Natural Conditions That Control Landsliding in the San Francisco Bay Region—an Analysis Based On Data From the 1968–69 and 1972–73 Rainy Seasons

GEOLOGICAL SURVEY BULLETIN 1424

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By TOR H. NILSEN, FRED A. TAYLOR, *and* ROBERT M. DEAN

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Nine-county study of landslide activity in relation to ancient landslide deposits, slope, bedrock geology, and rainfall pattern as keys to slope stability in land-use planning

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By Tor H. Nilsen, Fred A. Taylor, and Robert M. Dean

ABSTRACT

In the nine counties that constitute the San Francisco Bay region, 335 landslides were reported during the 1968–69 rainy season and 411 during the 1972–73 rainy season. The smaller number of landslides in 1968–69 caused damage to manmade structures amounting to $25,180,956, whereas the larger number of landslides in 1972–73 caused damage amounting to only $9,716,284.

Of the recorded landslides, 55 percent of those in 1968–69 and 69 percent of those in 1972–73 took place on or within 610 m (2,000 ft) of underlying ancient landslide deposits. Seventy-four percent in 1968–69 and 80 percent of those in 1972–73 took place on slopes steeper than 15 percent (8.5°). Sixty-one percent of those in 1968–69 and 65 percent of those in 1972–73 took place either in soils overlying or within bedrock geologic units generally considered to be highly susceptible to slope failures on the relative slope stability map of the San Francisco Bay region. Landslide activity is directly related to the pattern of rainfall: Large numbers of landslides are triggered during storm periods in which more than 150–200 mm (6–8 in.) of rain falls in areas where 250–380 mm (10–15 in.) of rain has already fallen during a rainy season.

Careful geologic mapping and slope stability analyses that consider ancient landslide deposits, slope, bedrock geology, and rainfall patterns can indicate areas susceptible to slope failures. Land-use planning based on such studies is an effective way of minimizing damage caused by landsliding.

INTRODUCTION

Landslides have caused considerable damage to public and private property throughout the San Francisco Bay region. They have caused inconvenience and financial hardship to individuals and have been a drain on public funds. The purpose of this study is to relate modern landslides in the San Francisco Bay region to ancient landslide deposits, slope, bedrock geology, and the seasonal distribution in time of precipitation, and by analyzing the amount and distribution of damage caused by these landslides, to point out the value of land-use planning based on careful analysis of slope stability and the natural factors that control landsliding in the bay region.

In the nine counties that flank San Francisco Bay—Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma (fig. 1)—336 landslides reported for the 1968–69 rainy season (Oct. through Apr.) caused damage to manmade structures estimated at $25,180,956; 411 landslides during the 1972–73 rainy season caused damage estimated at $9,716,284. For this study, data related to landslide damage in these counties for the two rainy seasons were analyzed in conjunction with information on slope stability compiled by the U.S. Geological Survey as part of the San Francisco Bay Region Environment and Resources Planning Study which was done in cooperation with the Department of Housing and

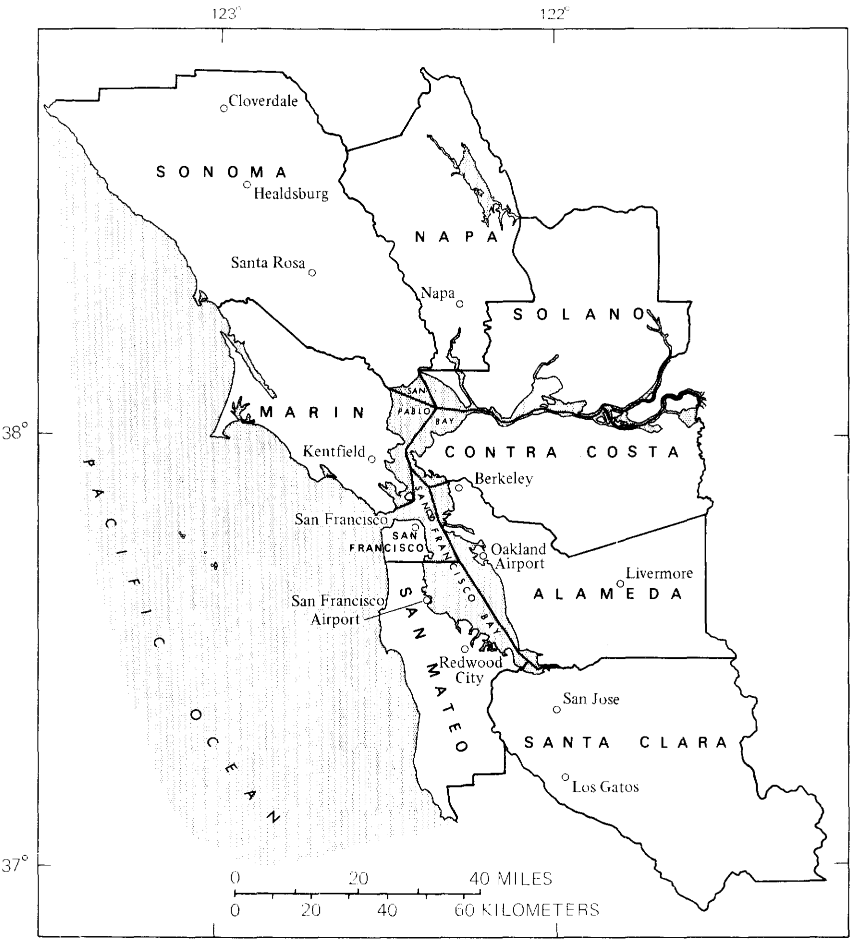


FIGURE 1.—Location of counties and selected precipitation recording stations in San Francisco Bay region.

Urban Development. For Contra Costa and Alameda Counties, we have incorporated some aspects of published analyses of landsliding that occurred through longer periods of time. Nilsen and Turner (1975) analyzed the influence of rainfall and ancient landslide deposits on modern landslides in Contra Costa County. Nilsen, Taylor, and Brabb (1975) analyzed the relations of slope, rainfall, and ancient landslide deposits to modern landslides in Alameda County.

These and other studies of slope stability in the bay region (Bonilla, 1960a; Radbruch and Weiler, 1963; Brabb and others, 1972; Frame, 1974; Anderson, 1974) have shown that the four parameters examined herein—ancient landslide deposits, slope, bedrock geology, and rainfall—are major factors controlling natural landslide activity and are keys to identifying slope stability problems. Although activities such as construction, grading, and runoff diversion can affect the degree of slope stability, most landslide problems probably can be avoided if sufficient information on the four controlling factors is available and prudently employed before projected human activity commences. In the city of Los Angeles, the application of modern grading codes and soils engineering and slope stability analyses to new hillside developments has greatly reduced the amount of damage caused by slope failures, from an average of $330 per site developed prior to 1952 to $7.00 for sites developed after 1963 (Slosson, 1969; Jahns, 1969).

Except for total seasonal rainfall, which was greater than average for both the 1968–69 and 1972–73 rainy seasons, seasonal factors or random events that might have contributed to the generation of landsliding do not appear to have been more active or more common in the bay region during these two rainy seasons. No major earthquakes or floods that would have triggered large numbers of landslides occurred. Construction of buildings and roads, which could have contributed locally or regionally to increased slope failures, proceeded at about the pace of previous years. Because these factors do not appear to have been abnormally high for these two seasons, our analysis and comparison of landslide damage with respect to the influence of the previously mentioned four factors is considered feasible.

METHOD OF STUDY

Data collected on landslides from the rainy seasons of 1968–69 and 1972–73 form the basis of the analyses presented in this report. These years were selected because they are representative of seasons with high landslide activity and because a great deal of data had previously been compiled for these two seasons in attempts to assess the magnitude and extent of landslide damage in the bay region. Taylor and Brabb (1972) collected and presented data from the nine bay region counties showing the location of landslides and the amount of public and private costs that resulted from these landslides during the rainy season of 1968–69. Taylor, Nilsen, and Dean (1975) reported results of a similar study for the 1972–73 rainy season, also including data provided by various cities within the region. The reader is referred to these reports for more detailed information regarding the sources of data, the manner in which the data were obtained and compiled, and minor differences in the manner of presenting the data for the two rainy seasons. The locations of all landslides recorded during the two rainy seasons are shown on plate 1.

The landslide and rainfall data for these two rainy seasons were presented in comparable format. However, some variations result from minor differences in the sources and type of data collected; these variations and differences are discussed below in the appropriate sections. All the data were collected by the same individual (Taylor), permitting relatively easy comparison and adjustment. The rainfall for both seasons was greater than the seasonal average for the bay region, and the resulting number of landslides was probably greater than during drier seasons; however, the amount of rain that fell during these two seasons is similar. The results of the comparitive analysis are relevant to studies of landsliding in the bay region, although such high landslide activity and costly damage to manmade structures would not be expected in drier rainy seasons.

ACKNOWLEDGMENTS

We wish to thank the many state, county, and city officials who provided data for this report, in particular, James Searfus of the Contra Costa County Grading Department, for his assistance with the landslide information for that county. A more detailed listing of sources of data for 1968–69 can be found in Taylor and Brabb (1972), for 1972–73 in Taylor, Nilsen, and Dean(1975).

TOTAL SEASONAL RAINFALL FOR 1968–69 AND 1972–73

Rainfall in the bay region for the 1968–69 and 1972–73 rainy seasons (Oct. through Apr.) was 31–78 percent higher than the seasonal mean rainfall 1930–74, as indicated by comparisons of four widely separated recording stations in table 1. Because rainfall in the bay region is seasonal, mean annual (Jan. 1–Dec. 31) and mean seasonal (usually Sept. or Oct. to Apr. or May) rainfall must be carefully distinguished. In this report, we shall use and refer to mean seasonal rainfall, rather than mean annual rainfall, since it better applies to the rainfall patterns of the bay region.

