Vol. 8, No. 8 August 1998

GSA TODAY

A Publication of the Geological Society of America

INSIDE

Slope Failure and Shoreline Retreat During Northern California's Latest El Niño

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ABSTRACT

Surface processes accelerated by severe storms during the 1997–1998 El Niño event scoured hillsides and damaged property across coastal California. Technological advances such as digital mapping, exemplified here for the San Francisco Bay area but applicable elsewhere, have enabled government agencies to better describe, monitor, and predict the effects of shoreline erosion and slope failure.

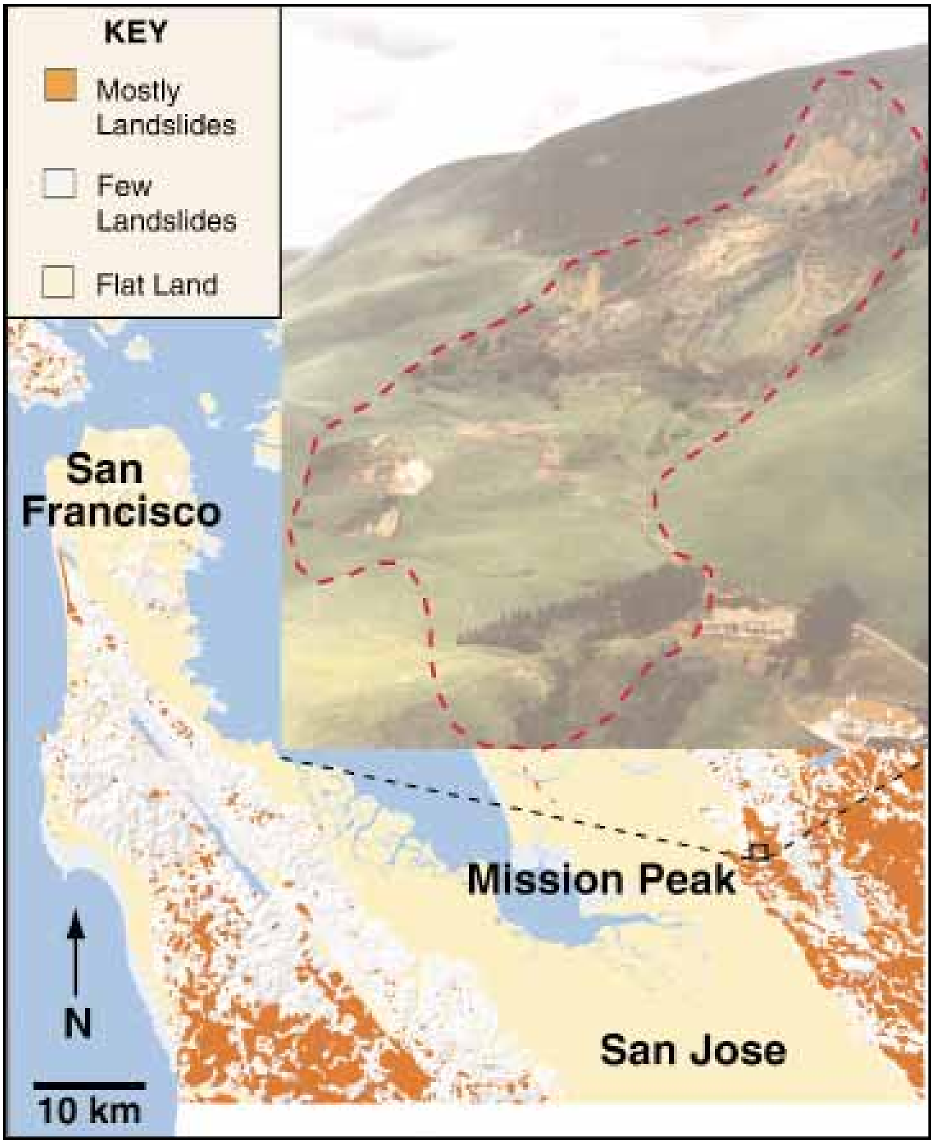

Figure 1. Existing landslides—slumps, slides, and earthflows (red) for part of San Francisco Bay area, on shaded-relief base (Wentworth et al., 1997). Photo: Reactivated 100-acre earthflow on Mission Peak, Fremont, and threatened homes (see Fig. 2 for location). In late March 1998, slide was still moving 1 m/day. Photo by J. D. Rogers.

