam	no	4.9%	7%
CV1	eucalyptus	gravelly loam	control unburnt	1.8%	5%
CV2	hardwoods and eucalyptus	gravelly loam	control unburnt	1.0%	3%

surface-lowering of about 0.004 inch (0.1 mm) during the winter. This amount is much smaller than the equivalent soil loss of 0.6 inch (14 mm) predicted by the interagency task force (1991) (Figure 3).

There was an overall decrease in sediment loss on all plots (treated, untreated, and control) through the winter, even though the largest storm events came later in the season. Similar results were noted in Colorado by Morris and Moses (1987). This observation suggests that sediment loss in the Oakland Hills is a function of sediment availability, rather than solely of potential runoff.

Artificial Rainfall Experiments

Because the winter immediately after the fire did not provide an opportunity to study the impact of a large storm on the Oakland firestorm area, we decided to simulate a 100-year storm. Artificial sprinkler experiments simulating 1-hour storms, of between 1 and 2 inches per hour (25 and 51 mm/hour) of rainfall, were conducted between July and October, 1992. Twenty artificial storms were applied to 11 plots: three control plots and eight burn plots, four of which had been monitored the previous winter. It could be argued that site conditions the following summer would be very different from those immediately after the Oakland fire. However, water repellent soils can be long lasting (DeBano, 1981), and we were able to find sites that still had ash layers and water repellent soils, and lacked understory vegetation. These additional sites included two plots in a eucalyptus grove prescribe-burned during the 1992 summer, and had similar soils and slopes to those of the Oakland fire area.

Our sprinkler experiments were conducted using two low-pressure nozzles mounted on trolleys and suspended from rails in a tubular aluminum frame. The frame stood about 10 feet high by 6 feet wide by 20 feet long (3 m x 2 m x 6 m) and was centered over the runoff and erosion plot (Photo 4). The nozzles were moved back and forth rapidly along the length of the rails using a pulley system, so that as one nozzle was pulled up the plot, the second nozzle descended. Nozzles were chosen that best simulated natural rainstorm drop sizes and produced a precipitation intensity of between 1 and 2 inches (25 and 51 mm) per hour, and had the ability to cover the plot with a relatively even distribution of spray. To estimate the average drop size for storms here in the East Bay Hills, we collected eight samples of natural raindrops using sifted white flour in a pan during three separate storms. The pans of flour were then baked, and the hardened raindrops sifted for size.

Two artificial storms were applied to most plots, and all vegetation was removed prior to the second sprinkler experiment. Runoff as a result of increased precipitation intensities never exceeded the winter maximum value for plots in the burn area. There was in fact a decrease in runoff for all plots in reseeded areas. This decrease in runoff can be attributed to an increase in gopher activity providing additional subsurface flow paths, and to increased infiltration provided by the grass cover (Photo 5).

Sediment loss as a result of increased precipitation intensities was minimal when compared to the SCS estimated equivalent soil loss of 0.6 inch (14 mm). The maximum sediment loss for a single 100-year storm was about 50 per cent of the total soil loss for the winter of 1991. The cumulative net soil loss for all winter storms monitored and a single simulated 100-year event was only 0.006 inch (0.15 mm), two orders of magnitude less than the equivalent maximum soil loss estimated by the SCS.

Bioturbation

During the winter, a lattice of deer trails developed across the slopes. Animal tracks and disruption of soil and rock fragments occasionally appeared in the plots. When cleaning out sediment troughs after storms, it was obvious from the large particle size of some of the stored sediment, that some of the material was a result of this disturbance.

As vegetation increased from the reseeding effort, gopher activity and total sediment flux within the plots increased. Previously undisturbed soils were churned up, with mounds of loose soil spilling downslope, and in some cases filling sediment troughs that had remained empty during the previous winter. This disturbance was most obvious in those areas that had a cover of reseeded grasses. The measured sediment loss as a result of this bioturbation