The increase in rainfall during the 1968–69 and 1972–73 seasons

TABLE 1.—*Comparison of 1968–69 and 1972–73 seasonal rainfall (Oct. through Apr.) for the San Francisco Bay region with mean seasonal rainfall for the period 1931–74*

[Data from Climatological Bulletins, U.S. Department of Commerce]

Precipitation recording station	Mean seasonal rainfall	Total seasonal rainfall, 1968–69	Percent by which 1968–69 is greater than mean	Total seasonal rainfall, 1972–73	Percent by which 1972–73 is greater than mean
Healdsburg	39.81 in. (1011 mm)	62.28 in. (1582 mm)	56	51.99 in. (1321 mm)	31
San Francisco	18.69 in. (475 mm)	28.28 in. (718 mm)	51	31.34 in. (796 mm)	68
Oakland Airport	17.93 in. (455 mm)	28.57 in. (726 mm)	59	28.60 in. (726 mm)	60
San Jose	13.11 in. (333 mm)	21.12 in. (536 mm)	61	23.35 in. (593 mm)	78

varied considerably from the northern to southern and western to eastern parts of the bay region (fig. 2). The largest increases in the 1968–69 total seasonal rainfall were in the northwestern (Cloverdale, Healdsburg, and Santa Rosa) and southwestern (San Francisco Airport, Redwood City, and San Jose) parts of the bay region. The largest increases in 1972–73 occurred in the central and southern parts of the bay region as shown by the totals for Berkeley, Oakland Airport, San Francisco, San Francisco Airport, Redwood City, Livermore, and San Jose (fig. 2)

Total seasonal rainfall fluctuates widely in the bay region, as is apparent from the rainfall graphs at four recording stations shown in figure 3. During the period 1930–31 to 1973–74, the 1968–69 amount was equaled or exceeded four times at Healdsburg, Oakland Airport, and San Jose, and five times in San Francisco. The 1972–73 amount was equaled or exceeded once in San Jose, four times in San Francisco and Oakland Airport, and twelve times in Healdsburg. From this pattern, similar seasonal totals of rainfall can be expected about once every 10 years on the average.

NUMBER OF LANDSLIDES AND COSTS OF DAMAGE

Of the $25 million worth of damage to manmade structures by landslides during the rainy season of 1968–69 and about $10 million in 1972–73, the greatest amount was to roads and private houses (figs. 4, 5, 6, 7). Other structures damaged included utilities, public buildings, parklands, and dams.

The number of landslides recorded in the nine bay area counties differed considerably for 1968–69 and 1972–73 (table 2). In 1972–73, Contra Costa, Marin, and Solano Counties reported significantly greater numbers of landslides than in 1968–69; Alameda and Sonoma Counties significantly fewer; and Napa, San Francisco, San Mateo, and Santa Clara Counties similar numbers. The public and private costs resulting from these landslides, however, are not necessarily

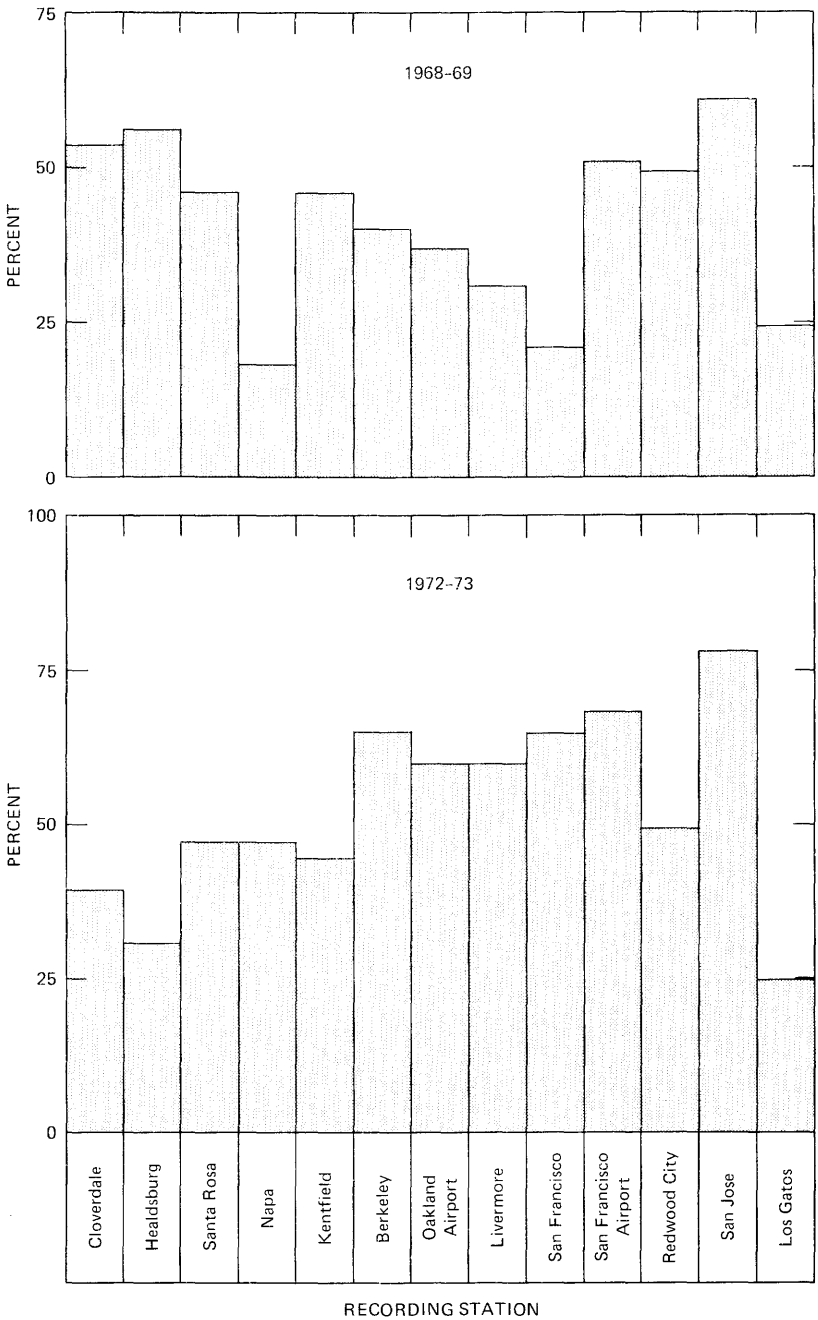


FIGURE 2.—Percentages by which total seasonal rainfall in 1968–69 and 1972–73 exceeded the 1931–60 average for 13 geographically separated recording stations. Location of stations shown on figure 1.

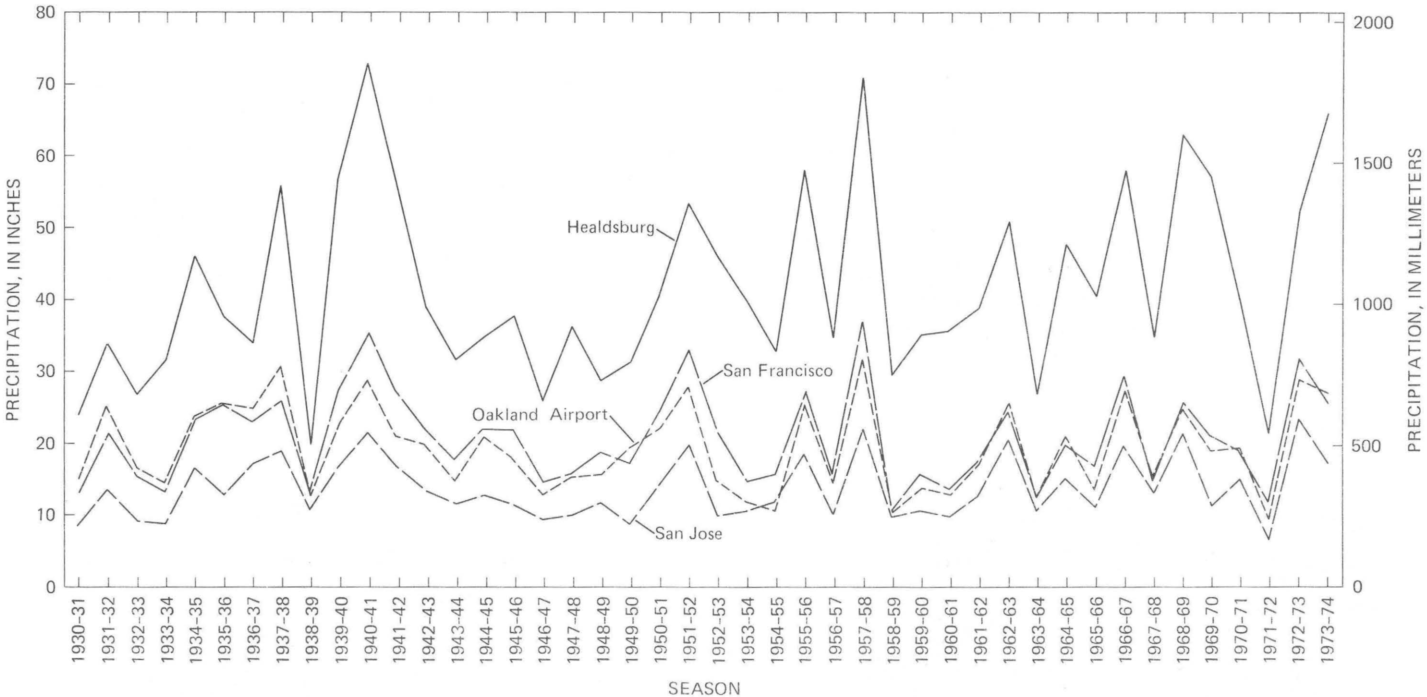


FIGURE 3.—Variations in total seasonal rainfall from 1930–31 to 1973–74 for Healdsburg, Oakland Airport, San Francisco, and San Jose. As data from the station at Oakland Airport were not available before 1938, data from the precipitation-recording station at Oakland were substituted.