INTRODUCTION

Major storms struck California in 1997–1998, ravaging the coast and spawning floods and landslides (Fig. 1). By late spring, property losses statewide had exceeded $550 million, and 35 counties were declared Federal Disaster Areas. Mindful of severe winters past (Ellen, 1988) and the predicted El Niño anomaly, the U.S. Geological Survey (USGS) joined other agencies to anticipate new areas of hazard while sustaining monitoring efforts already in place across the state (http://www.usgs.gov/elnino.html). Here, we illustrate some of the winter's destructive geomorphic effects in the San Francisco Bay area (Fig. 2) and describe attempts to forecast them at a regional scale.

Our efforts targeted shoreline erosion and slope failure. Permanent loss of coastal land and the structures on it to winter storms is an ongoing problem in northern California. Large waves coincide with the seasonally high tides (and in El Niño years, a sea level raised by thermal expansion) to erode beaches and undercut sea cliffs already weakened by saturated soil. Two types of landslides are common in the Bay area. Debris flows are slurries that run rapidly downslope and form thin, ephemeral deposits; the slower-moving slumps, translational slides and earthflows, covering up to several square kilometers and involving surficial mantle and bedrock 1 to 50 m thick (Fig. 1), can persist for thousands of years (Varnes, 1978).

Coastal California's Mediterranean climate contributes to these damaging processes (Fig. 3). Normal Bay area pre-

El Niño *continued on p. 2*

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GSA TODAY *August*
Vol. 8, No. 8 *1998*

GSA TODAY (ISSN 1052-5173) is published monthly by The Geological Society of America, Inc., with offices at 3300 Penrose Place, Boulder, Colorado. Mailing address: P.O. Box 9140, Boulder, CO 80301-9140, U.S.A. Periodicals postage paid at Boulder, Colorado, and at additional mailing offices. **Postmaster:** Send address changes to *GSA Today,* Membership Services, P.O. Box 9140, Boulder, CO 80301-9140.

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In Memoriam

Daniel I. Axelrod Davis, California June 2, 1998	**Philip Oxley** Washington, D.C. June 19, 1998	**Stuart L. Schoff** Maryville, Tennessee June 28, 1998
Ruth B. Curtis Boulder, Colorado June 5, 1998	**Hans Ramberg** Uppsala, Sweden May 5, 1998	**Ward C. Smith** Cupertino, California June 25, 1998

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cipitation peaks in mid-winter at 15 cm (6 in.)/mo, while evapotranspiration reaches its maximum 10 cm (4 in.)/mo) six months later. This phase-shift exaggerates the seasonal difference in soil moisture, from a nearly desiccated state (less than 10 cm [4 in.], July through October) to saturated (25 cm [10 in.], January to mid-April), providing waterlogged ground conducive to landsliding, slumping of coastal bluffs, and flooding during winter rainstorms.

El Niño-warming of the eastern tropical Pacific further increases the seasonal contrast by sending extra precipitation into northern California (http://www.pmel.noaa.gov/toga-tao/el-nino/home.html). The 1997–1998 rainy season began

Figure 2. The 10-county San Francisco Bay region covered by new digital maps of existing landslides, debris-flow sources, shaded relief, slope angle, and rainfall thresholds. Numbers show locations of Figures 1 (photo), 5–7, and 9–12.

