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Slope stability analysis of a protion of Santa Clara County, California

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SLOPE STABILITY ANALYSIS OF A PORTION OF SANTA CLARA COUNTY, CALIFORNIA

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ABSTRACT

SLOPE STABILITY ANALYSIS OF A PORTION OF SANTA CLARA COUNTY, CALIFORNIA

By Eileen M. Brennan

This study uses a Geographic Information System (GIS) to analyze and correlate available digital geologic, geomorphic and geotechnical data with a digital landslide inventory of a portion of Santa Clara County, California. Properties found to have the greatest influence on hillslope stability are lithology and degree of slope. Less influential properties are hillslope aspect and vertical land surface curvature. The results of the analysis are used to develop a method of determining relative hillslope stability across the study area, which is depicted in the form of a map at 1:62,500-scale. A comparison of the Relative Hillslope Stability map with a recent landslide inventory map reveals that the majority of the recent landslides mapped fall within stability groups of 5 to 10, (moderately to highly unstable). The strong correlation of these maps indicates that the Relative Hillslope Stability map is a useful tool for regional planning and development within the study area.

ACKNOWLEDGMENTS

This project could not have been completed without the help of many individuals to whom I am very grateful. I would like to thank the following people for their help and patience with my many ARC/INFO questions: Scott Graham, Russ Graymer, Sebastian Roberts, Michelle Roberts and David Ramsey, as well as many other individuals at the USGS in Menlo Park, California. I would also like to thank David Howell, John Williams, Paula Messina, and Richard Pike for their guidance, input, and direction throughout this study. In addition, I would like to thank Cindy Erceg for her logistical help and Robin Dornfest for his help and support in so many aspects of this project.

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INTRODUCTION

Lack of detailed landslide hazard maps at a scale of 1:24,000 or larger presents a problem for the development of public policy on landslide hazard within the San Francisco Bay Region (SFBR). Flooding hazard maps and earthquake shaking hazard maps are available for the region, but relatively few landslide hazard maps exist. Landslides in the greater San Francisco Bay Region from 1997-1998 El Niño storms caused one death and cost more than $150 million in direct property damage (Howell and others, 1999). Currently, slope stability is assessed on an individual landslide basis, or landslide inventory maps are used to designate general areas of instability. However, in addition to landslide inventory maps, analysis is needed to investigate landslide causes and to provide a more thorough and accurate understanding of slope instability in this region.

A large- to intermediate-scale, regional study is needed in the SFBR to determine which geomorphic, geologic, geotechnical and other properties influence slope stability. Several methods are available for such an analysis, including analyzing the slope stability of a small area and extrapolating the results across a larger, generally homogeneous region. However, many common landslide-influencing factors, such as topography, geology, and vegetation patterns are highly variable throughout the SFBR. Therefore an analysis which incorporates the diversity and complexity of this region is needed in order to determine landslide-influencing factors within the SFBR.

This study is a computer-based, intermediate-scale (1:24,000) analysis of factors influencing slope stability in the hills of the Diablo Range in the southern portion of the San Francisco Bay Region, California. A 1:24,000 digital landslide inventory map is analyzed in conjunction with the geologic, geomorphic, and geotechnical factors in the region to determine which factors most influence slope stability. The study area was chosen because although structurally complex, it is composed of generally lithologically and geomorphically homogeneous areas oriented in a northwest-southeast direction. In addition, it is a landslide-prone area within the SFBR; it is rapidly urbanizing and it has not been thoroughly analyzed with respect to slope stability. This study presents a practical method for analyzing available geologic, geomorphic, and geotechnical data with a Geographic Information System (GIS) in order to better understand regional slope stability. In addition, it uses conclusions of the GIS analysis to identify potentially unstable areas. The information resulting from this study can be used as a guide for regional planning and development within the study area, as well as an indication of areas that need further slope stability investigations before any development is considered.

Scope of Study

This study includes the analysis of available digital data such as degree of slope, lithology, structure, bedrock and soil mantle expansivity, hillslope aspect, vegetation, vertical land-surface curvature, elevation, and annual precipitation. This analysis was conducted primarily with ARC/INFO, a GIS program. The above properties were analyzed within and outside of areas mapped as landslides by Nilsen (1975a&b). Specific properties or combinations of properties inside areas of mapped landslides were interpreted to be probable causes of slope instability. Likewise, combinations of factors most commonly present outside areas of mapped landslides were interpreted to be conditions that do not cause slope instability. Subsequently, the results of the initial study were compiled and used to develop a method for determining relative stability within the study area. The resulting Relative Hillslope Stability Map indicates general areas of unstable hillslopes.

The data used in this study were generally limited to digital data that could be analyzed with a GIS program. In each case, the current, not historic data were used in the analysis. When viewed through geologic time, properties such as degree of slope, vertical land surface curvature, vegetation, and even elevation are constantly changing. However, because there is no accurate or accepted method of back-calculating the precise values of these data at the time each mapped landslide occurred, the current data are used in each analysis in this study. Additionally, the idea that hillslopes which have failed in the past are likely to fail again some time in the future is widely supported (Van Horn, 1972; Brabb and others, 1972; Nilsen, 1979; Pike and others, 2001). Therefore, analysis of mapped landslides in conjunction with current topographic and geomorphic conditions is very useful for determining relative hillslope stability.

STUDY AREA

Location

The study area comprises the Milpitas and Calaveras Reservoir 7.5-minute topographic quadrangles. The quadrangles are located east of the southern San Francisco Bay, in northern Santa Clara County, California. The study area is bounded on the north by the Santa Clara County boundary, the west by the Mountain View quadrangle, the east by the Mount Day quadrangle, and the south by the San José West and San José East quadrangles, respectively (see Fig. 1, location map).

Previous Investigations

No extensive geologic investigation had been conducted in the study area prior to the 1950s. In 1951, as part of a Ph.D. dissertation, Crittenden performed a geologic study of the San José – Mt. Hamilton area which includes the current study area. In 1968, the United States Soil Conservation Service conducted a survey of the type and distribution of soils in Santa Clara County. In 1971, Helley and Brabb published a 1:62,000-scale map of Cenozoic deposits in Santa Clara County. This map, created from the interpretation of aerial photographs, identified areas of Late Cenozoic alluvial, estuarine, and volcanic deposits. In 1975, Nilsen published 1:24,000 scale regional maps of landslide and other surficial deposits of both the

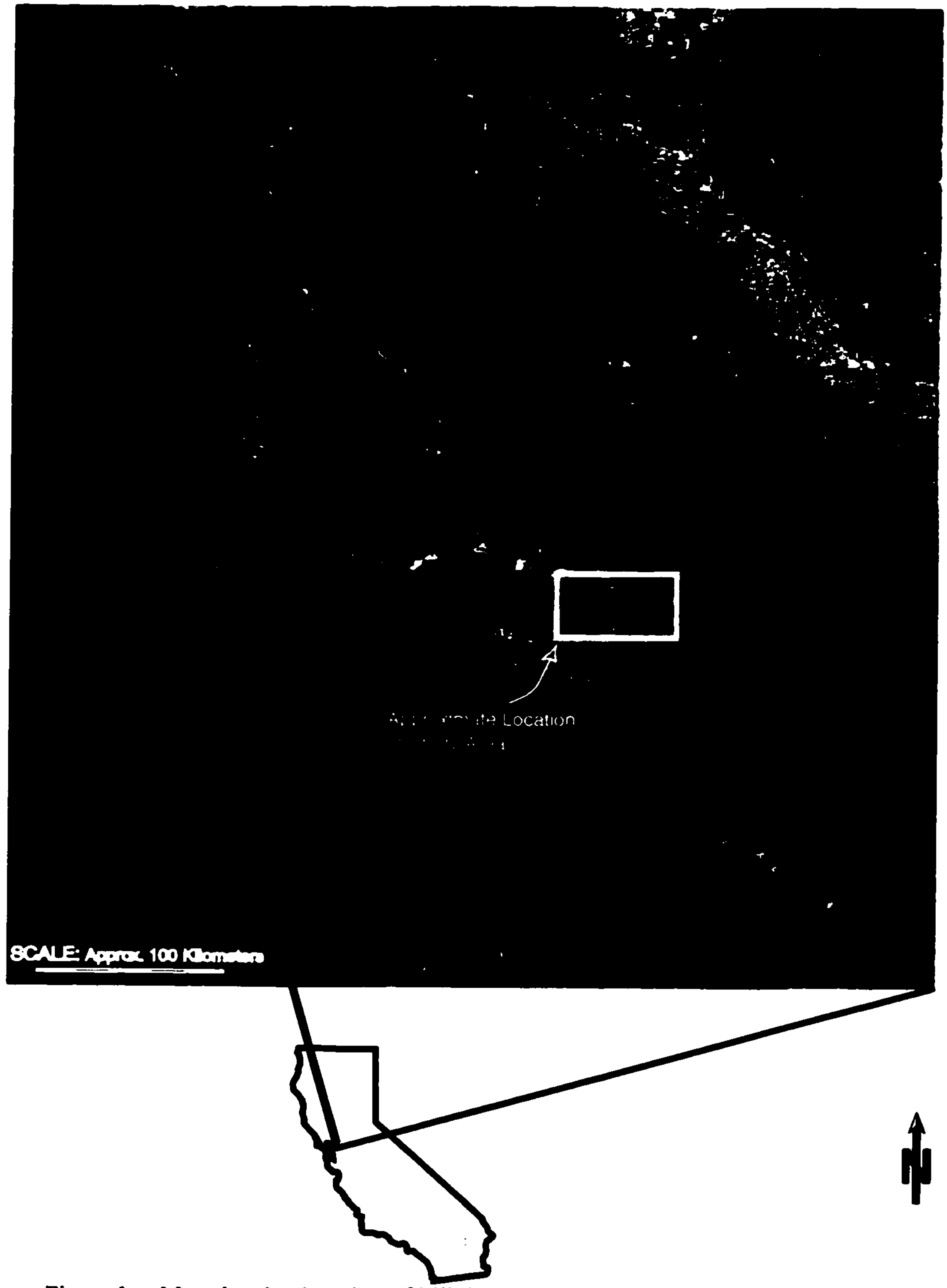


Figure 1. Map showing location of Milpitas and Calaveras Reservoir quadrangles, Santa Clara County, California.

Milpitas and Calaveras Reservoir quadrangles (1975a&b). These maps, which provide the basis for this study, outline areas of landslides, uncertain landslides, and other surficial deposits. These maps were based on aerial photograph interpretation (Nilsen, 1975a&b). In 1972, Dibblee published a preliminary geologic map of the Milpitas quadrangle, and in 1973, he published a preliminary geologic map of the Calaveras Reservoir quadrangle. In 1984, John Coyle produced a 1:12,000-scale geologic map of the San José – Milpitas foothill area, in which he categorized landslides based on activity level (Coyle, 1984). In 1989, Helley and Wesling produced a Quaternary geologic map of the Milpitas quadrangle. In 1995, Graymer and others compiled a digital map database of the Hayward Fault Zone, which includes a portion of the study area. In 1998, Wentworth and others compiled a digital map database of the geology of the San José sheet at 1:100,000-scale. This included the compilation and synthesis of many existing maps, in addition to their own fieldwork. In addition, many large-scale geotechnical and geologic investigations have been conducted within the study area by local consultants, as required by the City and County prior to any development in the area.

In 2001, in response to the *Seismic Hazards Mapping Act* of 1991, the California Department of Conservation, Division of Mines and Geology, released preliminary maps of seismic hazard zones for both the Milpitas and Calaveras Reservoir 7.5-minute quadrangles (California Department of Conservation, Division of Mines and Geology, 2001a&b). Included in this report is the study and resulting map of earthquake-induced landslide zones within the Milpitas and Calaveras Reservoir quadrangles. The study incorporated three factors into the analysis of earthquake-induced landslides: earthquake shaking estimates from California Division of Mines and Geology probabilistic shaking maps and past earthquake strong-motion records; strength of materials data gathered from geotechnical laboratory test results from reports prepared by consultants on file at local government offices; and slope gradient data from the 1960 USGS DEM (Weigers and others, 2001a&b). The study determined that areas most susceptible to earthquake-induced landslides are "steep slopes in poorly cemented or highly fractured rocks, areas underlain by loose, weak soils, and areas on or adjacent to existing landslide deposits" (Weigers and others, 2001a&b).

Outside of the study area, many landslide hazard maps have been created both with and without the use of GIS. In 1972, van Horn created a landslide hazard map which indicated four categories of instability. On this map, the areas of highest instability include both existing landslides as well as areas other than existing landslides. Previous to this, most maps generally indicated areas of existing landslides as areas with the highest instability. In 1972, Brabb and others developed a quantitative indication of landslide susceptibility for San Mateo County, based on landslide distribution, lithology, and ground slope. Nilsen and Wright (1979) compiled a susceptibility map of the entire 10-county San Francisco Bay Region at a scale of 1:125,000, based on landslide distribution, lithology, and ground slope. GIS facilitates the incorporation of multiple factors in creating a landslide hazard map. GIS has been used in many capacities for creating slope stability maps. Many stability maps are based on large scale, landslide-specific data (Miller, 1995, and Miller and Sias, 1998). Other GIS studies, such as those conducted by Brunori and others (1996), Rowbotham and others (1998), van Westen and others (1997), and Pike and others (2001) employed GIS at a smaller scale to determine which factors are commonly associated with mapped landslides. This list is not comprehensive, but offers several examples of slope stability studies using GIS.

Geomorphology

General

The study area is located within the northwest-southeast trending coast range province of California. The topography consists of highly variable slopes and elevations. The majority of the Milpitas quadrangle consists of relatively flat, undissected valley floor. In contrast, the majority of the Calaveras Reservoir quadrangle consists of the foothills of the Diablo Range. Most of the hills trend northwest. The hills are highly dissected by many drainages, and it is within these drainages that the steepest slopes are located. The maximum relief within the study area is 922 meters with the highest elevations located on the eastern edge of the Calaveras Reservoir quadrangle.

Drainage

The two largest water bodies in the study area are artificially dammed reservoirs, the Calaveras Reservoir, located in the northeast and the Cherry Flat Reservoir, located at the eastern edge of the Calaveras Reservoir quadrangle. There are several major drainages within the study area, including Arroyo Hondo, Calaveras Creek, Penitencia Creek, Arroyo Aguague, and Berryessa Creek. Smaller drainages include Scott Creek, Calera Creek, Tularcitos Creek, Arroyo de los Coches, Piedmont Creek, Cropley Creek, Crosley Creek, Sierra Creek, Dutard Creek, and Miguelita Creek. The majority of the major and minor drainages have an orientation that is either perpendicular to or at a high angle to the structure of the area. These drainages trend in an east-west or northeast-southwest direction. Several significant drainages parallel the overall structure, including Arroyo Hondo, Calaveras Creek, Arroyo Aguague, and the upper portions of Penitencia Creek.

Elevation and Slope

Elevation and slope are highly variable throughout the study area. Elevation ranges from 0 meters (above sea level) in the northwest to 922 meters in the east. Slopes range from very gentle to no slope on the valley floor to very steep (greater than 45 degrees) in drainages such as Penitencia Creek, Berryessa Creek, Arroyo Hondo, Calaveras Creek, and Arroyo Aguague.

Climate and Vegetation

The climate of this area is characterized as Mediterranean. This climate typically consists of warm, dry summers and mild, wet winters. There can be short periods of freezing weather in the winters, and typical summer temperatures can reach as high as 100 degrees Fahrenheit. Precipitation generally ranges from 35.6 cm (14 inches) per year on the valley floor to 63.5 cm (25 inches) per year in the higher elevations (Rantz, 1971).

Vegetation is variable within the study area. The majority of the valley floor is residentially and commercially developed, and vegetation consists mostly of landscaped trees and grasses. Vegetation on the hillside regions is classified into two categories: grasses and dense vegetation. In general, the majority of the hillsides are covered with grasses, brush, and sparse deciduous trees such as oaks. The drainages are covered with dense vegetation, including trees, grasses, and brush. In general, vegetation is more abundant on north-facing slopes than on south-facing slopes. Vegetation patterns will be discussed in more detail in the section entitled *Vegetation.*

Landslides

Number The study area contains 1160 mapped landslides (Nilsen, 1975a&b). These landslides account for 14.7 percent of the total area. These landslides are translational slides, rotational slides, soil creep, earthflows, slumps, or combinations of any of these types. In general, this study focuses on shallow and deep-seated landslides larger than 61 meters (200 ft) along the major axis. Debris flows have not been mapped in this area, and therefore are not included in this study. Many of the largest mapped landslides in the study area are actually groups of smaller, coalescing landslides, which could not be individually distinguished on 1:20,000-scale aerial photographs. The majority of these landslides are located within the Calaveras Reservoir quadrangle. Most are located on either the northwest-trending ridges or along the east- west-trending drainages. Figure 2 is a map of the study area showing the landslides as mapped by Nilsen (1975a&b).

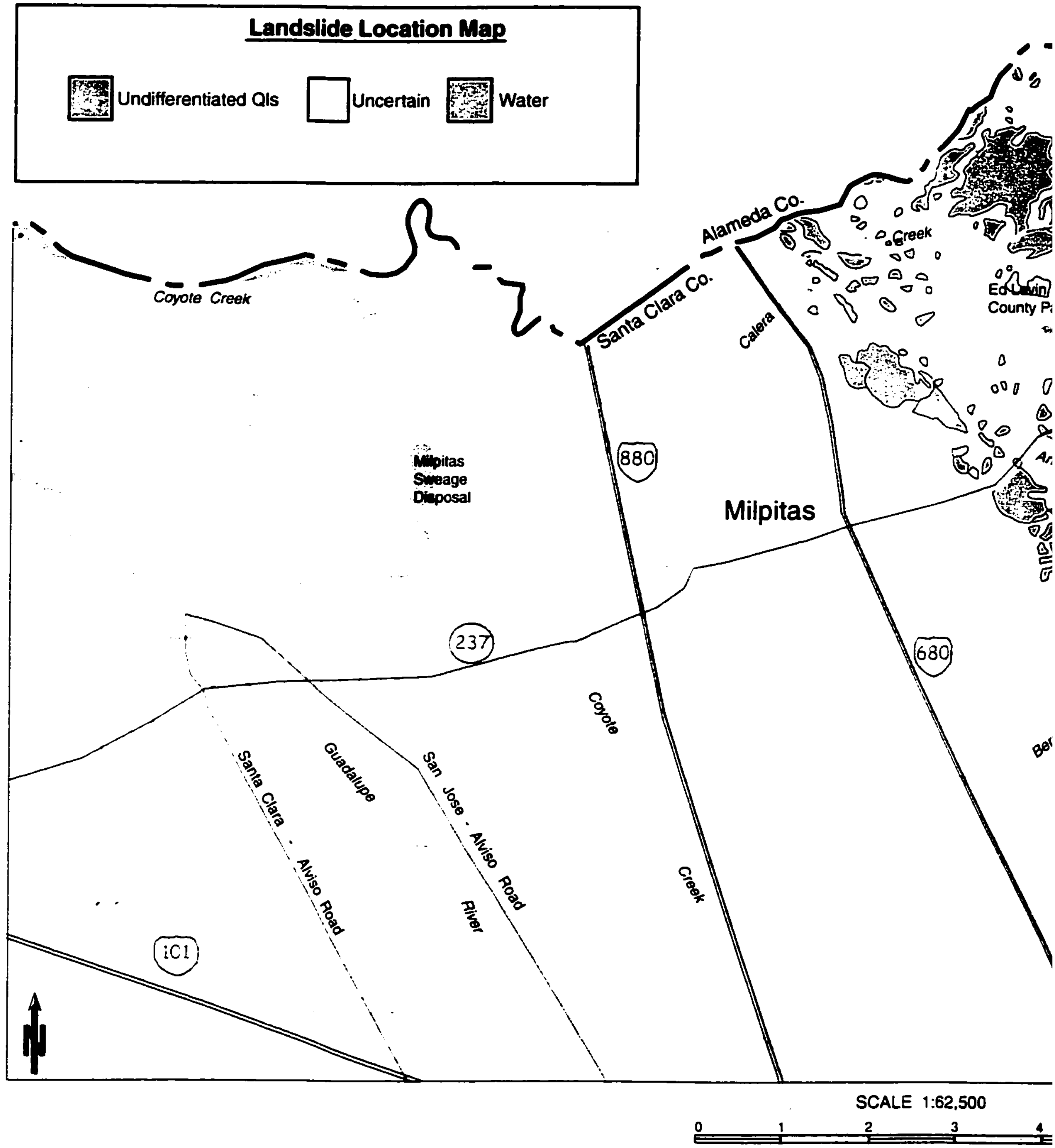
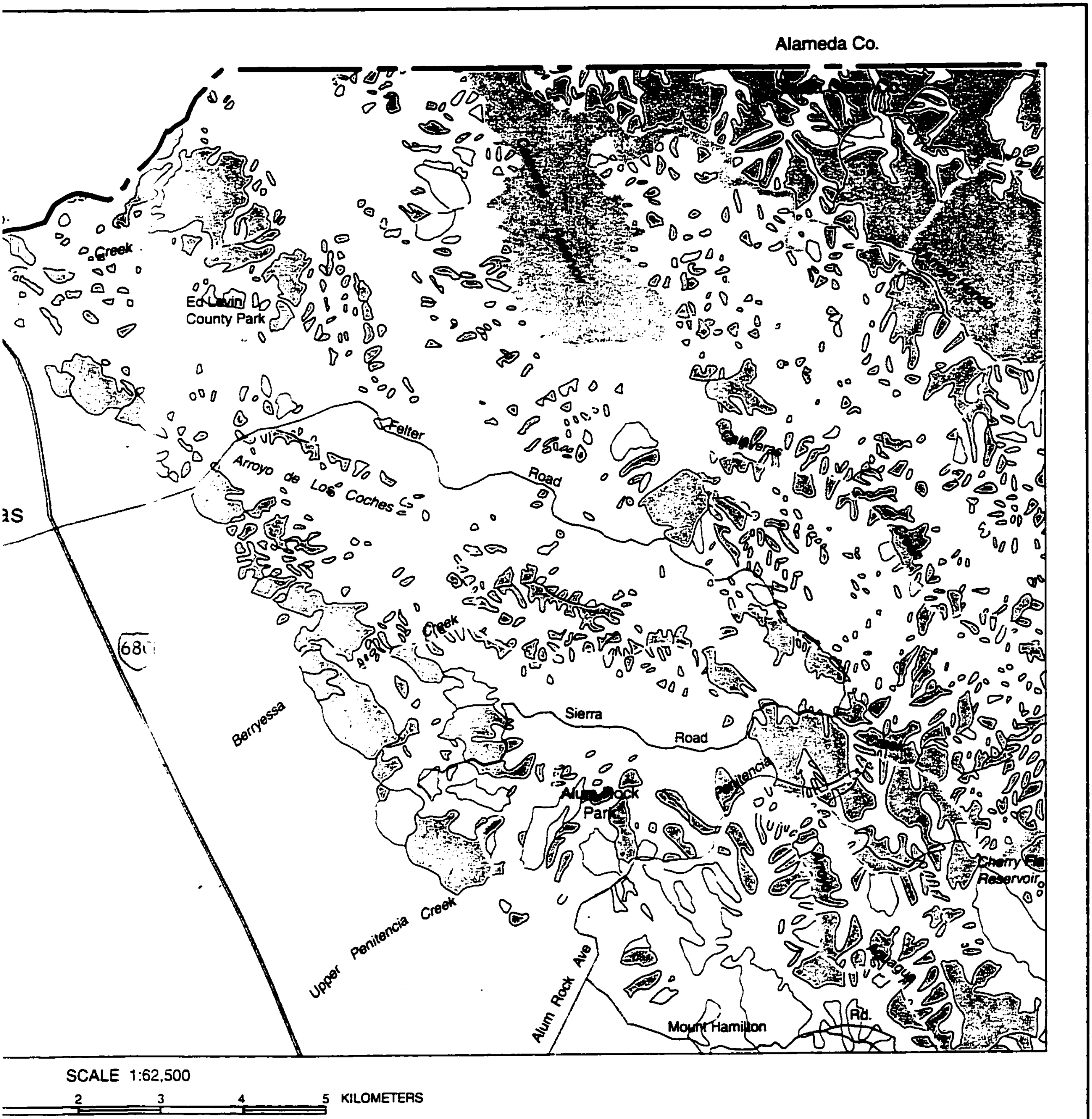


Figure 2. Map of landslides as mapped by Nilsen, (1975a&b). Landslides were classified as undifferentiated (
analysis.



lassified as undifferentiated Qls or Uncertain. A grid of these landslides provided the basic dataset for the slope stability

Age The ages of the landslides are highly variable, and possibly range from modern to 100,000s of years old. Some of these landslides record a single event of movement, whereas others record repeated movement distributed over time. In addition, some of these landslides are combinations of smaller slides of different ages, rates of movement, and methods of movement.

Size The landslides in the study area can be categorized into groups according to approximate size. The three different sizes are very large, medium, and small. The very large landslides are those that compose whole hillsides. The majority of these landslides are located either northeast of Arroyo Hondo or at the western edge of the foothills. The very large landslides exceed one kilometer in either length or width. The medium landslides compose only portions of hillsides, and are located primarily in drainages and along the western foothills on west-facing slopes. Medium-size landslides range in size from approximately 150 meters to one kilometer in a single axis. Small landslides are concentrated in drainages within the study area. Small landslides are defined as those less than 150 meters in either length or width.