FIGURE 4.—Landslide on Madera Avenue, city of San Carlos, San Mateo County, February 1969. Photograph by Bernard Burton, San Mateo County planning commission.

FIGURE 5.—Landslide damage to U.S. Interstate Highway 80 near Pinole, Contra Costa County, May 1969.

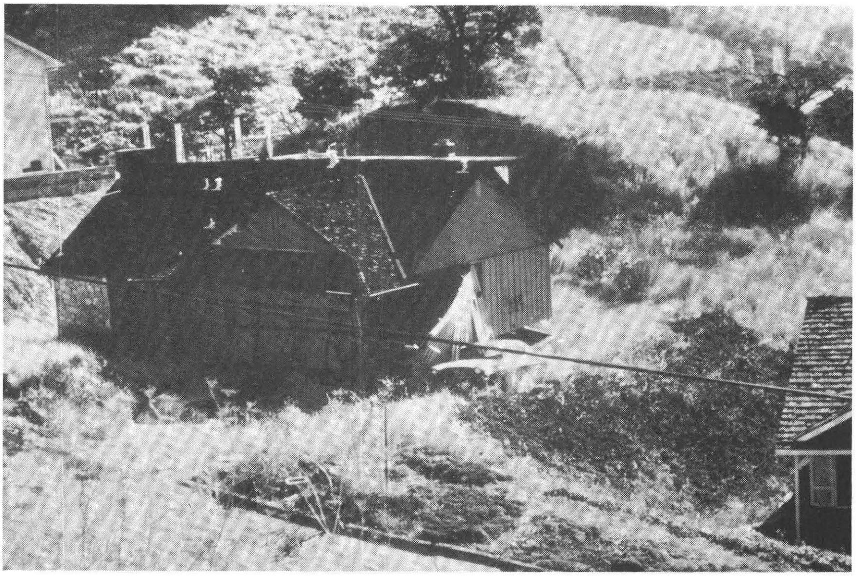


FIGURE 6.—Landslide damage to house on Claitor Way, San Jose Highlands, city of San Jose, Santa Clara County, December 1972. Photograph by Earl E. Brabb.

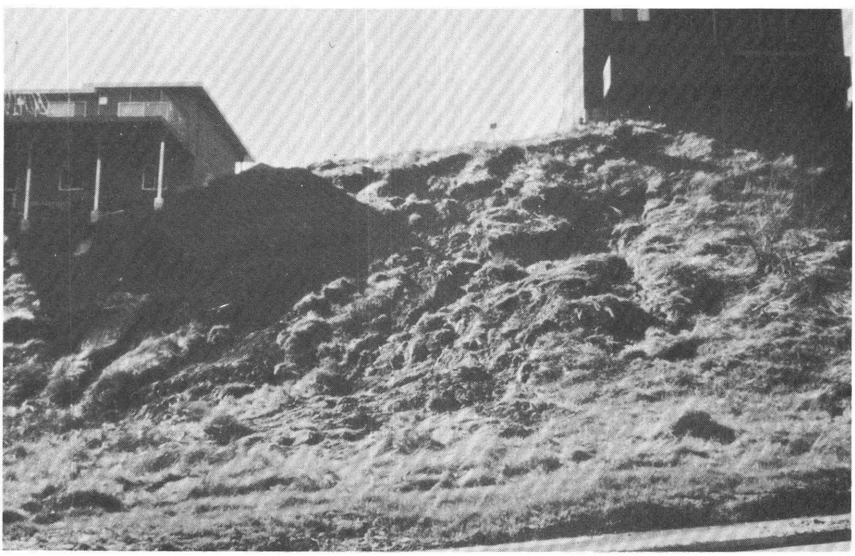


FIGURE 7.—Landslide below houses, Morningside Drive, Millbrae, San Mateo County.

proportional to the numbers of landslides reported. These apparent discrepancies between the number of landslides and resultant damage costs in 1968–69 and 1972–73 may have resulted from the inher-

TABLE 2.—*Detailed comparison by county of public and private costs due to landslides in the San Francisco Bay region during the 1968–69 and 1972–73 rainy seasons*

County	Number of landslides		Public								Private		Miscellaneous		Total	
			State		County		City[1]	Parks[1]	Tax loss							
	1968–69	1972–73	1968–69	1972–73	1968–69	1972–73	1972–73	1972–73	1968–69	1972–73	1968–69	1972–73	1968–69	1972–73	1968–69	1972–73
Alameda	58	27	$53,000	$191,000	$390,000	$20,000	$57,500	0	0	$2,345	$4,929,700	$88,400	$24,000	0	$5,396,700	$359,245
Contra Costa	70	110	1,970,000	40,243	1,682,190	901,400	0	$10,845	0	22,140	1,440,070	712,550	90,000	0	5,182,260	1,687,178
Marin	66	153	164,000	340,000	678,950	630,570	967,150	0	0	32,820	82,000	1,093,950	130,000	0	1,054,950	3,064,490
Napa	2	8	48,000	87,000	380,000	42,000	0	300	0	0	800,000	2,000	250,000	0	1,478,000	131,300
San Francisco	9	8	33,000	400,000	0	see city	90,000	0	0	0	100,000	0	0	0	133,000	490,000
San Mateo	70	60	735,000	2,182,500	448,500	50,000	49,000	0	12,000	29,810	1,245,518	1,284,000	1,158,000	0	3,599,018	3,595,310
Santa Clara	12	17	148,000	41,000	904,758	unknown	30,543	4,000	0	0	491,520	74,518	355,000	0	1,899,278	150,061
Solano	3	22	0	0	4,000	8,750	200	0	0	0	0	19,500	0	0	4,000	28,450
Sonoma	45	6	1,844,800	195,000	688,750	no report	1,000	4,250	0	unknown	0	10,000	3,900,200	0	6,433,750	210,250
Total	335	411	4,995,800	3,476,743	5,177,148	1,742,720	1,105,393	19,395	12,000	87,115	9,088,808	3,284,918	5,907,200	0	[2]25,180,956	9,716,284

[1]No data on cities or parks collected for 1968–69.
[2]An additional $213,000 was reported by the Pacific Gas and Electric Co. for the entire bay area, making the total $25,393,956.

ent problems with the manner in which the data were obtained and compiled, differences in landslide location and size, and other factors discussed below.

DISTRIBUTION OF DAMAGING LANDSLIDES

Landslide damage, though widespread throughout the bay region, is concentrated in certain areas as a result of the interaction of intense local rainfall acting together with slope conditions, bedrock geology, and surficial deposits favorable for landslide activity. Construction activities may also contribute to the concentration of landslide damage.

Landslide activity in 1968–69 was concentrated in the Lafayette-Orinda area of Contra Costa County, the west slope of the Berkeley and San Leandro Hills between Oakland and Castro Valley in Alameda County, and on the east slope of the northern Santa Cruz Mountains between San Mateo and Redwood City in San Mateo County.

Landslide activity in 1972–73 was highest in the Mill Valley and Fairfax-San Anselmo areas of Marin County, the Lafayette-Orinda area of Contra Costa County, and the west slope of the Berkeley Hills northeast of Berkeley in Alameda County. Landslide activity was also widespread in the northwestern part of San Mateo County.

It is apparent from the distribution of landslides as mapped on plate 1 that landslide damage takes place primarily in the hills directly adjacent to San Francisco Bay and is closely associated with urban areas on slopes steeper than 15 percent (8.5° slope) (shown on pl. 1). The moderate rainfall and high construction activity in these areas relative to the rest of the bay region is no doubt also a contributing factor.

Conclusions about geographic centers of landslide activity are difficult to make on the basis of only two seasons. However, the Lafayette-Orinda area is the only center of high landslide activity common to both seasons. The western slope of the Berkeley and San Leandro Hills extending from Richmond to Hayward and the eastern slope of the northern Santa Cruz Mountains between Daly City and Menlo Park appear to be prone to landslide activity, although a concentration is not apparent in both seasons. The urbanized southeastern part of Marin County is prone to landslide activity, and although few landslides were reported in 1968–69 relative to 1972–73, the greatest activity for both seasons appears to be concentrated in these urban areas, particularly in the cities of Mill Valley, Fairfax, and San Anselmo.

COSTS OF LANDSLIDE DAMAGE

The data on costs of damage related to landslides that are presented herein were obtained by Taylor in interviews with engineers and geologists in city, county, and State governments, county planners and assessors, the news media, and consulting engineering geologists in the nine bay region counties. Two categories of costs are reported—public and private. Public costs are dollars spent or lost by governmental agencies, costs ultimately paid by the taxpayer. Public landslide costs ideally include such emergency expenses as salaries for firemen, policemen, and others responsible for protecting public health and safety, but these expenses are rarely available and are not included in this report. Most of the public landslide cost is the direct expense of repairing, restoring, or relocating roads. This includes expenses readily attributable to specific large landslides and an educated guess for smaller landslides included within budgets for routine road maintenance and repair. Some expense for damage to sewerlines, street lighting, sidewalks, and other publicly owned facilities is included, but this is a small percentage of the total cost.

To further protect property or to repair existing landslides, it sometimes becomes necessary for a public agency to obtain title to privately owned land. Because it becomes more economical to obtain title to property and have it vacated than attempt to maintain services that are continually disrupted by active landsliding, the agency assumes, in addition to the original cost of procurement, costs for erosion control, weed abatement, and other minor costs.