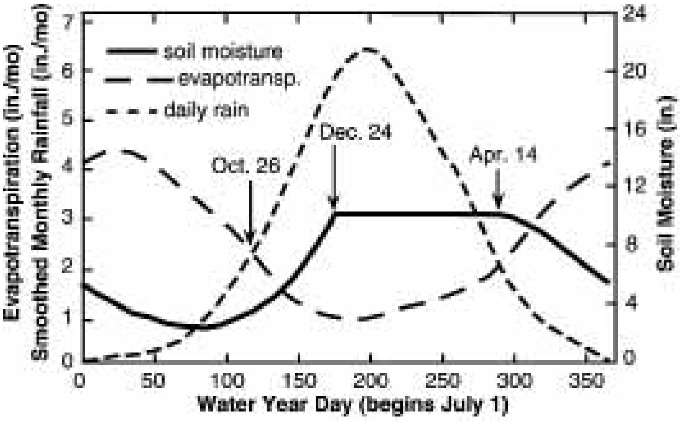

Figure 3. Preconditions for slope failure. Rainfall, evapotranspiration, and soil moisture for normal July 1–June 30 "water year" in uplands south of San Francisco (Wilson, 1997). Saturation (soil moisture ≥10 in.) for 1997–1998 winter (not shown) was achieved early, by December 8.

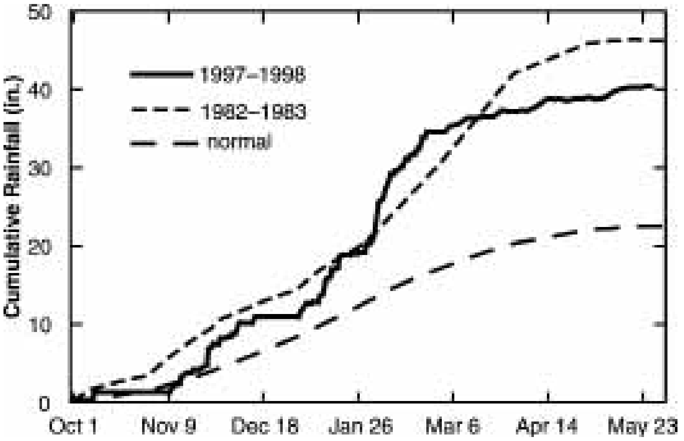

Figure 4. Winter rainy season in San Francisco Bay area, showing excess of rainfall for two El Niño years, 1982–1983 and 1997–1998, over that for normal year at Berkeley, California. Similar trends are observed across entire region. Data from NWS and NOAA.

normally in autumn, but turned unusually wet in late November (Fig. 4). By late January, rainfall totals were above those for January 1983, the last El Niño year. Frequent, heavy February rains far exceeded 1983 levels, bringing about the season's most damaging events. A drier March brought 1998 totals back below those for 1983, but were still well above normal, and light rains persisted into June. Total accumulation across the Bay region was about 200% of normal.

GETTING READY

Anticipating above-average winter rainfall for northern California (although El Niño does not necessarily bring the most damaging storms; Ellen, 1988), we began in September to prepare maps and refine existing techniques that locate areas most vulnerable to slope failure. To promote use of the new information before onset of the most severe (January) storms, we released all of it on the Internet as digital databases (http://elnino.usgs.gov/landslides-sfbay/). We also delivered paper maps and explanatory briefings to the state Office of Emergency Services and all ten counties (Fig. 2), and announced the information widely through local media and in meetings with the public and specialized groups.

The new Bay region maps required a digital elevation model (DEM), which we assembled from 35,000,000 heights (30 m spacing) from 200 small 7.5-minute DEMs. Its derivatives include shaded relief (Graham and Pike, 1997), ground-surface slope, and predicted locations of debris-flow source areas (Ellen et al., 1997). To further aid local decision makers in applying the information, we compiled the maps for major administrative units (counties) rather than by quadrangle (Brabb et al., 1972).

