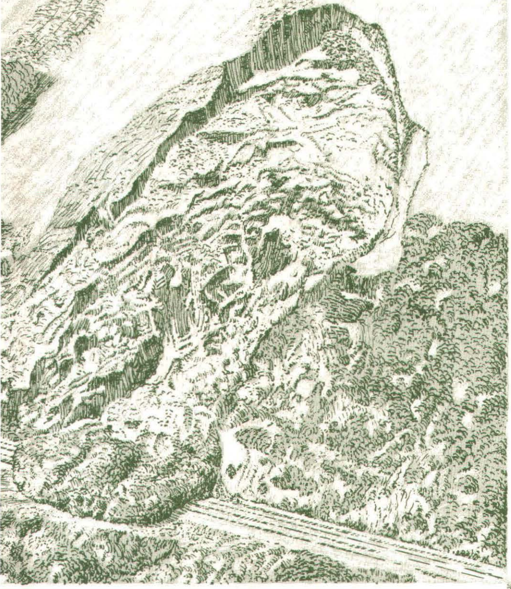

# INFLUENCE OF RAINFALL AND ANCIENT LANDSLIDE DEPOSITS ON RECENT LANDSLIDES

## CONTRA COSTA COUNTY, CALIFORNIA

## GEOLOGICAL SURVEY BULLETIN 1388

# Influence of Rainfall and Ancient Landslide Deposits on Recent Landslides (1950–71) In Urban Areas of Contra Costa County, California

*By* TOR H. NILSEN *and* BARBARA L. TURNER

GEOLOGICAL SURVEY BULLETIN 1388

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*By* TOR H. NILSEN *and* BARBARA L. TURNER

ABSTRACT

Most of the landslides that caused damage to manmade structures in the urbanized parts of Contra Costa County from 1950 to 1971 occurred on preexisting ancient landslide deposits. The ancient landslide deposits were reactivated as a result of grading, construction, the addition of water to slopes, or combinations thereof.

Most of the landslides occurred during or immediately after storm periods in which more than 7 inches (18 cm) of rain fell, particularly if the ground was already wet from previous storms. Amounts of rain required to generate abundant landslides are smaller in the spring than in the fall. The pattern of rainfall is more important than the total amount—long periods of relatively continuous rainfall produce more landsliding than short discrete storms separated by dry periods.

Regional prediction of landsliding is possible if old landslide deposits have been correctly mapped, if accurate records of past landsliding have been kept, and if the sequence and amount of rainfall can be accurately forecast. Further development in the upland regions of Contra Costa County should be preceded by careful evaluation of the potential economic losses to the public from landslides that damage manmade structures.

## INTRODUCTION

### PURPOSE OF STUDY

As the subdivision and development of hillside areas in the San Francisco Bay region increased during the 1950's and 1960's, slope stability problems became more costly to local governments and taxpayers. Some subdivisions were constructed on old landslide deposits, and because of renewed movement of the landslide deposits, buildings, roadways, and utilities were damaged. Other subdivisions were constructed on marginally stable land, and because of extensive oversteepening of slopes associated with cuts for roads and houses, excessive watering of the ground, removal of natural stabilizing vegetation, or changing of loads on slopes by the construction of buildings, slope failures occurred. Unusually heavy rainfall or ground shaking caused by earthquakes has also led to slope failures.

Many interrelated factors contribute to the generation of landslides. The most important controlling factors are probably the degree of slope, as most landslides in the San Francisco Bay region occur on slopes greater than 15 percent, and the nature of the underlying bedrock, as particular rock formations are known to be very susceptible to landsliding (Bonilla, 1960; Brabb and others, 1972; Radbruch and Weiler, 1963). These two factors together control other factors such as: soil type and thickness, vegetation type, and erosion rate. Landslide susceptibility and slope stability maps of the bay region that evaluate and weigh the effects of slope and bedrock geology are generally very useful for land-use planning. This report evaluates two additional factors that contribute to slope failures—rainfall and ancient landslide deposits. Information about the effects of these factors has been obtained by mapping ancient landslide deposits and studying both rainfall records and records from 1950 to 1971 of landslides that have damaged manmade structures in the urban areas of Contra Costa County.

The costs to the public of landslide damage in urbanized parts of the bay region have only recently been estimated to a reliable degree. For example, the public, private, and miscellaneous costs of landslides generated during the winter of 1968–69 in Contra Costa County totalled more than $5 million (Taylor and Brabb, 1972), although complete data and cost figures were not available. Preliminary estimates of damage and repair costs for landsliding in the San Jose Highlands area of the northeastern part of the city of San Jose in Santa Clara County totalled about $1.2 million during a 5-year period; most of these costs were absorbed or paid by the city (Nilsen and Brabb, 1972). It is clear from these and other studies of landsliding in the San Francisco Bay region (Harding, 1969; Bonilla, 1960; Brabb and others, 1972; Radbruch, 1969; Radbruch and Weiler, 1963; Radbruch and Wentworth, 1971; and Nilsen, 1972b) that slope failures in urban areas are very costly and widespread, and that local and regional governments must carefully consider slope stability problems in planning future growth and expansion.