Litigation results in another public cost. However, no data were obtained on costs of preparing and conducting court proceedings, and only limited data are available on settlements of civil suits resulting from landslide damage.

Land that is transferred from private to public ownership and therefore removed from the tax roll results in lost tax revenue. Revenue losses also result from the devaluation of private property followed by a lowering of tax on the land because of landslide damage.

Private costs are those resulting from loss of real property, improvements, furnishings, and personal effects. Although furnishings and personal effects can often be replaced by individuals who are financially able, real property may be rendered unusable. In addition to the direct costs of repairs, property that has been damaged by a landslide often depreciates in value. A reappraisal by the tax assessor's office that shows a difference between the fair market value had a landslide not occurred and the valuation since one did occur represents a loss to the property owner as well as the community. Houses located adjacent to houses damaged by landsliding may be lowered in market value because of fears of prospective buyers and may be difficult to sell.

No attempts were made to evaluate the costs of inconveniences such as time lost taking detours or the costs that resulted from a home being evacuated—the cost of food and lodging, for example.

Very few counties keep written records that can be easily applied to an analysis such as ours and much of the data is based on oral communication and is general in nature. Federal Storm Damage Reports filed by Marin and Contra Costa Counties provided the most consistent and accurate damage estimates. We attempted to follow in 1972–73 the procedures used in 1968–69, adding data from individual cities and public parks. By following the same procedures, any differences between the counties should be fairly consistent and the data comparable.

Table 2 shows the actual costs recorded for 1968–69 and 1972–73. In table 3, which is based on data presented in table 2, the values are rounded off and adjusted (see notes at the bottom of table 2) to facilitate comparison. The miscellaneous costs recorded for 1968–69 (see table 3) represent primarily costs related to litigation and unusual events; these were not reported in 1972–73. The $3.9 million total given for the Warm Springs Dam in Sonoma County in 1968–69 is a long-term depreciation value based on the initial cost of the dam and long-term reduction of capacity due to landslide activity. Since only a

TABLE 3.—*Comparison of actual and adjusted costs of landslide damage in the San Francisco Bay region during 1968–69 and 1972–73 rainy seasons*

	Actual damage		Adjusted and rounded values	
	1968–69	1972–73	1968–69	1972–73
Total public	$10,184,948	$6,431,366	$12,100,000	$6,450,000
State	4,995,800	3,476,743	5,000,000	3,500,000
County	5,177,148	1,742,720	5,000,000	1,750,000
City[1]	----------	1,105,393	2,000,000	1,100,000
Parks[2]	----------	19,395	----------	----------
Tax loss	12,000	87,115	100,000	100,000
Total private	9,088,808	3,284,918	9,000,000	3,200,000
Total public and private	19,273,756	9,716,284	21,100,000	9,650,000
Dam and litigation[3]	5,373,200	----------	----------	----------
Total	24,646,956	9,716,284	21,100,000	9,650,000

[1]Based on 1972–73 data. If costs for individual cities had been collected for 1968–69, their combined losses, in proportion to the state and county, would have been about $2,000,000.

[2]Data for parks were not obtained in 1968–69 and were available from only four counties in 1972–73; park expenses are excluded from the rounded and adjusted cost comparison.

[3]Since the dam costs in 1968–69 were anomalous and no litigation costs were compiled for 1972–73, these figures are excluded from the rounded and adjusted cost comparison.

fraction of this capacity reduction was realized in 1968–69, the cost has been excluded from our adjusted comparison.

SUMMARY OF RESULTS BY COUNTY

The county-by-county summary of the number of landslides and the resultant damage costs (table 2) is taken from data recorded in 1968–69 and 1972–73. Much of the difference between landslide damage costs for the two seasons can be attributed to the type and (or) location of landslide activity. In general, less damage is caused by a smaller and more slowly moving landslide consisting of surficial material than by a larger landslide involving bedrock or a rapidly moving landslide. How much damage is caused by any landslide depends partly on its velocity, size, and composition, parameters that are extremely variable and depend on the slope, bedrock, surficial deposits, and rainfall at the site of the landslide. The location of the landslide movement is critical; i.e., a landslide falling on a road will normally cause less damage than one that undermines the roadbed. Whether a landslide affects an isolated house or a large development will make a great difference in damage costs. As the scope of this study did not allow for extensive field investigation, we are not able to account for the differences in the county comparisons in more than a general way.

In Alameda County, 27 landslides were reported in 1972–73, compared to 58 in 1968–69; yet, damage costs amounted to $0.36 million in 1972–73, and more than $5 million in 1968–69. The lesser cost of damage in 1972–73 can be largely explained by the smaller number of devalued land parcels (710 in 1968–69, 9 in 1972–73), a cost difference of $3.8–3.9 million. It appears that most of the damaging landslides in 1972–73 affected private property (table 3). As the rate of housing construction in Alameda County was approximately the same from 1968 to 1973 (Security Pacific Bank, 1968–73), the lesser amount of damage in 1972–73 probably resulted from the location and type of landslide activity.

Contra Costa County sources reported 40 more landslides in 1972–73, yet nearly $3.5 million less damage than in 1968–69. The individual cities contacted in 1972–73 did not report a significant number of landslides or related costs; substantial difference between the two rainy seasons probably results from differences in the location and type of damage resulting from the landslides.

In Marin County, both the number of landslides and costs were two to three times greater in 1972–73, mainly because data from individual cities was included (table 3). This difference amounted to 43 landslides and nearly $1 million damage.

In Napa County, two landslides were reported in 1968–69, compared to eight in 1972–73; yet, the reported costs in 1968–69 were more than $1 million greater. The difference between the two rainy seasons was probably due to differences in location and type of the landslides.

San Francisco City and County sources reported no significant difference between the two rainy seasons. All the 1972–73 landslides affected roadways, whereas some private costs were reported in 1968–69.

In San Mateo County, the number of landslides and amount of damage for the two rainy seasons were similar. Several larger landslides in 1972–73 caused an increase in State expenditures, and continued movements in existing problem areas kept private expenditures at the 1968–69 level.

Santa Clara County showed no substantial difference in the number of reported landslides for both rainy seasons, although damage costs decreased markedly in 1972–73. The low costs recorded for this season can be explained by the fact that landslides were mostly on county roads, for which county officials provided no estimates of costs of repair or maintenance.

Most reported landslides in Solano County were small and affected roads. Three landslides caused $4,000 damage in 1968–69; 22 caused about $9,000 damage in 1972–73. Damage to residential units was $19,500 in 1972–73; no information on such units was available for 1968–69.

For 1968–69, Sonoma County sources reported 45 landslides. Nearly $1.9 million damage from one landslide and nearly $4 million of landslide damage related to the Warm Springs Dam represent most of the damage costs for that season. County officials provided no data on landslides in 1972–73. Damage reported from other sources was $210,250, and six landslides were recorded. Because of the anomalous costs in 1968–69, it is difficult to make any definite conclusions.

We have calculated in table 4 the cost per capita, the cost per dwelling unit, and the cost per urban square mile for each of the nine counties. These figures give a relative comparison between the density of population and housing and the landslide damage recorded in each county. In Contra Costa, Marin, Napa, San Mateo, and Sonoma Counties, the damage costs are high relative to the population, housing density, and urban area, but in San Francisco and Solano Counties the damage costs are low relative to population, housing density, and urban area. These figures further emphasize how costly landslide damage can be in some parts of the bay region. Much of this cost represents public funds and therefore is a financial drain on the gen-

TABLE 4.—*Per capita costs, costs per dwelling unit, and costs per urban square mile from landslides in the San Francisco Bay region during the 1968–69 and 1972–73 rainy seasons*

		1968–69		1972–73										
	1970 population[1]	Cost	Per capita cost	Cost	Per capita cost	Average per capita cost	Number of dwelling units	1968–69 cost per dwelling unit	1972–73 cost per dwelling unit	Average cost per dwelling units	Square miles of urban land	1968–69 cost per urban square mile	1972–73 cost per urban square mile	Average cost per urban square mile
Alameda	1,073,184	$5,396,700	$5.03	$359,245	$0.33	$2.68	365,000	$14.79	$0.98	$7.89	162	$33,313	$2,218	$17,766
Contra Costa	555,805	5,182,260	9.32	1,687,178	3.04	6.18	173,000	29.96	9.75	19.86	102	50,806	16,541	33,674
Marin	206,038	1,054,950	5.12	3,064,490	14.87	10.00	68,000	15.51	45.07	30.29	40	26,374	76,612	51,493
Napa	79,140	1,478,000	18.68	131,300	1.66	10.17	25,000	59.12	5.25	32.19	10	147,800	13,130	80,465
San Francisco	715,674	133,000	.19	490,000	.68	.44	295,000	.45	1.66	1.06	39	3,410	12,564	7,987
San Mateo	556,234	3,599,018	6.47	3,595,310	6.46	6.47	185,000	19.45	19.45	19.45	90	39,989	39,948	39,969
Santa Clara	1,064,714	1,899,278	1.78	150,061	[2]0.14	.96	323,000	5.88	.46	3.17	184	10,322	816	5,569
Solano	171,989	4,000	[2].02	28,450	.17	.10	51,000	.08	.56	0.32	27	148	1,054	601
Sonoma	204,885	2,533,750	[2,3]12.37	210,250	[2]1.03	6.70	68,000	37.26	3.09	12.06	26	97,452	8,087	52,770

[1]Based on the U.S. Bureau of Census figures.

[2]These counties did not report a great part of their costs; hence these values will be lower than the actual amount.

[3]Costs attributed to the Warm Springs Dam totaled $3.9 million in 1968–69, but no costs were reported in 1972–73. This is an anomalous cost (see text) and has been omitted from this comparison.

eral populace rather than on just a few individuals or families.