Also needed were maps that linked the debris-flow hazard to precipitation. Debris flows are triggered by rain that is both sustained and intense, but the amount/unit time necessary for failure (the "threshold") differs from site to site (Fig. 5). These differences exist because slopes in the Bay region reached equilibrium, and are now stable, under different conditions of precipitation, terrain, soil, and vegetation. Our new maps (Fig. 5) based on annual precipitation (Cannon, 1988) and number of rainy days (Wilson, 1997), show rainfall/debris-flow thresholds for rainfall durations of 6 and 24 h (Wilson and Jayko, 1997). The maps also locate 98 radio-telemetered rain gauges in the National Weather Service (NWS) ALERT (Automatic Local Evaluation in Real Time) network for the Bay area. Local agencies monitor the gauges during storms to determine whether rainfall is approaching threshold levels that may initiate debris flows.

DEBRIS FLOW

Most debris flows in coastal California begin as shallow landslides in wet colluvial soil perched on slopes exceeding 25° (Fig. 6; Ellen, 1988). A single major storm can trigger thousands of them if the soil is already very wet, as during January 3–5, 1982 (a non–El Niño year), when about 18,000 debris flows occurred around San Francisco Bay, killing 25 people and causing $65 million in property damage (Figs. 6, 7; Ellen, 1988). Summer wildfires further increase the hazard (Spittler, 1995), especially on chaparral hillsides in southern California where debris flows can be triggered earlier on burned than unburned ground and by briefer, less intense storms; no prior rainfall is necessary (http://geohazards.cr.usgs.gov/html_files/landslides/scfires/scfiresloc.html).

Our approach to predicting sources of future debris flows is broad-scale, based on measures of topographic form (Mark and Ellen, 1995; Dietrich et al., 1995). The source areas for shallow landslides that are capable of fluidizing are primarily steep slopes (Fig. 7) that concentrate moisture and thus tend to be concave (Fig. 8; Ellen, 1988). The map made from the new DEM (Fig. 6) infers source areas by measuring terrain slope and curvature (concavity) of actual debris-flow sources mapped from air photos after storms, and then delineating as potential sources those parts of the region with similar slope and curvature. Coarseness of the 30-m DEM, lack of data on watershed area, and the fact that debris flows travel well beyond their sources (Fig. 8) preclude using the map to pinpoint the hazard at specific sites.

Debris flows occurred at expected localities in 1997–1998, but far fewer than

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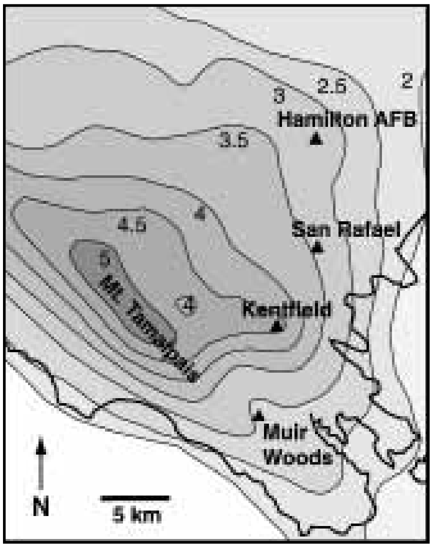

Figure 5. Rainfall thresholds for southern Marin County. Different amounts of rain (here, 2 to 5 in.) in the same period (6 h) are needed to upset the slope-stability equilibrium in different localities and trigger debris flows. Rainfall contours at 0.5 in. (12.5 mm) intervals. Triangles are ALERT rain gauges. After Wilson and Jayko (1997).