## LOCATION OF AREA

Contra Costa County extends across the north-central part of the Coast Ranges of California from San Francisco Bay on the west to the Great Valley on the east (fig. 1). It is bounded on the north by waters of the confluent delta of the Sacramento and San Joaquin Rivers and their extension westward through Suisun Bay, Carquinez Strait, and San Pablo Bay. Alameda County forms the southern boundary. Twenty-five U.S. Geological Survey 7½-minute quadrangle maps cover the county (fig. 2). The San Ramon Valley and its northward extension to Carquinez Strait divides the county into two separate

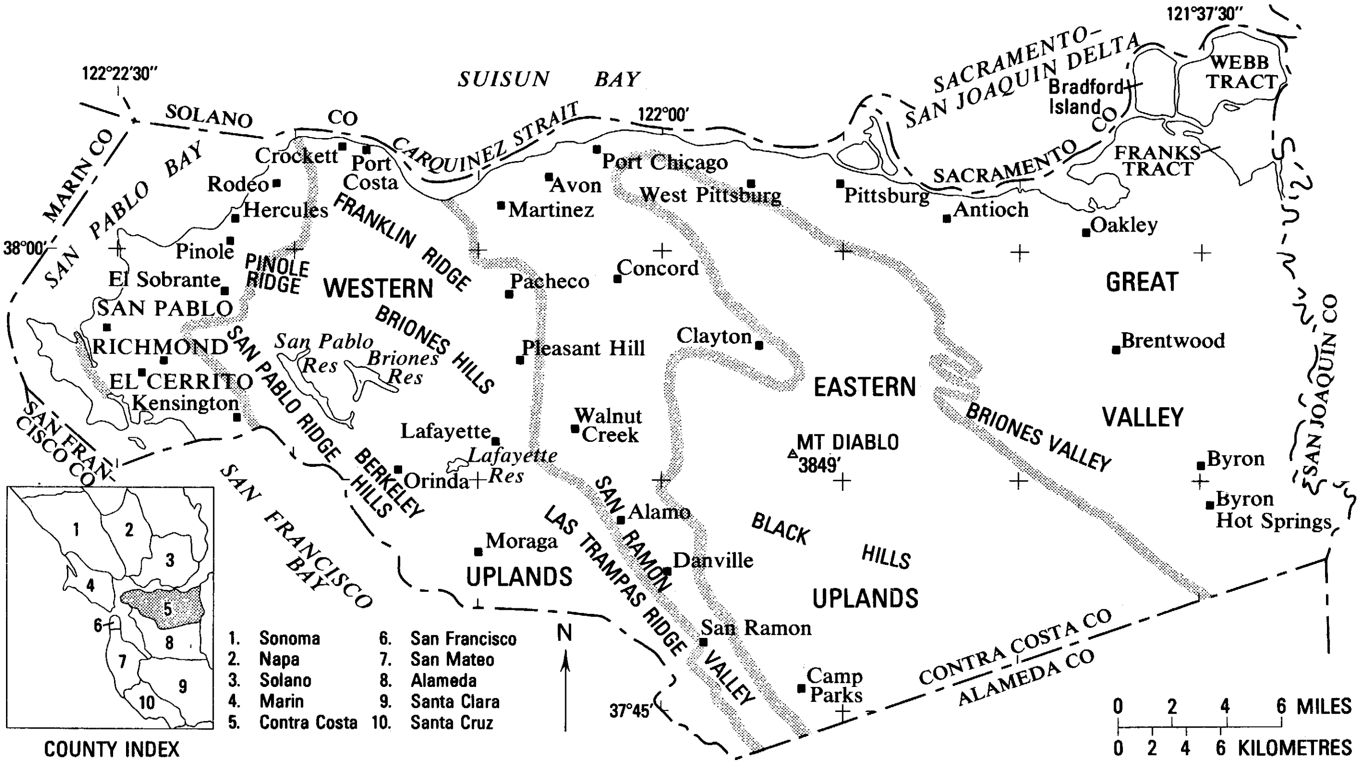


FIGURE 1.—Index map showing the location and geographic elements of Contra Costa County.