The costs of landslide damage for the 1968–69 and 1972–73 rainy seasons differ by $11,500,000 even though the adjusted numbers of landslides (no landslide data from cities were collected in 1968–69, whereas 90 landslides were reported in 1972–73) is nearly the same: 335 in 1968–69, 321 in 1972–73. In general, the total amount, maximum rates, and sequence of rainfall, as shown later in this report, appear to have been generally similar; cost is the only real difference. An in-depth analysis for the specific causes of this anomaly would require additional data not made available to us; the suggestions inherent in the county analyses made here may explain some of the differences.

DISTRIBUTION OF 1968–69 AND 1972–73 LANDSLIDES RELATIVE TO ANCIENT LANDSLIDE DEPOSITS

INTRODUCTION AND ANALYSIS

Much controversy exists regarding the influence of ancient landslide deposits on renewed landsliding and the stability of slopes that have already failed relative to those that have not. Cogent arguments can be made that ancient landslide deposits, because materials are broken and weakened, are likely sites for continued landsliding and settling, especially if slopes are later modified by construction activities or other human-related activities. Moreover, landsliding characteristically produces a steeply sloping scarp above the landslide deposit which may have a high propensity to slide; under these conditions, the locus of sliding will generally migrate upslope. In addition, the general conditions that produce landsliding in one area—stream erosion at the base of a slope, broken and fractured rock, thick and weak soils—will probably continue to prevail in the area, inducing further sliding.

It can be argued, however, that once landsliding has taken place, a natural slope may have attained a stable configuration and will not be susceptible to further movement. Stream erosion may actually remove the landslide deposit, leaving a relatively stable slope defined by the former slip surface of the landslide. It can also be argued that many of the ancient landslide deposits may have been triggered under markedly different environmental conditions, particularly during wetter climatic intervals of the Pleistocene; these old landslide deposits may be relatively stable under present climatic conditions if the present climate is drier than the earlier one.

The distribution of recent landslides was compared with that of ancient landslide deposits to determine the usefulness of ancient landslide deposits in evaluating slope stability in the bay region.

Maps showing the locations of 1968–69 and 1972–73 landslides (derived from pl. 1) were superimposed on a series of maps that show the distribution of ancient landslide deposits mapped primarily by photointerpretation but with some field checking. The maps showing ancient landslide deposits were compiled from many sources by T. H. Nilsen and R. H. Wright (unpub. data) for the purpose of preparing a relative slope stability map of the bay region. The mapping of ancient landslide deposits in the bay region is not complete; some large gaps exist, particularly in northern parts of the region. In addition, the mapping is generally of variable quality and detail, having been completed by a number of individuals with differing capabilities and interests. As a result, the comparison is not consistent in character throughout the region.

The locations of 1968–69 and 1972–73 landslides were originally plotted on 7½-minute quadrangles on the basis of information supplied by officials contacted in the bay region. These locations were checked in the field when possible, but many had to be approximated from oral or written reports. In order to facilitate the comparison made herein, the locations were transferred to 1:125,000-scale maps, further reducing location accuracy. For these reasons, the final locations as mapped are necessarily represented as larger areas than the original landslides. It was determined that a landslide of roughly 610 m (2,000 ft) is the smallest that could be plotted with any accuracy at the 1:125,000 scale. In order to standardize our results, a 4.9 mm (3/16 in.) diameter circle, roughly 610 m (2,000 ft) in diameter at the 1:125,000 scale, was centered over each 1968–69 and 1972–73 location. If any part of an ancient landslide deposit was in contact with the circle, the location was counted as being associated with an ancient landslide deposit. Because this analysis is necessarily generalized, for the comparison, the results are regarded as estimates rather than precise numerical values.

RESULTS

From the reported distribution of landslides in 1968–69 and 1972–73, summarized in table 5, an average of 63 percent appears to be associated with ancient landslide deposits. The correlation appears to be lower for 1968–69 (55 percent) than for 1972–73 (69 percent). Because of the generalized nature of the analysis, these values should be considered only approximately correct.

Considerable variation exists in the correlation from county to county and from 1968–69 to 1972–73. The reasons for these variations are not entirely clear. The strongest correlations exist for Contra Costa and Marin Counties (82 and 75 percent, respectively), the two counties that probably kept the best records of the number and locations of recent landslides and for which the mapping of ancient land-

TABLE 5.—*Number and percent of 1968–69 and 1972–73 landslides in the San Francisco Bay region located on or near ancient landslide deposits*

County	1968–69				1972–73				Total			
	Landslides in association with ancient landslide deposits		Landslides not in association with ancient landslide deposits		Landslides in association with ancient landslide deposits		Landslides not in association with ancient landslide deposits		Landslides in association with ancient landslide deposits		Landslides not in association with ancient landslide deposits	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Alameda	12	39	19	61	16	70	7	30	28	52	26	48
Contra Costa	52	84	10	16	82	82	18	18	134	83	28	17
Marin	26	67	13	33	89	78	25	22	115	75	38	25
Napa	0	0	1	100	2	25	6	75	2	22	7	78
San Francisco	0	0	4	100	3	37	5	63	3	18	9	82
San Mateo	19	37	33	63	29	52	27	48	48	44	60	56
Santa Clara	4	67	6	33	8	50	8	50	12	46	14	54
Solano	1	33	2	67	10	48	11	52	11	46	13	54
Sonoma	15	50	15	50	5	83	1	17	20	56	16	44
Total	129	56	103	44	244	69	108	31	373	64	211	36

slide deposits is excellent and complete. Relatively complete and good mapping of ancient landslide deposits is available from Alameda and San Mateo Counties, which keep relatively good records of landsliding; these counties show high correlations in 1972–73 (70 and 51 percent, respectively) and low correlations (39 and 38 percent) in 1968–69. Moderate correlations exist in Santa Clara and Solano Counties, low correlations in San Francisco and Napa Counties; because the total number of landslides recorded in these four counties was relatively small, however, the results may not be statistically significant. In Sonoma County, a total of 56 percent of the 1968–69 and 1972–73 landslides are reported in association with ancient landslide deposits, although ancient landslide mapping is not complete and recordkeeping not especially good.

A relatively high proportion of recent landslides occur in association with ancient landslide deposits. A substantial number of the recent landslides that do not follow this relation may represent small landslides that resulted directly from human activities where stable natural slopes were disturbed by roadcuts, housing developments, and other related alterations of natural slopes and drainage. Other recent landslides may represent thin surficial debris flows of the type that do not leave deposits large enough or thick enough to have been mapped as areas of ancient landslide deposits.

CONCLUSIONS

The results of this comparison indicate that the distribution of ancient landslide deposits in the San Francisco Bay region is a useful guide to relative slope stability and is a useful tool for the development of relative slope stability maps. Because more than 60 percent of the recent landslides that caused damage to manmade structures in 1968–69 and 1972–73 took place in areas immediately adjacent to or on ancient landslide deposits, development on or near ancient landslide deposits must be undertaken with great care and after careful engineering geologic studies of particular sites.

In southern California, Kojan, Foggin, and Rice (1972) found that 81 percent of the natural debris slides triggered during storms of 1969 in the Santa Ynez and San Rafael Mountains occurred in areas of previous landsliding. Morton (1971) concluded that a substantial number of the landslides triggered by the 1971 San Fernando, Calif., earthquake represented renewed movement of old landslide deposits. By this analysis, distribution of ancient landslides is a key to predicting future landslide activity on both natural and man-modified slopes.

Cleveland (1971) and Douglas M. Morton (oral commun., May

1975), who have studied landsliding in southern California extensively, found that in some areas, recent landsliding, particularly soil slips developed on steep slopes during intense storms, commonly occurs on slopes where earlier sliding is not known. In summary, although not all types of landsliding may reoccur in areas of previous landsliding, the relations in the bay region indicate that developments on old landslide deposits must be subject to careful site studies.

RELATION OF 1968–69 AND 1972–73 LANDSLIDES TO SLOPE

CATEGORIES OF SLOPE AND ANALYSIS

Landslides that caused damage in 1968–69 and 1972–73 were compared with slope using slope maps of the bay region prepared by photomechanical procedures by the U.S. Geological Survey (1972). The results of this comparison support conclusions from earlier studies in the bay region on the frequency of landsliding on slopes of various inclination (Bonilla, 1960a; Brabb and others, 1972; Nilsen and others, 1975) that determined that 85 percent or more landslides took place on slope of 15 percent (8.5°) or greater.

Three slope categories from simplified slope maps of the bay region prepared by T. H. Nilsen and R. H. Wright (unpub. data) are used in our analysis: 0–5 percent (0°–3°), 5–15 percent (3°–8.5°), and greater than 15 percent (8.5°). A circle 4.9 mm (3/16 in.) in diameter, corresponding to 610 m (2,000 ft) at the map scale of 1:125,000, was placed over each landslide location as in the previous comparison with ancient landslide deposits. Where a landslide location intersected more than one slope category, it was counted as being on the one under most of the circle, unless the landslide obviously took place on another slope.

RESULTS

Our comparison by county and rainy season of landslides in the three categories of slope (table 6) shows the data for the two rainy seasons to be generally comparable, except that in 1968–69 a higher percentage (14 vs. 6) of landslides occurred on slopes of 0–5 percent (0°–3°), and in 1972–73 a higher percentage (80 vs. 74) was on slopes steeper than 15 percent (8.5°). Except for Napa County in 1968–69 (when one landslide was recorded), the majority of landslides occurred on slopes greater than 15 percent (8.5°). In general, the highest percentage of landslides on slopes greater than 15 percent took place in Marin, Contra Costa, San Mateo, and Santa Clara Counties; the significance of this is not clear, although each of these counties shows considerable development on slopes of this category (pl. 1).