Geology

The study area is located within the structurally complex, relatively young and seismically active San Francisco Bay Region (SFBR). This region consists of accreted terrain of the Franciscan Complex, overlain by younger marine and non-marine sediments, and simultaneous and subsequent movement of major blocks along several of the major dextral strike-slip faults within the SFBR. The SFBR is dominated by the San Andreas Fault System (SAFS). The SAFS consists of numerous northwest trending dextral strike-slip faults such as the San Gregorio, San Andreas, Hayward, and Calaveras, in addition to many smaller faults.

Figure 3 is the geologic map of the study area by Wentworth and others (1998). The lithologic range from Jurassic to Quaternary in age. In general, the study area is composed of Franciscan rocks of Jurassic-Cretaceous age, overlain by younger units. Mesozoic sedimentary, volcanic and metamorphic rocks overlie the Franciscan Complex. These younger units are unconformably overlain by Tertiary and Quaternary sandstones, shales, and conglomerates. Portions of the Tertiary and Quaternary units are overlain by alluvial, colluvial, fluvial, and soil deposits. In general, the Tertiary sediments are located northeast of the Hayward fault, and the Mesozoic sediments are located southwest of the Hayward fault (Coyle, 1984).

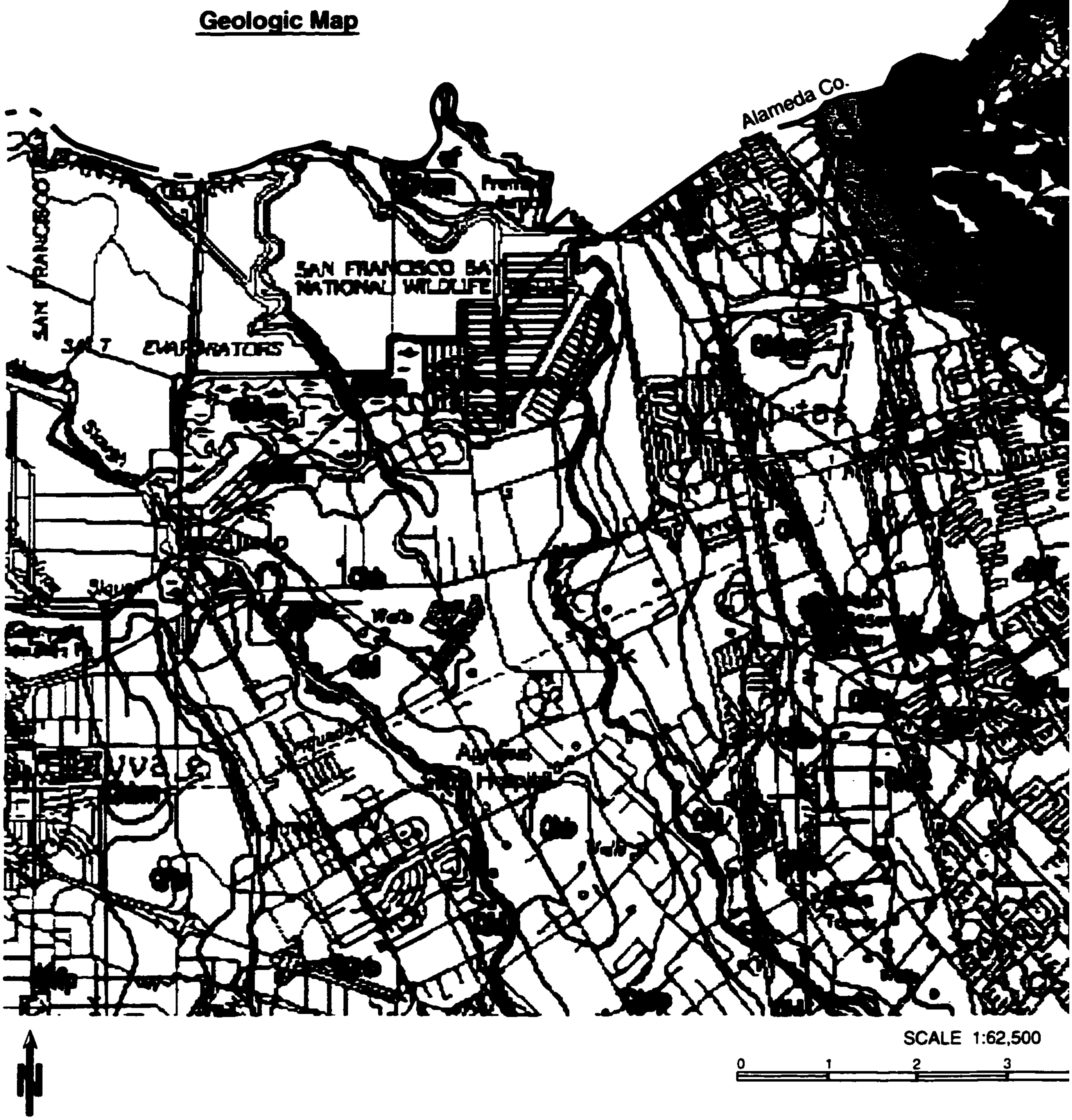
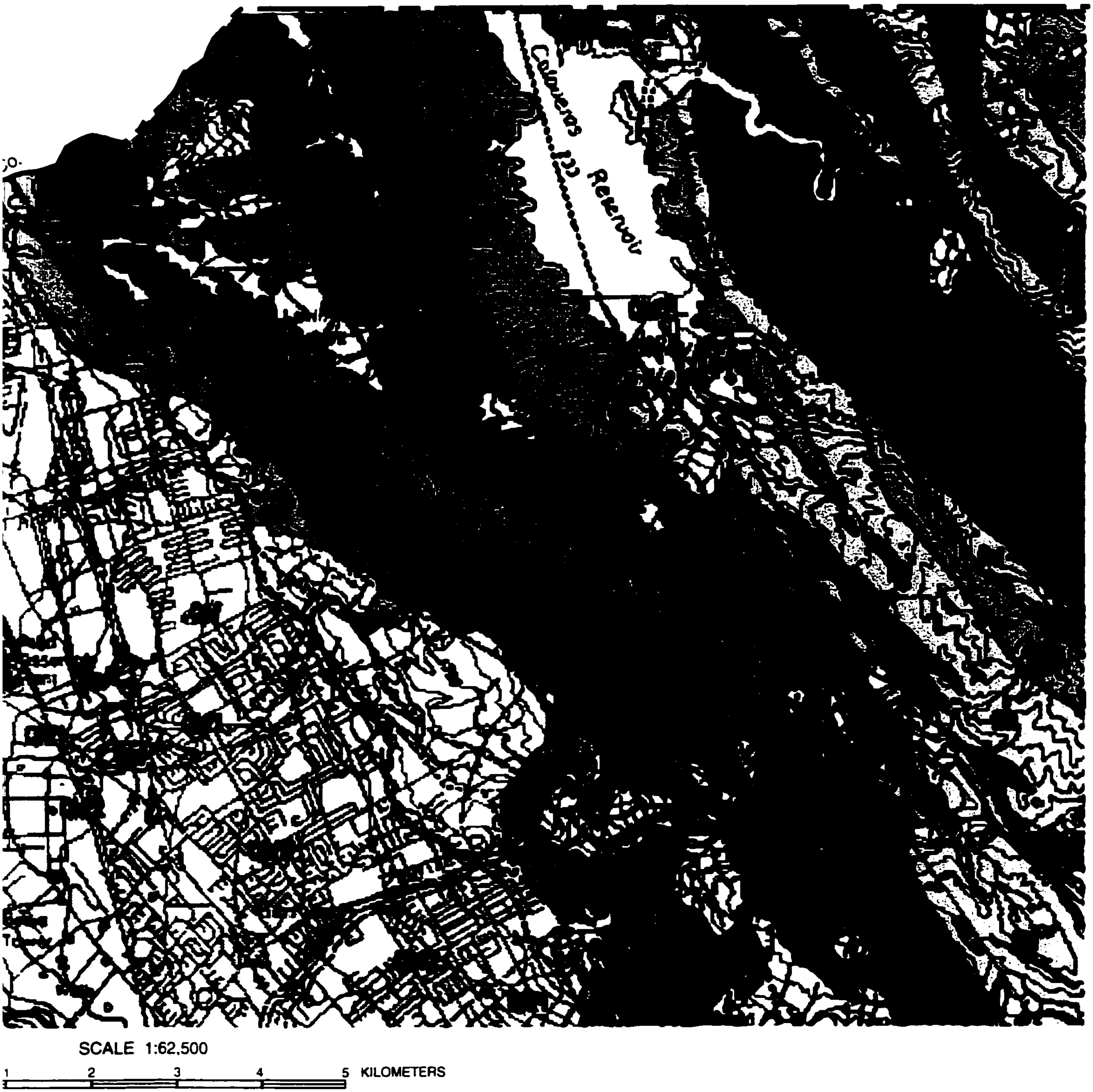


Figure 3. Geologic map from Wentworth and others (1998). A derivative of this map was used in the lanc
the underlying bedrock units with the mapped landslides from Nilsen (1975a&b). The legend on the following



ɜ map was used in the landslide analysis. Landslides shown on this figure were digitally removed in order to compare ıe legend on the following page describes the units.

GEOLOGIC MAP LEGEND

Artificial fill (MODERN)

se - Salt evaporation ponds (MODERN)

Qhc - Stream Channel Deposits (HOLOCENE)

Qha - Alluvium (HOLOCENE)

Qhb - Basin deposits (HOLOCENE)

Qhfp - Flood plain deposits (HOLOCENE)

Qhl - Levee deoposits (HOLOCENE)

Qhc - Stream Channel Deposits (HOLOCENE)

Qht - Stream terrace deposits (HOLOCENE

Qhbm - Bay Mud (HOLOCENE)

Alluvial fan deposits (HOLOCENE)

Qhf1 - younger

Qhf2 - older

Qc - Colluvium (QUATERNARY)

Landslide deposits (QUATERNARY)

Qa - Alluvium, undivided (QUATERNARY)

Qt - Stream terrace deposits (QUATERNARY)

Qti - Irvington Gravels (PLEISTOCENE AND PLIOCENE?)

Qpf - Alliuvial fan deposits (UPPER PLEISTOCENE)

Qpa - Alluvium (UPPER PLEISTOCENE)

Tbr - Briones Formation (UPPER MIOCENE)

Tor - Orinda Formation (UPPER MIOCENE

Torv - Basalt and andesite (Upper Miocene)

Tcc - Claremont Formation (UPPER TO MIDDLE MIOCENE)

Tts - Temblor Sandstone (MIDDLE MIOCENE TO OLIGOCENE?)

Kau - Sandstone, mudstone, and conglomerate (UPPER CRETACEOUS)

Berryessa Formation (CRETACEOUS)

Kbs - Sandstone and mudstone

Kbc - Conglomerate

Franciscan Complex (CRETACEOUS AND JURASSIC)

fm - Melange (LOWER TERTIARY? AND UPPER CRETACEOUS)

♦ High-grade schist block

gs - Greenstone

bl - Blueschist

ch - chert

Kjk - Knoxville Formation (LOWER CRETACEOUS AND UPPER JURASSIC)

Yolla Bolly Terrane (CRETACEOUS? AND JURASSIC)

fy2 - Middle, irregularly cleaved metagrawacke unit

fys - Metagraywacke, undivided

Coast Range Ophiolite (JURASSIC)

Jbk - Basalt, andesite, dacite and quartz keratophyre

Jsp - Serpentinized harzburgite and dunite

Figure 4. Description of lithologic units to accompany Figure 3, modified from Wentworth and others (1998).

Structural Geology of the Study Area

The geology and topography of the study area are controlled by the faults and bedrock structures in the area. The two major dextral strike-slip faults which transect the study area are the northwest-striking Hayward and Calaveras faults. In addition, several other smaller faults, such as the Clayton, Crosley, Berryessa, and Quimby faults are located within the study area as well. The activity and kinematics of these faults are highly debated topics. Several of these faults demonstrate a reverse sense of motion, indicating compression, as well as shear (Coyle, 1984). The majority of bedrock units strike northwest, and dip gently to moderately toward the northeast. Several Tertiary sedimentary units west of the Calaveras Reservoir have been folded into a northwest-plunging syncline, known as the Tularcitos Syncline. According to Crittenden (1951), the youngest unit folded in the syncline is the Briones sandstone and the oldest unit, which forms the outer limbs of the syncline, is the Berryessa shale.

INVESTIGATION OF LANDSLIDE-INFLUENCING FACTORS

Background

Because of the large amount of digital data available, a Geographic Information System (GIS) was used for the primary analysis in this study. GIS facilitated analyzing numerous landslide-influencing factors and provided the means to analyze and synthesize the large amount of available data.

In the 1960s, Nilsen and others (1975a&b) mapped landslides within fifty-six 7.5-minute quadrangles in the SFBR. They mapped landslides that were at least 61 meters (200 ft) in a dimension. A comparison of these photointerpretive landslide maps (Nilsen, 1975a&b) with the geologic map (Wentworth and others, 1998) showed a discrepancy in the number and location of mapped landslides. Only 72 percent of the unit mapped as Qls on the geologic map contains mapped landslides from the Nilsen study. Likewise, only 63 percent of the unit mapped as Qls? contains mapped landslides from the Nilsen study. Units Qls and Qls? on the geologic map by Wentworth and others were also mapped from aerial photographs, though at the smaller scale of 1:80,000 (personal comm., Wentworth, 6/2000). These were then added to the completed bedrock geologic map. Therefore, the units Qls and Qls? on the geologic map represent only those landslides discernable on aerial photographs at a scale of 1:80,000. These landslides are not to be considered a complete inventory of the landslides within the study area (personal comm., Wentworth, 6/2000). For the purpose of this study, therefore, those landslides mapped on the geologic map (Figure 3) were digitally removed, and only the underlying bedrock units were used for further analysis. Therefore, analysis of the propensity toward landsliding in each bedrock unit is based on the bedrock unit mapped on the geologic map by Wentworth and others, and the landslides mapped by Nilsen (1975a&b).

Method

The basic datasets for this study consist of the original 1:24,000-scale landslide inventory maps on Mylar greenlines of the Milpitas and Calaveras Reservoir 7.5-minute topographic quadrangles. (Nilsen, 1975a&b). These greenlines were scanned at 400 dots per inch, converted from raster to vector form, and imported into ARC/INFO, a commercial GIS. The resulting coverages were georeferenced in order to spatially orient them, and then edited in ARC/INFO to remove all information from the scan except the landslide polygons (Roberts, 1999). The two coverages were then combined into a single coverage, and the portion of the coverage outside Santa Clara County was removed. The result is a landslide coverage of the entire study area (Figure 2). On this coverage, landslides are classified as either *landslide* or *uncertain*, as they are on the original Mylar greenlines (Nilsen, 1975a&b). However, for the subsequent analysis with ARC/GRID, all these polygons were all treated as *landslide* for a more conservative approach. No attempt beyond this was made at classifying landslides regarding style of movement, type of slide, or relative age.

The initial landslide coverage was converted to a grid in ARC/GRID, for further analysis. ARC/GRID is a fully integrated cell-based geoprocessing system for use with ARC/INFO. ARC/GRID enables data analysis within the coverage by dividing it up into 10-m cells or pixels. Each pixel has a unique identifier, or value, depending on the location of the pixel. For example, in the grid of the landslide coverage, each pixel has one of two values, *landslide*, or *non-landslide*. The grid of the landslide coverage served as the basic grid used for comparison with all of the other landslide-influencing factors in this study.

Digital datasets of factors that commonly influence slope stability were then compiled and analyzed. Data analysis was generally limited to those data that were available in digital form. The majority of the data are from the U.S. Geological Survey. The data available in digital form and used for analysis in this study area are as follows: landslides mapped at a scale of 1:24,000 (Nilsen, 1975a&b); geology and structure (Wentworth and others, 1998); geomorphic data derived from a USGS DEM with 10-m resolution, including degree of slope, hillslope aspect, vertical land surface curvature, elevation; geotechnical properties of lithologic units such as expansivity of the soil and bedrock (Ellen and Wentworth, 1995); and precipitation data from Rantz (1971).

The digital data were analyzed quantitatively with ARC/GRID on a SUN/Solaris UNIX computer, and qualitatively with maps of the area at a scale of 1:24,000. Vegetation was considered in this study, but data were not available in digital form. Therefore, vegetation was analyzed qualitatively with respect to mapped landslides. All the aforementioned factors were analyzed with respect to their occurrence with either landslide pixels or non-landslide pixels. Those factors which were found most often in landslide areas were concluded to play a significant role in hillslope instability. These factors were ranked according to their relative influence on landslide occurrence.

Data

Degree of Slope

Degree of topographic slope is commonly found to influence slope stability (Bonilla, 1960; Brabb and others, 1972; Nilsen and others, 1976; Nilsen and others, 1976; Nilsen and others, 1979; and Pike and others, 2001). Figure 5 is a graph showing the percentage of area of each one degree of slope that is mapped as landslides (Pike and others, 2001). This graph indicates a correlation between slope and landsliding. First, few landslides within the study area occur on slopes gentler than 5 degrees. Second, as a general rule throughout the study area, as slope steepness increases, the percentage of area mapped as landslide increases. As Figure 5 shows, this trend is true for slopes less than approximately 45 degrees. There are very few slopes within the study area which are steeper than 45 degrees. The representation of these few very steep slopes results in the erratic nature of the graph at slopes steeper than 65 degrees. In general, however, Figure 5 shows that for the majority of hillsides, as slope steepness increases the percentage of area mapped as landslides at each slope increases.

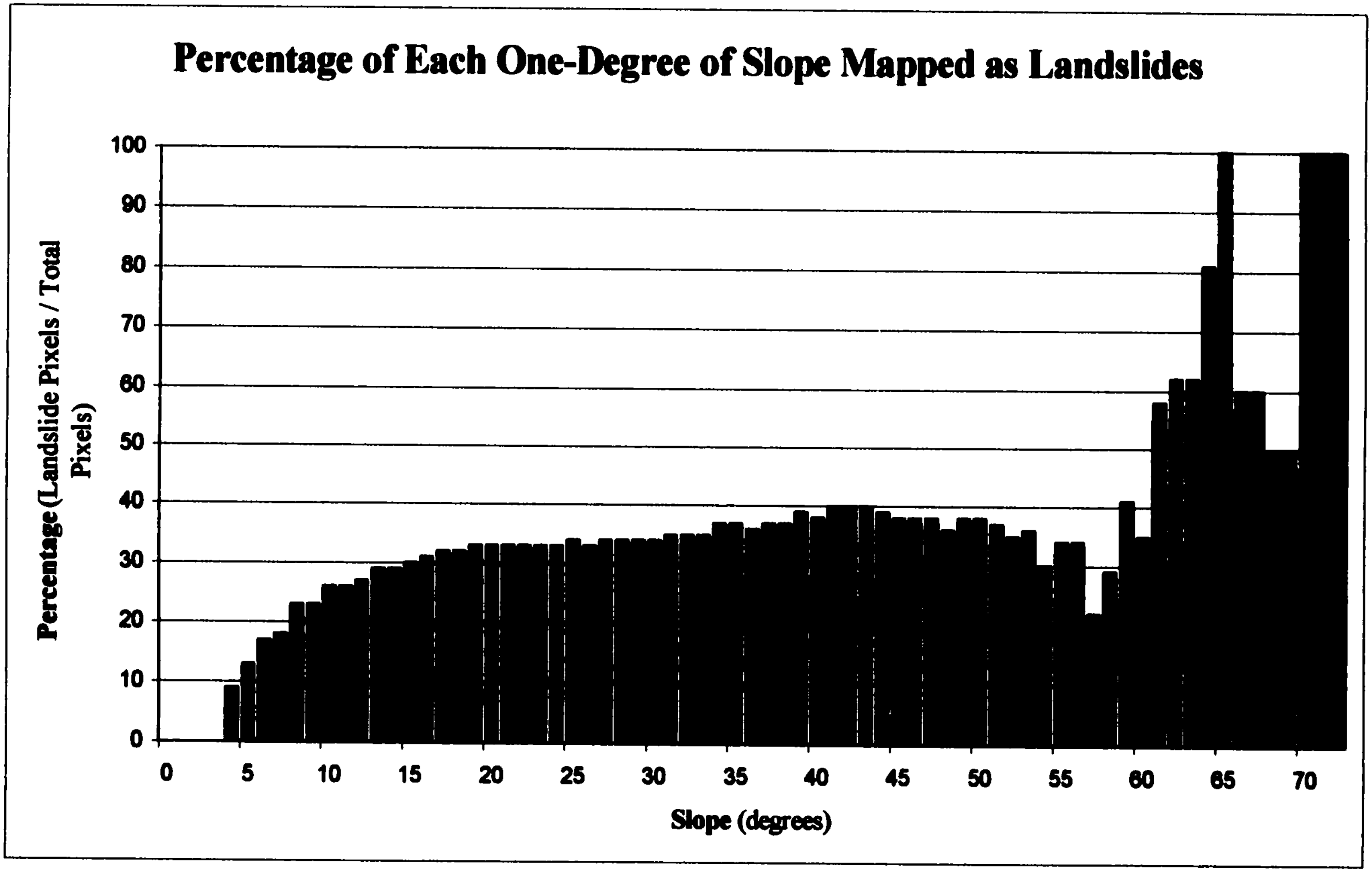


Figure 5. Percentage of area at each one-degree of slope that is mapped as landslides. Slope data derived from USGS 10-m DEM and landslide data from Nilsen (1975a&b).

Although this trend is true in general for the entirety of the study area, the distribution of the percentage of area mapped as landslides at each one-degree of slope within individual geologic units is highly variable. For example, Figure 6 is a graph showing the percentage of area mapped as landslides at each one-degree of slope within unit Tcc. Likewise, Figure 7 is a graph showing the percentage of area mapped as landslides at each one-degree of slope within unit Jbk. Figure 6 shows a distribution similar to that of the entire study area, wherein steeper slopes generally have a greater percentage of their area mapped as landslides than do gentler slopes. However, Figure 7 shows a different relationship between slope steepness and landslide abundance. According to Figure 7, slopes of approximately 4 to 10 degrees within unit Jbk contain the largest percentage of area mapped as landslides. In addition, in unit Jbk, landslide coverage decreases as slope steepness increases. Because the distribution of the percentage of area mapped as landslides at each one-degree slope within each individual lithologic unit is highly variable from unit to unit, a general correlation between degree of slope and mapped landslides cannot be made for the study area as a whole. Although slope strongly influences landslide occurrence, it is closely linked to lithology, and cannot be regarded as an independent landslide-influencing variable for the types of failures examined in this study.

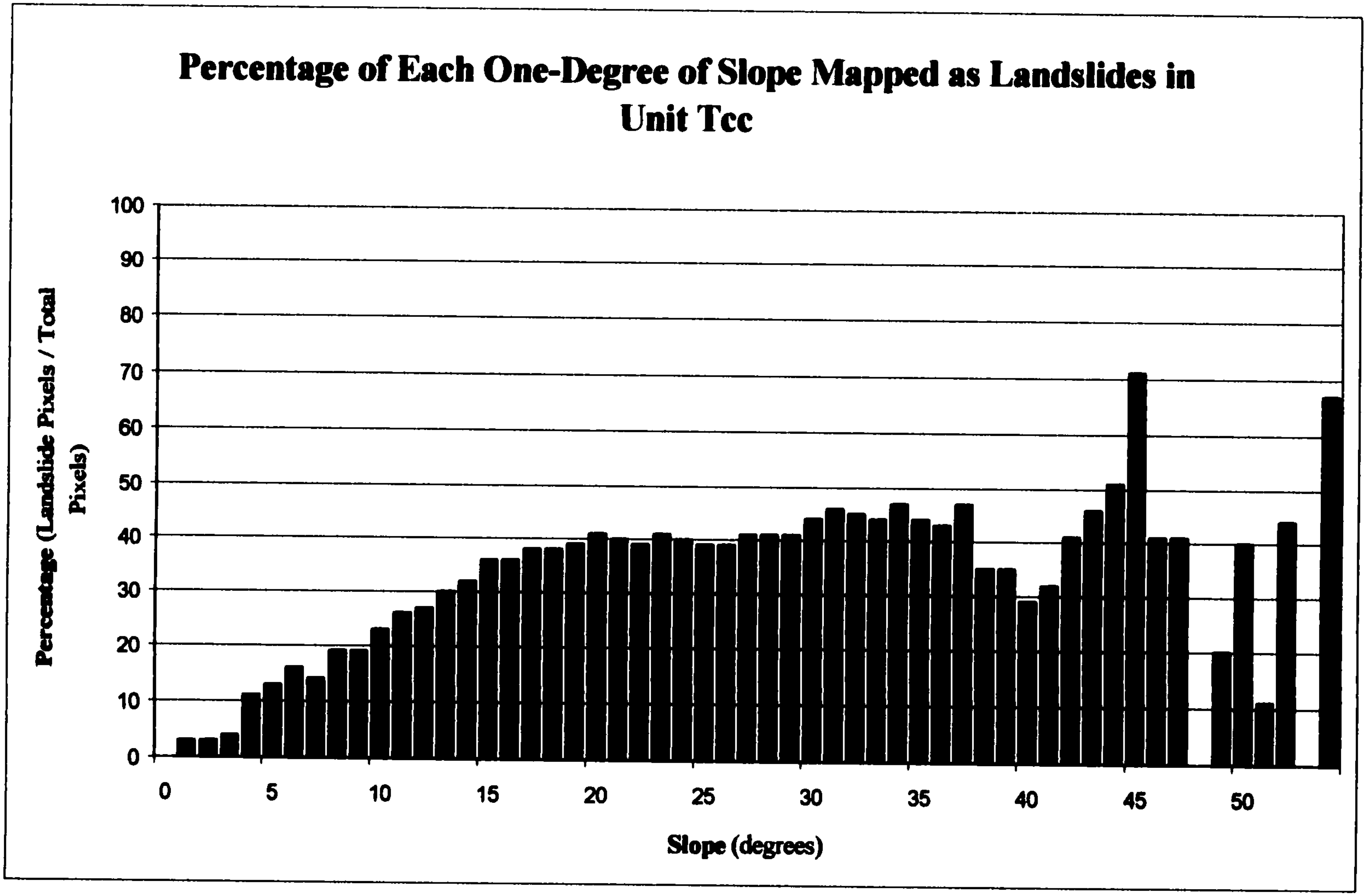


Figure 6. Percentage of area at each one-degree of slope that is mapped as landslides in unit Tcc. Slope data derived from USGS 10-m DEM, geology derived from Wentworth and others (1998), and landslide data from Nilsen (1975a&b).