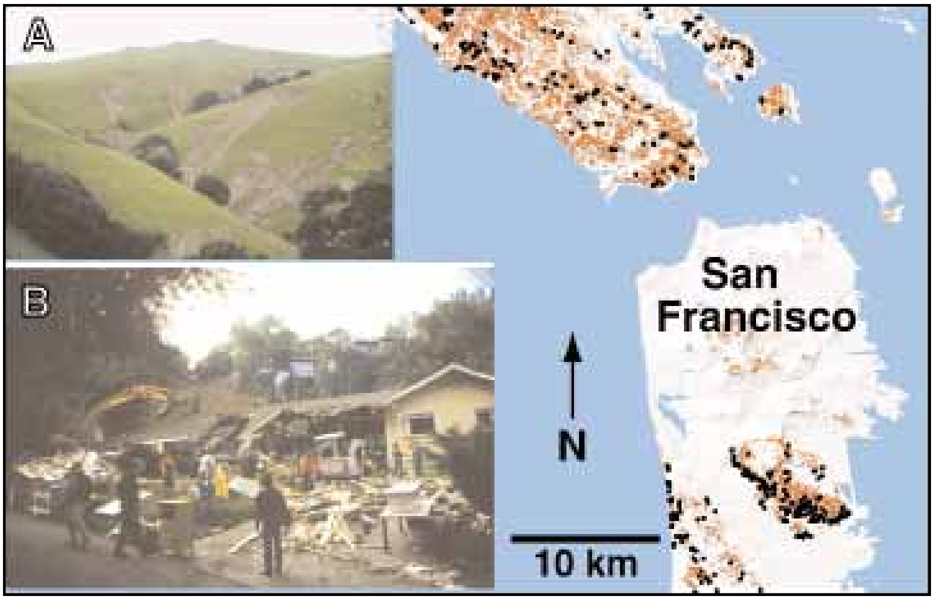

Figure 6. Debris flows. Source areas modeled from terrain slope and curvature (red) commonly coincide with debris-flow sources (dots) mapped after the January 1982 storm (Ellen et al., 1997). A. Source areas and tracks of 1998 debris flows in Alameda County (photo by S. D. Ellen). B. Home destroyed by 1998 debris flow in Marin County (photo by M. E. Reid).

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in the catastrophic storm of January 1982 (Figs. 6, 7, 8). In southern California, the abnormally severe erosion predicted by USGS was confirmed for 23 study areas burned in 1997 wildfires and then monitored during winter rains. Response ranged from flooding at canyon mouths to debris flows along canyon interiors. All ten counties around San Francisco Bay reported some debris flows, although only in the storm of February 2–3 did rainfall exceed mapped thresholds, and then in few places. This belt of intense debris-flow activity extended from the San Mateo coast, causing the sole known fatality, into northwest Santa Clara County, where a rain gauge recorded 10.75 cm (4.3 in.) in 12 h (threshold 9.25 cm [3.7 in.]).

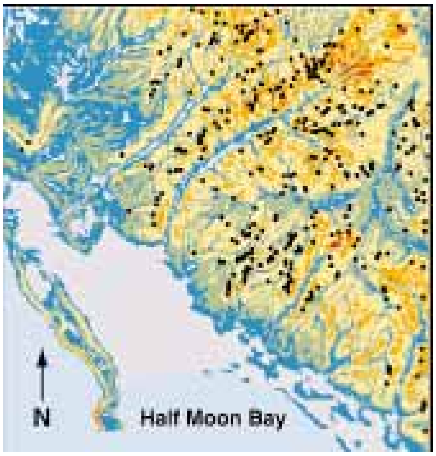

Figure 7. Coincidence of source areas for 1982 debris flows (dots) with steeper slopes in coastal San Mateo County. Slope angle ranges from 0% to 5% (violet) to over 70% (red). Compiled by S. E. Graham. Area shown is about 3 km across.

One subsequent failure was spectacular. On the rainy evening and early morning of February 6–7, tons of mud, trees, and debris rumbled 200 m down a steep ridge in Sonoma County, destroying or damaging a dozen homes in the small town of Rio Nido. The series of debris flows originated near the ridge top, from the toe of a known active rotational landslide in weathered sandstone bedrock. Because the remaining landslide block—at 125 000 m^3, about 10 times the volume of the original debris flows—might fail catastrophically, 140 homes in the canyon below were evacuated.