TABLE 6.—*Landslides on slopes of 0–5 percent (0°–3°), 5–15 percent (3°–8.5°), and greater than 15 percent (8.5°) in the San Francisco Bay region during the 1968–69 and 1972–73 rainy seasons*

	Slope angle, 1968–1969						Slope angle, 1972–73					
	15 + percent (8.5°+)		5–15 percent (3°–8.5°)		0–5 percent (0°–3°)		15 + percent (8.5°+)		5–15 percent (3°–8.5°)		0–5 percent (0°–3°)	
County	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Alameda	19	61	5	16	7	23	12	52	10	44	1	4
Contra Costa	50	81	7	11	5	8	78	76	20	19	5	5
Marin	35	90	0	0	4	10	96	84	10	9	8	7
Napa	0	0	1	100	0	0	8	100	0	0	0	0
San Francisco	2	50	1	25	1	25	6	75	1	12.5	1	12.5
San Mateo	39	75	8	15	5	10	49	88	4	7	3	5
Santa Clara	7	70	1	10	2	20	16	100	0	0	0	0
Solano	2	67	1	33	0	0	14	67	5	24	2	9
Sonoma	16	53	6	20	8	27	4	67	1	16.5	1	16.5
Total	170	73	30	13	32	14	283	80	51	14	21	6

CONCLUSIONS

The strong demonstrated relation between slope and landsliding is not surprising, as earlier investigations had produced similar results. We feel that these results represent a low estimate of the actual correlation, since many landslides on slopes of less than 15 percent (8.5°) were actually on roadcuts, streambanks, or other short slopes probably steeper than 15 percent but too small to be shown at the map scale used in this study. Our analysis demonstrates that slope maps can be very useful in predicting, in a general sense, places where landslides are most likely to occur in the natural environment. These slope maps can provide regional planners, developers, and the public with preliminary information on areas where slope stability may be a problem, and such maps have indeed been helpful in planning for urban development. It is necessary to point out that many landslides result from modification of natural slopes by man, commonly in areas that might at first appear to be stable.

RELATION OF 1968–69 AND 1972–73 LANDSLIDES TO BEDROCK GEOLOGY

BEDROCK UNITS SUSCEPTIBLE TO LANDSLIDING

Slope stability investigations in the bay region and other parts of California have indicated that certain geologic formations, because of their physical and engineering characteristics, are more susceptible to landsliding than others (see, for example, Radbruch and Weiler, 1963; Brabb and others, 1972; Morton, 1971). This characteristic permitted Radbruch and Wentworth (1971) to prepare a generalized map of estimated landslide abundance for the bay region. T. H. Nilsen and R. H. Wright (unpub. data), through discussion with geologists familiar with the characteristics of various bedrock units in the region, examinations of the published descriptions of various units, and field observations, determined a number of bedrock geologic units to be highly susceptible to landsliding on slopes greater than 15 percent (8.5°). These units were utilized in the preparation of a relative slope stability map of the San Francisco Bay region.

For this paper, we decided to check independently the validity of the selections of bedrock units by Nilsen and Wright by carefully examining the distribution of the 1968–69 and 1972–73 landslides with the bedrock units suspected to be susceptible to landsliding. Although the distribution of recent landslides is biased, inasmuch as only those that damaged manmade structures have been recorded, the units outcropping in or underlying developed hillside areas should nonetheless, if Nilsen and Wright's method is valid, be involved in a number of the 1968–69 and 1972–73 landslides.

To determine whether these units have in fact behaved in an unstable manner during recent times, the location of recorded landslides that caused damage to manmade structures in 1968–69 and 1972–73 were compared with mapped bedrock geologic units using the procedure described in the comparison of landslides with slope. Because most of the recent landslides occurred on slopes that had been modified by the activities of man, rather than on completely natural slopes, we suspected that uneven correlation might result, particularly for those landslide-prone units not present in developed areas.

RESULTS

The number of landslides of the 1968–69 and 1972–73 rainy seasons that were located on bedrock units judged to be susceptible to slope failures by Nilsen and Wright are shown in table 7. Quaternary deposits were excluded because they are not considered to be bedrock units and because many landslide locations that were mapped as being within nearly flat Quaternary deposits actually originated on adjacent slopes in bedrock units. Because the resulting deposits rest on or lie within Quaternary deposits, they might otherwise be interpreted as having originated within these deposits. We therefore confined our analysis to those locations that could be indentified with specific bedrock units but for comparison have included below the number of landslides recorded on Quaternary deposits.

Landslides recorded on Quaternary deposits

(not shown on table 7)

County	1968–69	1972–73	Total
Alameda	13	17	30
Contra Costa	17	28	45
Marin	6	25	31
Napa	0	1	1
San Francisco	4	4	8
San Mateo	18	20	38
Santa Clara	5	5	10
Solano	1	6	7
Sonoma	14	1	15
Total	78	107	185

The results show that on a regional basis, recent landslides have taken place more frequently in the bedrock units considered by Nilsen and Wright to be especially susceptible to landsliding; 63 percent of all recorded landslide locations in the bay region from 1968–69 and 1972–73 (not including those mapped as Quaternary deposits) took place on these bedrock units. Contra Costa, Marin, and San Mateo Counties, having the greatest number of landslides, provide

TABLE 7.—*Number and percentage of landslides in the San Francisco Bay region on bedrock units considered to be stable or unstable by T. H. Nilsen and R. H. Wright (unpub. data); this compilation of landslides does not include those located on Quaternary deposits*

County	1968–69				1972–73				Total			
	Unstable rock units		Stable rock units		Unstable rock units		Stable rock units		Unstable rock units		Stable rock units	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Alameda	5	28	13	72	5	83	1	17	10	42	14	58
Contra Costa	40	78	11	22	65	76	20	24	105	77	31	23
Marin	17	51	16	49	65	73	24	27	82	67	40	33
Napa	1	100	0	0	5	71	2	29	6	75	2	25
San Francisco	0	0	0	0	0	0	4	100	0	0	4	100
San Mateo	25	68	12	32	14	40	21	60	39	54	33	46
Santa Clara	4	80	1	20	5	50	5	50	9	60	6	40
Solano	0	0	2	100	5	33	10	67	5	29	12	71
Sonoma	9	56	7	44	4	80	1	20	13	62	8	38
Total	101	62	62	38	168	66	88	34	269	64	150	36

the most significant results. The other counties generally had too small a number of landslides to be representative, and as a consequence, their correlations differ widely.

CONCLUSIONS

The distribution of landslides in the bay region is closely related to the distribution of bedrock geologic units, for certain rock types are especially susceptible to landsliding and soils developed by weathering of these units may also be weak and prone to landsliding. Those units shown by T. H. Nilsen and R. H. Wright (unpub. data) to be especially susceptible to landsliding are designated by asterisk on the list of the bedrock units on which landslides developed in the 1968–69 and 1972–73 rainy seasons (table 8).

Bedrock characteristics can change markedly over a few hundred feet within the same rock unit, particularly in the bay region, where the formations are complex and often locally sheared and faulted. The bedrock units need therefore to be carefully studied and examined at local construction or development sites. Although we have shown that on a regional basis recent landslides are most numerous within certain rock units, further research is necessary to determine the complex role that bedrock geology plays in controlling landsliding.

RELATION OF RAINFALL PATTERNS TO NUMBER OF LANDSLIDES

Rainfall has been shown to be a major natural factor in initiating landslide activity in the bay region (Nilsen and Turner, 1975; Nilsen and others, 1975). Because of the substantial difference in the amount of damage caused by landslides in 1968–69 and 1972–73, despite nearly the same total amount of rainfall, we compared the sequence and pattern of rainfall for the two seasons. The most critical rainfall factors appear to be (1) the duration of a storm period (any interval of nearly continuous precipitation), (2) the intensity of the storm period, and (3) the amount of previous rainfall for a particular season.

METHOD OF ANALYSIS

Contra Costa County is used as an example for this study because records have been accurately kept there and are readily available. The occurrence of a landslide that has damaged a manmade structure in the county is generally recorded within the same day, and the rainfall is generally recorded once per day, making a general comparison of rainfall and landsliding possible. More detailed analyses such as that by Campbell (1974) for southern California using continuously recording gauges were not possible. An earlier analysis of

TABLE 8.—*The number of landslides recorded by county during the 1968–69 and 1972–73 rainy seasons for bedrock units in the San Francisco Bay region*

[Asterisk (*) denotes rock unit judged to be susceptible to slope failure (by T. H. Nilsen and R. H. Wright, unpub. data)]