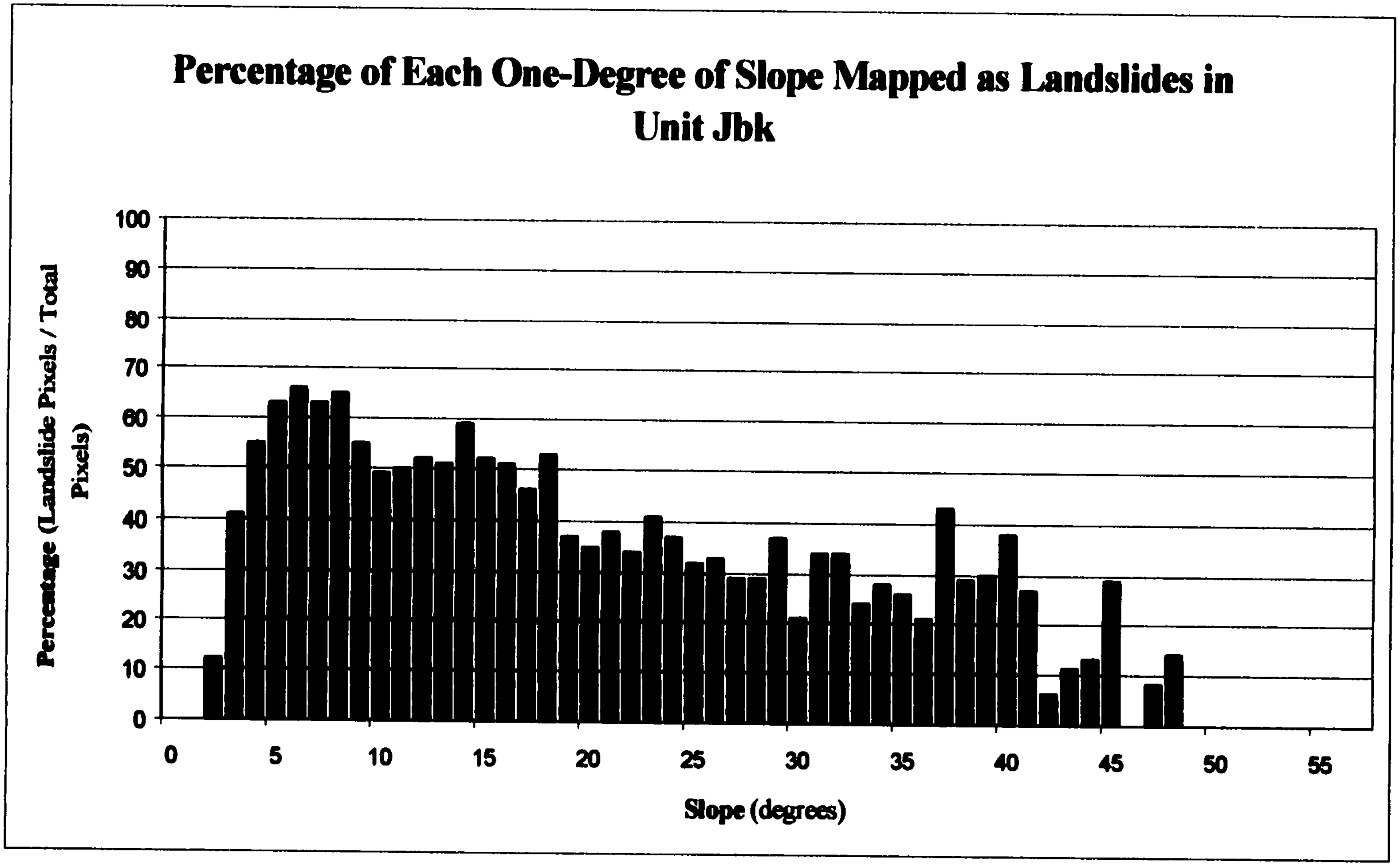


Figure 7. Percentage of area at each one-degree of slope that is mapped as landslides in unit Jbk. Slope data derived from USGS 10-m DEM, geology derived from Wentworth and others (1998), and landslide data from Nilsen (1975a&b).

Lithology

Bedrock geology is known to be a dominant factor affecting landsliding (Cleveland, 1971; Brabb and others, 1972; Nilsen and others, 1976; Newman and others, 1977; and Bechini, 1993). Figure 3 is a geologic map of the bedrock units within the study area. The geologic map used in this analysis contained no mapped landslides, so it was slightly different than that shown in Figure 3. Figure 3 was compiled from a geologic database of various published and unpublished maps, supplemented with field mapping and field checking (Wentworth and others, 1998), and the addition of landslides and other surficial deposits, as mapped from 1:80,000-scale aerial photographs (Wentworth personal comm., 6/2000). This geological database was compiled at a scale of 1:24,000.

There are 35 units mapped within this study area (Wentworth and others, 1998). They range in age from Jurassic to Quaternary, and in spatial extent from approximately 26 km^2 (Tbr, the Briones Formation) to 200 m^2 (Jsp, serpentinized harzburgite and dunite). Of these, 14 are mostly flat-lying Quaternary deposits in near-horizontal terrain, composing approximately 56 percent of the study area. The remainder of the units are found in the hillside areas, where the majority of landslides are concentrated.

After the practice of Brabb and others (1972), and Pike and others (2001), Table 1 lists each geologic unit mapped within the study area (Wentworth and others, 1998) and the percentage of each unit that is made up of mapped landslides. Table 1 indicates that while landslides dominate certain units, they are almost nonexistent in others. Hillside units with at least 30 percent of their total area mapped as landslide are Torv, sp Qt, Qti, fm, Kjk?, Kbs, Tts, Jbk, fy2, Kbc, Tor, fys, and gs. Hillside units with less than 30 of their total area mapped as landslide are Kau, Tcc, Tbr, ch, bl, Qa, Qpf , and Qpa. The remaining units have no landslides mapped within them. The majority of these units are on the valley floor, where there is little to no relief.

Table 1. Geologic units mapped within the study area, listed by the percentage of each unit that is mapped as landslides. (Geologic units from Wentworth and others, 1998).

SYMBOL	UNIT	LANDSLIDE PIXELS / TOTAL PIXELS [illegible]
Torv	Basalt and andesite (Upper Miocene)	67
sp	Serpentinite (Jurassic)	55
Qt	Stream Terrace Deposits (Quaternary)	55
QTi	Irvington Gravels (Pleistocene and Pliocene?)	51
fm	Mélange (Lower Tertiary? And Upper Cretaceous)	48
KJk?	Knoxville Formation (Lower Cretaceous and Upper Jurassic)	48
Kbs	Berryessa Formation-sandstone and mudstone (Cretaceous)	47
Tts	Temblor Sandstone (Middle Miocene to Oligocene?)	41
Jbk	Basalt, andesite, dacite and quartz keratophyre (Upper to Middle Jurassic)	40
fy2	Yolla Bolly Terrane - Lower Unit (Cretaceous? and Jurassic)	36
Kbc	Berryessa Formation-conglomerate (Cretaceous)	35
Tor	Orinda Formation (Upper Miocene)	33
fys	Yolla Bolly Terrane - Undifferentiated metagraywacke (Cretaceous? and Jurassic)	33
gs	Greenstone (Lower Tertiary? And Upper Cretaceous)	33
Kau	Sandstone, mudstone, and conglomerate (Upper Cretaceous)	22
Tcc	Claremont Formation (Upper to Middle Miocene)	19
Tbr	Briones Formation (Late Miocene)	18
ch	Chert Block (Lower Tertiary? And Upper Cretaceous)	18
bl	Blueschist Block (Lower Tertiary? And Upper Cretaceous)	12
Qa	Alluvium, undivided (Quaternary)	3
Qpf	Alluvial fan deposits (Upper Pleistocene)	2
Qpa	Alluvium (Upper Pleistocene)	2

SYMBOL	UNIT	LANDSLIDE PIXELS / TOTAL PIXELS [illegible]
Qhfp	Flood plain deposits (Holocene)	0
Qhb	Basin deposits (Holocene)	0
Qhf2	Alluvial fan deposits-older (Holocene)	0
se	Salt Evaporation Ponds (Modern)	0
Qhl	Levee deposits (Holocene)	0
Qhbm	Bay Mud (Holocene)	0
H20	Water	0
Qhfl	Alluvial fan deposits-younger (Holocene)	0
Qc	Colluvium (Quaternary)	0
Qhc	Stream channel deposits (Holocene)	0
af	Artificial Fill (Modern)	0
Qha	Alluvium (Holocene)	0
Qht	Stream terrace deposits (Holocene)	0
Jsp	Serpentinized ultramafic rocks (Jurassic)	0

According to Brabb and others (1972), a geologic unit's susceptibility to landsliding can be expressed as the percentage of the total area of the unit that is covered with landslides. Therefore, in each unit, dividing the number of 10-m landslide cells by the total number of 10-m cells in the unit yields the percentage of the unit that is covered by landslides. This percentage provides an approximate indication of each unit's instability or susceptibility to failure. As Table 1 shows, the percentage of each unit that is covered by landslides varies from 67% in Torv to 0% in units Qhfp, Qhb, Qhf2, se, Qhl, Qhbm, Qhfl, Qc, Qhc, af, Qha, Qht, and Jsp.

Bedding-dip Direction and Topographic Slope Orientation

The angle between bedrock attitude and the orientation of the topographic slope can often significantly influence slope stability in areas of layered sedimentary rocks. Units that have a strike and dip oriented similarly to that of the topographic slope or a similar strike and a dip slightly less than the topographic slope can be the locus of planar or bedding plane failures. However, similar bedding and topographic slope orientations do not always result in slope instabilities (Keefer and others, 1998), and instability cannot necessarily be assumed in areas where these conditions exist.

A study of the Orinda Formation in Contra Costa County, California, (Radbruch and Weiler, 1963) found that landslides are more prevalent in locations where sedimentary beds dip into the hillside. Pike and others (2001) conducted a thus-far unpublished digital bedding-dip direction analysis in a portion of the Oakland Impact Project Area, an area with similar geological and structural characteristics to this study area. Their analysis determined that only a small percentage of landslide pixels existed in which the difference between bedding-dip direction and hillslope aspect was less than 20 degrees. They found that in the majority of areas mapped as landslides (83%), hillslope aspect and bedding-dip direction differed by more than 40 degrees. They concluded that the occurrence of landsliding within their study area increases with divergence of bedding-dip direction and hillslope aspect.

In this study of the Milpitas and Calaveras Reservoir quadrangles, a qualitative analysis compared bedding-dip direction as indicated on the geologic map

(Wentworth and others, 1998) with the general aspect of the areas mapped as landslides, as shown in Figure 8.

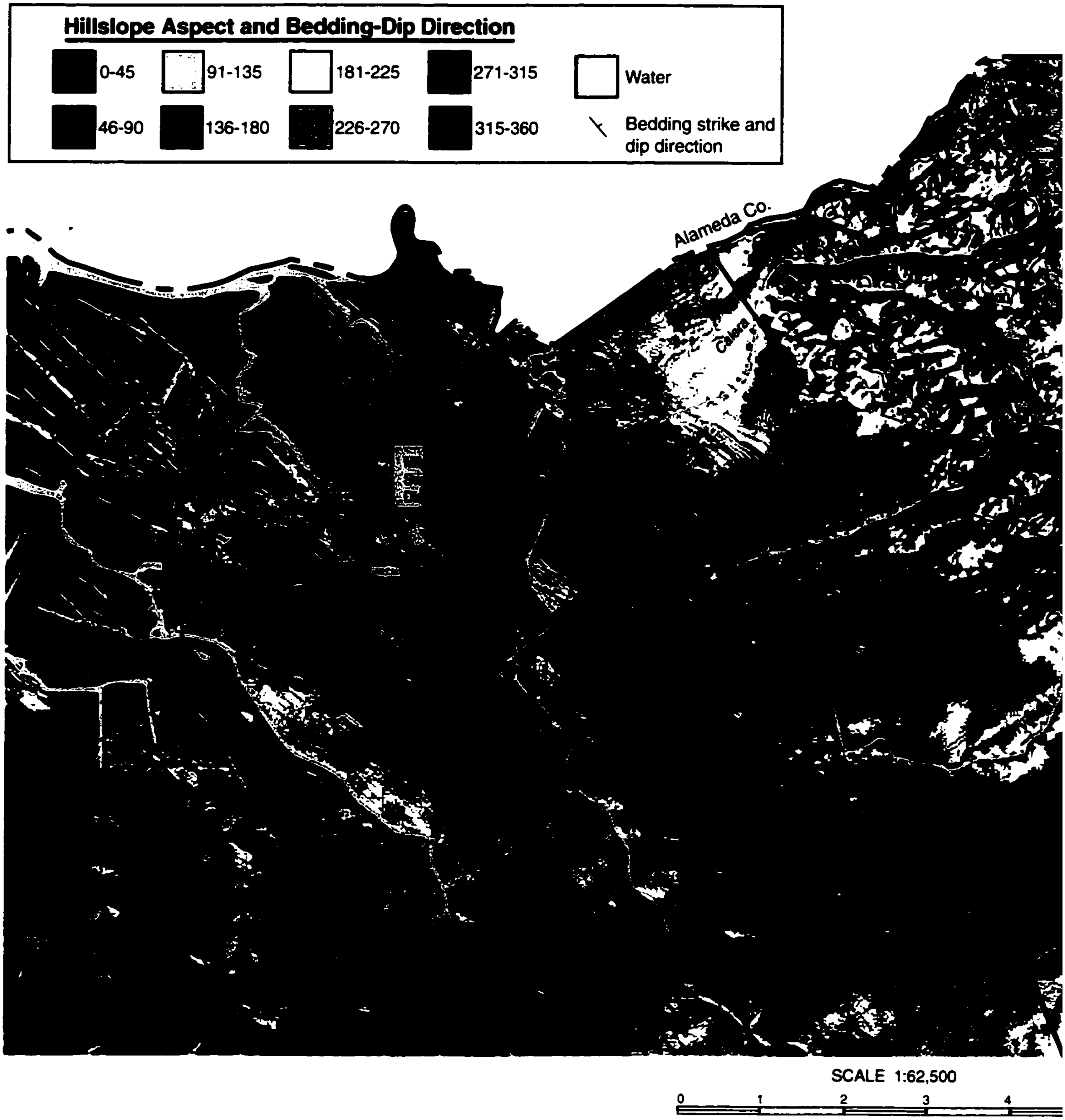
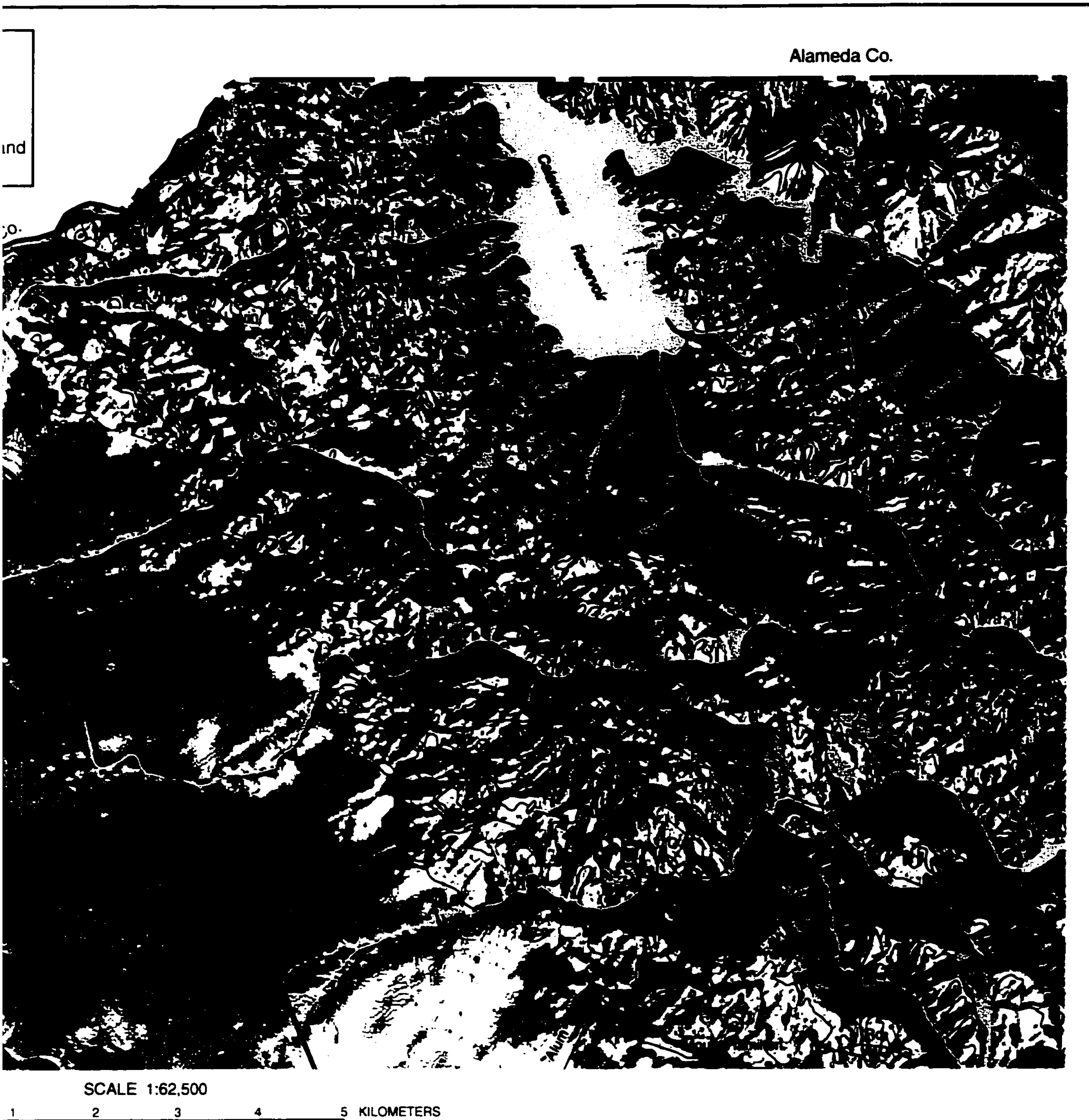


Figure 8. Aspect of the entire study area, measured in degrees clockwise from north. Also shown are landslide outli others (1998). A map similar to this was used to qualitatively analyze the influence of combinations of bedding-dip direc USGS 10-m DEM of the San Francisco Bay Region.



ırth. Also shown are landslide outlines from Nilsen (1975a&b) and bedrock strike and dip directions from Wentworth and
f combinations of bedding-dip direction and topographic slope aspect on hillslope stability. Hillslope data derived from

This analysis was an attempt to determine if bedding plane failures are common within the study area, or if conclusions by Radbruch and Weiler (1963), and Pike and others (2001) apply to this study area as well. This analysis did not use the precise strike and dip of the bedrock or strike and dip of the topographic slope. Instead, it involved the dip direction as indicated on the geologic map by Wentworth and others (1998), and a digital map of hillslope aspect of landslide areas created from the U.S. Geological Survey 10-m DEM of the study area.

The majority of units within the study area strike north-northwest, and dip toward the east-northeast. In the area between the Tularcitos Syncline and Calaveras Reservoir, bedrock strikes north-northeast and dips toward the west-northwest. In general, there are no measured bedrock attitudes in areas mapped as landslides. Therefore, bedding attitudes of bedrock beneath areas mapped as landslides were extrapolated from nearby locations of bedding attitudes.

The majority of large landslides within the study area are located along the range-front on the eastern edge of Santa Clara Valley, east of the range-front in the north-central portion of the study area, northeast of Arroyo Hondo, and in the southeast portion of the study area. The majority of these landslides have a southwest aspect and a bedding-dip direction of north-northwest. Yet, there are several large landslides in the central and southeast portions of the study area which have both a hillslope aspect and dip direction of northeast. These landslides are located in drainages and their slide directions are controlled by drainage orientations. They are located on northeast-facing slopes of northwest-trending drainages such as Arroyo Aguague and Calaveras Creek.

Drainages such as Calera Creek, Scott Creek, Penitencia Creek, Berryessa Creek, portions of Arroyo de Los Coches, and small drainages on the west side of Calaveras Reservoir cut across the bedrock structure. In these locations, the majority of landslides are oriented northwest and southeast. Here, the landslides are parallel to, or at low angles to, the strike of the bedrock. In contrast, drainages such as Calaveras Creek, upper Arroyo Hondo, and Arroyo Aguague are oriented approximately parallel to structure. Landslides in these drainages tend to be oriented northeast and southwest, and the bedrock is oriented northwest. These landslides are more or less parallel to dip direction, but show no preference for sliding toward or opposite from the direction of dip.

In conclusion, it appears that large landslides appear to occur preferentially in areas where bedrock dip direction is opposite from that of topographic slope direction. These hillslopes, however, are generally those which are south-facing and relatively unvegetated, which may account for some instability. Within the study area, there is no support for the conclusion that landslide occurrence increases as divergence between dip direction and topographic slope direction increases (Pike and others, 2001). Contrarily, it appears that landslide occurrence is not influenced by certain combinations of bedrock dip direction and topographic slope orientation. This conclusion is only preliminary, and is based solely on a qualitative map interpretation. A more thorough investigation, similar to that conducted by Pike and others (2001) might determine the specific relationship between dip direction, hillslope aspect, and landslide occurrence.

Bedrock Expansivity

Digital bedrock and soil expansivity data are derived from a publication by Ellen and Wentworth (1995). Ellen and Wentworth classified lithologic units based on geotechnical engineering properties of the land, such as soil texture, and soil and bedrock expansivity and permeability. The units, as described in Ellen and Wentworth (1995) were classified into a relative ranking of soil and bedrock expansivity in an unpublished USGS study by R.J. Pike, C. Wentworth, and S. Roberts. As stated in Pike and others, 2001, verbal descriptors ("largely," "severely," "possibly," "significantly," "some," "much," "most," "minor") in Ellen and Wentworth (1995) were interpreted to express semi-quantitatively both the severity of expansivity and proportion of each unit so affected. These relative expansivity rankings were compiled into a digital database, in which the units were ranked on a relative expansivity scale from 1.0 (lowest) to 7.0 (highest). Subsequently, a coverage was created in ARC/INFO for the bedrock and soil expansivity of the entire SFBR. The bedrock and soil expansivity values extracted from this coverage for the Milpitas and Calaveras Reservoir quadrangles are used here to determine the influence of expansivity on landslide occurrence. Figure 9 shows the relative bedrock expansivity of the study area, and Figure 10 shows the relative soil expansivity of the study area. Figure 9 shows valley deposits within the study area which are not bedrock, but are included in the figure to show that some of the areas with the highest expansivity values are located on horizontal terrain.