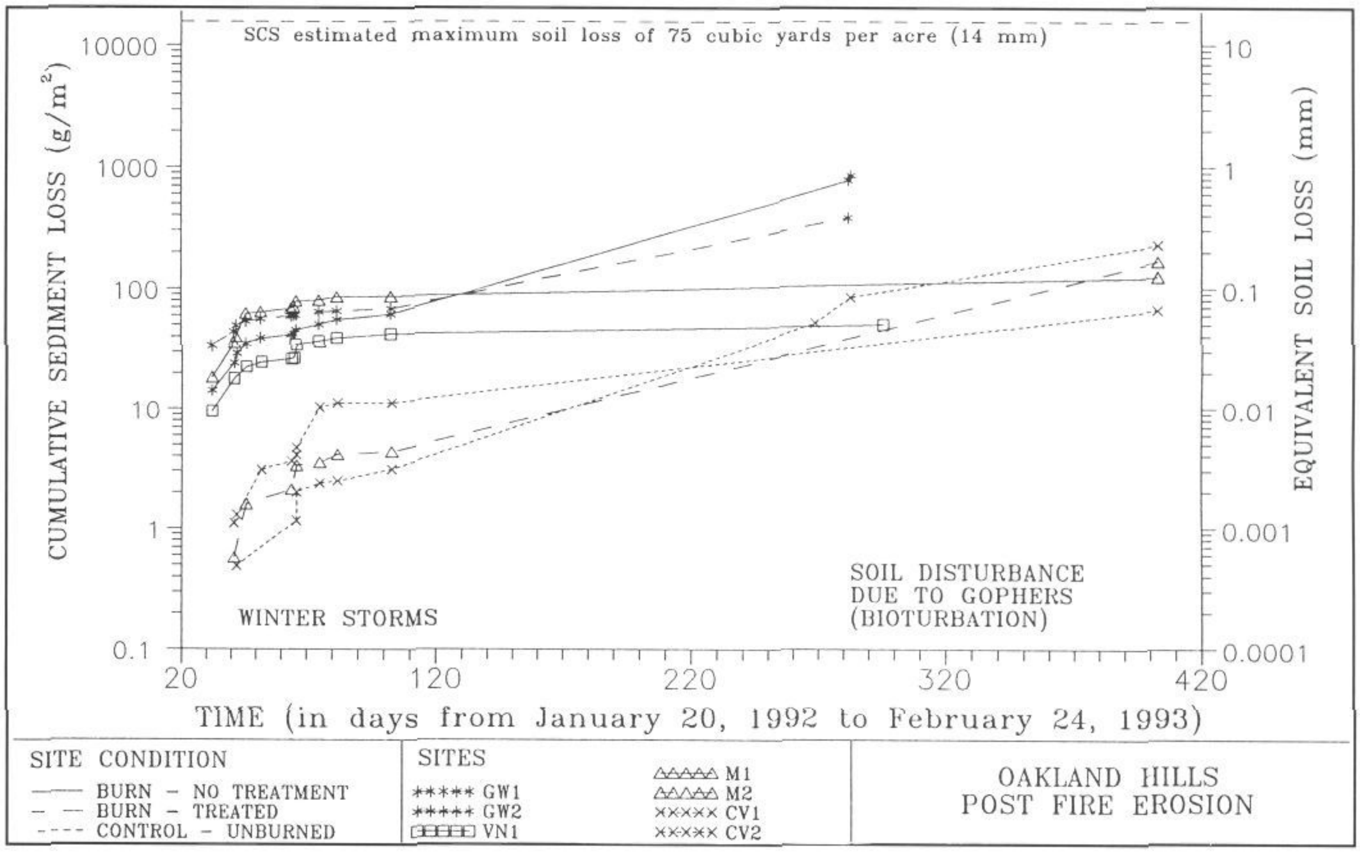


Figure 3. The graph depicts cumulative sediment loss and equivalent soil loss at the seven runoff and erosion plots between January 20, 1992 (day 20), and April 10, 1992 (day 100), and the increased soil disturbance by gophers at the same sites, monitored between September 27, 1992 (day 270) and February 24, 1993 (day 420). Both vertical axes use a logarithmic scale because it is an efficient way to plot data when there is a large spread in values, as between 0.5 g/m² and 14,000 g/m² (SCS estimated maximum soil loss). The left-hand axis represents the weight of sediment collected in the troughs of the seven plots, whereas the right-hand axis represents the equivalent lowering of the soil surface, assuming a density of 1 gram per cubic centimeter for the eroded sediments.

during the spring, summer, and fall of 1992 was an order of magnitude greater than sediment loss due to overland flow during the winter following the fire. This process is very similar to that reported by Taskey and others (1989) following the Las Pilitas burn in 1985. Hence, as odd as it may sound, the largest natural slope response was cause by gophers (Figure 3).