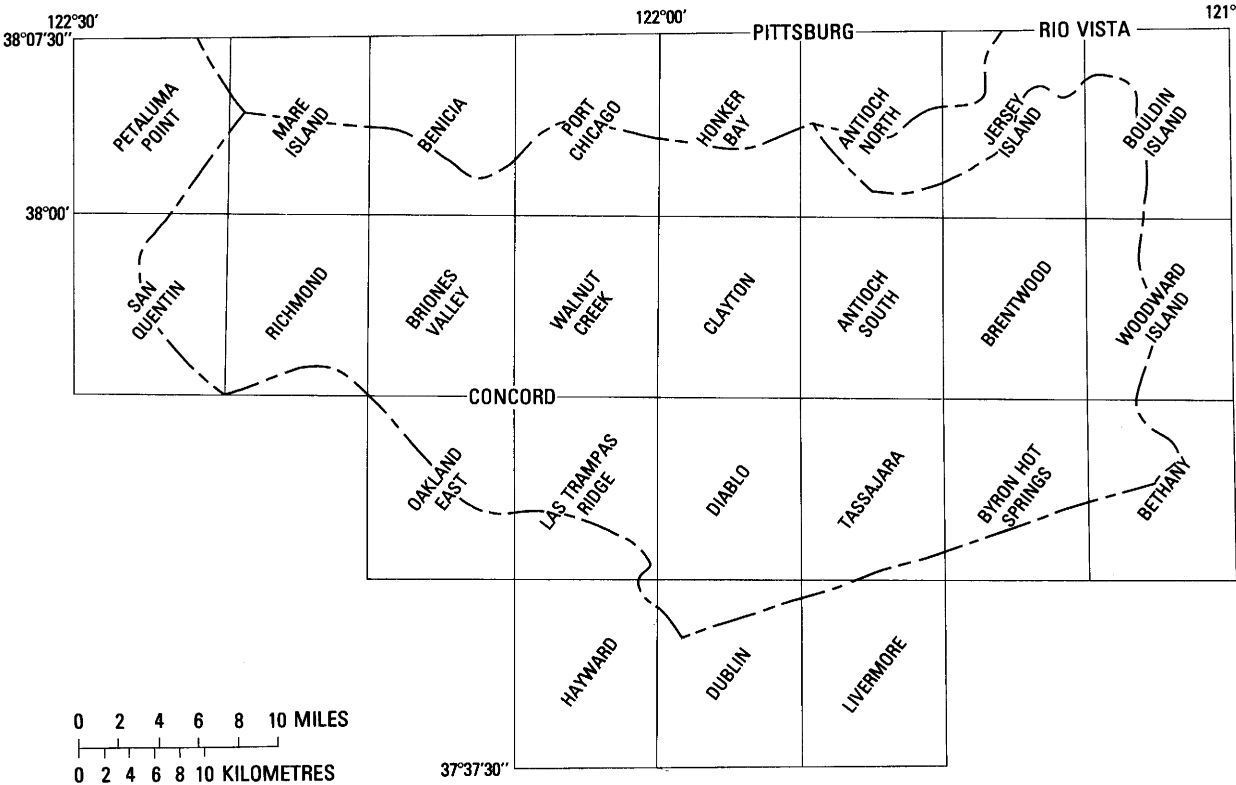


FIGURE 2.—Index of U.S. Geological Survey topographic maps in Contra Costa County.

upland areas, the Berkeley Hills and other ridges to the west, and Mount Diablo and its surrounding high country to the east. Another smaller isolated upland area is located in the northwestern part of the county west of the city of Richmond. The greatest relief in the county is near Mount Diablo, which attains an elevation of 3,849 feet (1,173 m) and dominates the entire county. The remaining upland areas, both to the west and east, are steep and irregular, with highest elevations ranging from 1,000 to 2,000 feet (300–600 m).

The first non-Indian settlements in Contra Costa County were large ranchos on grants of land made by the Spanish and Mexican governments. The influx of Americans during and after the gold rush of the 1850's led to the establishment of some towns and cities, especially along the north edge of the county in Martinez, Pittsburg, and Antioch. In the 1900's, growth took place along the west edge of the county in the flatlands marginal to San Francisco Bay from El Cerrito to San Pablo and in the flatlands of the San Ramon Valley, from Martinez southward to Pacheco, Concord, Pleasant Hill, Walnut Creek and Danville. Prior to World War II, the hillside areas were not extensively developed because flatland was abundant and the population was relatively small. However, the rapid growth of the county during the postwar years and the construction of an extensive freeway system connecting the county to San Francisco have led to considerable development of hillside areas, especially in the western uplands. Large parts of El Cerrito, Richmond, El Sobrante, Pinole, Crockett, Pleasant Hill, Walnut Creek, Lafayette, Orinda, and Moraga, as well as many unincorporated areas, are sited on hillsides with slopes greater than 15 percent. As yet, very little growth has taken place in the eastern upland area surrounding Mount Diablo or in the eastern flatlands of the county south of the delta area.

## SOURCES OF DATA AND ACKNOWLEDGMENTS

The map of ancient landslide deposits of Contra Costa County (pl. 1) is compiled from published and unpublished maps by Nilsen (1971, 1972a, 1973a, 1973b) and Sims and Nilsen (1972). The maps were prepared by photointerpretation of vertical aerial photographs from 1:20,000 to 1:80,000 in scale. The landslide deposits are recognized on the photographs by unique morphological characteristics such as scarps, toes, hummocky topographic surfaces, and transverse and longitudinal fissures and ridges (Nilsen and Wentworth, 1971; Nilsen, 1972b). The smallest landslide deposits mapped are about 200–300 feet (60–90 m) in smallest dimension. They vary in age from probably several hundred thousand years up to the date of the most recent photography used, or to 1966. Most of the photography used is pre-1960. We use the term "landslide deposit" for these mapped features because we are uncertain when they were last active or whether they were actively moving at the time of the photography; the outlines of the landslide masses are shown on plate 1.

The data on landslides that have damaged manmade structures were compiled by Turner from November 1971 to March 1972 (pl. 1). Mainly landslides recorded by officials of state, county, city or local governments, military authorities, or utility companies since 1950 were studied. A small amount of data has been provided by private consulting firms. Although the amount of information available about the landslides varied, we attempted to ascertain the date and location of movement, the amount of damage, and the type of movement that occurred. Some landslides that caused damage were not officially recorded, and of these we have no information. Landslides in rural and underdeveloped areas were not recorded and analyzed unless they caused damage to roads, utilities, or other public or private property.

The cooperation and assistance of many agencies, companies, and individuals was required to compile the data for this study, and we acknowledge it gratefully. The Contra Costa County Offices of Public Works and Assessment provided the location of 400 parcels of land affected by landslides from 1957 to 1971; records prior to 1957 are incomplete, and the landslide data are of limited usefulness. Each reported parcel does not necessarily indicate a separate landslide event because large landslides may affect more than one lot and may be reported by more than one homeowner.