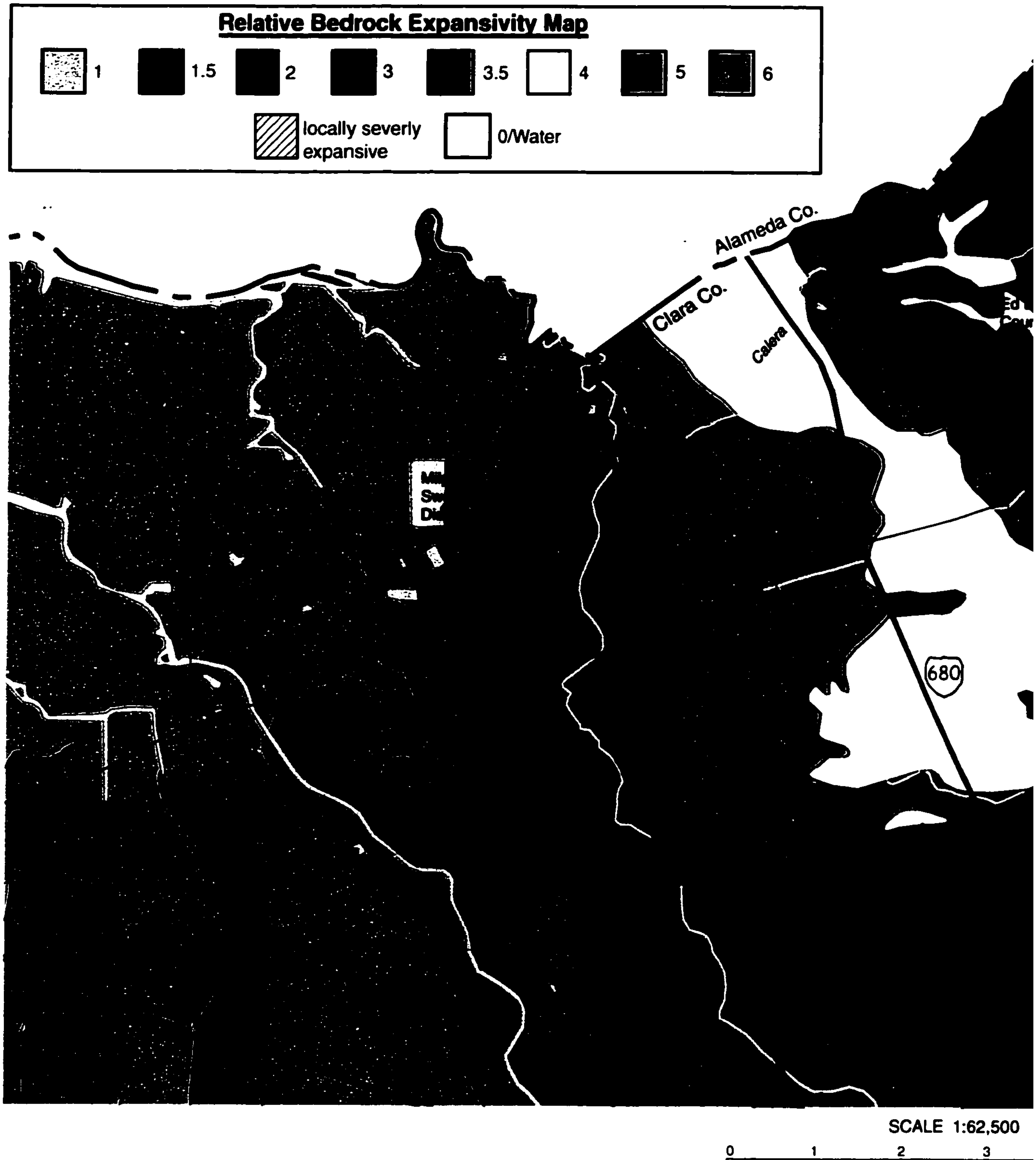


Figure 9. Relative bedrock expansivity, based on Ellen and Wentworth (1995), and unpublished USGS. data

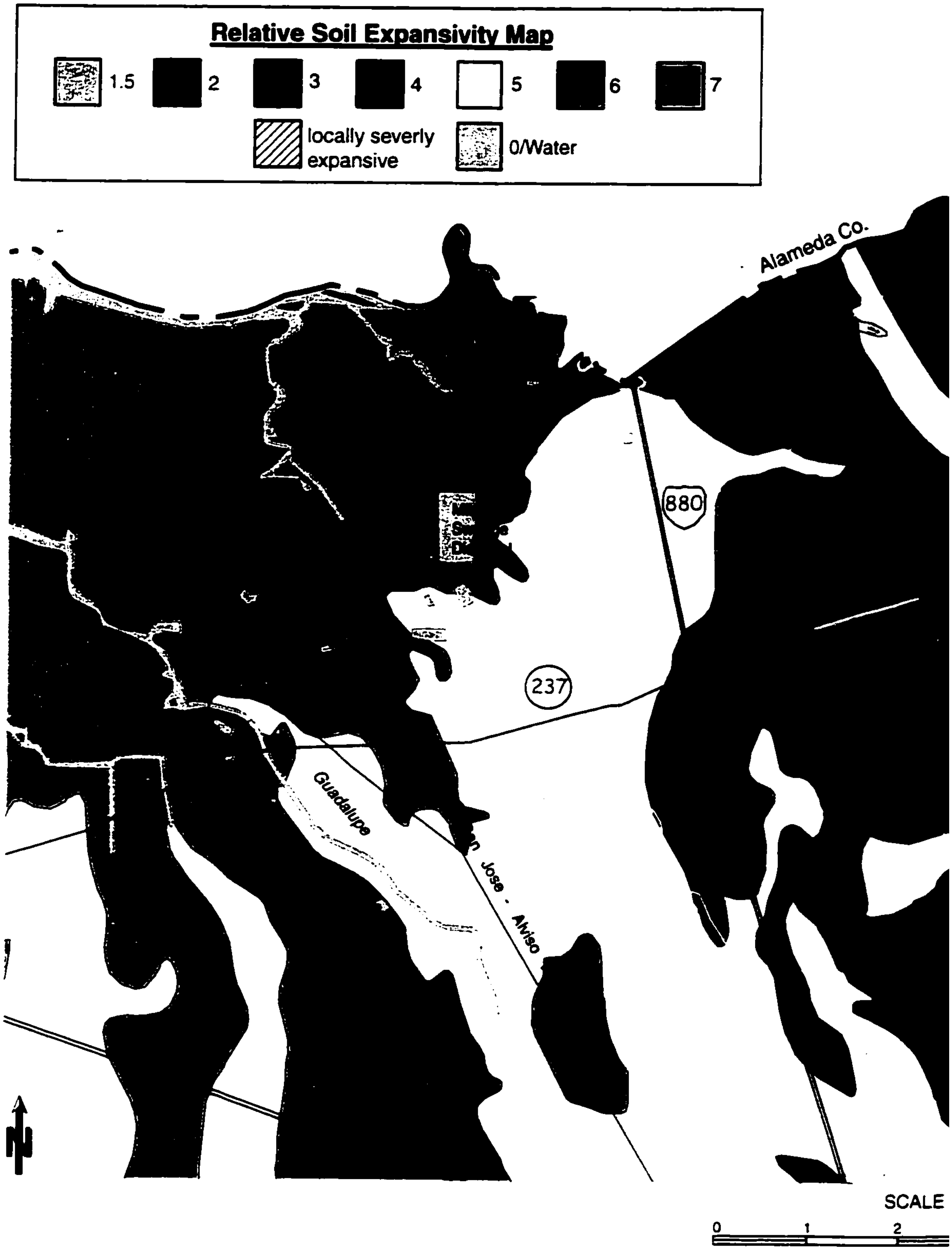
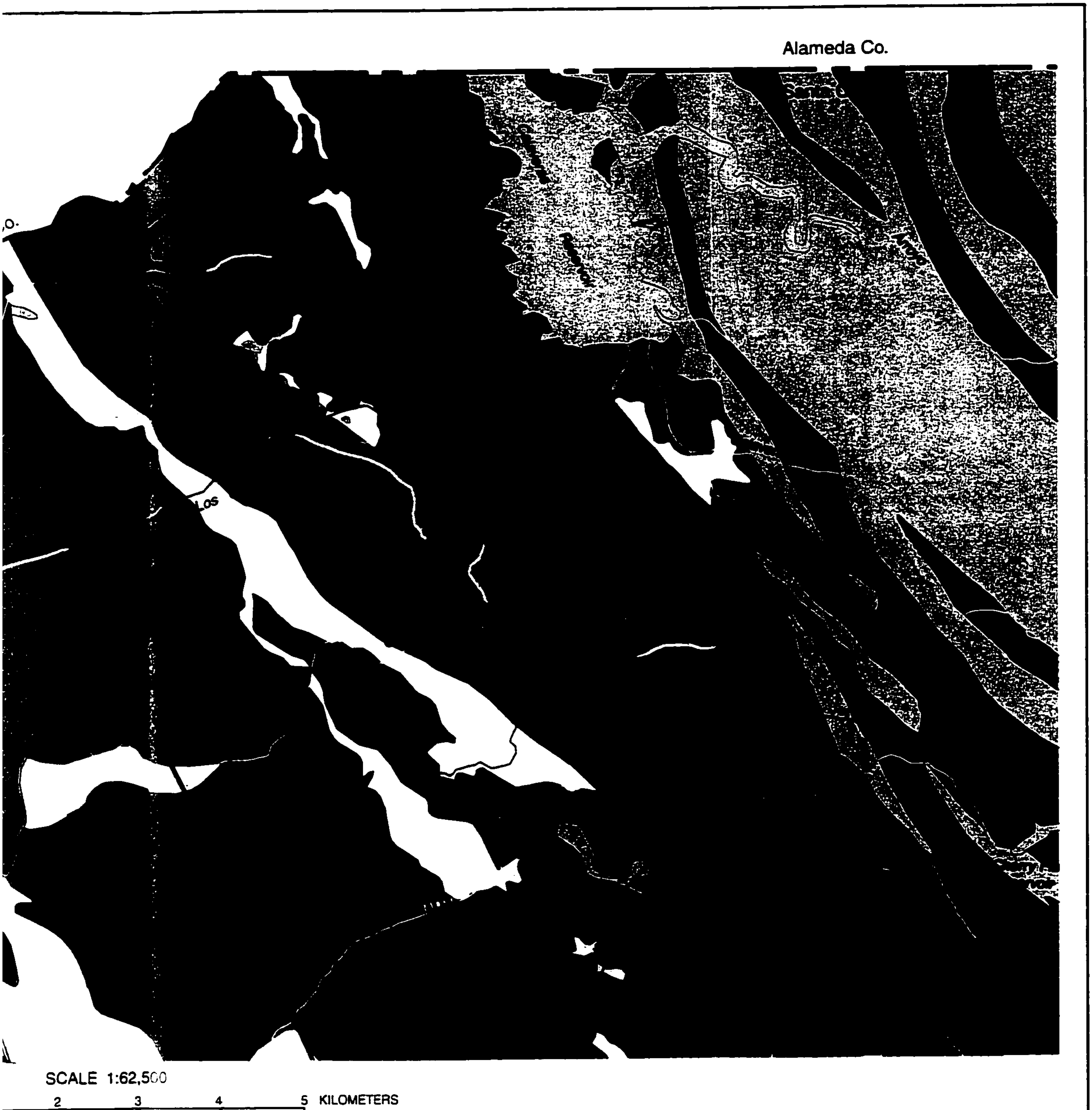


Figure 10. Relative soil expansivity, based on a Ellen and Wentworth (1995), and unpublis



ıd unpublished USGS data by Pike, et al., 2001. Expansivity values are relative, and range from 0 to 7 in increments of .5.

The map of these bedrock and soil units as classified in Ellen and Wentworth (1995) predates the newly-compiled geologic map of Wentworth and others. (1998) utilized in this study. Therefore the units in the two studies do not correspond exactly, but they are close enough for comparison.

A grid was created of bedrock expansivity of all areas with slope greater than 5 degrees in order to account for the fact that the majority of landslides in the study area (99.99%) are mapped on slopes steeper than 5 degrees. Bedrock expansivities of hillside areas with no landslides were compared to expansivities of hillside areas with landslides. The flatlands were excluded from this analysis, because they typically have the highest expansivity rankings, but the fewest landslides, and therefore an analysis of the entire study area would be skewed by the highly expansive areas with no landslides. The majority of hillside units within the study area have a relatively low bedrock expansivity ranking of 1.5. This includes units such as fys, fy2, fm, Kau, Tcc, Tbr, Kjk?, Qti, and parts of Kbc and Kbs.

A comparison of bedrock expansivities of hillside areas with those of landslide areas determined that, with one exception, the bedrock expansivity distribution of landslide areas is very similar to the bedrock expansivity distribution of hillside areas. The one exception to this conclusion is that areas of mapped landslides have a proportionately larger amount of bedrock with an expansivity ranking of 2 than do hillside areas. Bedrock with an expansivity ranking of 2 makes up 16 percent of the hillside areas, whereas it accounts for 27 percent of the landslide areas. Figure 11 also indicates that bedrock with an expansivity ranking of 2 contains the largest percentage of area mapped as slides (approximately 55 percent).

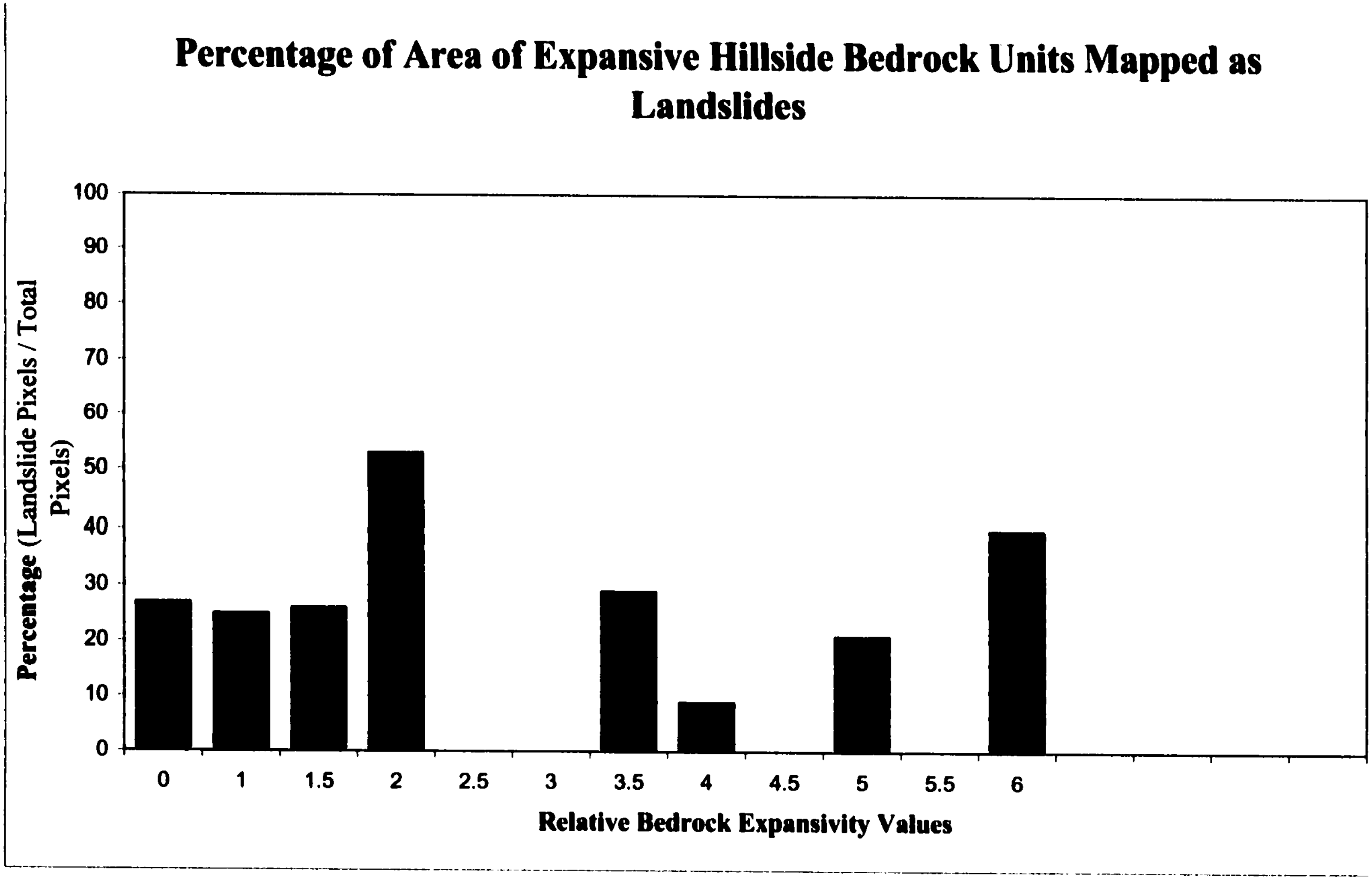


Figure 11. Percentage of area mapped as landslides within each unit of bedrock expansivity (hillside areas only included on this graph). Bedrock data derived from Pike and others, 2001.

In addition, approximately 40 percent of the area with an expansivity of 6 is mapped as landslides. The Franciscan Complex, a unit dominated by landsliding, is the unit which comprises most of area with a bedrock expansivity of 2. Also, units Qti and Kbc, both of which have greater than 30 percent of their area mapped as landslides, make up most of the area with a bedrock expansivity of 6.

Figure 11 does not indicate that landslides are more prevalent in areas of highly expansive bedrock than in areas of less expansive bedrock. In fact, no obvious relation exists between bedrock expansivity and landslide coverage. Figure 11 shows that the majority of expansivity rankings have similar percentages of their total area mapped as landslides (approximately 20 to 30 percent), with those areas ranked as 2 and 6 having a much greater percentage of landslide coverage. Therefore, within the Milpitas and Calaveras Reservoir quadrangles, high bedrock expansivity does not indicate low slope stability. Because the bedrock expansivity values are derived from geotechnical properties and descriptions of the lithologic units, the expansivity values and their respective percentage of landslide coverage are likely a reflection of the characteristics of the bedrock units contained within them. Therefore, bedrock expansivity is intimately linked to lithology, and is not an independent variable. For example, the proportionately large amount of landslide area in areas with a bedrock expansivity ranking of 2 is a reflection of the landslide-prone units that have a bedrock expansivity value of 2, fm and sp. Therefore, two conclusions can be made about bedrock expansivity and landslide coverage: There does not appear to be a significant relation between high bedrock expansivity and landslide occurrence; and any relation that does exist between bedrock expansivity and landslide coverage will also exist between lithology and landslide coverage, and is therefore incorporated into the lithology analysis of this study.

The digital dataset of bedrock expansivity also indicates areas of locally severely expansive bedrock. An analysis of mapped landslides and locally severely expansive bedrock in hillside areas (slopes greater than 5 degrees) concludes that severely expansive bedrock does not appear to influence slope stability occurrence. For example, 31 percent of hillside areas with no severely expansive bedrock is mapped as landslides. In comparison, 33 percent of hillside areas with severely expansive bedrock is mapped as landslides. Because these values are so similar, it appears that within the study area, locally severely expansive bedrock is not any more susceptible to landsliding than non severely expansive bedrock.

Soil Expansivity

Figure 10 shows the distribution of soil expansivity values across the study area. As with bedrock expansivity, the distribution of expansive soils within landslide areas reflects the distribution of expansive soils within hillside areas (slopes steeper than 5 degrees), with some exceptions. Most of the hillside units have an expansivity ranking of 4. However, landslide areas have only a very slight majority of soils with an expansivity of 4, and those with an expansivity ranking of 2 are almost as abundant. Therefore, landslide areas have relatively more area with a soil expansivity ranking of 2 than do hillside areas.

Figure 12 shows that those areas with a soil expansivity ranking of 2 have the largest percentage of area mapped as landslides (approximately 55 percent). Soils with an expansivity ranking of 2 include those derived from units such as fm, sp, bl, gs, and Qha. Aside from those areas with an expansivity ranking of 2, Figure 12 indicates that areas with the other soil expansivity rankings have a similar percentage of landslides mapped within them. For example, soils with expansivity rankings of 1.5, 5, and 7 all have a similar amount of their total area mapped as landslides. Similarly, Figure 12 does not show any trend of increasing landslide coverage with increasing soil expansivity values. Figure 12 indicates that, within the study area, an increase in soil expansivity does not necessarily indicate an increase in landslide coverage.

As is the case with bedrock expansivity values, soils with expansivity values which contain a large percentage of landslide coverage seem to reflect the geologic unit from which the soils are derived. For example, the majority of areas with a soil expansivity ranking of 2, the ranking which contains the largest percentage of area mapped as landslides, include landslide-prone units such as fm and sp, both of which have greater than 45 percent of their area mapped as landslides. Therefore, the relative abundance of landsliding in areas with a soil expansivity ranking of 2 likely reflects the abundance of landslides in the units from which these soils were derived. Consequently, it can be concluded that soil expansivity does not play an important role in slope stability this particular study. There does not appear to be a certain correlation between soil expansivity and slope instability.

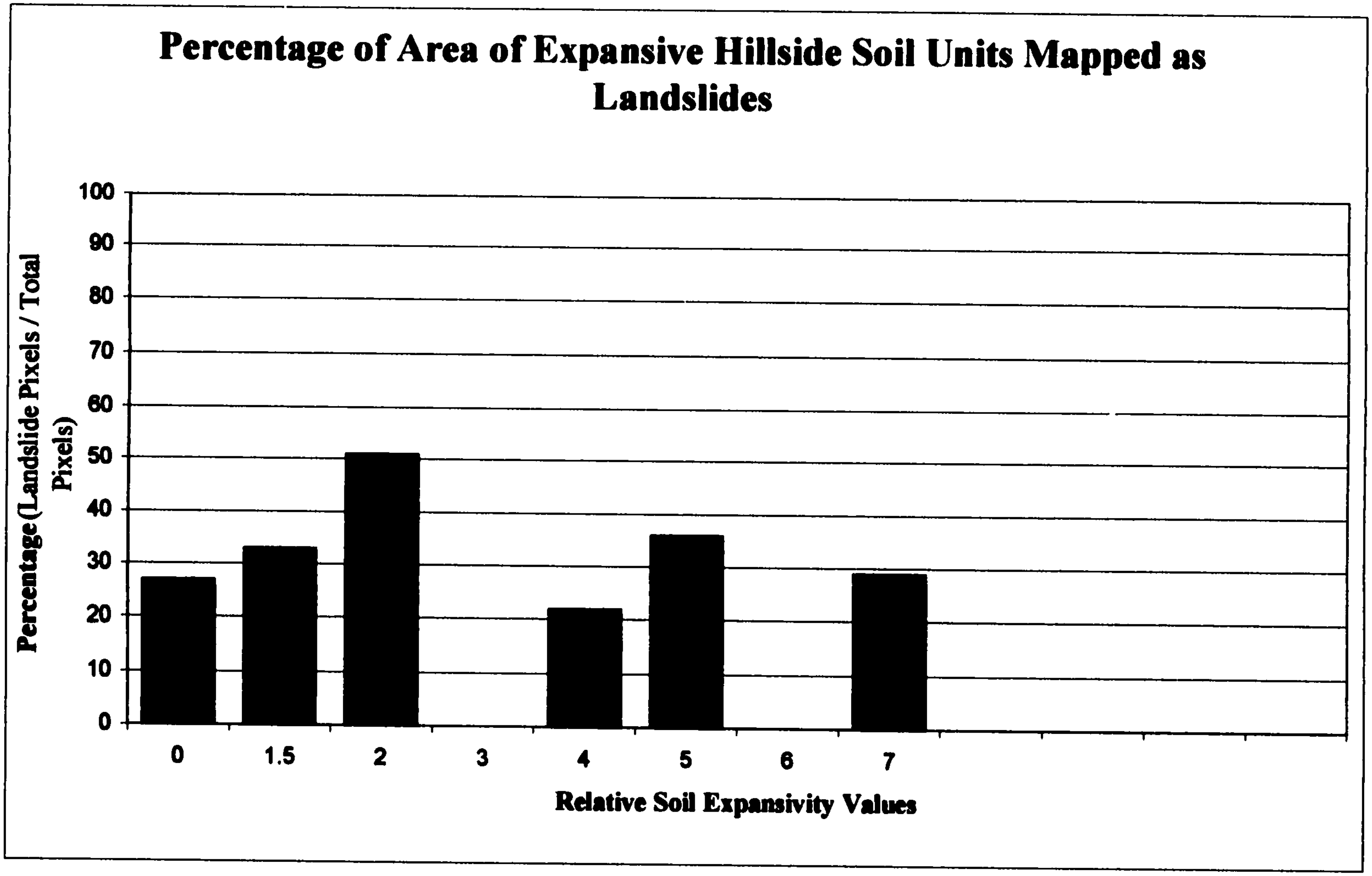


Figure 12. Percentage of area mapped as landslides within each unit of soil expansivity (hillside areas only included on this graph). Soil data derived from Pike and others, 2001.

Finally, an analysis of areas of locally severely expansive soils within the study area leads to an unanticipated conclusion. Locally severely expansive soil areas of hillsides were compared with those of mapped landslides. Thirty-eight percent of non-severely expansive soils are mapped as landslides. In contrast, only 22 percent of locally severely expansive soil are mapped as landslides. From these data it appears that locally severely expansive soils do not induce deep-seated slope instability.

Hillslope Aspect

Hillslope aspect, or the compass direction toward which a hillslope faces, is often thought to influence landslide occurrence (Beaty, 1956; Bonilla, 1960; and De Coster, 1979). Digital hillslope aspect data are derived from the USGS 10-m DEM of the area. Aspect is typically measured in degrees clockwise from north, and ranges from 0 to 360 degrees.