Soil Moisture

Soil moisture was measured six times between January and late March, 1992. Cores were taken to bedrock, which was typically 2 to 3 feet (0.6 to 0.9 m) at most sites. Samples were then analyzed for soil moisture content by drying at 221°F (105°C) for 24 hours. Soil moisture averaged over the length of the

Photo 4. The simulated greater-than-100-year storm was applied by rapidly moving two nozzles on trolleys suspended from central rails in the tubular frame 10 feet (3 m) above the plot. Runoff and sediment were collected from two troughs, an upper trough to monitor overland flow, and a lower trough to monitor flow through the wettable soil layer.

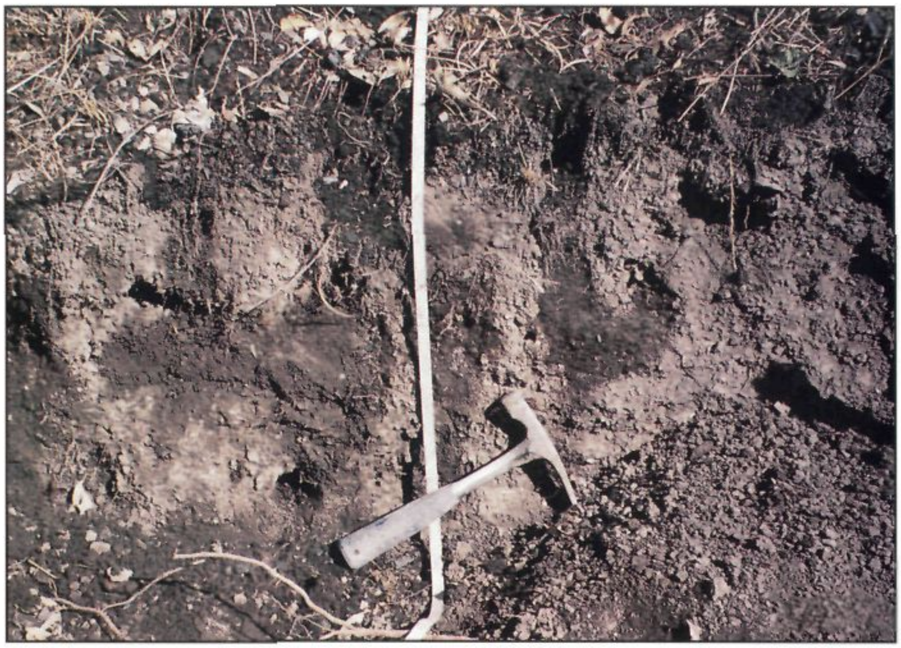


Photo 5. Reseeded plot after two simulated storms (4 inches or 10 cm of applied rainfall). The saturated surface horizon overlies a hydrophobic layer that is interrupted by vertical flow paths created by roots and gophers.

sample was used to compare sites. Except for the first sampling period in January, sites treated with hydromulch and the grass seed mixture always had a higher soil moisture content than untreated sites. By the end of March 1992, soil moisture contents at treated sites (26 percent soil moisture) were, on the average, 23 percent higher than those at sites with similar soils that received no treatment (19 percent soil moisture). While the increased moisture content in the treated sites points to the success of the treatments in retaining water and thus reducing overland flow and potential surface erosion, it raises another issue. Many areas that had landslide scars, or were steep enough to generate landslides, received treatments of hydromulch, erosion mats, or straw bales, and presumably would have had elevated soil moisture contents (Photo 6). Although the moisture increase is relatively small, increasing soil moisture in potential slide areas decreases the amount of precipitation needed to cause landsliding. It has even been argued by some (Morton, 1989) that burned slopes may be less susceptible to landsliding where significant overland flow due to shallow water repellency reduces soil moisture content.