We were provided with maps by the city of El Cerrito showing 26 landslides and by the city of Richmond showing 4 landslides near Point Richmond. Additional landslide data were obtained from the East Bay Municipal Utilities District, the State Highway Department, some consulting engineering geology firms, and earlier reports by Radbruch and Weiler (1963) and Taylor and Brabb (1972).

Precipitation records were obtained from the Climatology Bulletins of the Bureau of Commerce and from the Contra Costa County Flood Control District. T. R. Simoni, Jr., assisted in the preparation of several maps and diagrams.

## DISTRIBUTION OF RECENT LANDSLIDES

The location and distribution of all landslides that damaged manmade structures in Contra Costa County for which we have records are shown on plate 1. Although the oldest landslides are from 1950, most are from the period 1958 to 1971 when more accurate records were kept. The nature of the slope prior to landsliding is indicated in 167 landslide records. About 80 percent of these occurred in places where the natural ground surface was cut or filled by construction activity; only 20 percent occurred on natural slopes without manmade modifica-

TABLE 1.—*Types of slopes affected by recent landslides that have caused damage to manmade structures (1950–71)*

| Type of slope | Number |
|---|---|
| Natural slope | 15 |
| Natural creek bank | 10 |
| Cut slope | 56 |
| Fill slope | 55 |
| Filled creek bank | 5 |
| Complex slope (cut and fill, cut and natural, and so on) | 26 |
| Total | 167 |

tions (table 1). A substantial number (45) represented renewed activity on landslides that had already moved at least once during the period from 1950 to 1971.

The landslides are heavily concentrated in the Orinda-Moraga and El Cerrito to El Sobrante areas; lesser concentrations are present west of Richmond and near Pinole, Crockett, Pleasant Hill, Lafayette, Walnut Creek, and Danville (pl. 1). Almost all the landslides are in the western upland area; only a scattered few are in the eastern upland area. Landslides are abundant along the road on the west shore of San Pablo Reservoir and adjacent to Briones Reservoir. Relatively few landslides are present in the flatland areas on the margin of San Francisco Bay, and in the San Ramon Valley, Great Valley, and delta areas, presumably because extensive cutting and filling has not been necessary in these areas, and slopes are very low. More lots were damaged by landsliding in El Cerrito than in Orinda. Part of the reason for this is the difference in the size of the lots in the cities; the lots are smaller in El Cerrito, which was developed at an earlier date. Because of the smaller lot size, more lots are involved in individual landslide movements.

The distribution of landslides that have caused damage to manmade structures is shown on plate 1, and it shows that virtually every major development in upland areas of Contra Costa County has had some slope stability problems. Orinda and El Cerrito have been particularly susceptible to landsliding. Careful regional mapping and analysis of the factors that contribute to the landsliding can permit the identification of those areas that will probably be unstable when developed.

## INFLUENCE OF RAINFALL ON LANDSLIDING

### DISTRIBUTION OF MEAN ANNUAL RAINFALL

Rainfall of high intensity generally leads to increased landslide activity as well as to flooding, as the damaging effects of the heavy rainstorms of 1964 in northern California and 1969–70 in southern California have amply demonstrated. The amount, type, and yearly distribution of precipitation also affect other factors that control landsliding such as vegetation, soils, and steepness of slope. In addition to the mean annual rainfall, the recurrence interval of major storms, the yearly pattern of rainfall, and longer term changes in rainfall must be considered. High rainfall may affect natural slopes differently than slopes that have been extensively cut and filled, logged, or burned.

The mean annual rainfall is unevenly distributed in Contra Costa County. Because the source of precipitation is moisture-laden air flowing eastward from the Pacific Ocean, the western part of the county receives far more rainfall than the eastern part (pl. 1). The highest rainfall of more than 28 inches (71 cm) per year occurs in the Orinda area and the lowest of less than 12 inches (30 cm) per year in the Great Valley. The western upland area receives between 20 and 30 inches (51 and 76 cm) per year, and the eastern upland between 12 and 20 inches (30 and 51 cm) per year, except for the area surrounding Mount Diablo, which receives somewhat higher amounts.

More than 90 percent of the precipitation occurs during the winter months of November through April. It falls as rain except for some snow in the very highest parts of the county, especially the upper slopes of Mount Diablo. Rain rarely falls during the summer months. However, the annual as well as monthly rainfall is highly variable from year to year, and the standard deviation for mean annual rainfall at any locality is quite high. During the past 12 years, for instance, the Burton Ranch Precipitation Station in Lafayette recorded a low mean annual rainfall of 15.31 inches (38.89 cm) in 1959–60 and a high of 36.00 inches (66.04 cm) in 1970–71 (fig. 3).