Predominant geologic structures in the study area strike northwest-southeast, and the majority of hillsides face toward the southwest or the northeast. An analysis of a graph of the distribution of aspect throughout the study area, Figure 13, shows that most of hillsides face southwest, with fewer facing northeast. Figure 14 is a map showing the aspect of the entire study area. This map shows the distribution of aspect by assigning each 45-degree interval of aspect a different color. A visual analysis of this map indicates that several directions of aspect prevail throughout the area. Most of the Milpitas quadrangle, which is the flatland of the Santa Clara Valley floor, has an aspect of 0-45 degrees clockwise from north, or an aspect of north-northeast.

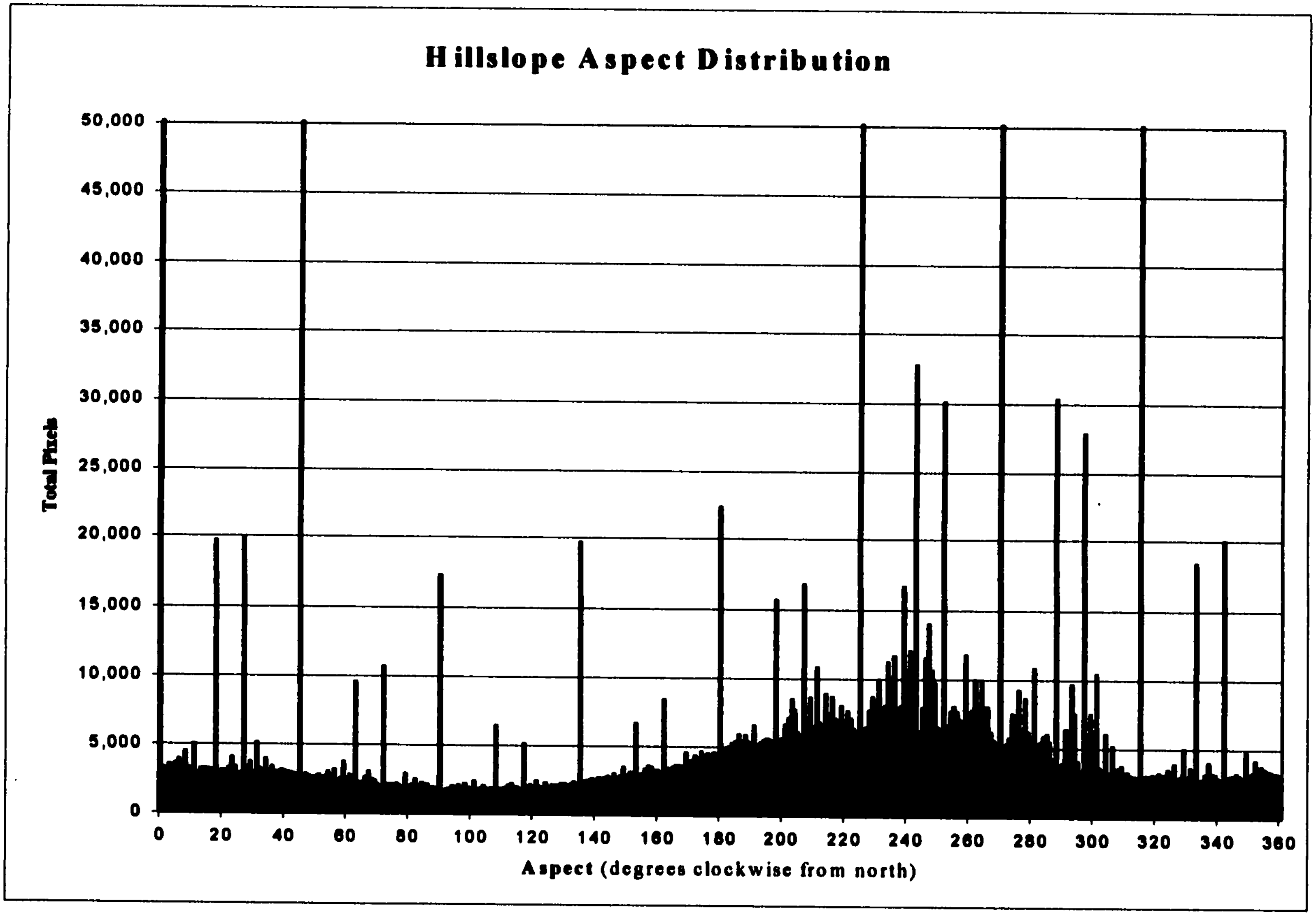
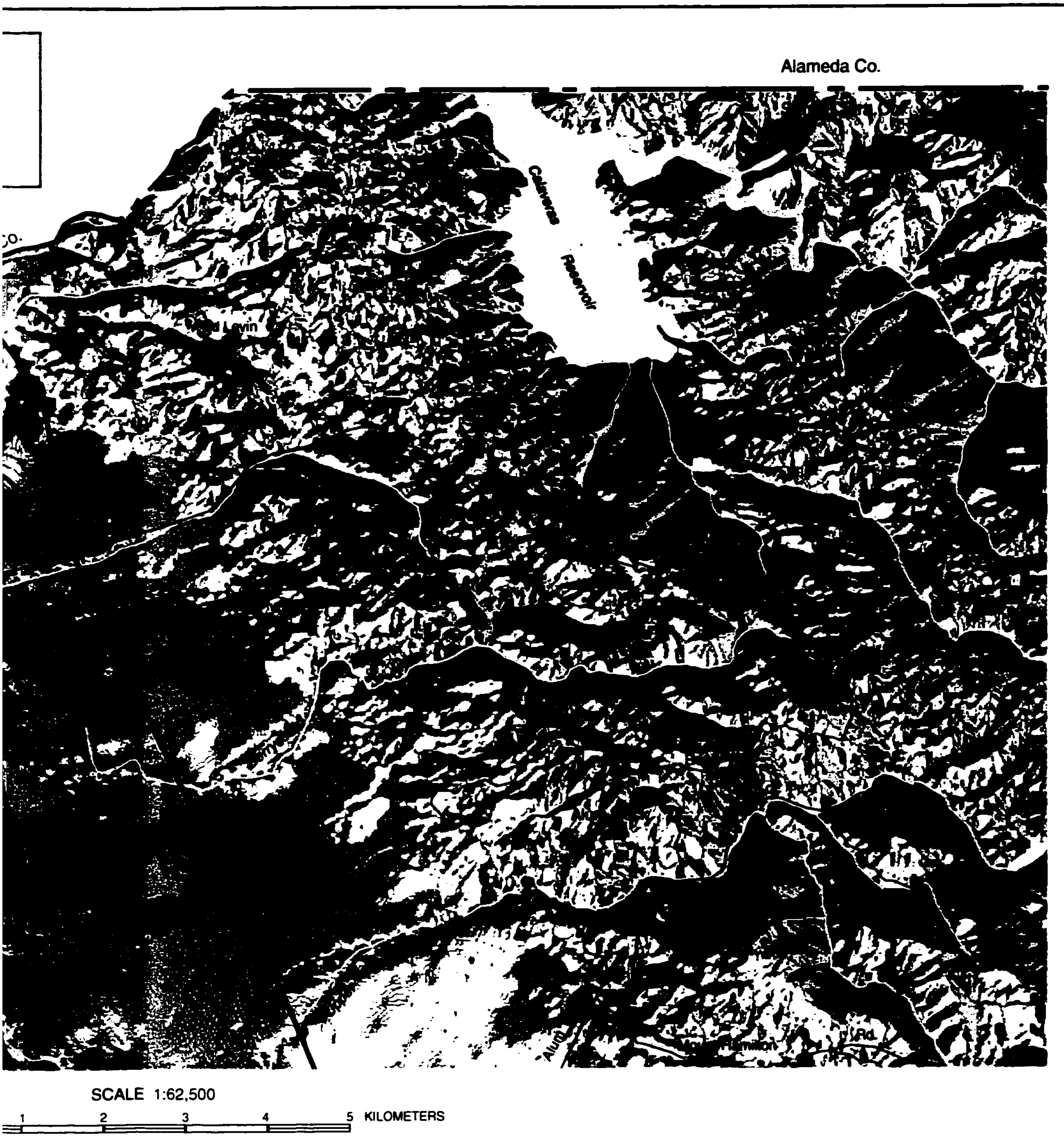


Figure 13. Aspect distribution of entire study area. Aspect data derived from USGS 10-m DEM of SFBR.



ɪrth. Aspect data derived from USGS 10-m DEM of San Francisco Bay Region.

Most of the hillslopes within the study area have aspects of 180-270 degrees clockwise from north, or south to west, and fewer have aspects between 0-90 degrees clockwise from north, or north to east.

The aspect distribution of mapped landslides reflects the overall aspect distribution of the hillslopes within the study area. The majority of mapped landslides have an aspect of southwest as shown in Figure 15. In addition, Figure 15 also shows that very few areas mapped as landslides have an aspect of east. Figure 16 is a map of aspect of those areas mapped as landslides. A visual inspection of this map indicates that the majority of landslide areas face south to west, or between 180-270 degrees.

Landslide aspect also appears to reflect the size of the landslide. Most of the very large landslides (greater than one kilometer in one dimension) have an aspect of 180-270 degrees, or south to west. The medium and small landslides (one kilometer to 150 meters, and less than 150 meters, respectively) vary much more in aspect. They do not appear to have a preferential aspect. This is most likely because the majority of the medium and small landslides are located in drainages and therefore are influenced primarily by the orientation of the drainages and the overall trend of the ridges in the study area.

Figure 17 indicates that hillslopes that face south-southeast to south-southwest, approximately 155-200 degrees, contain the greatest percentage of landslide coverage (approximately 30-33 percent). Figure 17 also shows that northeast-facing slopes are somewhat affected by landsliding and east- and northwest-facing slopes are less affected by landsliding.

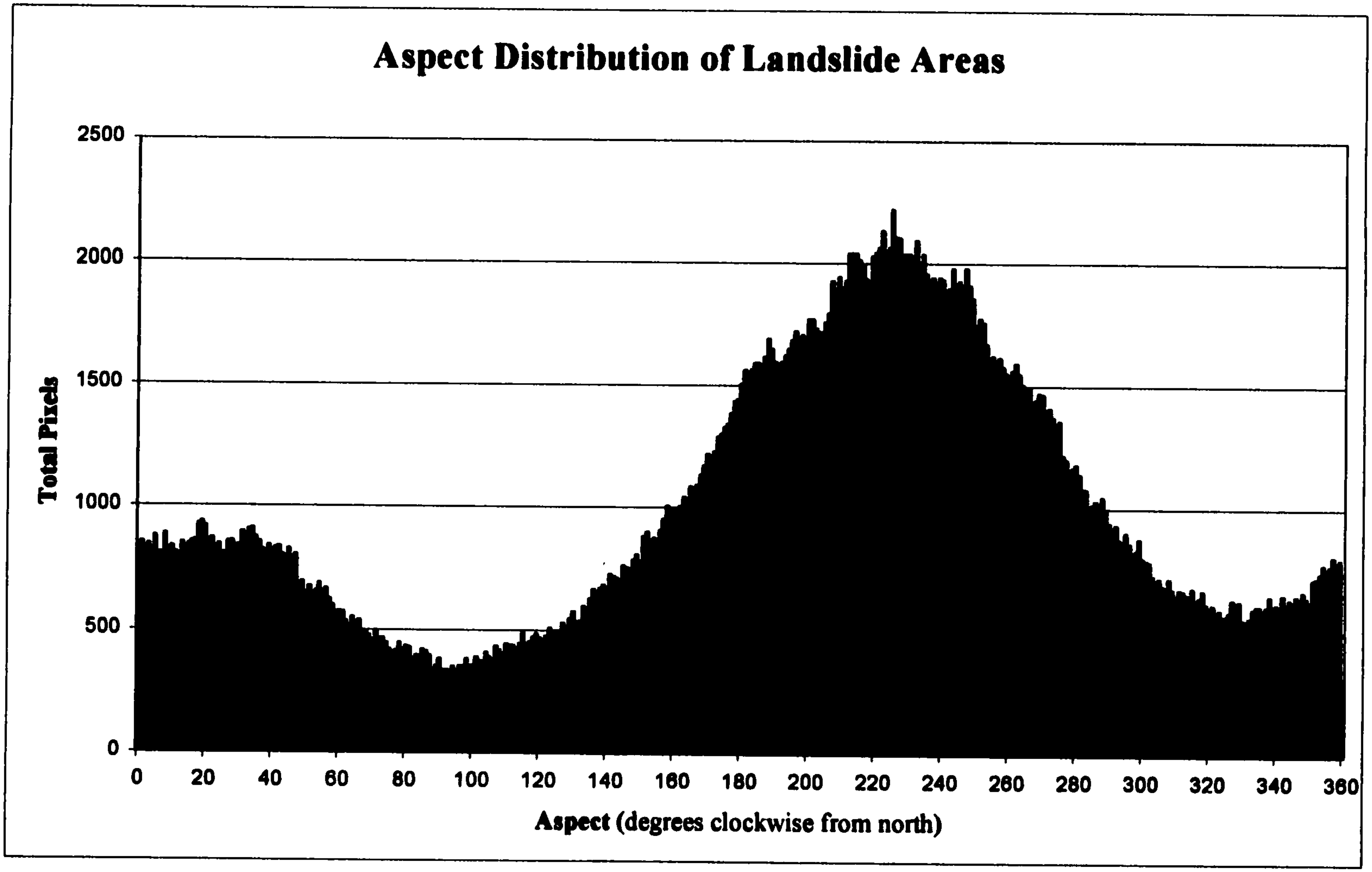


Figure 15. Distribution of hillslope aspect in landslide areas. Hillslope aspect derived from USGS 10-m DEM and landslide data derived from Nilsen (1975a&b).

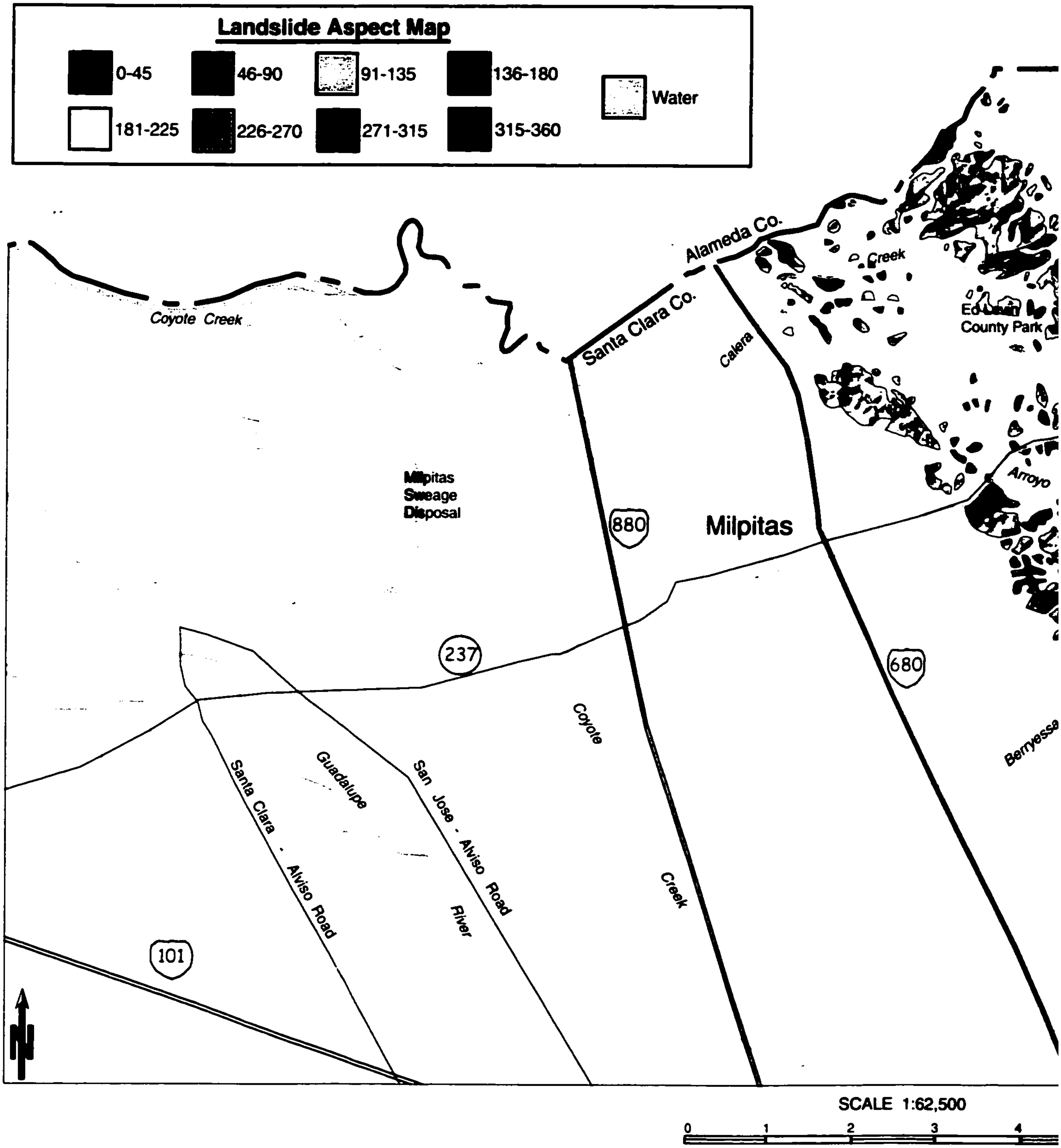
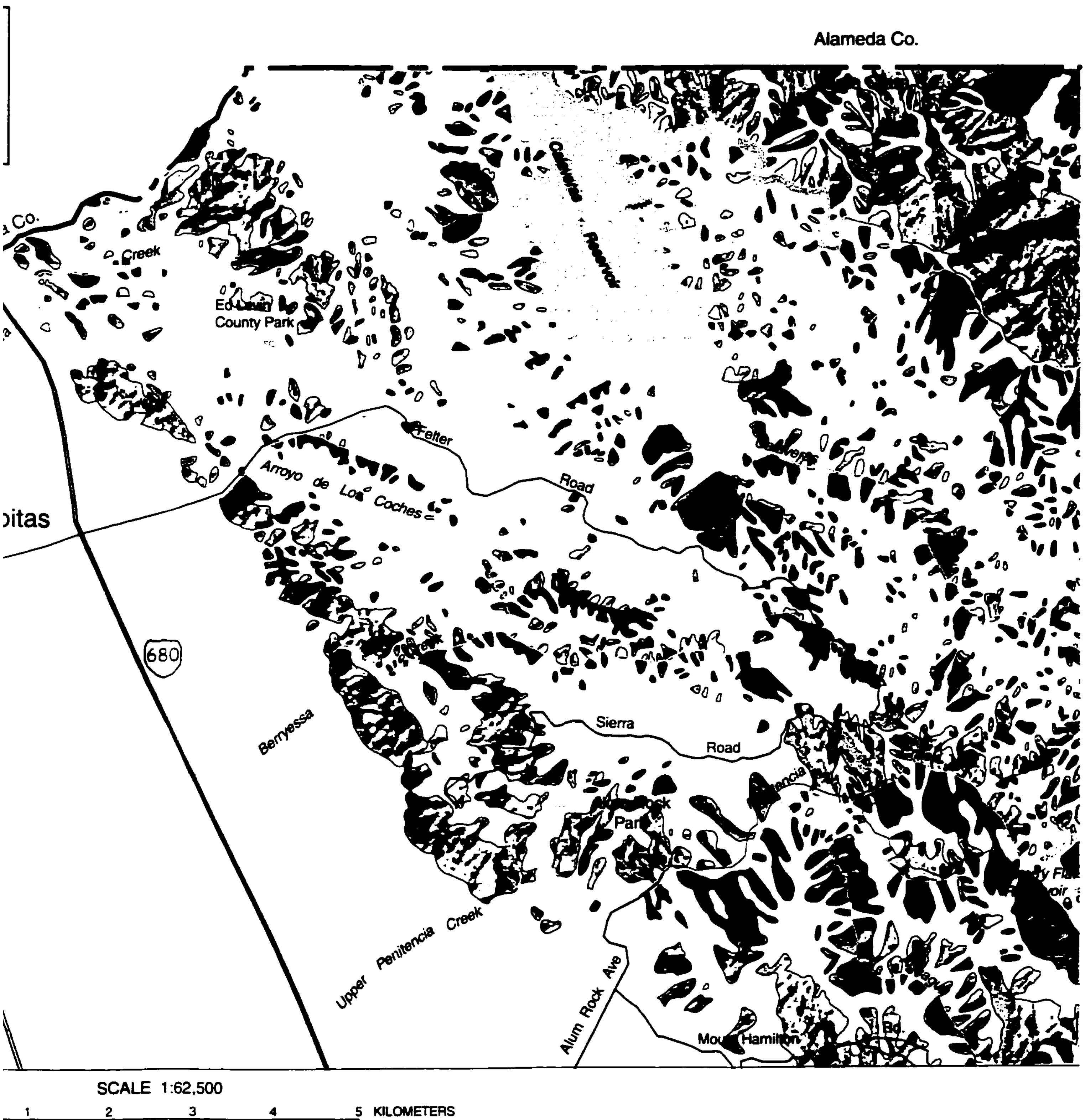


Figure 16. Hillslope aspect of mapped landslides, shown in degrees clockwise from north. Aspect data derived fron from Nilsen (1975a&b).



om north. Aspect data derived from USGS 10-m DEM of San Francisco Bay Region. Locations of mapped landslides

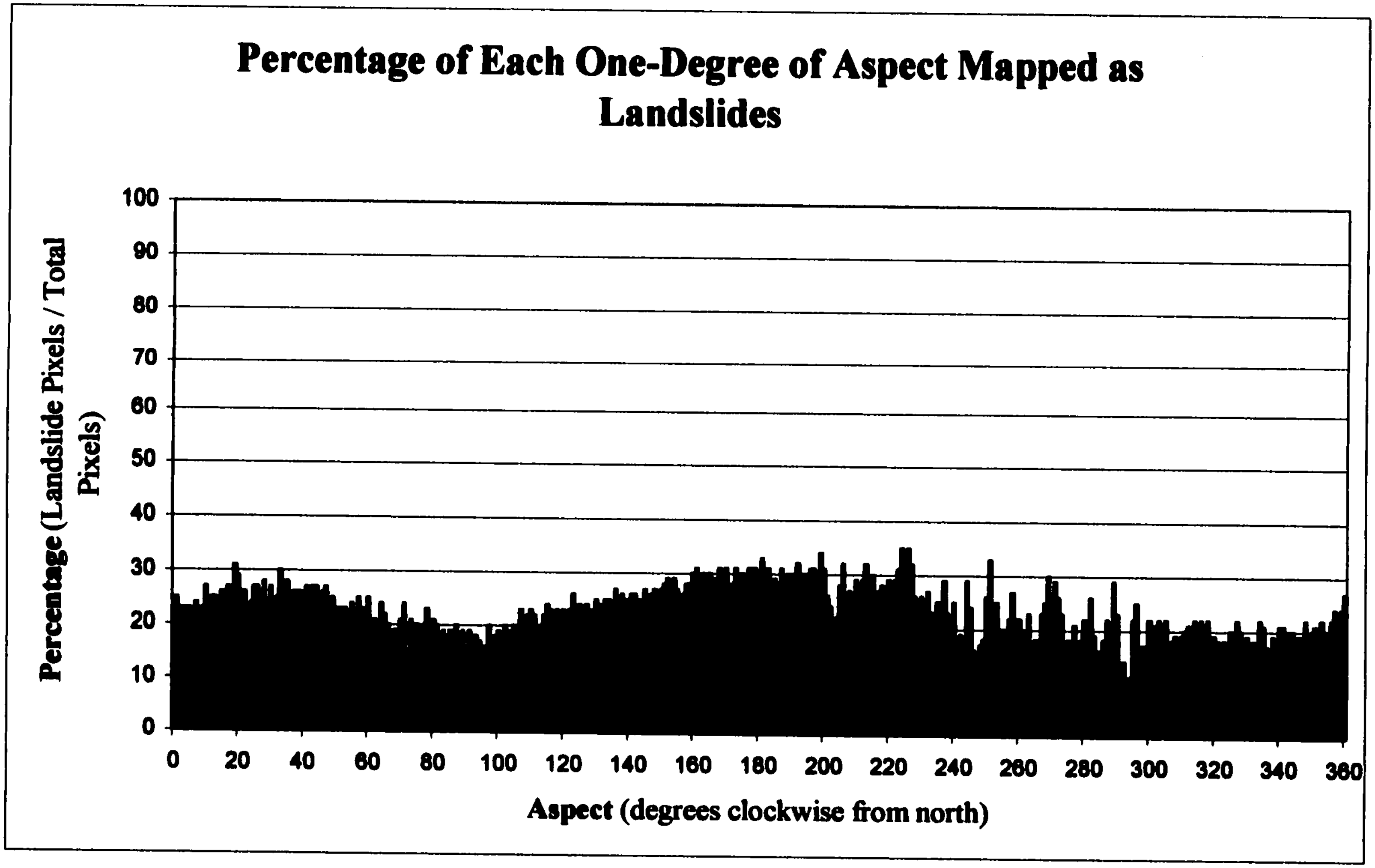


Figure 17. Percentage of area at each one-degree of aspect that is mapped as landslides. Aspect data derived from USGS 10-m DEM and landslide data from Nilsen (1975a&b).