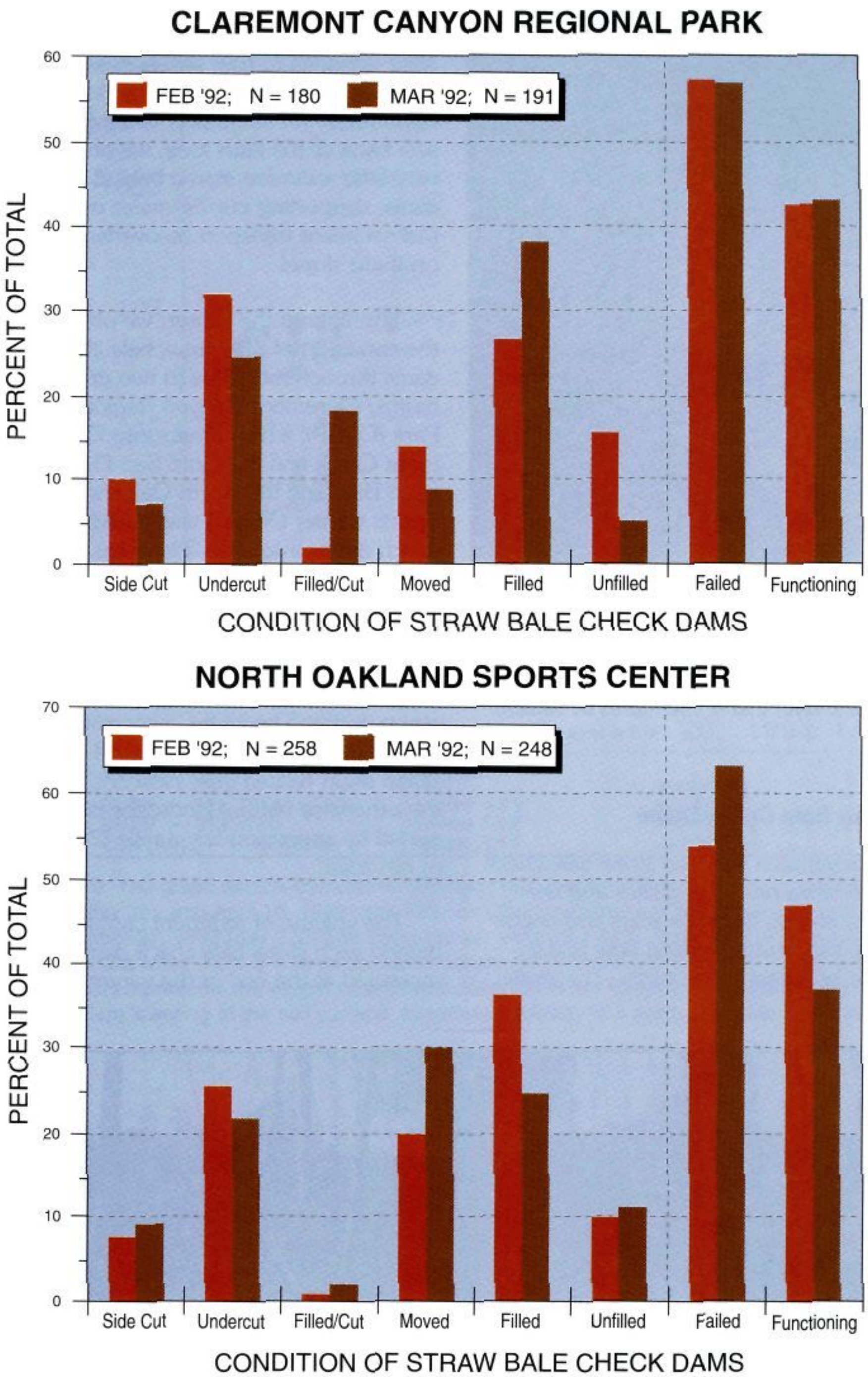
Straw Bale Check Dams

Seventeen hundred straw bale check dams were placed in gullies and hollows, and on landslide scars and deposits to moderate overland flow and to store sediment temporarily. The straw bale dams on landslides and in hollows were designed to trap sediment and increase infiltration, thus furthering the opportunity for saturation. During several tours of the burn area, we observed very little sediment stored behind these dams, supporting our estimates of minimal sediment transport by overland flow on these slopes.