County	Rock unit	Number of landslides recorded in each rock unit 1968–69	1972–73
Alameda	Quaternary deposits	13	17
	*Great Valley sequence; sandstone and shale	5	----
	Lawlor Tuff	5	----
	Joaquin Miller Formation	4	----
	Franciscan Formation; serpentinite	2	----
	*Franciscan Formation; undivided	------	2
	Briones Sandstone; undivided	1	----
	Great Valley sequence; conglomerate	1	----
	*Orinda Formation	------	5
	Sobrante Sandstone	------	1
	*Unnamed Cretaceous shale	------	1
	*Markley Formation of Fulmer (1964), undivided	------	1
Contra Costa	*Contra Costa Group, undivided	19	28
	Quaternary deposits	11	19
	*Mulholland Formation of Ham (1952), lower member	7	12
	*Mulholland Formation of Ham (1952), upper member	1	8
	*Unnamed formation; sandstone and shale	5	2
	Briones Sandstone; upper member	2	5
	*Orinda Formation	2	5
	Neroly (?) Sandstone	3	5
	Unnamed formation	2	2
	*Meganos Formation; Division C	2	----
	*Briones Sandstone; undivided	------	2
	*Franciscan, undivided	------	2
	Domengine Sandstone; lower member	------	2
	*Unnamed Cretaceous shale	1	1
	Franciscan Formation; serpentinite	1	1
	Rodeo Shale	1	1
	*Sonoma Volcanics; ash-flow tuff	1	----
	*Markley Formation of Fulmer (1964), undivided	1	----
	*Moraga Formation	1	----
	Markley Formation of Fulmer (1964), lower member	1	----
	Franciscan Formation; schist	1	----
	*Meganos Formation; Division C	------	1
	Hambre Sandstone	------	1
	Meganos Formation; Division D	------	1
	Sobrante Sandstone	------	1
Marin	*Franciscan Formation; undivided and sheared	15	61
	Quaternary deposits	6	25
	Franciscan Formation; sandstone with interbedded shale	7	13
	Monterey Shale	1	5
	*Franciscan Formation; metamorphic rock, variably sheared	2	3
	Cretaceous granitic rocks	4	----
	Franciscan Formation; greenstone	3	1
	Franciscan Formation; chert, with shale	1	2
	*Petaluma Formation	------	1
	Franciscan Formation; graywacke-type sandstone	------	1
	Franciscan Formation; greenstone	------	1
	Franciscan Formation; serpentinite	------	1
Napa	*Unnamed formation; mudstone, shale, and siltstone	1	4
	Quaternary deposits	------	1
	Sonoma Volcanics; andesitic to basaltic lava flow	------	1

TABLE 8.—*The number of landslides recorded by county during the 1968–69 and 1972–73 rainy seasons for bedrock units in the San Francisco Bay region*—Continued

County	Rock unit	Number of landslides recorded in each rock unit 1968–69	1972–73
	*Franciscan Formation; metamorphic rock, variably sheared	----------	
	Knoxville Formation	----------	
San Francisco	Quaternary deposits	4	4
	Franciscan Formation; sandstone with interbedded shale	------	3
	Franciscan Formation; greenstone	------	1
San Mateo	Quaternary deposits	16	21
	*Franciscan Formation; sandstone, with shale	13	4
	*Franciscan Formation; sheared rocks	10	9
	Butano (?) Sandstone	4	7
	Franciscan Formation; greenstone	3	8
	Unnamed formation; sandstone, shale, and conglomerate	2	4
	Franciscan Formation; chert	2	----
	Joaquin Ridge Sandstone of Goudkoff (1945); shale interbeds	------	2
	*Tahana Member of Purisima Formation of Touring (1959); sandstone and siltstone	1	1
	*Mindego Basalt with related volcanic rocks	1	----
Santa Clara	Quaternary deposits	5	6
	*Franciscan Formation; sandstone with shale	2	4
	*Franciscan Formation; sheared rocks	2	1
	Unnamed sandstone	1	1
	Franciscan Formation; greenstone	------	1
	Briones Sandstone; upper member	------	1
	Unnamed formation; dark fissile shale	------	1
	Vaqueros Sandstone	------	1
Solano	Quaternary deposits	1	6
	*Unnamed formation; sandstone and shale	------	4
	Venado Formation of Kirby (1943)	------	2
	Yolo Formation of Kirby (1943)	1	1
	Sites Formation of Kirby (1943)	1	----
	*Funks Formation of Kirby (1943)	------	1
	Neroly Sandstone	------	1
	Guinda Formation of Kirby (1943)	------	1
Sonoma	Quaternary deposits	14	1
	*Franciscan Formation; sheared rocks	6	3
	Franciscan Formation; serpentinite	2	----
	*Petaluma Formation; sandstone, clay shale, and conglomerate	1	1
	Franciscan Formation; sandstone with interbedded shale	1	1
	*Petaluma Formation; massive claystone, siltstone, and mudstone	1	----
	*Franciscan Formation; metamorphic rock variably sheared	1	----
	Franciscan Formation; chert with shale	1	----
	Franciscan Formation; greenstone	1	----
	Sonoma Volcanics; andesitic to basaltic lava flow	1	----
	Sonoma Volcanics; rhyolite breccia	1	----

landslides and rainfall patterns in Contra Costa County (Nilsen and Turner, 1975) indicated that considerable landsliding will occur after

250–380 mm (10–15 in.) of previous seasonal rainfall and 150–200 mm (6–8 in.) of continuous rainfall during a storm period.

For our analysis of the occurrence of damaging landslides in Contra Costa County relative to the accumulation of rainfall during the months of September through June in 1968–69 and 1972–73, we used the records of Burton Ranch Station (U.S. Department of Commerce, Climatalogical Data) near the Lafayette-Orinda area. This area is very landslide-prone, and much of our data on landslide damage was obtained from it (figs. 8, 9). The average annual rainfall at this station, about 560 mm (22 in.), though high for Contra Costa County, is representative of many of the landslide-prone areas within the county.

The relation of landslide activity to the rainfall accumulation pattern is schematically represented in figure 8. In both seasons there appears to be an initial period of light to moderate accumulation followed by an intense period of storms representing most of the seasonal precipitation and a tapering-off period of light rainfall into late spring (also see fig. 9).

In 1968–69 the initial period was characterized by a series of light storms from November through December, totaling about 230 mm (9 in.) of rainfall accumulation. The following period of intense storms from about mid-January to late February was one of nearly continuous precipitation, amounting to 560 mm (22 in.). There was moderate landslide activity during this period, commencing after approximately 380–510 mm (15–20 in.) of total seasonal rainfall. Although rainfall in the final tapering-off period was very light, intense landslide activity commenced at the start of this period and continued through most of March.

In 1972–73 the initial period of rainfall consisted of several heavy storms from mid-October through late December, resulting in a total rainfall accumulation of about 330 mm (13 in.). The period of intense storms commenced in early January and lasted through February. Precipitation was 450 mm (17.6 in.) during this period, within which landsliding became intense after the first storm. During the tapering-off period, beginning in March, landslide activity decreased markedly as a consequence of rapidly declining rainfall. Starting in March during the tapering-off period, rainfall decreased rapidly, and as a consequence, so did landslide activity.

RESULTS

It is evident from the graphs of figure 8 that for the two rainy seasons total rainfall and number of recorded landslides are nearly the same: nearly 890 mm (35 in.) and 62 landslides in 1968–69, 880 mm (34 in.) and 55 landslides in 1972–73. The records for both rainy

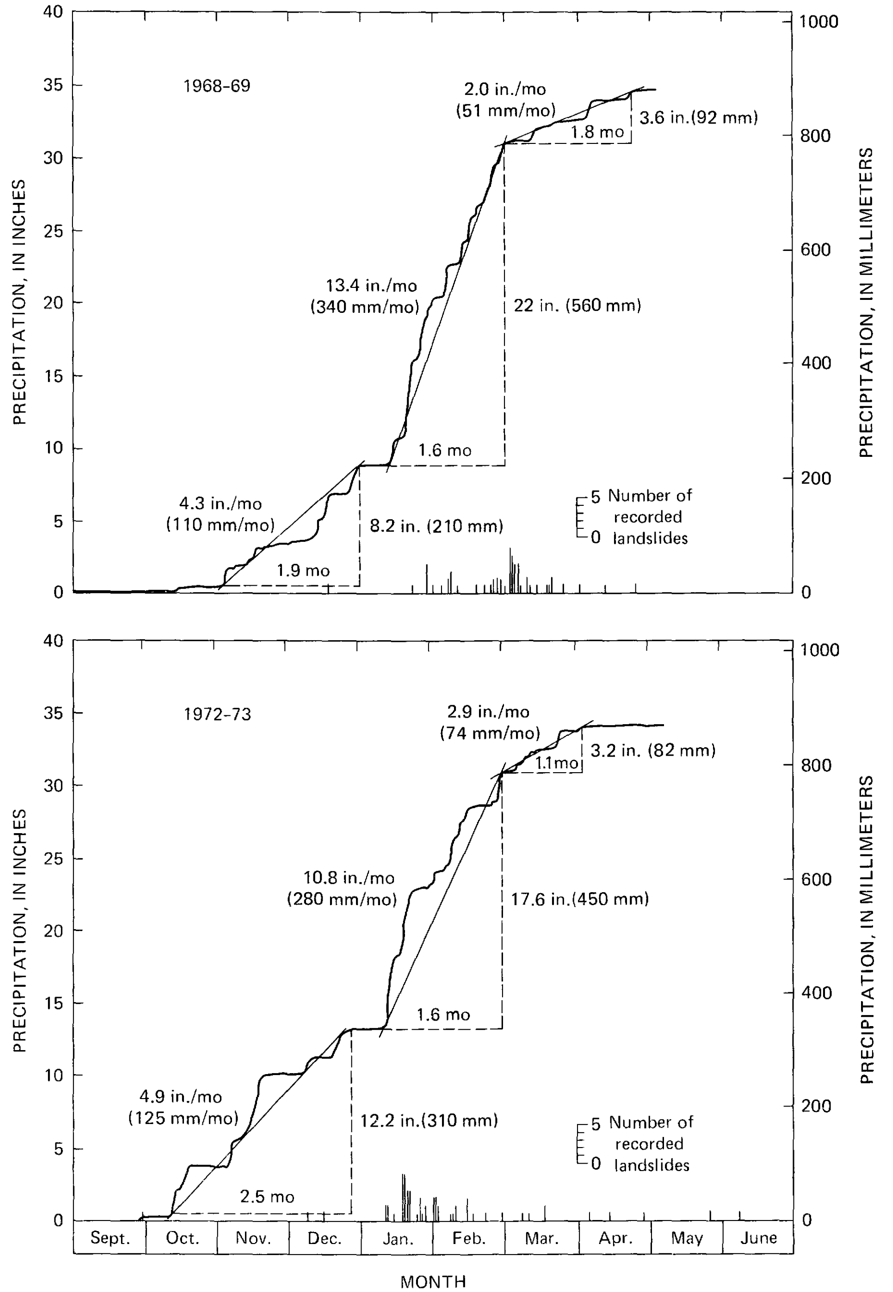
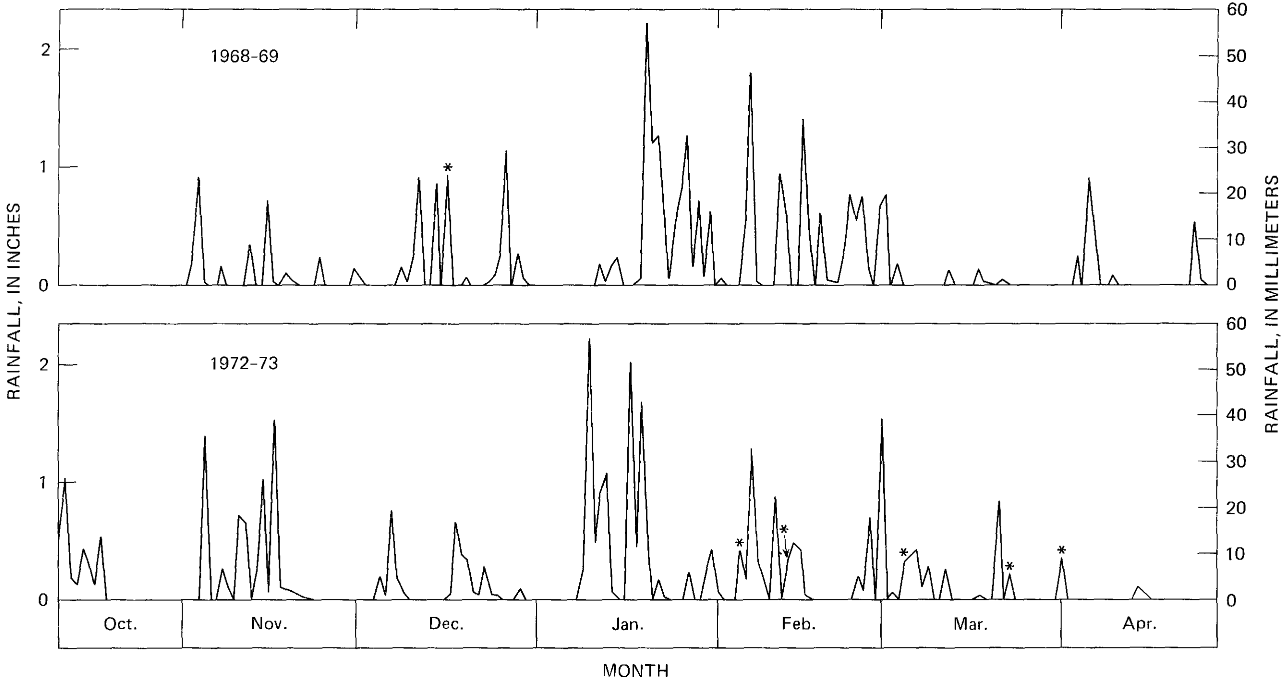