This could be explained by the fact that few hillsides within the study area have an eastern aspect, and therefore relatively few landslides are located on east-facing slopes. In addition, the majority of northwest-facing hillslopes are found in drainages that run perpendicular to structure, or northeast. Within these drainages, northwest-facing slopes are commonly highly vegetated, and few, small landslides occur.

In conclusion, there is a moderate correlation between landslide occurrence and hillslope aspect. Hillslopes with aspects of north-northeast and southeast to southwest appear to be more susceptible to landsliding than hillslopes with other aspects.

Vegetation

In general, vegetation acts as a stabilizing mechanism for hillsides (Cleveland, 1971). Therefore, vegetation is an important consideration when determining which areas are most susceptible to future landsliding. The data for this investigation were from two 7.5-minute topographic quadrangles and a set of small-scale (1:80,000) aerial photographs. An attempt was made to determine whether a relation exists between distribution of vegetation and distribution of mapped landslides.

In general, dense vegetation is localized in and around the major and minor drainages. The open hillsides are primarily vegetated with grasses and sparse trees. In most drainages, the north-facing slopes have more abundant dense vegetation than the south-facing slopes. Therefore, orientation influences the vegetation distribution of the study area.

Analysis of 7.5-Minute Topographic Quadrangles On the topographic maps, vegetated areas are primarily within the drainages. However, the maps do not define the type or density of vegetation of these green areas. The areas of dense vegetation were compared with the landslide distribution within and around the major drainages. In most drainages, the north-facing slopes are more vegetated than the south-facing slopes. With few exceptions, most of the drainages have more numerous and larger landslides on the less vegetated, south-facing slopes than on the north-facing slopes. There are exceptions, however, such as Calera Creek, where a significant portion of the drainage is mapped as one very large landslide, and most of the landslide is located on the north-facing slopes within the drainage. However, because there are several large landslides that encompass areas of both dense and sparse vegetation, vegetation does not appear to have a significant influence on the very large landslides.

Analysis of 1:80,000 Scale Aerial Photographs The second visual analysis of vegetation, using aerial photographs, was an attempt to verify the results of the topographic map analysis. Although different types of vegetation could not be discerned in the small-scale aerial photographs, the overall vegetation distribution was evident. The 1:80,000-scale aerial photographs were taken in July 1982, by an unknown aerial photography service. In this analysis, vegetation refers to dense vegetation easily seen at a small scale, which expresses itself photographically as dark landscape coverage.

The aerial photograph analysis resulted in many of the same conclusions as the topographic analysis. Most drainages have dense vegetation on the north-facing slopes and much less on south-facing slopes. In addition, the vegetated north-facing slopes appear to host smaller landslides, whereas larger landslides are typically mapped on the less vegetated south-facing slopes. Some areas, such as near Arroyo Hondo, that appear to be densely vegetated on the north-facing slope also have landslides on both sides of the drainage. However, it appears that the south-facing slope has much larger landslides and more of its area mapped as landslides, whereas the north-facing slope has smaller and fewer landslides.

Vegetation influences not only the location of landslides, but also the type of landslides that occur in different locations. It appears that landslide areas within drainages occur on the south-facing, less vegetated hillslopes. In addition, these landslides are generally larger than those that occur in the more vegetated areas of drainages. Small landslides seem to be preferentially located on north-facing slopes.

Vertical Land-Surface Curvature

Curvature of the land-surface in profile influences landslide occurrence. Areas of concave curvature, or hollows, can trap surface water runoff, leading to an unstable slope (Lanyon and Hall, 1983). In contrast, areas of convex curvature tend to shed water more quickly, are less likely to become saturated and are therefore more stable. Digital curvature data for the study area were derived from the 10-m USGS DEM of the SFBR. ARC/INFO defines curvature as the amount of vertical convexity or concavity of the land-surface, expressed as 1/100 z-units. In this case, the amount of vertical curvature is expressed for each 10-m x 10-m pixel. Negative curvature values indicate concave curvature, whereas positive curvature values indicate convex curvature. Curvature of +/- 0.5 indicates gently rolling hills, whereas a curvature of +/- 5.0 indicates very rugged terrain.

Figure 18 is a map showing the vertical land-surface curvature of the Milpitas and Calaveras Reservoir quadrangles. Curvature values range from -50 to 34, with 98.6 percent of the study area having a curvature value between –5 and 5. Analysis of curvature indicates that the majority of the study area has a curvature of zero, or no curvature at all, as analyzed in each 10-m x 10-m pixel. Additionally, 21 percent of the land-surface has a convex curvature, and 11 percent of the land-surface has a concave curvature. Land-surface curvature within the study area ranges from very subtle or nonexistent, such as on the Santa Clara Valley floor, to extreme values found within the drainages. The land-surface curvature within areas of mapped landslides reflects the general curvature distribution of the hillside areas. Thirty-seven percent of the area mapped as landslide is convex, whereas 25 percent is concave. The remaining 38 percent of landslide areas have low or negligible curvature.

An analysis of the percentage of landslide coverage at each one unit of curvature, as shown in Figure 19, indicates that there is a correlation between land-surface curvature and areas mapped as landslides. Figure 19 shows only those areas of curvature between -10 and +10 because this includes the majority of the study area (greater than 99.99%), and results in a graph that is much easier to interpret. It appears that concave land surfaces have a larger percentage of area mapped as landslides than convex land surfaces. This trend appears consistent throughout the range of curvature values, with those areas of concave curvature having approximately 10-15 percent more landslide coverage than those areas with convex curvature.

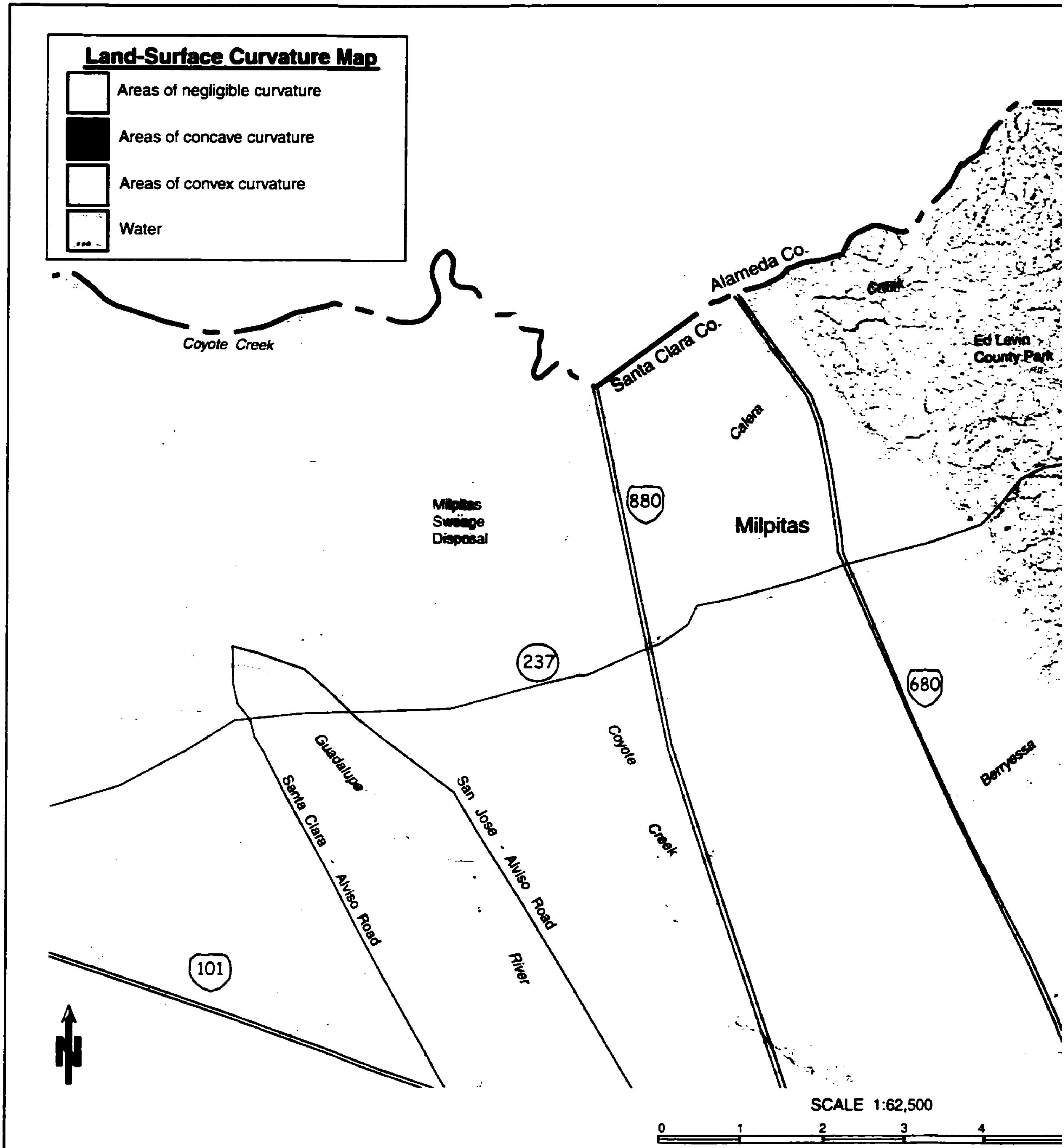
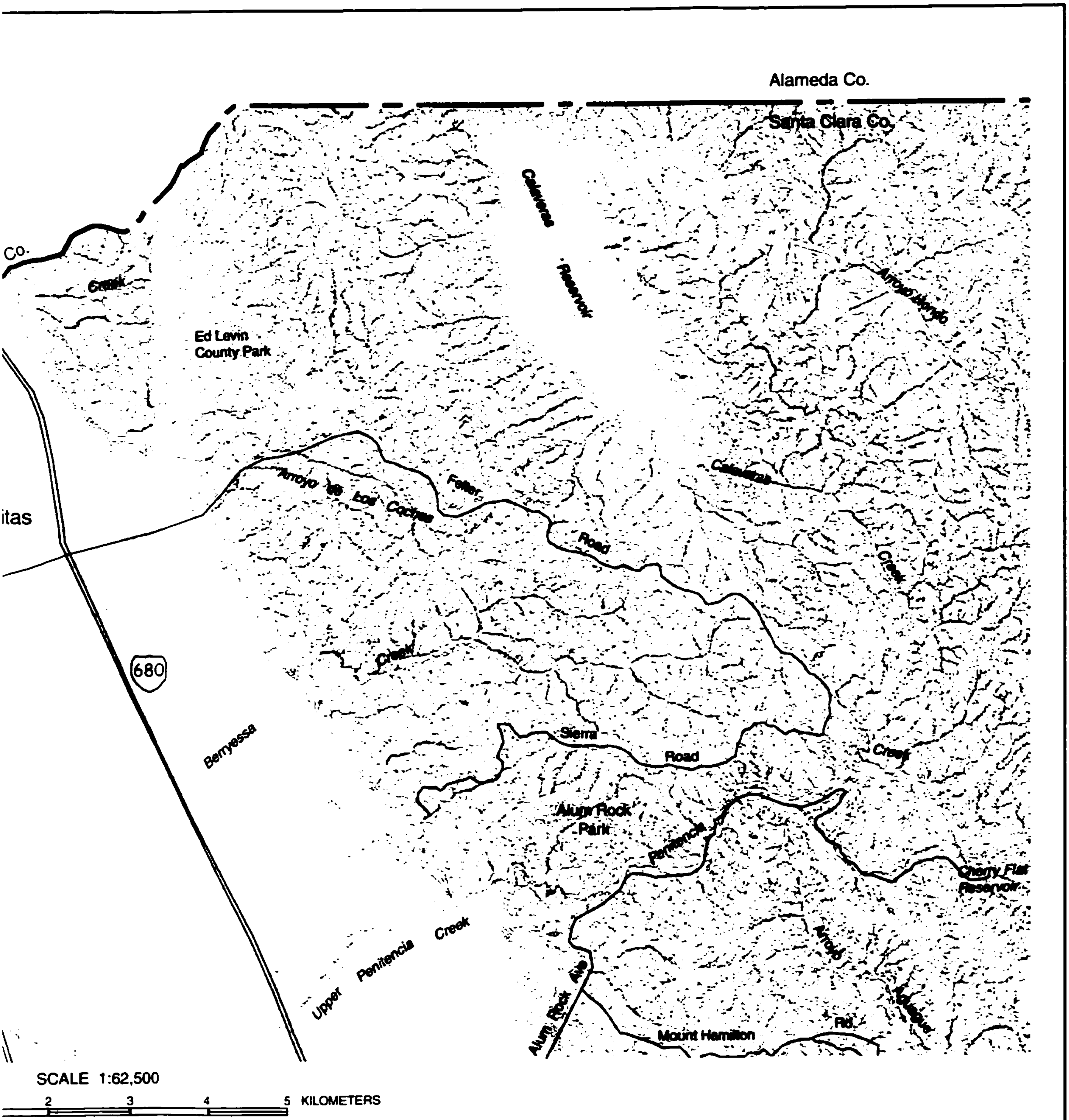


Figure 18. Vertical land-surface curvature of the study area. Very light yellow areas indicate negligible curvature Curvature data derived from USGS 10-m DEM of San Francisco Bay Region.



ıreas indicate negligible curvature. Orange areas indicate concave curvature and yellow areas indicate convex curvature.

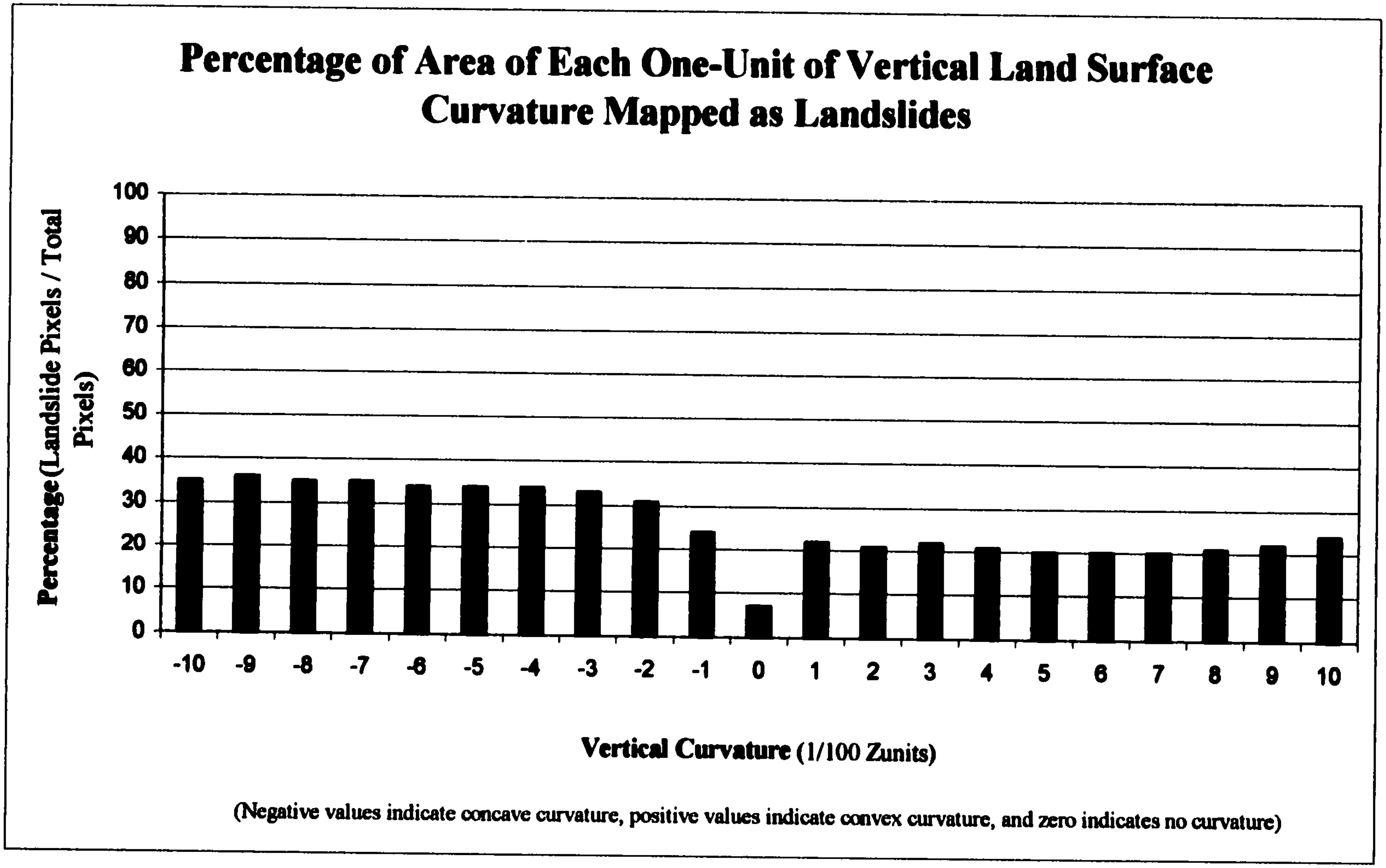


Figure 19. Percentage of area of each one-unit of surface curvature that is mapped as landslides. Curvature data derived from USGS 10-m DEM and landslide data from Nilsen (1975a&b).

There is no indication, however, that as the concavity of the land-surface increases, the percentage of area covered by landslides increases. Nor is there any indication that as the convexity of land-surface increases the percentage of area covered by landslides decreases. The data support the fact that concave areas have a higher percentage of area mapped as landslides than convex areas and that areas of concave land-surface curvature are substantially more susceptible to landsliding than those of convex curvature.

Elevation

Figure 20 shows the elevation distribution within the study area by subdividing the area into increments of 150-m above sea level. Much of the area lies below 100-m. Overall elevation ranges from 0-m in the northwest portion at the San Francisco Bay to 922-m on the eastern edge of the study area. Figure 21 shows the percentage of area mapped as landslides at each one-meter of elevation. This graph shows a spike at low elevations, between 60 meters and 130 meters, indicating a relatively large percentage of landslides. These data mostly likely represent the range-front hillslopes located in the center of the study area, which are largely mapped as landslides. Figure 21 shows an irregularly undulating distribution of percentage of landslide coverage with elevation. In general, landslide coverage exceeds 30-35% on slopes with elevations greater than 270 meters. This decays suddenly at approximately 850 meters, indicating that not many landslides occur on the highest hilltops. No significant relation between elevation and landsliding can be determined from Figure 21, from which it appears that elevation does not have a notable influence on landsliding.

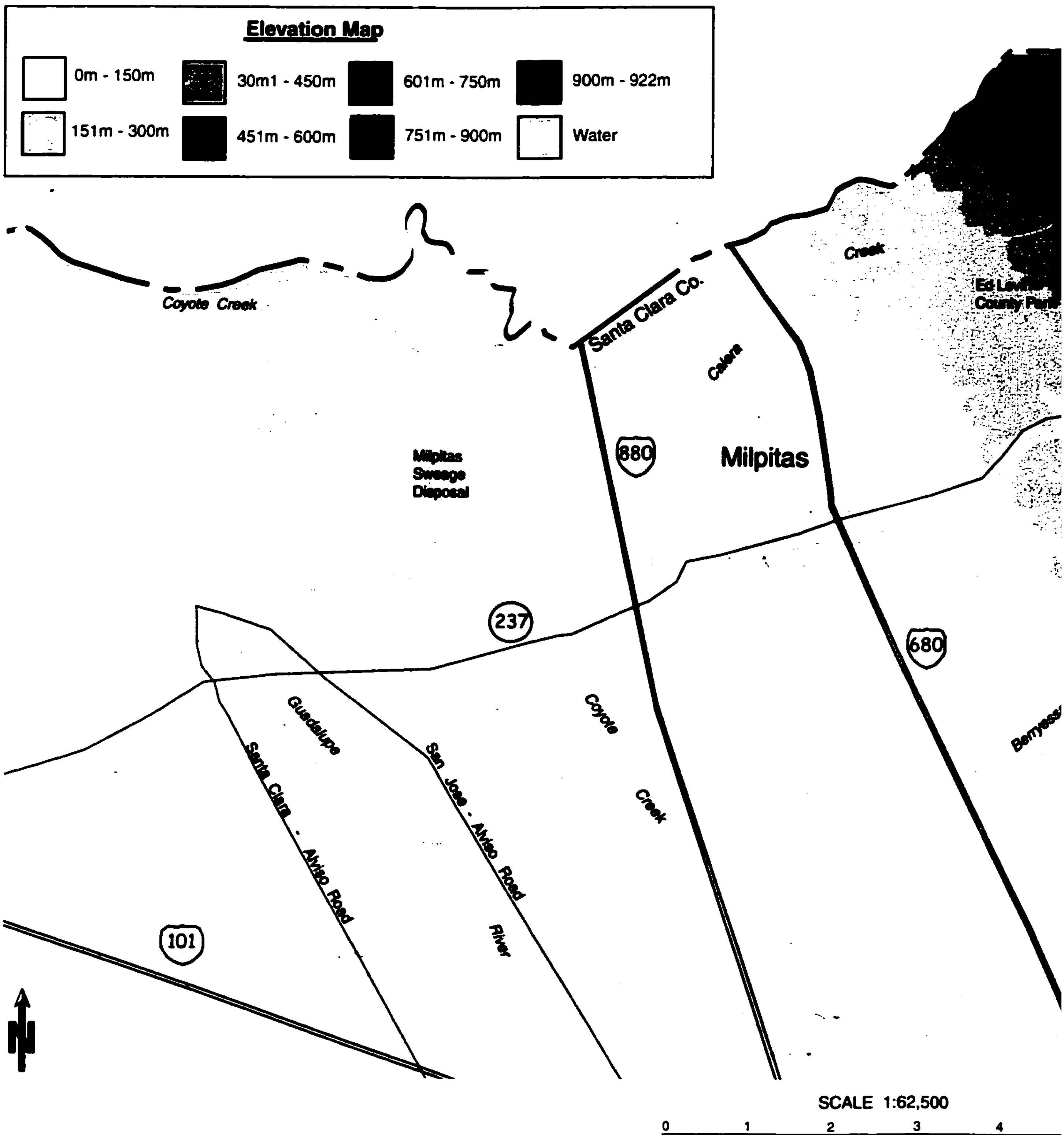
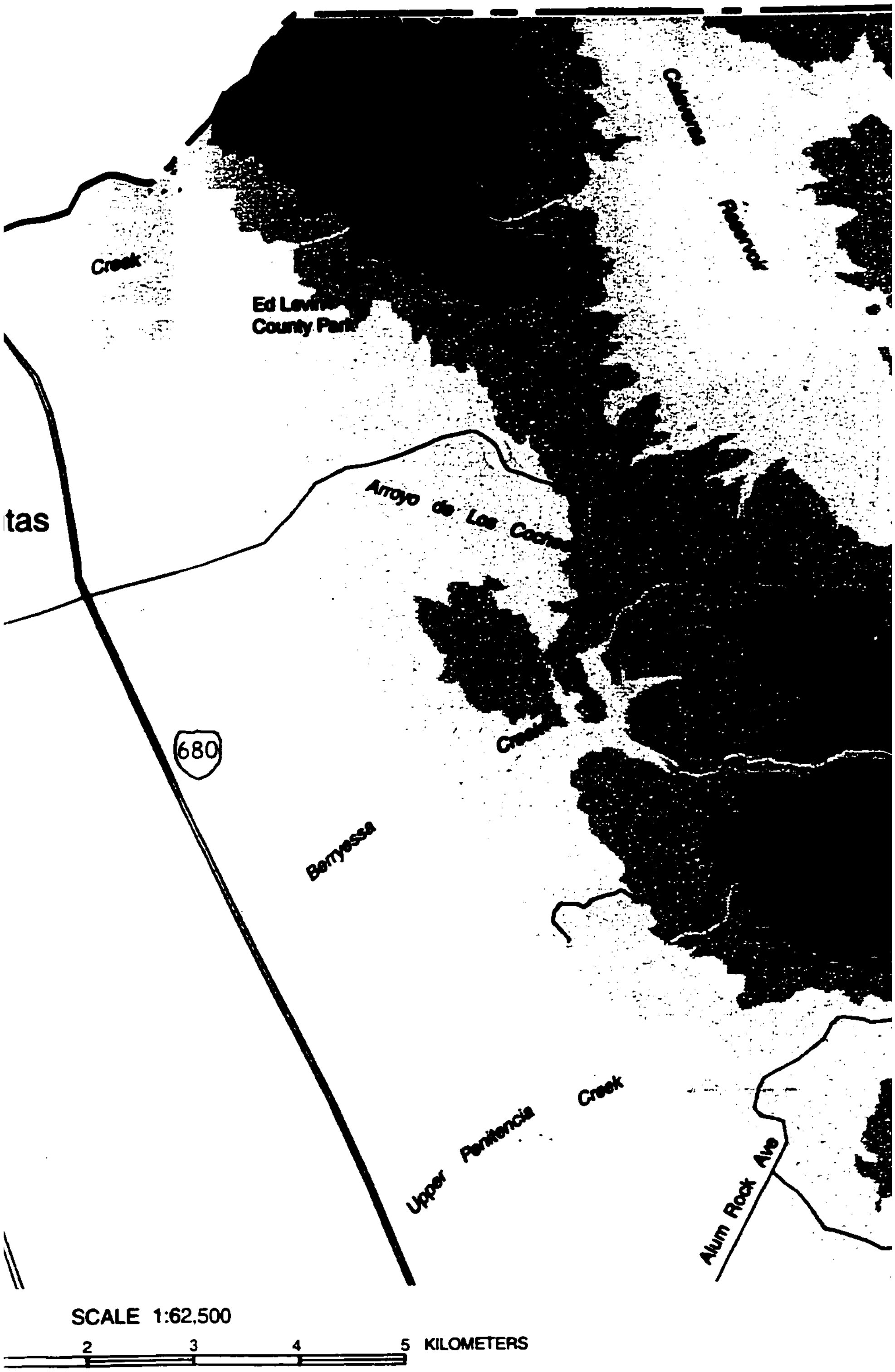


Figure 20. Elevation, shown in increments of 150 meters above sea level. Elevation data derived from USGS 10



ation data derived from USGS 10-m DEM of San Francisco Bay Region.