Throughout the winter, we observed the condition of 438 straw bale check dams throughout gullies in two drainage basins: Claremont Canyon Regional Park (CCRP), which drains into Claremont Creek and then into San Francisco Bay; and the North Oakland Sports Center (NOSC) watershed, which drains into Lake Temescal (Photo 1). The CCRP watershed is a relatively natural landscape with a few hiking trails and an urban boundary along its upper perimeter with a continuous gully network emanating from urban storm drains. The NOSC watershed has a similar urban boundary and storm drain related gully network, but the otherwise natural landscape is dissected by approximately a mile (2 km) of dirt road.

The volume of sediment captured behind each straw bale check dam was measured at the end of the winter rains.

Photo 6. Straw bale check dams or dikes are paced in rows on an old landslide feature. In the foreground the hillside has been treated with the seed and hydromulch application which was eventually sprayed over the entire area.



Figures 4a and 4b. Percentage of functioning and non-functioning straw bale check dams in two watersheds.

The dams were evaluated once during February 1992 and again at the end of March 1992. Their condition was rated as: 1) sidecut (water flowed around the dam thereby minimizing sediment storage); 2) undercut (water flowed beneath the dam thereby minimizing sediment storage); 3) filled but cut (dam may have partially or totally filled with sediment but was subsequently undercut or sidecut, so stored sediment is subsequently mobilized); 4) moved (dam is usually blown out by flows exceeding 1 cubic foot [0.03 m^3] per second, no sediment storage); 5) filled (unable to store any additional sediment but still allowing water to flow over the dam); 6) unfilled (functioning properly).

The results of the straw bale analysis are shown in Figures 4a and 4b. If filled and unfilled dams are combined as "functioning properly," then by late February only 43 percent of the CCRP dams and 46 percent of the NOSC dams were moderating sediment transport. By the end of March only 43 percent and 37 percent, respectively, were functioning. At the CCRP site, labor crews repaired most of the dams after February storms, which most likely accounts for the consistent number of functioning bales at this site. In the NOSC watershed, no maintenance was performed on check dams within the upland gullies. However, several straw bale dams were replaced or repaired on an alluvial fan at the base of the upland watershed. Because the broad flat fan is a natural deposition zone, it was one of the few sites where sediment could be quantified in subsequent winters.

Following the end of the first rainy season, sediment volume behind the straw bale check dams in gullies of the CCRP site was conservatively estimated to be 73 cubic yards (56 m^3). For the NOSC site, the volume of stored sediments within the gullies was about 71 cubic yards (54 m^3), and an additional 162 cubic yards (124 m^3) was stored in the alluvial fan for a total volume of 233 cubic yards (178 m^3). The volume of sediment deposited on the alluvial fan during the second winter was estimated to be 300 cubic yards (230 m^3), an increase over the preceding winter even though slopes were fully vegetated with reseeded grasses. This change represents a 30 percent increase in sediment (Table 3) for the watershed and results from increases in rainfall during the second winter following the fire, gullying

Table 3. Volume of Stored Sediment In Two Gully Networks.

Parameters	CCRP Site	NOSC Site
Number of dams	191	248
Drainage area	40 acres (0.16 km^2)	77 acres (0.31 km^2)
Check dams 1991-92	73 yd^3 (56 m^3)	71 yd^3 (54 m^3)
Alluvial fan 1991-92		162 yd^3 (124 m^3)
Alluvial fan 1992-93		301 yd^3 (230 m^3)

Photo 7. Construction initiated rilling and gullying. There was no erosion control at this site in the burn area.

of the dirt road network, and sloughing along the cut and fill embankments. Interestingly, no erosion control measures were applied to the road network during either winter following the fire, even though dirt roads are known to be major contributors of sediment.

Using the total volume of stored sediments and drainage area, we can estimate an equivalent hillside surface erosion rate for the NOSC watershed of between 0.024 and 0.028 inch (0.6 mm to 0.7 mm) per year, values that reflect the impacts of urbanization (Table 4).