To detect changes in landslide movement, monitor rainfall and ground water, and possibly anticipate massive failure, USGS installed a real-time data-collection system on the perched block (Reid and LaHusen, 1998). Twelve sensors adapted from remote monitoring of active volcanoes provide near-continuous measurements (LaHusen, 1996). Within a day of authorization, real-time data on the Rio Nido slide were arriving at USGS computers via radio telemetry, and within five days, data were accessible to Sonoma County geologists on their intranet. Sampled every second and transmitted routinely every 10 minutes, the information is sent immediately in the event of ground vibrations associated with massive landslide movement. The monitoring continues to date.

LOSSES ON THE COAST

Technological advances also have improved the ability to measure coastal change. Both before and after the 1997–1998 winter, USGS mapped long segments of the U.S. west coast by high-precision airborne laser radar (LIDAR) to obtain quantitative estimates of land lost to wave erosion. (Results are under evaluation.) Frequent low-altitude photography recorded the effects of each large storm. To further alert the public to potential hazards, USGS released a catalog of damage incurred along the San Mateo County coast during the 1982–1983 El Niño (Lajoie and Mathiesson, 1998).

Monthly 1997–1998 profiling of central California beaches has already revealed exaggerated seasonal changes. Normally, sand on west coast beaches is moved offshore by large waves during winter storms and returned by smaller waves in the calmer summer months. Last winter, surveys in Santa Cruz County documented up to a 4-m decrease in beach elevation and up to a 60-m retreat of the shoreline, about twice the normal amount (http://elnino.usgs.gov/coastal/). Monitoring of beach recovery continues to assess any permanent loss of sand.

Diminished beaches exposed much coastal land to damaging storm waves. Massive slope failure claimed several homes in Pacifica, which is fronted by a low sea cliff in Pleistocene fluvial sands and gravels overlain by Holocene dune sands (Figs. 9, 10). This fragile coast had been stable from 1853 to 1946. When 12 houses were built on the seaward side of Esplanade Drive in 1949, the street still lay 45 m east of the 20-m-high bluff. Although by 1973 this distance had halved, it changed little thereafter, even in 1982–1983 El Niño storms (Fig. 9).

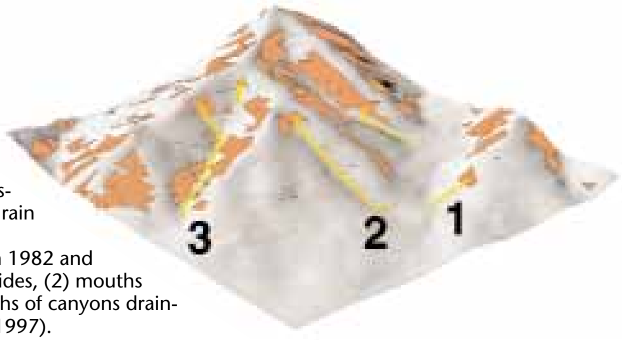

Figure 8. Source areas (red) and runout tracks (yellow) modeled from a digital elevation model for typical debris flows. The locations posing greatest risk during heavy rain are those where debris flows debouched most frequently in 1982 and 1998 storms: (1) bases of hillsides, (2) mouths of sidehill drainages, (3) mouths of canyons draining steep terrain (Ellen et al., 1997).

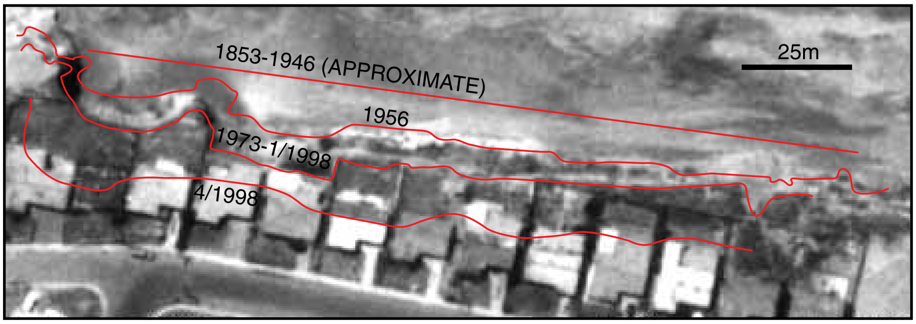

Figure 9. Historic retreat of sea cliff at Esplanade Drive, Pacifica, and the 12 houses imperiled (10 were condemned and demolished) in 1998. Aerial photo (1973) courtesy of K. R. Lajoie.