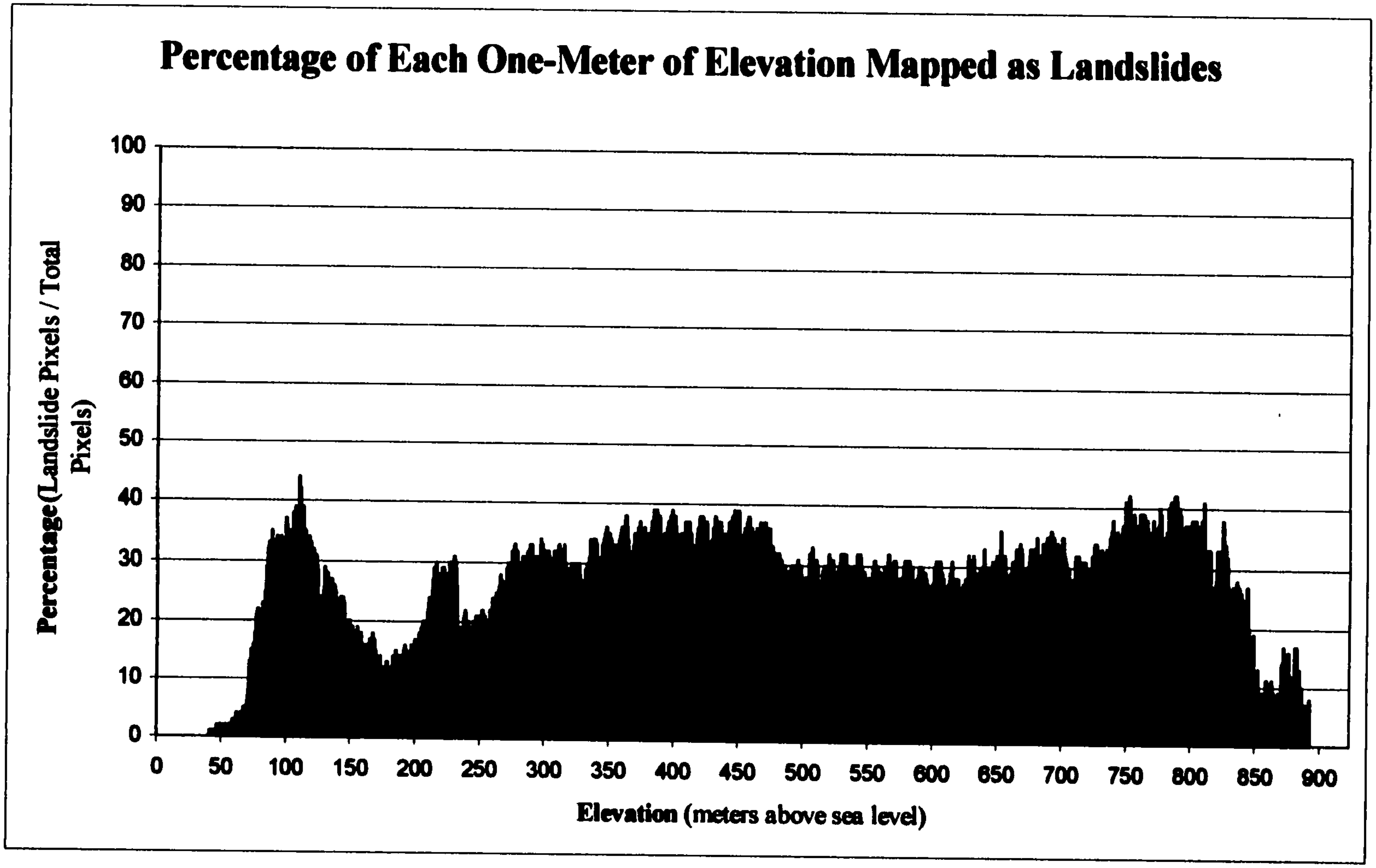


Figure 21. Percentage of area at each one-meter of elevation that is mapped as landslides. Elevation data derived from USGS 10-m DEM of the San Francisco Bay Region and landslide data from Nilsen (1975a&b).

Annual Precipitation

Precipitation commonly is regarded as a major slope-destabilizing factor (Bonilla, 1960; Radbruch, 1963; Cleveland, 1971; Nilsen and Turner, 1975; Nilsen and others, 1976; Nilsen and others, 1976; Nilsen and others, 1979; Cannon and others, 1998; and Miller and Sias, 1998). Often, landslide occurrence can be correlated with long duration or high intensity storms (Nilsen and others, 1976; Cannon and others, 1998). Although individual storm data were not available for this study, digital data on mean annual precipitation for the SFBR are available from the U.S. Geological Survey. These are from the maps of Rantz (1971), and are available only at 200-meter resolution, much lower resolution than any other data in this study. Still, they indicate how annual precipitation varies across the two quadrangles.

Mean annual precipitation increases from west to east, ranging from approximately 35.6 cm (14 in) per year in the northeastern Santa Clara Valley, to about 63.5 cm (25in) per year at the northeastern edge of the study area (Figure 22). The bands of annual precipitation trend in a northwest direction, subparallel to the structural ridges within the study area.

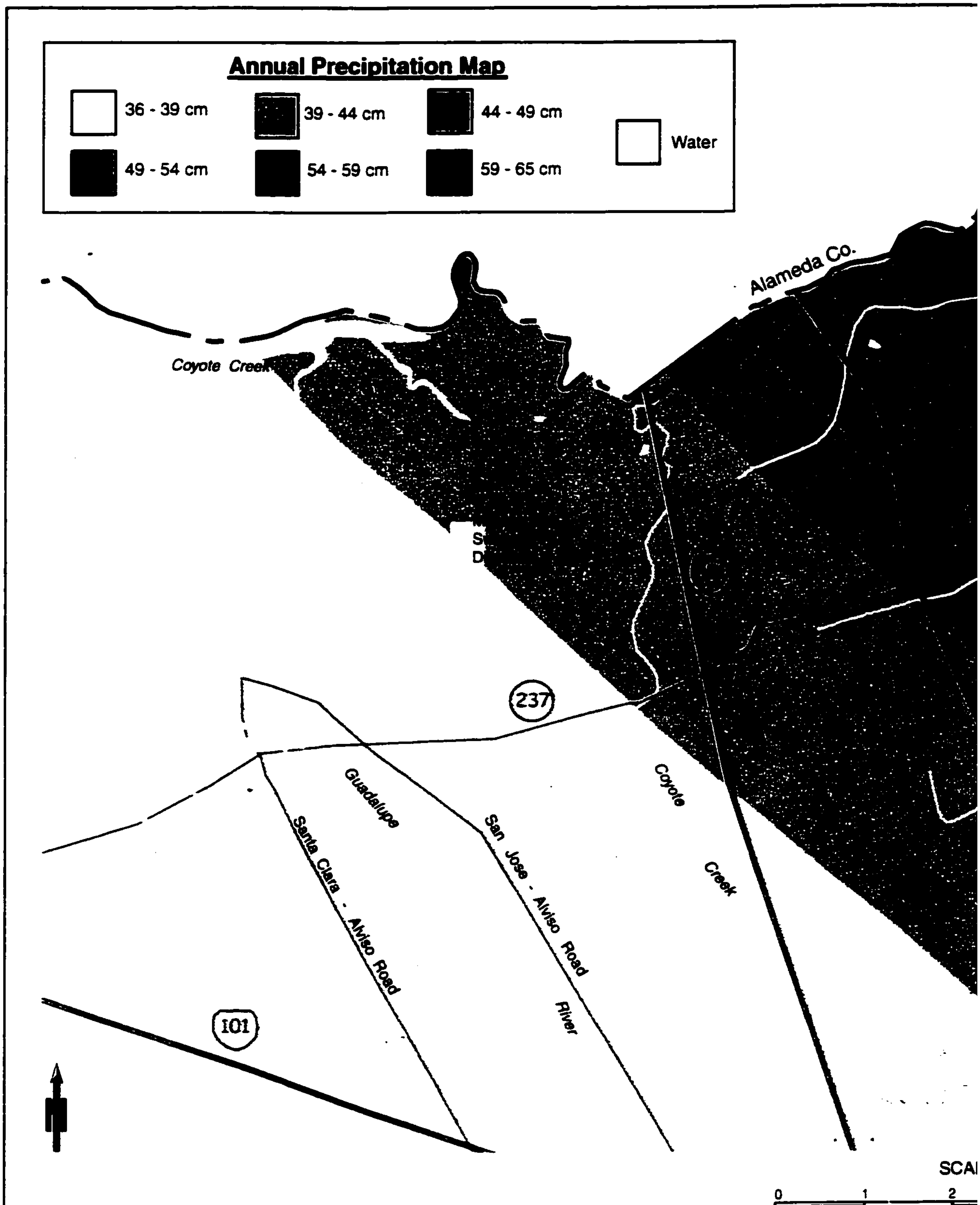


Figure 22. Annual precipitation, based on Rantz (1971). Annual precipitation data was recorded

:a was recorded in inches per year.

Landslides are mapped in the area where annual precipitation is greater than 40.6 cm/yr (16 in/yr); areas that receive less than 43.2 cm/yr (17 in/yr) are located on the Santa Clara Valley floor. Therefore, 43.2 cm/yr (17 in/yr) is not the threshold precipitation value for landslide occurrence, but rather landslides are not common in areas which receive less than 43.2 cm/yr (17 in/yr) of precipitation because these are also areas with very gentle slopes and little relief. Figure 23 is a graph of the percentage of area mapped as landslides within each 2.6 cm (1 in) range of annual precipitation. This graph shows that as annual precipitation increases across the study area, the percentage of landslide coverage also increases. (Because insufficient data exist for areas that receive greater than or equal to 63.5 cm/yr (25 in/yr) data for this region of the study area were not included in this analysis.) However, a comparison of Figure 2 with Figure 22 indicates that landslide coverage does not increase as steadily west to east across the study area as the amount of annual precipitation. There does appear to be an increase in the abundance of landslides from west to east in the southern portion of the study area, but not in the northern or central portions. Therefore the precipitation analysis suggests that, as determined from the available data, precipitation has a minor influence on landslide location and occurrence.

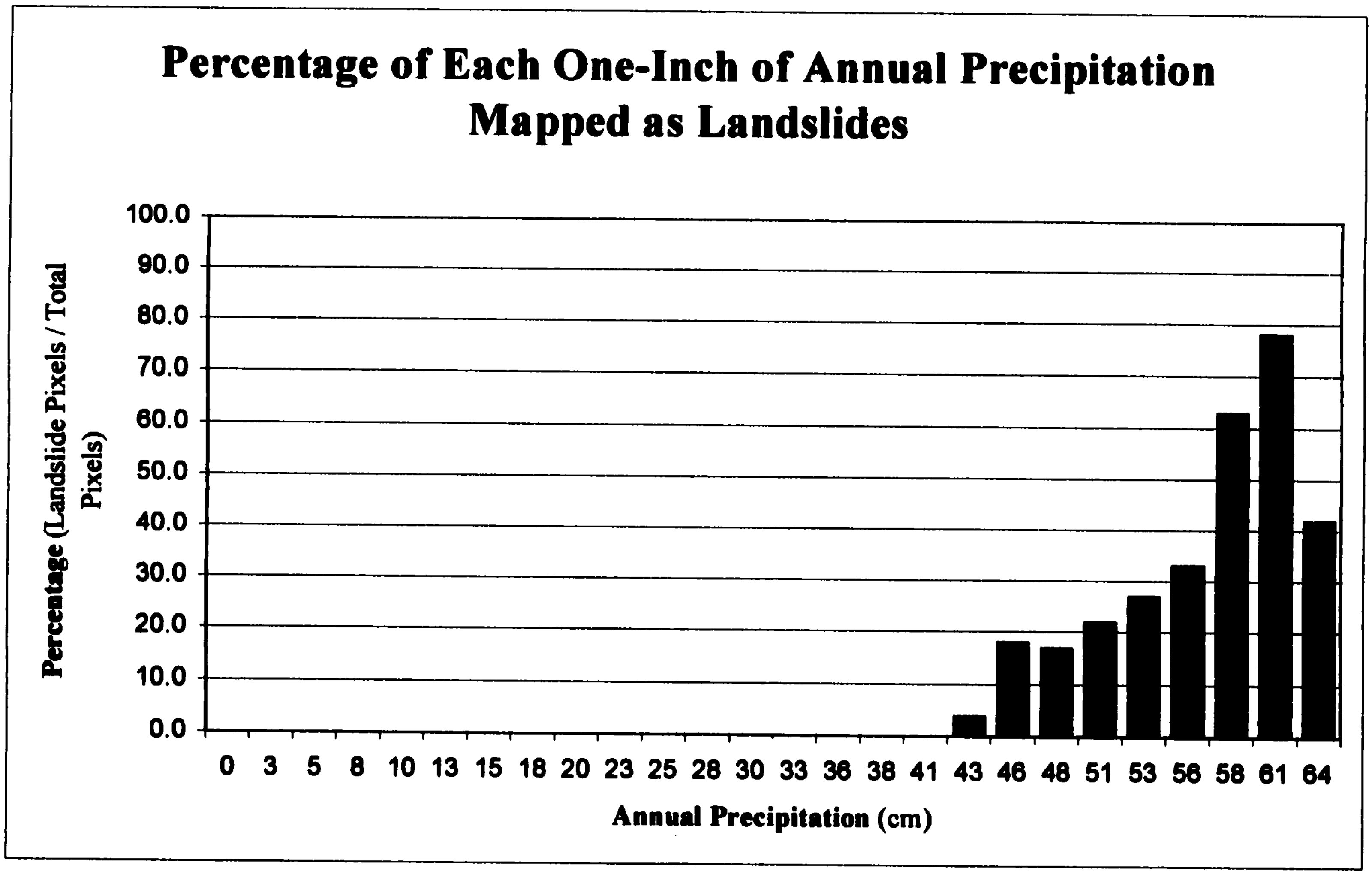


Figure 23. Percentage of area of each one-interval of annual precipitation that is mapped as landslides. Precipitation data derived from Rantz (1971) and landslide data derived from Nilsen (1975a&b). Original precipitation data was recorded in inches per year.

Geotechnical Investigation

Geotechnical data often are used in slope stability calculations for individual landslides (Miller and Sias, 1998). They are also used at smaller, regional scales, in which case generalizations are often made with respect to shear strength values (phi and cohesion values) in order to include them in a slope stability model (Miller, 1995; Jibson, and others, 1998; and Sitar and Khazai, 1999). Within the study area, data such as shear strength are available for locations which have been developed and where geotechnical investigations have been conducted. These locations cover only a small portion of the study area, primarily on the range-front hills and the valley floor. Upon investigation at the City of San José and the County of Santa Clara geologists' offices, geotechnical data for only a small percentage of the lithologic units within the study area could be compiled and a complete dataset could not be created.

Another way to include geotechnical data into an intermediate-scale study is to devise general classifications of shear strength based on properties and characteristics of the individual lithologic units. Jibson and others (1998) assigned phi and cohesion values to a variety of lithologies, ranging from Quaternary deposits to silts and shales to basalt to conglomerate. These values were based on direct shear tests from samples taken within many of the units, in addition to the input of experienced professionals and consultants who had worked within the study area. However, because the analysis used by Jibson and others (1998), relied heavily on slope, geotechnical data played only a minor role in the calculation of seismically induced landslides. A similar method of data compilation and extrapolation could have been used in the Milpitas and Calaveras Reservoir quadrangles, but was decided against in order to minimize the amount of error involved. Phi and cohesion values can vary widely within a unit, and shear strength data for all of the units could not be obtained. Although the author realizes the importance of geotechnical properties of soil and their influence on slope stability, there was no accurate way to include these data into the study. Therefore, the only geotechnical data utilized in this study are that of bedrock and soil mantle expansivity interpreted by the USGS from Ellen and Wentworth (1995).

Conclusions

From the above analyses, it is evident that some factors correlate strongly with areas of mapped landslides, whereas others show only a very weak correlation. Table 2 shows the factors that were analyzed in this study, and their relative influence on landsliding. The two factors that seem to correlate most strongly with mapped landslides are lithology and degree of slope. Some lithologic units are much more susceptible to landsliding than others. In addition to lithology, degree of slope appears to be a major influence on landslide occurrence. Although it was determined that slope does not correlate directly with landslide coverage over the entire study area, it correlates strongly with landslide occurrence within individual lithologic units. Therefore, it can be concluded that slope is strongly linked to lithology in this area.

Table 2. Table showing factors analyzed and their relative influence on landsliding within the study area.

Landslide Influencing Factor	Relative Influence on Landsliding within Study Area
Degree of Slope	Strong
Lithology	Strong
Bedding-dip direction and topographic slope orientation	Weak
Bedrock Expansivity	Weak
Soil Expansivity	Weak
Hillslope Aspect	Moderate
Vegetation	Moderate to Strong
Vertical Land-Surface Curvature	Moderate
Elevation	Weak
Precipitation	Weak

Two other factors that exhibit a moderate correlation with landslide occurrence and location are hillslope aspect and land surface curvature. Although these two factors do not appear to have as great an influence on landslide occurrence as lithology and slope, they are consistent in their correlations with landslide areas, and should be considered landslide-influencing factors. In general, slopes with aspects of northeast and south to southwest, and concave land surfaces both tend slightly toward instability.

Although vegetation data in digital form are not available for the study area, a qualitative analysis of vegetation and mapped landslides concluded that vegetation does influence landslide occurrence. Vegetated north-facing slopes do not appear as susceptible to landsliding as less vegetated south-facing slopes. Vegetation therefore appears closely related to hillslope aspect, and the results of the vegetation analysis are similar to those of the hillslope aspect analysis. It can be concluded that the influence of vegetation on landsliding is reflected in the correlation of hillslope aspect and landslide occurrence; that southwest aspects are the most susceptible to landsliding and are the most unstable. Therefore, for the purposes of this study, further use of hillslope aspect data and any correlation of these data with landsliding will represent vegetation data as well.

The results of these analyses provide additional insight into which factors control hillslope stability within the study area. The aforementioned four factors, lithology, slope, hillslope aspect, and land-surface curvature are those which appear to be most influential in landslide occurrence. These four factors, therefore, provide the basis for preparing the Relative Hillslope Stability Map discussed in detail in the next section, entitled *The Hillslope Stability Map.*

THE HILLSLOPE STABILITY MAP

Many different types of landslide hazard maps have been created for varying terrains, using a variety of methods. Methods such as the MATRIX method (Cross, 1998; Fernandez and others, 1999) exclude author subjectivity in making the hazard map. Others, such as bivariate statistical analysis, (van Westen, 1997) are based upon an author-created ranking system, composed of factors which commonly tend toward slope instability. The landslide map devised here is based on analysis of the digital data available for the study area. The results and conclusions of the analysis provide the basis of the system developed to rank factors according to their influence on slope stability. This system was developed to create a map that indicates the relative slope stability of the study area. This map is based completely on the conclusions of the data analysis and includes only those factors determined to correlate moderately to strongly with locations of previously mapped landslides. This map does not indicate precise locations of future landslides. Nor does it offer any temporal constraints on landslide occurrence. Rather, it suggests which hillslopes are less stable than others, and indirectly, the general areas in which future landsliding is probable. It is based on locations of past landslides, and conditions at these locations which influenced the stability of the slope before failure occurred. Therefore, this map should be used to determine relative slope stability, not the exact location of future landslides.

Method

The ARC/INFO analysis of landslide-influencing factors determined that the stability of the hillslopes within the study area is most influenced by lithology, degree of slope, hillslope aspect, and land-surface curvature. The Relative Hillslope Stability Map was constructed to indicate locations of hillslopes with different combinations of landslide inducing factors and therefore different relative degrees of stability.

The method devised for creating the Relative Hillslope Stability Map was determined from the conclusions of the ARC/INFO analysis. This method involved ranking the four factors: lithology, slope, hillslope aspect, and land-surface curvature, according to their influence on slope stability. Because this map indicates relative slope stability, the numbers assigned in this ranking system are only relative indications of influence, with higher numbers indicating greater instability. For example, if a particular lithologic unit has a relative susceptibility ranking of 5 and another unit has a relative susceptibility ranking of 20, the unit ranked as 20 is not necessarily 4 times more unstable than that ranked as 5. The ranking system is only intended to produce a wide range of stability values.

Lithology

According to the practice of Brabb and others (1972), lithologic units were grouped into categories of relative instability based on the percentage of landslides mapped within the unit (Fig. 24). This grouping is based on the assumption that those units that have the most landslides are less stable and will continue to be unstable into the future. The four rankings of lithology for the Relative Hillslope Stability Map were 5, 20, 40, and 60, and these relative stability rankings were assigned in the following manner:

1) Units in which mapped landslides occupy less than 1 percent of the unit's area received a stability ranking of 5.
2) Units in which mapped landslides occupy between 1 percent and 20 percent of the unit's area received a stability ranking of 20.
3) Units in which mapped landslides occupy between 21 percent and 40 percent of the unit's area received a stability ranking of 40.
4) Units in which mapped landslides occupy greater than 40 percent of the unit's area received a stability ranking of 60.
5) Water received a relative stability ranking of 0.