Effects of Urbanization and Rebuilding

Although one of the concerns following the fire was protection of downstream water bodies, the pre-fire effects of urbanization on sediment production in the Oakland Hills has been great. Concentrated road runoff has caused significant gullying of hillsides and scouring of the channel network, leaving little sediment in storage, and delivering much sediment to downstream water bodies such as Lake Temescal and San Francisco Bay (Mahoney and others, 1979). Lake Temescal, the receiving water body for approximately 50 percent of the burn area, was dredged three times between 1963 and 1979. A total of 80,520 cubic yards ($61,560\ m^3$) of sediment has been removed from the lake, yet the volume of the lake in 1979 was still only 20 percent of its 1907 volume (Mahoney and others, 1979). Using the sedimentation of Lake Temescal, we determined erosion due to urbanization within the 2.4-square-mile ($6.2\text{-}km^2$) watershed to be at a rate of 0.028 inch (0.7 mm) per year for the last 72 years.

In partially urbanized watersheds like those in the Oakland Hills, accelerated erosion due to fire may be dominated by post-fire reconstruction. In the second winter after the fire, construction and grading operations were unabated throughout the burn area. Rilling was common, and many small failures occurred on freshly cut slopes. During rain storms, we observed streams of sediment-laden water leaving construction sites and entering storm sewers and drainage channels (Photo 7). Based on estimates reported by the East Bay Regional Park District (EBRPD) in 1981 for construction-induced erosion within the Lake Temescal watershed, sediment loading as a result of reconstruction following the Oakland fire is probably 10 to 100 times greater than background erosion rates (Table 4).

Effectiveness of Erosion Control Procedures

The identification of the soil erosion hazard of hydrophobic soils following the fire served as the basis for a predicted hillside response—the "fire-flood" sequence. However, the practice of using the water drop test to determine the hydrophobic nature of the soil yields information about infiltration and water repellency at test points only. Several points at each site must be tested to acquire useful information. The test also does not reflect the true flow paths or the runoff process mechanisms for an area larger than a water drop. Hydrophobicity in the Oakland Hills was spatially discontinu-

Table 4. Soil Loss for Natural Slopes and Urbanized Watersheds in the Oakland Hills.

Site	Undisturbed Slopes	Watersheds Affected by Urbanization
Background erosion rate (Reneau, 1988)	0.08 mm/yr (0.003 in/yr)	
Erosion plots 1991-92	0.1 mm/yr (0.004 in/yr)	
Erosion plots 1991-92, plus simulated 100 year storm	0.15 mm/yr (0.006 in/yr)	
NOSC straw bale site 1991-92		0.6 mm/yr (0.024 in yr)
NOSC straw bale site 1992-93		0.7 mm/yr (0.028 in/yr)
Lake Temescal 1907-1979 (Mahoney and others, 1979)		0.7 mm/yr (0.028 in/yr)
Maximum construction site soil loss (East Bay Regional Park District, 1981)		46.0 mm (1.8 in) per site