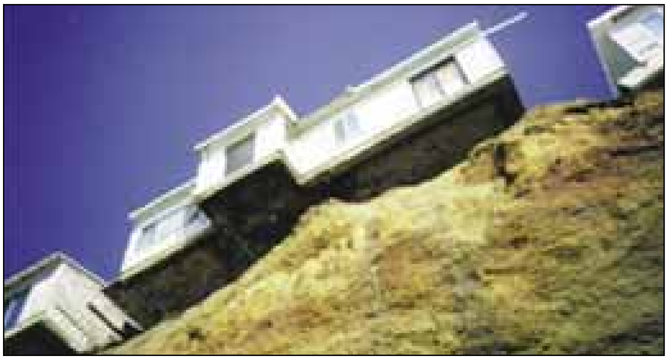

Figure 10. Doomed houses on Esplanade Drive, Pacifica, perched on retreating sea cliff, from beach below. Photo taken April 1, 1998, by K. R. Lajoie.

By early March 1998, however, six foundations were undercut and all but two homes condemned (Fig. 10). By April, the cliff had retreated up to 15 m, and parts of three houses had dropped to the beach.

The primary agent was heavy surf, which stripped the narrow beach and directly attacked soft sediments further weakened by ground-water saturation. Breaking waves undercut the cliff face, inducing block falls and slumps in the oversteepened bluff. Dry sand pouring from dune deposits highest in the section, just beneath the houses, accelerated the collapse. Retreat was greatest where a buried bedrock ridge deflected the abnormally high ground-water flow out of the cliff face, inducing erosive piping in two cohesionless sand beds lower in the section. This loss was not unique. Coastal dwellings just to the north in Daly City face a similar fate, and seven cliffside homes north of Sonoma County were destroyed in February 1998.

Figure 11. Ancient landslide reactivated in early 1998, at Scenic Drive, La Honda. Head scarp has deformed house in upper right. After Jayko et al. (1998).

SLUMP, SLIDE, AND EARTHFLOW

Landslides other than debris flows pose hazards to property (Figs. 1, 11, 12), but their slower movement rarely threatens life directly (Varnes, 1978). When they move—in response to such changes as increased water content, seismic shaking, added load, or removal of downslope support—slumps, slides, and earthflows (hereafter "landslides") can destroy foundations, offset roads, and break buried pipes as well as override property downslope.

Because one of the better predictors of movement is the presence of past landslide deposits (Nilsen and Turner, 1975), maps of old slides are helpful in locating potential hazards. Most of the 85,000 landslides around San Francisco Bay, shown on 1:12 000 to 1:62 500-scale maps (Pike, 1997), show no fresh movement. However, in any given year a few of them may be reactivated (Figs. 1, 11, 12), and new failures may occur. A 1:125 000-scale summary of Bay area landslides (Wentworth et al., 1997) revises the map of Nilsen et al. (1979), adding data and converting the original to digital form (Fig. 1). The new map distinguishes hillsides rich in evidence of movement from those with few recognized failures. The map is a generalized depiction of potential hazard; any area thus identified may require a detailed site analysis by a geotechnical engineer.

One such ancient landslide underlies much of the rural village of La Honda in San Mateo County (Fig. 11). Parts of the 1.25-km^2 complex have moved in historic times, and a segment measuring 160 m × 140 m and about 8 m deep was reactivated early in 1998 at the Scenic Drive locale (Jayko et al., 1998). Homes on the landslide began to deform even before the two weeks of heavy rain in early February, when deformation then accelerated from millimeters to centimeters per day and continued until rainfall slackened late in the month. Movement recommenced following March rains, and the slide was still moving slowly in April.