Although the mean annual rainfall varies widely throughout the county, the distribution of precipitation at the various recording stations for any particular rainy season is generally proportionate. Intense storms will generate more rainfall at stations with higher mean annual rainfall than at those with lower mean annual rainfall, but the cumulative precipitation curves generally have similar shapes. This relationship is demonstrated by the comparison of five cumulative precipitation curves for the 1968–69 rainy season in west-central Contra Costa County (fig. 4). Although these stations range in elevation from 295 feet (90 m) to 626 feet (191 m) above sea level, and the mean annual precipitation ranges from approximately 20 inches to 28 inches (51–71 cm) per year, the five curves have remarkably similar shapes. Storm periods are indicated by steeply sloping parts of the curves and dry periods by flat parts of the curves. Although precipitation during the 1968–69 season was higher than average, the cumulative curves for other years have similar shapes and generally have the same ranking. We have selected the yearly cumulative precipitation curves of the Burton Ranch station (fig. 3) for comparisons of rainfall and landsliding because good precipitation records were kept at this

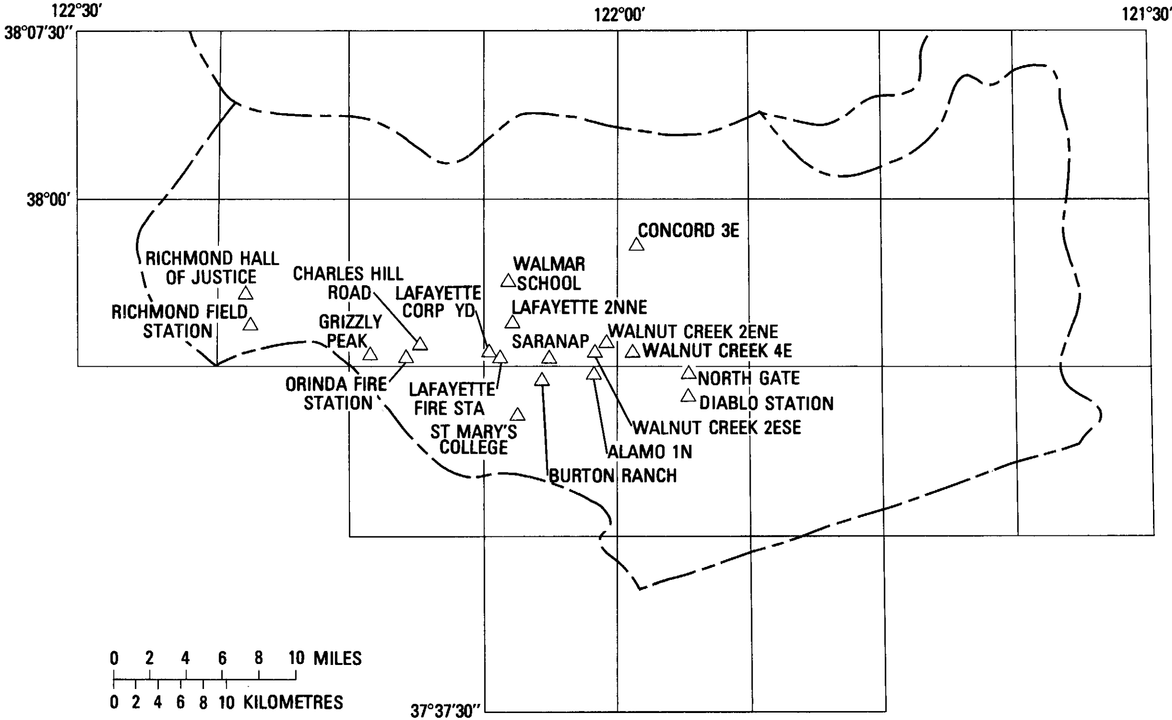


FIGURE 3.—Location and names of selected stations recording precipitation in Contra Costa County.