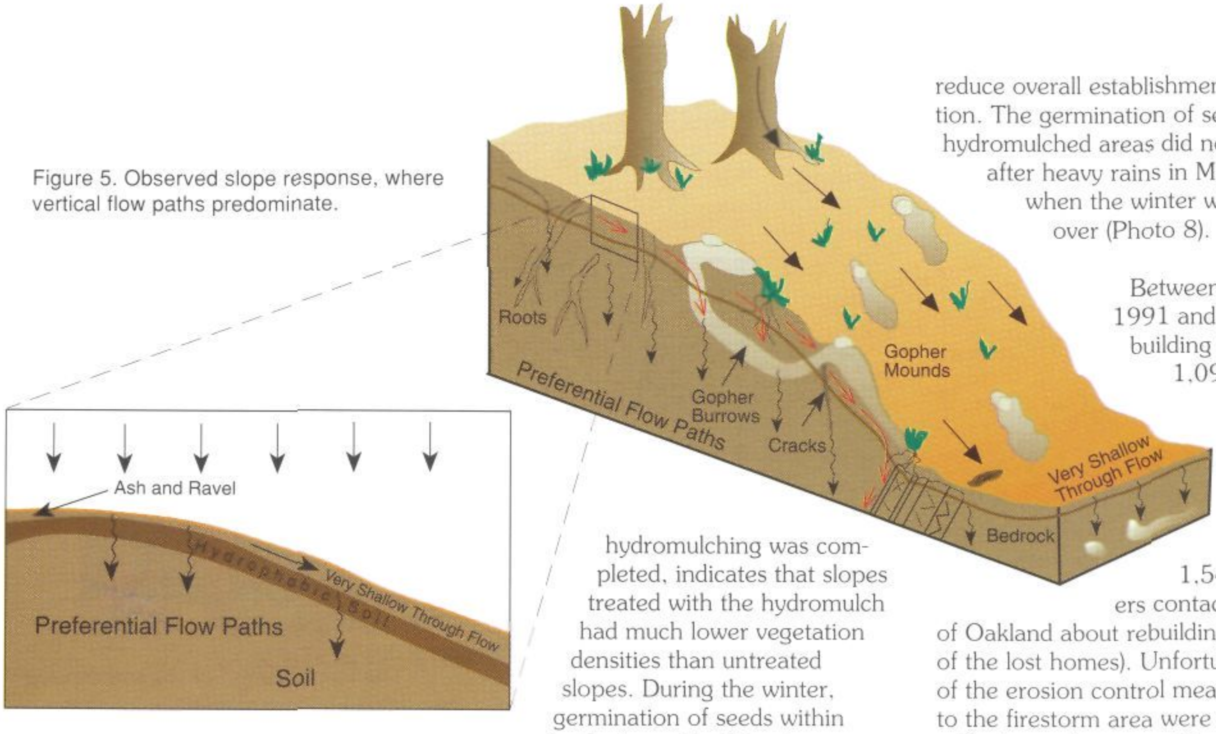


Figure 5. Observed slope response, where vertical flow paths predominate.

ous. Areas that were typed as highly water repellent did not generate the predicted response because of the predominance of flow paths into the deeper soil horizons (Figure 5).

There is no record of how the estimated soil loss of 75 cubic yards per acre (142 m^3/hectare) (unpublished Interagency Task Force soil erosion treatment meeting notes, October 24, 1991) following the Oakland fire was derived, but it is thought that the SCS used the Universal Soil Loss Equation (USLE). In the development of the USLE, much of the work characterizing storm erosion and raindrop impact on soil detachment was performed on disturbed soils, namely agriculture and rangeland (Goldman and others, 1986). Such soils have been affected by activities that weaken and break up soil structure and particle cohesion. In fact, it is generally considered appropriate to apply the USLE to construction sites to estimate soil loss due to erosion. However, the undisturbed urban wildland soils of the types found in the Oakland Hills should not be considered highly erosive, especially when subjected only to low intensity storms.

A comparison of aerial photographs taken on March 12, 1992 with those taken in December, 1991, shortly after hydromulching was completed, indicates that slopes treated with the hydromulch had much lower vegetation densities than untreated slopes. During the winter, germination of seeds within the hydromulch did not occur in many cases until the hydromulch was disturbed by animals, leaving islands of green in an otherwise gray landscape. Burgess Kay (1976) at the University of California Agricultural Experiment Station at Davis has noted that acrylic copolymers of the type used in the hydromulch application following the Oakland fire often delay and reduce total germination of seeds, and may reduce overall establishment of vegetation. The germination of seeds in these hydromulched areas did not occur until after heavy rains in March, 1992, when the winter was essentially over (Photo 8).

Between October 1991 and July 1993, building permits for 1,094 homes were approved (39 percent of the lost homes) and 1,540 homeowners contacted the City of Oakland about rebuilding (55 percent of the lost homes). Unfortunately, none of the erosion control measures applied to the firestorm area were designed to mitigate erosion caused by reconstruction activities. A year after the fire, Lake Temescal is experiencing increased sedimentation and a decrease in water quality (Freestone, 1993) as a result of construction and the deterioration of temporary straw bale sediment-monitoring structures in channels and gullies (which allowed the stored sediment to be flushed into Lake Temescal and San Francisco Bay).