Landslides elsewhere across the state destroyed homes, disrupted utilities, and closed roads for months (40 breaks in the Pacific Coast Highway alone). On April 23, 1998, an ancient, previously mapped earthflow cut the pipelines supplying natural gas to 95% of Santa Cruz County (Fig. 12). (Only half of these residents lost service in the 1989 Loma Prieta earthquake.) Many damaging landslides occurred in southern California; they are being studied jointly by USGS and the state Division of Mines and Geology (http://geology.wr.usgs.gov/wgmt/elnino/scampen/products.html).

Waning of the prolonged 1997–1998 rainy season did not end the landslide hazard in the San Francisco Bay area. The

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Figure 12. Reactivated earthflow near town of Aromas (see Fig. 2 for location), that cut natural gas service to 60,000 Santa Cruz County residents on April 23, 1998. Photo by W. R. Cotton.

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water table in some places remained high or continued to rise, reactivating such ancient slides as Mission Peak (Fig. 1) and foretelling possible slope movements well into summer.

IMPACT AND PROSPECT

USGS digital maps dramatically sharpened public awareness of the links between surface processes and prudent land use in the Bay area. Newspapers carried maps showing landslide-prone terrain (from Fig. 1) overlapping areas zoned for residential construction, kindling anew the debate on suburban sprawl, stability of engineered hillslopes, and financial liability. In six months, the USGS El Niño Web site attracted 185,000 visits, a quarter of them in February alone. Local officials used the new information in pre-storm exercises to train emergency-service crews and, during storms, direct them to hillsides most likely to fail. The data also are being incorporated into county and municipal planning for disaster relief. During the height of the storm season, the Office of Emergency Services, USGS, and NWS maintained a hazard advisory system through daily telephone contact, and USGS Landslide Program staff assisted the Federal Emergency Management Agency at its Disaster Field Office in the state capitol.

Preliminary field surveys by USGS and local agencies in April and May estimated $140 million in damage across the Bay region from 470 major slope failures, mostly slumps, slides, and earthflows—debris flows were less important (in marked contrast to 1982). Hardest hit was San Mateo County, with 29 damaging slides, 31 homes condemned, and $45 million in losses. Many more small failures, many of them unreported, in undeveloped areas did not affect roads or dwellings.

Obstacles remain to reducing future losses, both in the Bay area and elsewhere. For example, no quantitative maps of landslide susceptibility exist on which to base public policy for the hazard and the elusive goal of landslide insurance. This need can be met by examining the multiple controls on slope failure (Brabb et al., 1972). Computer capabilities now enable us to combine landslide distribution, the properties of geologic materials, and terrain geometry to map landslide susceptibility and devise models of debris-flow runout (Soeters and van Westen, 1996). In west coast metropolitan areas, the possibility of a severe earthquake during the rainy season increases the urgency of such work.

Historically, quite apart from El Niño years, landslides and shoreline erosion accompany all large winter storms along the Pacific coast (Ellen, 1988). Our field studies, digital maps, and monitoring thus apply well beyond 1997–1998 and the Bay region. Slope failure is a land-use problem in all 50 states (Schuster, 1996), moreover, and much of the U.S. coastline is eroding. By mapping localities at risk and studying the processes and timing of accelerated geomorphic activity, USGS is preparing not only the San Francisco Bay region but Los Angeles, Seattle, and other growing urban centers to face the hazards posed by future storms. Just as Californians have learned to live, however uneasily, with earthquakes, a similar wary accommodation with slope failure and coastal retreat can be reached by residents everywhere.

ACKNOWLEDGMENTS

Authorship includes direct contributors to this article. We thank the many other colleagues who supported USGS response to the 1997–1998 El Niño in California and who are named in Open-File Report 97-745 and in USGS Web sites. Tom Bullard, Bill Cotton, Dave Rogers, Skip Stoddard, and an unidentified referee reviewed the manuscript.

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Manuscript received May 1, 1998; accepted June 2, 1998 ■

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