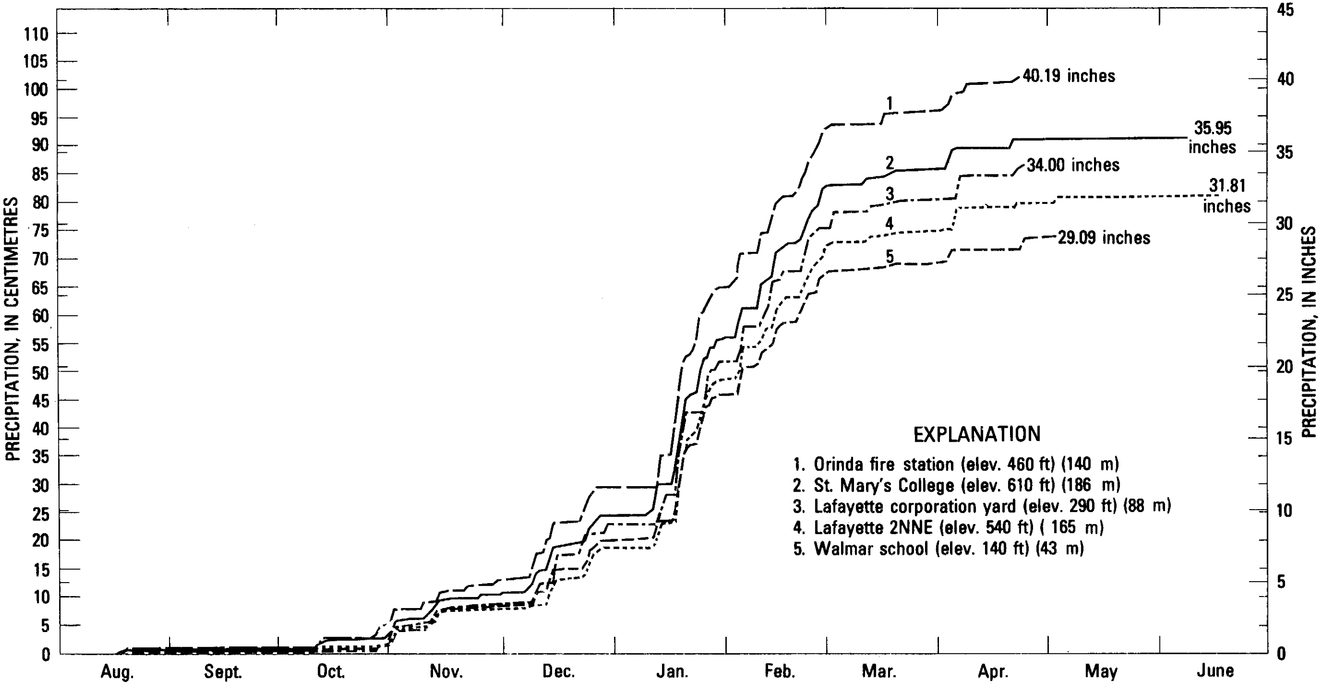


FIGURE 4.—Cumulative precipitation for the 1968–69 season in west-central Contra Costa County.

station during the entire period of 1950 to 1971, and the mean annual rainfall at this station is an intermediate value for stations in the Lafayette-Orinda area.

### COMPARISON OF AREAL DISTRIBUTION OF LANDSLIDING AND MEAN ANNUAL RAINFALL

Areas with high mean annual rainfall are generally associated with abundant recent landslides (pl. 1). Most of the landslides along the west edge of the western upland area of the county fall within the contour lines for 22–28+ inches (56–71+ cm) mean annual rainfall. The Orinda area, containing the largest number of recent landslides, is located in the area of highest mean annual rainfall.

However, several areas with smaller amounts (16–22 inches (41–56 cm)) of mean annual rainfall, such as Crockett, Pinole, and Point Richmond, have had abundant landslide activity. In addition, the belt of abundant landslides that extends from San Pablo through Richmond, El Cerrito, and Kensington receives only about 22 inches (56 cm) of rain per year, considerably less than other areas with fewer landslide problems.

We believe that the apparent correlation between mean annual rainfall and landsliding is very weak and that other factors strongly influence the relationship. First, although the orographic effect of the upland areas causes them to receive more rainfall than lowland areas, nevertheless the lower slope angles of lowland areas probably cause them to have fewer landslides. Second, because only the west edge of the western upland area has been extensively urbanized, the correlation may not be very meaningful, and the sample may not be large enough to draw conclusions regarding the relations between landsliding and the areal distribution of mean annual rainfall. Third, other factors such as soil type, bedrock geology, slope angle, and the type of construction probably control the distribution of landslide movement more than the distribution of mean annual rainfall.

The maximum annual rainfall may be a better indicator of landsliding potential than the mean annual rainfall. An annual precipitation threshold may exist above which extensive landsliding will occur and below which only minor amounts of landsliding will occur. The yearly distribution of rainfall is probably more meaningful than either the mean or maximum annual rainfall—whether it occurs primarily in the beginning or end of the rainy season, after a previously very dry or very wet rainy season, and if it accumulates slowly and steadily during the rainy season or in just a few major storms.

### COMPARISON OF LANDSLIDE ACTIVITY AND RAINFALL CYCLES

The spacing of major storms during the rainy season significantly affects landslide activity and explains otherwise anomalous situations, such as the 56 landslide reports recorded during 1969–70, when precipitation amounted to 25.84 inches (65.63 cm) at the Burton Ranch Station, compared with only 11 reports the following year when rainfall amounted to 25.44 inches (64.62 cm). The cycle or pattern of rainfall varies considerably from year to year, as seen from cumulative precipitation curves at the Burton Ranch Station during the years 1959–71 (pl. 2). The curves indicate that an annual rainfall of less than about 23 inches (58 cm) recorded at Burton Ranch Station will not trigger many landslides and also that the many different patterns of rainfall have varying effects on landslide activity. Three factors seem to be important: the intensity of individual storm periods (expressed as the slope of the cumulative precipitation curve), the amount of rainfall accumulated prior to the onset of the storm, and the duration of the storm period.

In this report we define a storm as any number of days during which there is continuous precipitation. A storm period is defined as an interval of nearly continuous precipitation, involving a series of closely spaced storms with less than 4 days between. Storm periods generally plot as fairly smooth and constantly sloping parts of the cumulative precipitation curves.

Intense storms of even very short duration are clearly capable of generating widespread landslide activity, as shown by the rainy season storms of October and January 1962–63, January 1966–67, and December 1969–70 (pl. 2). Many smaller landslides that were generated during such brief but heavy periods of rainfall are mudflows and earthflows that involve surficial materials rather than underlying bedrock.

A comparison of the storms of the 1969–70 rainy season suggests that storms occurring after large amounts of rain have already fallen will generate more landslides than storms occurring at the beginning of the rainy season (table 2). Even though the intensity of the first storm of 1969–70 was significantly greater, the second storm generated many more landslides. A higher rainfall intensity is probably required to generate landslides during the early months of the rainy season than the later months. Landsliding apparently occurs more

TABLE 2.—*Comparison of the effects of two storm periods during 1969–70 on landslide activity*

| Storm period | Rainfall prior to storm period (inches) | Duration of storm period (days) | Total rainfall during storm period (inches) | Average intensity (inches/day) | Number of structurally damaging landslides generated during or shortly after storm |
|---|---|---|---|---|---|
| December | 4.15 (10.54 cm) | 8 | 7.70 (19.56 cm) | 0.96 (2.44 cm/day) | 7 |
| January | 11.85 (30.10 cm) | 17 | 10.09 (25.63 cm) | 0.59 (1.50 cm/day) | 43 |

easily when the ground is saturated or has been previously wetted and the ground-water table is high.