Photo 8. Contrasting grass germination success is seen in this photo taken in early March 1992. Grasses are coming up in the foreground, which has not been hydromulched. In the background, the predominant plants emerging on these treated slopes are local bracken ferns, not grass from the seeding effort.

Photo 9. In March 1992, after an average rainfall season, 63 percent of all straw bale check dams in the North Oakland Sports Center watershed had failed.

Standard erosion control manuals state explicitly that straw bale check dams should not be placed in areas that receive more than 1 cubic foot per second (1.7 m^3/minute) flow; that the dams have a useful life of about 3 months; and that if they fail there is frequently more damage than if no barrier had been installed (Goldman and others, 1986). These assertions were reconfirmed in the Oakland fire area. The straw bale check dam data suggests that sediment storage is less than 50 percent effective for average winter rainfall conditions, and much less effective for the extreme rainfall event for which planners were preparing (Photo 9). Additionally, much of the sediment caught behind the dams may have come from keying or benching the bales into gully walls. Because many gullies are at least 10 feet (3 m) deep, the sediment that was excavated to install the bales was not removed from the active channel. Sediment was thereby provided to the next downstream dam.

RECOMMENDATIONS

Our analysis suggests that, even if heavy winter rains had arrived, there would not have been a higher landslide potential on burned lands, and erosion by overland flow would have been minimal. Contradictions between expectations and observations suggest the following:

1) Geology, topography, geomorphology, climate, and historical records can be analyzed in advance to predict whether the "fire-flood" sequence applies. Landscape response is site specific; processes that occur in the steep mountains of southern California as a result of fire are not necessarily the processes that will occur in other landscapes.

2) The water drop test is useful in testing for local hydrophobicity, but it may not be a reliable method for estimating potential runoff or subsequent erosion. Improved field testing, perhaps involving a simple portable sprinkler, is needed.

3) Sediment flux is largely a function of availability and transport. The SCS soil erosion index and the USLE appear in this case to overestimate the erosion potential for undisturbed wildland soils. Application of these empirical procedures for estimating soil erosion involves considerable uncertainties when they have not been calibrated with local quantitative field measurements. Methods that do not rely on uncalibrated soil erosion indexes for estimating soil erosion for undisturbed wildland soils should be considered.

4) Reseeding burn areas and the heavy application of hydromulch appear to be inappropriate responses on burned slopes not having severe ground disturbance. The most appropriate response after a similar urban/wildland burn may be to do nothing. However, intense public pressure to "act" may not permit this response, even when it is correct.

5) On-site erosion and sediment control measures that increase infiltration and subsequently soil moisture should not be used on slopes that have a high probability of landslide failure.

6) Ground disturbance by fire suppression and post-fire reconstruction activity may be the primary source of accelerated erosion. Perhaps the erosion control effort should be focused on these specific areas rather than on the wholesale effects of the burn.

7) The receiving water bodies in the Oakland fire area (Lake Temescal and San Francisco Bay) are sediment sinks; all available sediment will find its way into the sinks, and will remain there until removed. Money spent on hundreds of temporary straw bale structures that decayed and then released their stored sediments did not prevent sedimentation in these water bodies. This remedial measure was not cost-effective. A better solution would be long-term sediment retention basins at road crossings that can and should be easily cleaned, or permanent measures that involve preventing gully erosion.

8) In many environments, particularly at the urban/wildland interface, shallow landsliding may constitute the most significant hazard, and slope stability may or may not be affected by fire. Maps developed by the City of Oakland even without hillside exposure by fire, as part of a land-use management plan, should identify landslide features and hazards. This information in conjunction with the use of systems such as the USGS real-time storm

warning system (Keefer and others, 1987), could be used to predict debris flow occurrence and pathways.

9) Erosion control efforts should be motivated by the value of downslope resources, and evaluated in the context of the predominant processes that are potentially detrimental to that resource. In following this approach, agencies need to reassess how money is allocated for erosion control following fires. Money spent on temporary and limited-use erosion control efforts is not necessarily cost-effective.

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Laurel Collins received her undergraduate degree in geology at the University of California at Berkeley where she is now a researcher in the Department of Geology and Geophysics. At the time of the fire, Laurel was the geologist for the East Bay Regional Parks, parts of which were in the fire area.

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