FIGURE 8.—Rainfall accumulation at the Burton Ranch Station and landslide activity in Contra Costa County, 1968–69 and 1972–73 rainy seasons.



*Time distribution unknown, amount includes rainfall of previous day

FIGURE 9.—Frequency and amount of rainfall at the Burton Ranch station, Contra Costa County, 1968–69 and 1972–73 rainy seasons.

seasons support the finding of Nilsen and Turner (1975) that for Contra Costa County, an accumulation of 250–380 mm (10–15 in.) and a 150–200-mm (6–8-in.) storm triggers landslide activity, even though the timing of most of the activity differs markedly for these seasons.

Landslide activity in 1968–69 commenced after about 280 mm (11 in.) of seasonal rainfall and during a storm period of about 230 mm (9 in.); intense landslide activity did not begin until 790 mm (31 in.) of seasonal rainfall had accumulated. In contrast, intense landslide activity in 1972–73 began during a storm of 180 mm (7 in.) after about 330 mm (13 in.) of seasonal rainfall had accumulated. As both 1968–69 and 1972–73 were preceded by similar rainy seasons in 1967–68 and 1971–72, respectively (fig. 2), a large difference in near-surface ground-water levels was not expected. Curves for the total monthly evaporation at the two precipitation stations in the bay region where evaporation is recorded, Newark and Burlingame (fig. 10), showed greater evaporation during the rainy season of 1972–73 than in 1968–69, possibly as a result of some longer dry periods between storms, higher temperatures, or other climatic factors. The evaporation rate does not, however, explain the differences in landslide activity between the two rainy seasons.

CONCLUSIONS

We believe that the variation in intensity of storm periods produced the variation in intensity of landslide activity. The more intense storm periods of the early part of the 1972–73 rainy season are believed to have produced earlier ground saturation and therefore earlier intense landsliding. Further research is required to determine the effect of ground water, rainfall storm duration and intensity, and evapotranspiration on subsurface conditions related to landslide propagation.

It seems from this and the earlier study by Nilsen and Turner (1975) that a simplified system of landslide prediction is possible. By plotting a cumulative graph of precipitation, one could estimate when the ground was saturated (after 250–380 mm (10–15 in.) of rainfall) and when high landslide frequency would be expected to commence (after a continuous storm period of 150–200 mm (6–8 in.)). Such a system is not precise because other factors—local evapotranspiration, vegetation, slope angle, and geology—help determine when and where landslides will occur as well as how large or potentially damaging they will be. Nonetheless, these data from Contra Costa County can be applied to the bay region in a general fashion, and with more studies in other counties, a fairly refined system of landslide prediction based on rainfall patterns might be developed for the entire bay region.

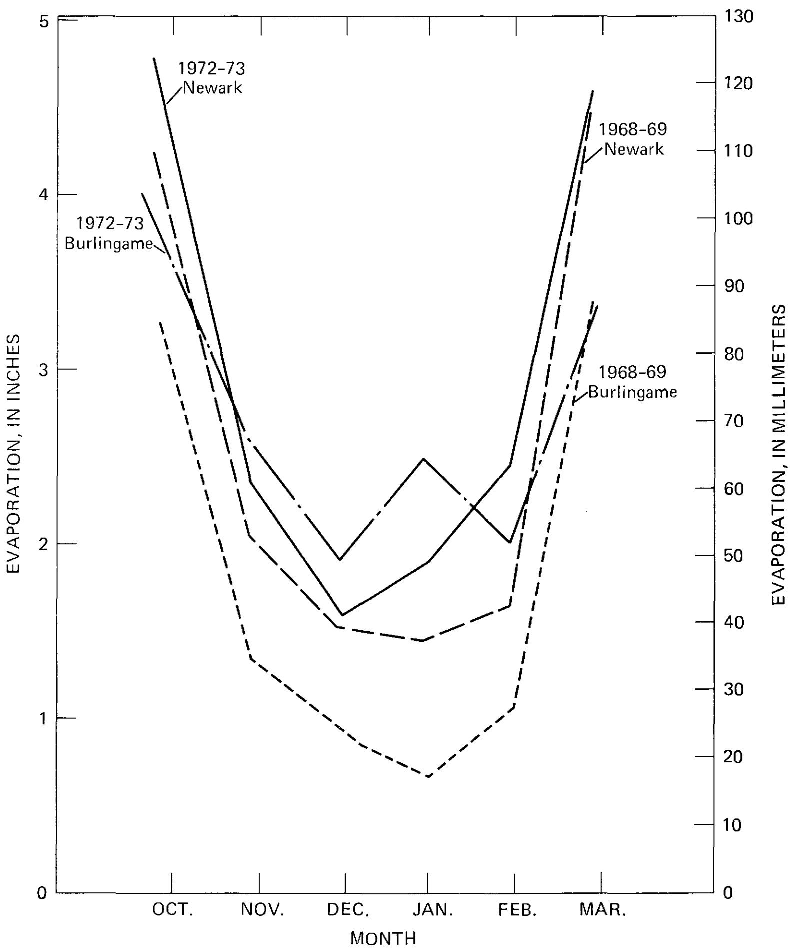


FIGURE 10.—Monthly evaporation from October to March, 1968–69 and 1972–73, for the Newark and Burlingame stations.

SUMMARY AND CONCLUSIONS

We have found that at least 50 percent of all landslides in the 1968–69 and 1972–73 rainy seasons were in areas associated with previous landslide activity, 74 percent or more were on slopes steeper than 15 percent, and more than 60 percent took place on rock units considered to be susceptible to slope failures on the basis of regional considerations and their physical properties. Accurate maps of ancient landslide deposits, slope, and bedrock geology are available and should prove to be a valuable aid in determining slope stability on a regional basis.

Almost all landslides develop during the rainy season, generally during or after a continuous storm period of greater than 150–200 mm (6–8 in.) of rainfall that follows a prior seasonal rainfall of 250–380 mm (10–15 in.). An advisory system could be established to supply information, based on analyses of precipitation patterns, as to when intense landslide activity is probable.

Planners, public officials, and citizens must be acutely aware of the hazard that landslides pose, yet realize that they may be avoidable if sound planning and engineering methods are employed. Slope stability maps at both regional and local scales can be prepared for the bay region that will permit planners to identify areas susceptible to slope failure before development begins. Depending upon local land-use needs and preferences, potentially hazardous areas can either be avoided or minimized by building design and planning criteria that consider the potential hazard and damage from slope failure. More detailed information about the natural factors evaluated herein that control landsliding and the effects of human activities is needed to fully develop safe and useful regional and local criteria.

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