The duration of the storm period is the third major factor that affects the generation of landslides. The long storm periods of December 1964–65, January-February 1968–69, and January 1969–70 produced more landsliding than other periods of less continuous or intense precipitation. These three storm periods are responsible for the largest number of landslides generated in the county during the 1959–71 period.

The 62 storm periods from 1959 to 1971 that have a precipitation of 1 inch or more are plotted in three categories in figure 5: those that generated three or more landslides that damaged manmade structures during or immediately after the storm, one or two landslides, and no landslides. Storm periods during which only one or two landslides occurred are plotted separately in order to distinguish those cases where the landslides may have been random events not necessarily initiated by the storm precipitation. All but one storm period from the first category generated six or more landslides; this indicates that these landslides were not random events, but were directly related to the precipitation.

The cumulative amount of rainfall that had fallen prior to each storm period is also shown in figure 5; the least-mean-squares fit of the storm periods that generated three or more landslides indicates that the amount of storm precipitation required to generate three or more landslides in the developed areas of Contra Costa County is inversely related to the amount of rainfall accumulated earlier in the rainy season. In other words, spring storm periods need not be as severe as fall storm periods to generate numerous landslides.

Cleveland (1971) examined the effects of rainfall on landsliding in Southern California by studying flood records, and he concluded that the ground in California becomes saturated with water after 8–12 inches (20–30 cm) of rainfall has accumulated during a single storm period. Rainfall in excess of 8–12 inches (20–30 cm) that cannot be absorbed into the subsurface, runs off and may cause flooding in adjacent areas. The increased pore pressure in the subsurface may initiate slope failures. Cleveland suggested that the "threshold value" for such flooding and concurrent landsliding is probably closer to 12 inches (30 cm) in northern California where vegetation is somewhat denser and soils are thicker. Our incomplete data for the urbanized areas of Contra Costa County indicate that such a threshold value probably does exist, and that a storm precipitation greater than 7 inches (18 cm) will commonly cause considerable landsliding (fig. 5). In the Orinda-Lafayette area, with an average of 10 inches (25 cm) of prior precipitation, a storm period having 7.5–12 inches (19–30 cm) of rain will

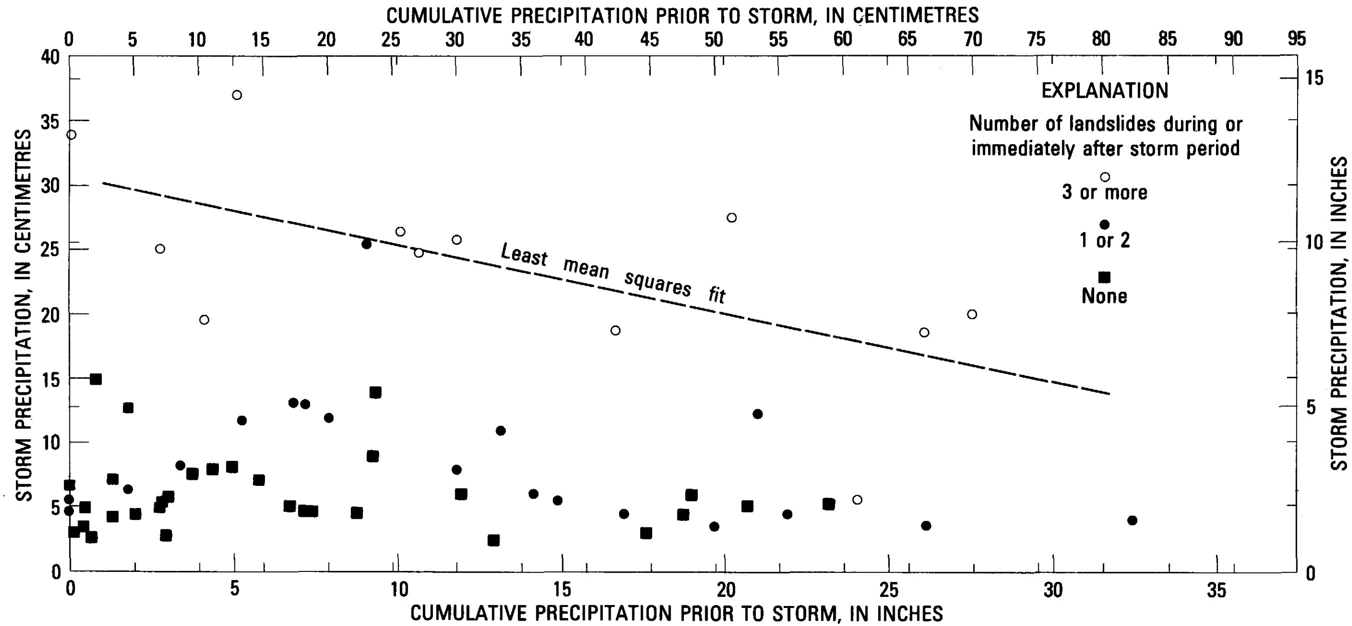


FIGURE 5.—Relations between storm precipitation, cumulative precipitation prior to the storm, and the number of landslides recorded during or immediately after the storm period. Dashed line represents least-mean-squares fit of storm periods generating three or more landslides.

probably generate extensive landsliding.

The sequence of wet and dry spells during the rainy season is another important factor affecting landslide activity. Loss of ground moisture from evapotranspiration during the dry period of December and January of 1966–67 probably accounts for the fact that only 38 landslides were reported that year as opposed to 66 during the 1968–69 season which had a comparable total rainfall. The dry period probably reduced the effects of the prior precipitation on the landslide-generating capabilities of succeeding storms. This effect probably increased the threshold for the storm period of February 1962; of the 46 days preceding the storm period, only 5 had any recorded precipitation. Thus, despite the 10 inches (25 cm) of rainfall during the storm period, few landslides were generated.

The records of landsliding during the past 12 years in Contra Costa County indicate that storm periods recording more than 7 inches (18 cm) of rainfall have generated large numbers of landslides when the ground has already received close to 10 inches (25 cm) or more of rainfall without long intervening dry periods. With adequate weather-forecasting abilities and careful analysis of cumulative rainfall patterns, public officials could predict to some degree the landslide hazard during a particular rainy season. If it appears that an oncoming storm will bring rainfall exceeding the threshold, then the public can be warned of the potential landslide hazard, and those homes situated in areas where landsliding has occurred in the past may be safely evacuated or closely observed so that lives and property might be saved in the event landsliding is renewed. It seems possible to devise a landslide warning system, based on observations and predictions of rainfall patterns, that would be similar to those devised for flooding, tsunamis, tornadoes, or other environmental hazards. At the very least, more and better records should be kept regarding the date, nature, and types of damage caused by landsliding so that more detailed and illuminating studies regarding the influences of rainfall on landsliding may be made in the future.

## INFLUENCE OF ANCIENT LANDSLIDE DEPOSITS ON RECENT LANDSLIDING

A comparison of the distribution of landslides that caused damage to manmade structures during the period 1950–71 in Contra Costa County with the distribution of ancient landslide deposits mapped by photointerpretive techniques indicates that most of the recent landsliding in urbanized areas has occurred in areas where abundant landsliding has taken place in the past (pl. 1). The ancient landslide deposits appear to be loci for renewed slope movements. The renewed movements in the areas underlain by ancient landslide deposits may result either from movements of the ground in response to rainfall, erosion, or other natural factors, or from movements caused by the modifications of the natural ground surface by man. Construction on ancient landslide deposits appears to have caused much of the recent landslide activity. Proper planning, designing, engineering, and geological studies would probably avoid many of these problems and certainly seem to be a prerequisite to future growth in the county if the landslide hazard is to be diminished.

The large number of structurally damaging landslides and damaged land parcels in the Richmond-El Cerrito-Kensington area is related to the presence of very large inferred ancient landslide deposits underlying the west-facing slopes of those cities. Large numbers of ancient landslide deposits underlie many of the recent structurally damaging landslides at the north end of San Pablo Ridge, along the west side of San Pablo Reservoir, and in the Orinda-Moraga-Lafayette area.

The large areal extent of ancient landslide deposits throughout the western upland area of Contra Costa County suggests that future growth and development in this area will probably lead to increased public and private costs resulting from slope failures. Such costs can be substantially diminished by improved and possibly more expensive construction design and by low-density zoning in landslide-prone areas. The resultant long-term savings would probably justify the greater initial investments in time and money, inasmuch as maintenance and repair costs for landsliding and landslide-caused damage have been shown to be high and commonly recurrent (Taylor and Brabb, 1972; Nilsen and Brabb, 1972). The eastern upland area, in addition to having lower rainfall, also has a lower density of ancient landslide deposits, and in general probably is considerably less prone to slope stability problems.

## SUMMARY AND CONCLUSIONS

The record of landslides that caused damage to manmade structures in Contra Costa County during the 1950–71 period indicates that most of them have been in urbanized hillside areas along the west edge of the county. They have occurred primarily in areas where ancient landslide deposits are abundant; this relationship suggests that the ancient landslide deposits are commonly reactivated by the addition of water to and by the cutting and filling of these slopes. Maps showing the distribution of ancient landslide deposits may be useful indicators of areas that may be unstable if developed.

The history of landslide activity also indicates that the distribution, amount, and pattern of rainfall exert a strong influence on landsliding. Rainfall in excess of 7 inches (18 cm) per storm period generally causes large numbers of landslides, particularly if the ground is already wet from previous storms. In general, more rainfall is required at the beginning of the rainy season than at the end to produce large numbers of landslides. The pattern of rainfall during the rainy season is more important than the total amount, so that periods of relatively continuous rainfall produce more landsliding than discrete storms that are separated by dry periods and during which ground moisture content decreases as a result of evapotranspiration.

Our study indicates that careful analyses of well-kept records of yearly landslide activity and rainfall patterns can result in some capability for predicting both the time and location of future landslide activity. Old landslide deposits are particularly susceptible to renewed movement during storms in which more than 7 inches (18 cm) of rainfall occur. Further development of the upland regions of Contra Costa County should be made with careful attention to and analysis of the landslide hazard.

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