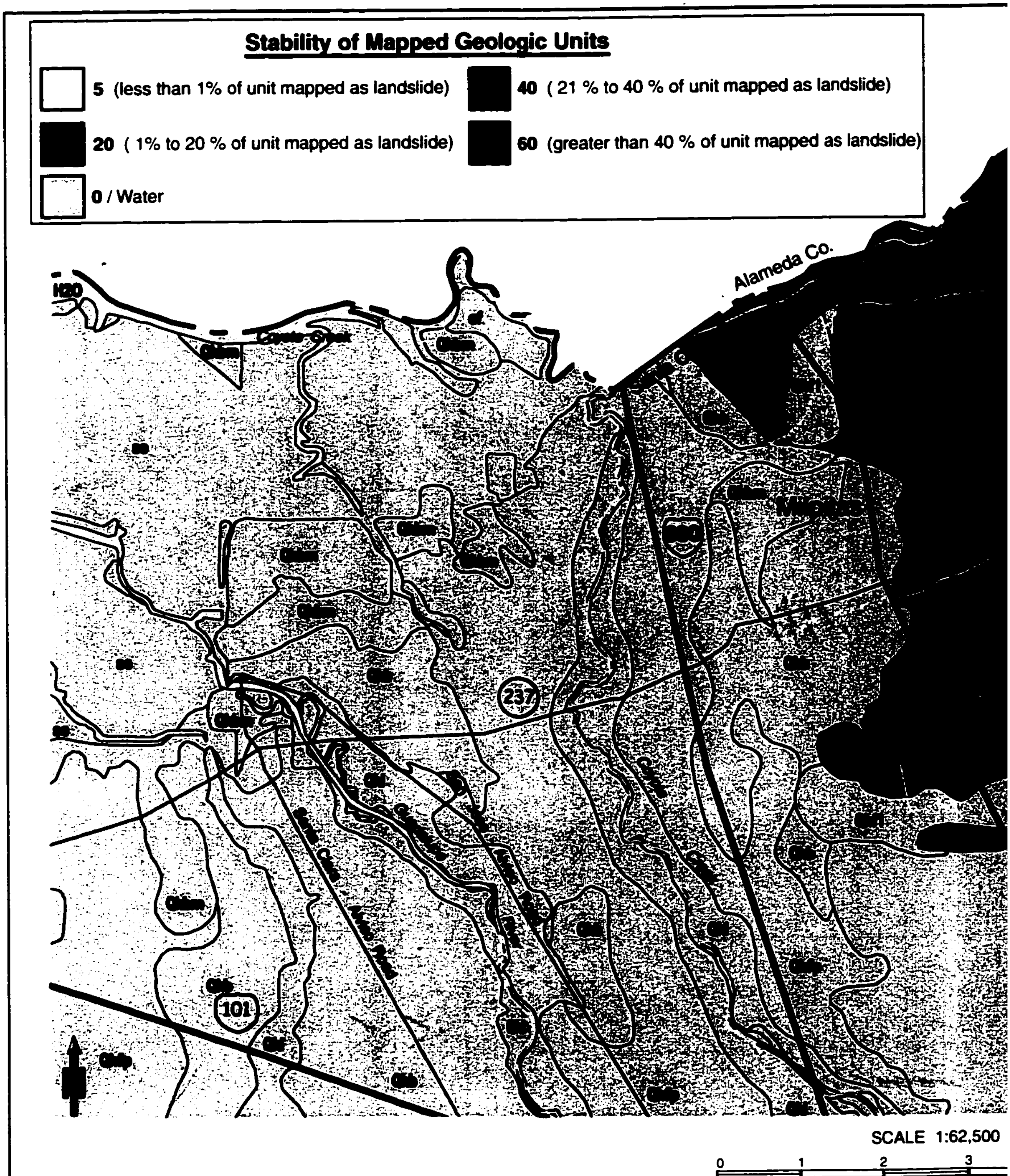
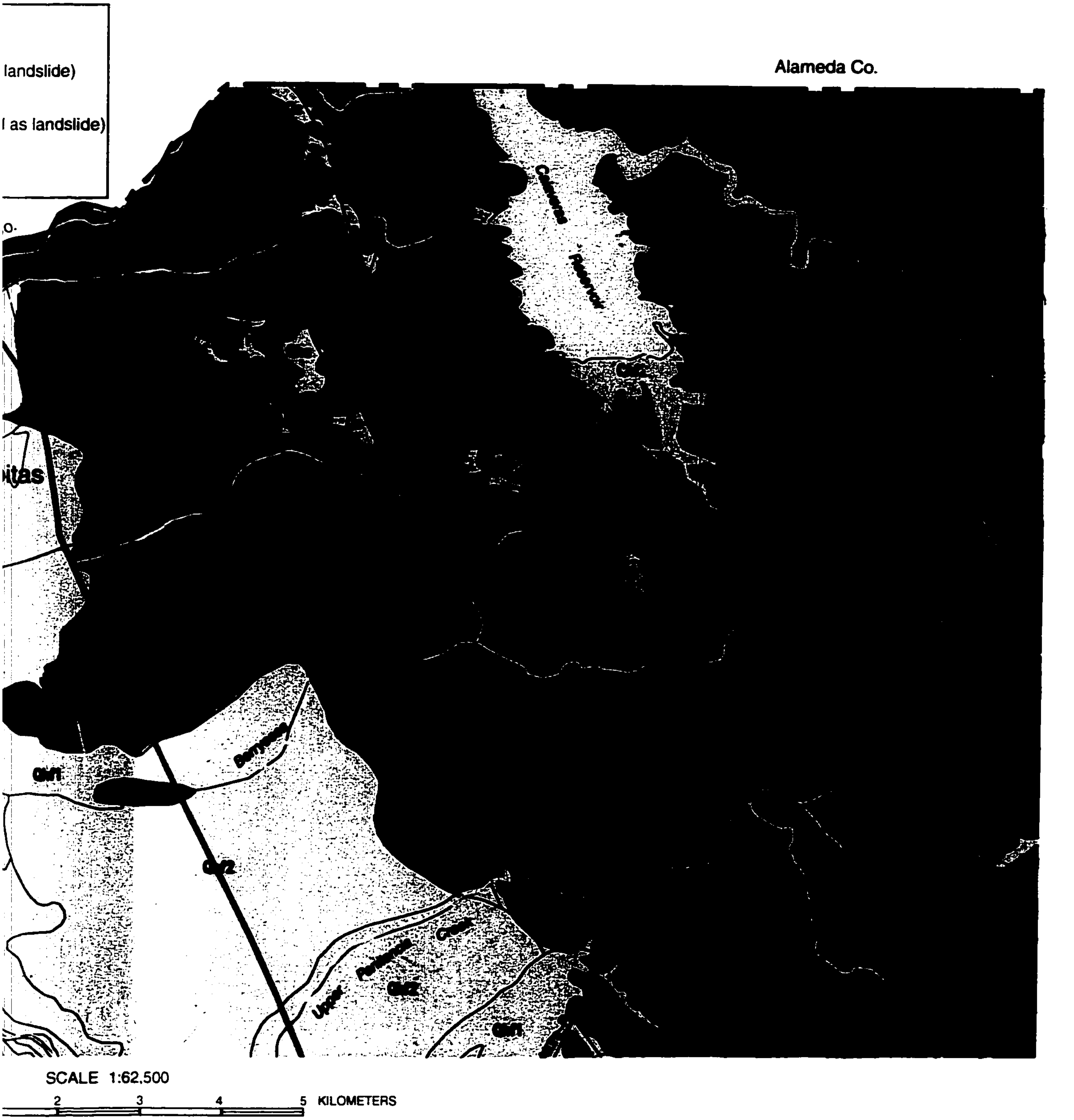


Figure 24. Relative stability ranking of mapped geologic units, as used in the relative stability analysis. Geologic data derived from Wentworth and others (1998), and landslide data derived from Nilsen, (1975a&



ve stability analysis. Bedrock stability rankings are based on the percentage of each unit that is mapped as landslides. om Nilsen, (1975a&b). See Figure 4 for a description of map units.

24. Stability of Mapped Geologic Units

Degree of Slope

The analysis determined that degree of slope is not an independent variable that can be independently categorized into relative stability values. Therefore, a method that reflects slope steepness' dependence on lithology was developed in order to assign relative stability rankings to degrees of slope. Slopes were grouped into categories of relative stability based on the percentage of area at each one degree of slope within each lithologic unit that is made up of mapped landslides (Pike and others, 2001). The relative stability categories for slope are the same as those for lithology; 5, 20, 40 and 60. For each individual unit, the following slope categorizations were made:

1) Slopes that have less than 20 percent of their total area (within each lithologic unit) mapped as landslides received a relative stability ranking of 5.
2) Slopes that have between 20 percent and 39 percent of their total area (within each lithologic unit) mapped as landslides received a relative stability ranking of 20.
3) Slopes that have between 40 percent and 59 percent of their total area (within each lithologic unit) mapped as landslides received a relative stability ranking of 40.
4) Slopes that have greater than 59 percent of their total area (within each lithologic unit) mapped as landslides received a relative stability ranking of 60.

Hillslope Aspect

Hillslope aspect was determined to have a moderate correlation with mapped landslides. Southeast to southwest aspects have a larger percentage of their total area mapped as landslides than any other aspect. However, other aspects, such as northeast, also have a slightly higher percentage of landslide coverage as well. In order to reflect the complex relationship between hillslope aspect and landslide coverage, as seen in Figure 17, the following ranking system was developed:

1) Aspects that have greater than 23 percent of their total area mapped as landslides received a relative susceptibility ranking of 10.
2) Aspects that have less than 24 percent of their total area mapped as landslides received a relative susceptibility ranking of 7.

These relatively low stability values reflect the lesser degree of influence that aspect has on landslide occurrence than either lithology or slope. In addition, the small amount of difference between areas ranked as 7 or as 10 limits the amount of influence that aspect has on the final values of the Relative Hillslope Stability Map. Figure 25 is a map of the study area showing aspects with a ranking of 10 and those with a ranking of 7.

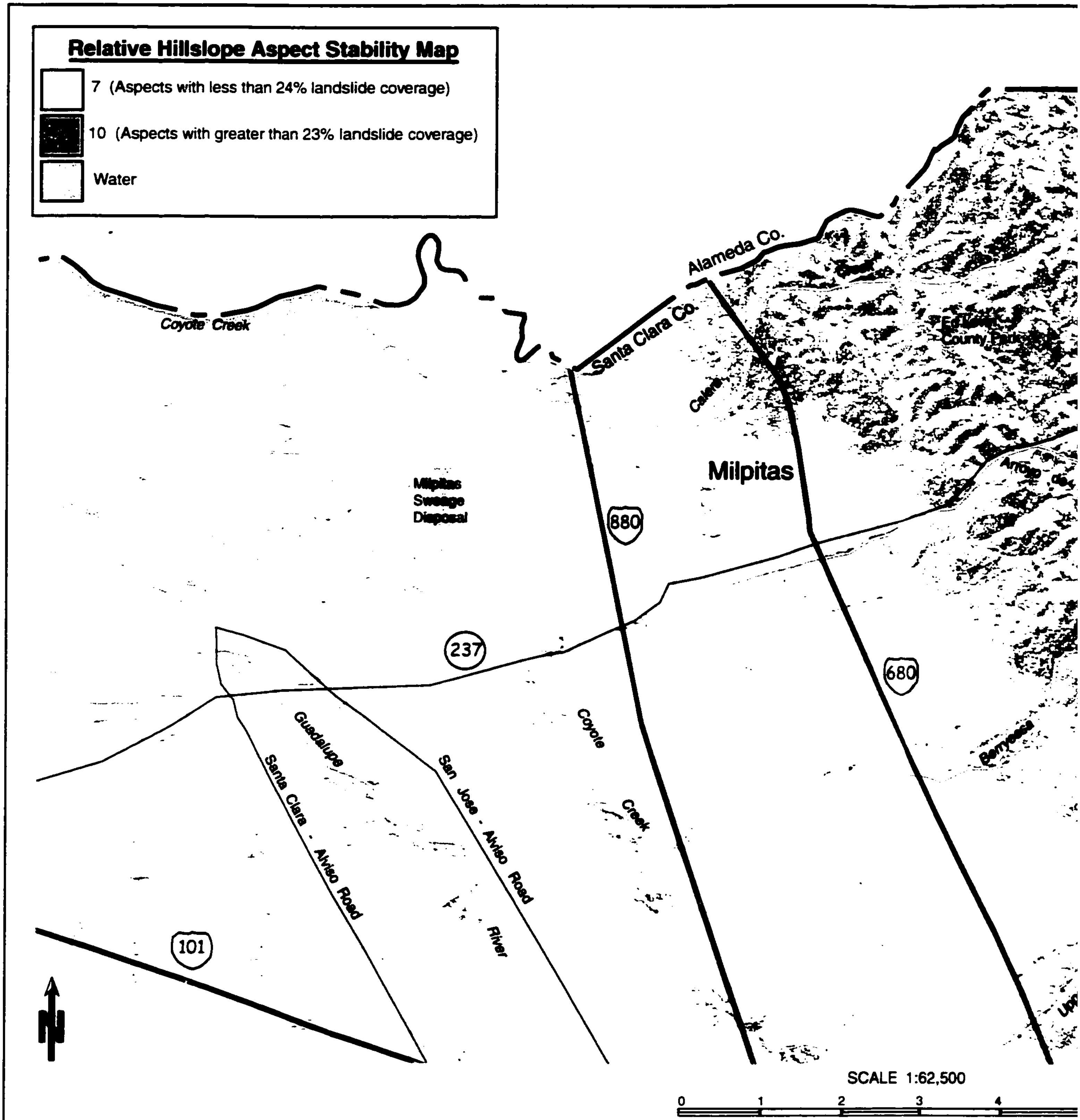
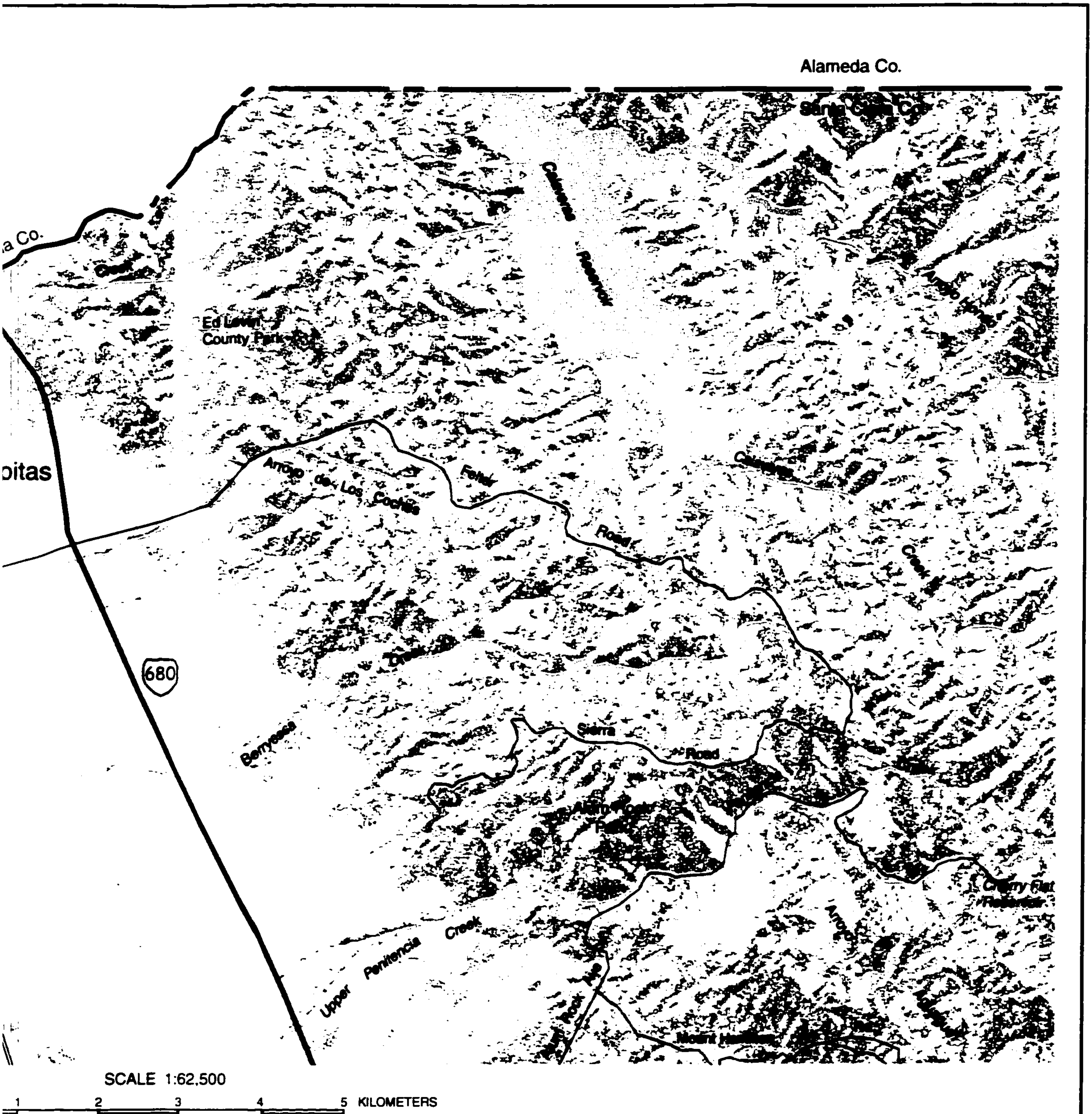


Figure 25. Aspect of study area, as ranked for relative susceptibility analysis. Yellow indicates aspects with less than 24% of their aspects with greater than 23% of their area mapped as landslides and a relative susceptibility ranking of 10.



ıdicates aspects with less than 24% of their area mapped as landslides and a relative susceptibility ranking of 7. Orange areas indicate
⁄ ranking of 10.

Vertical Land-Surface Curvature

Results of the landslide analysis concluded that areas of concave curvature have slightly more area mapped as landslides than areas of convex curvature or no curvature. Like hillslope aspect, land-surface curvature is not as influential on landslide occurrence and location as are slope and lithology. Therefore, in order to reflect the lesser influence of curvature on landslide occurrence, the following ranking system was developed:

1) Areas with concave curvature received a relative stability ranking of 10.
2) Areas with convex curvature or no curvature received a relative stability ranking of 7.

Figure 26 is a map showing concave areas, and convex and flat areas, as they are ranked for the creation of the Relative Hillslope Stability Map.

After the ranking system categorized the relative stability of the area according to lithology, slope, aspect, and curvature, the results of the individual rankings were created into grids. A grid was created for each of the four factors, in which each pixel in the grid had a relative stability value that was determined according to the method outlined above. These four grids were then combined into one final grid. The final grid contains 44 unique combinations of lithology, slope, aspect and curvature stability rankings. Accordingly, each pixel on the final grid had one of 44 possible values resulting from combinations of lithology, slope, aspect, and curvature.

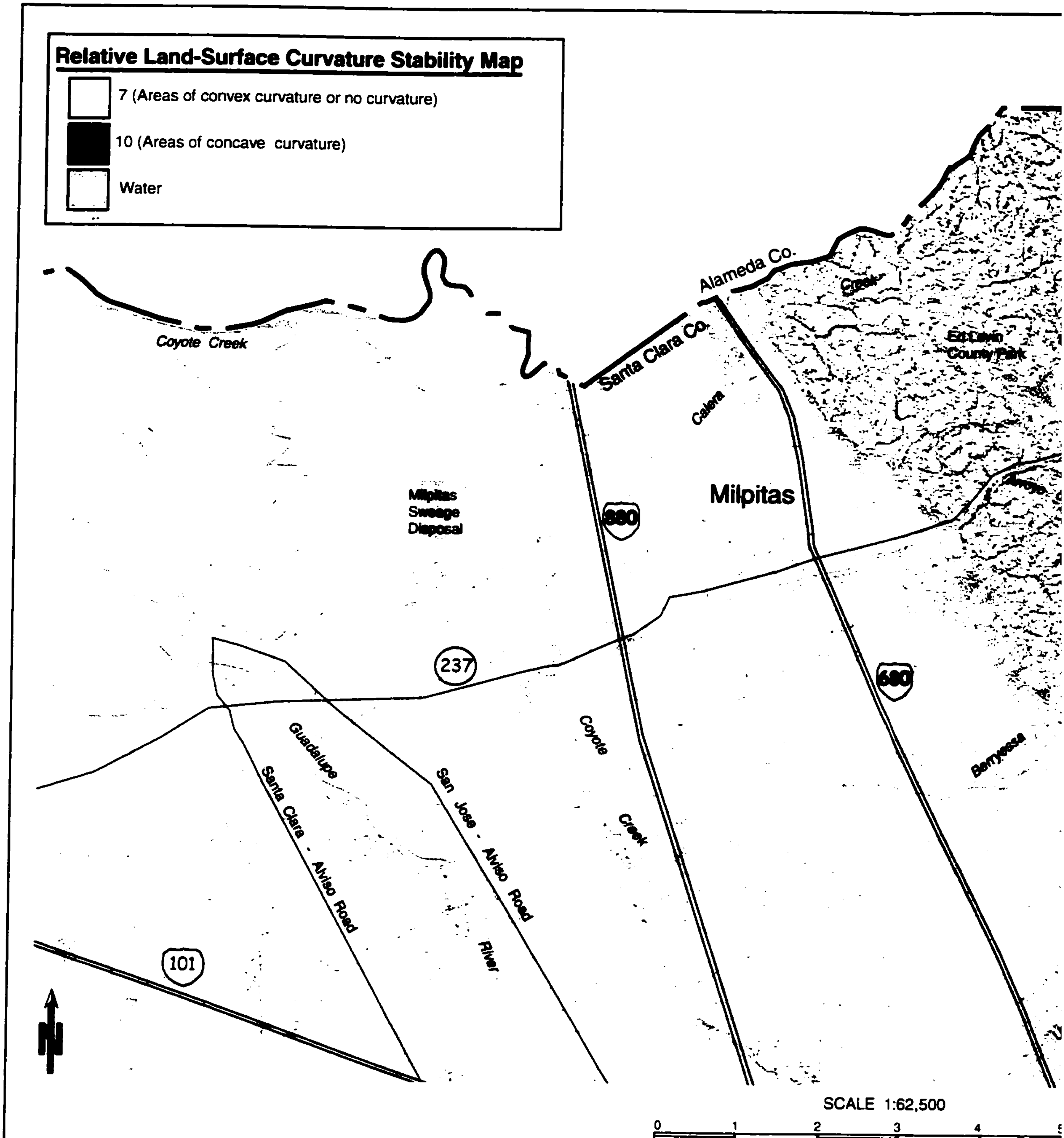
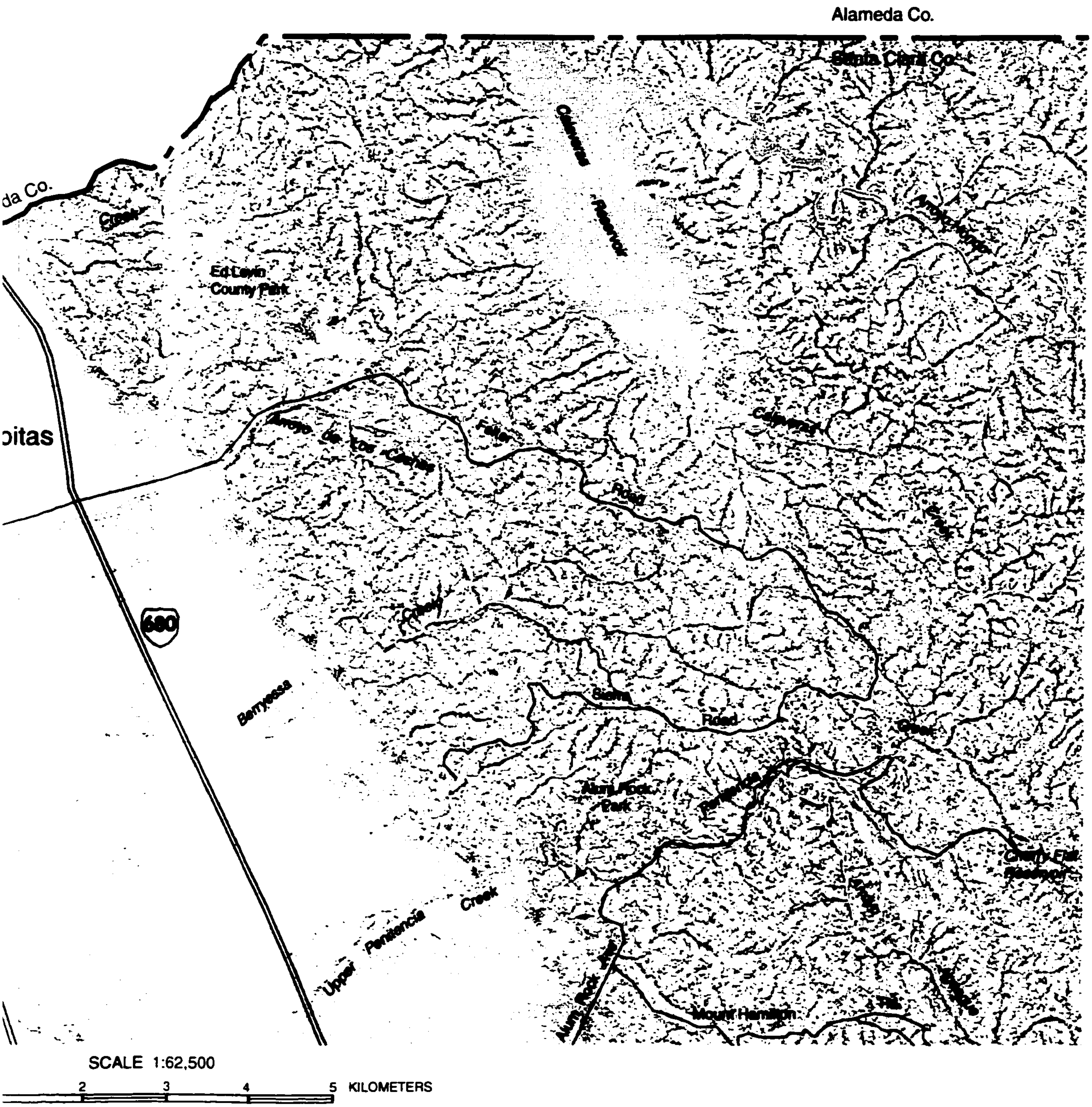


Figure 26. Vertical land surface curvature, as used in relative susceptibility analysis. Orange areas are concave areas with a relative stability ranking of 7. Curvature data derived from USGS 10-m DEM of the San Francisco Bay Area.



ılysis. Orange areas are concave areas with a relative stability ranking of 10. Yellow areas are either convex or flat areas
ꟽ of the San Francisco Bay Area.

For each pixel, the values of the lithology, slope, aspect, and curvature rankings were multiplied together to produce a final relative stability number, as shown in Table 3. These numbers range from 360,000, the value of the least stable areas, to zero, the value of the most stable areas.

Table 3 shows three examples of pixels with different final stability values, and how these values were obtained. For example, the first pixel has a lithology of fm, a 22 degree slope, an aspect of 206 degrees, and concave curvature. Forty-eight percent of the unit fm is mapped as landslides, so each pixel within this unit receives a stability ranking of 60 for lithology. Fifty-two percent of the area of fm with a slope of 22 degrees, the slope of this particular pixel, is mapped as landslides. This pixel therefore receives a stability ranking of 60 for slope. This pixel has an aspect of 206 degrees clockwise from north. Thirty-two percent of the total area in the study area with an aspect of 206 degrees is mapped as landslides. Therefore, this pixel receives a stability ranking of 10 for aspect. Finally, this pixel is concave and therefore receives a stability ranking of 10 for curvature. The final stability value of this particular pixel 360,000, or the most unstable value possible (60*60*10*10 = 360,000).

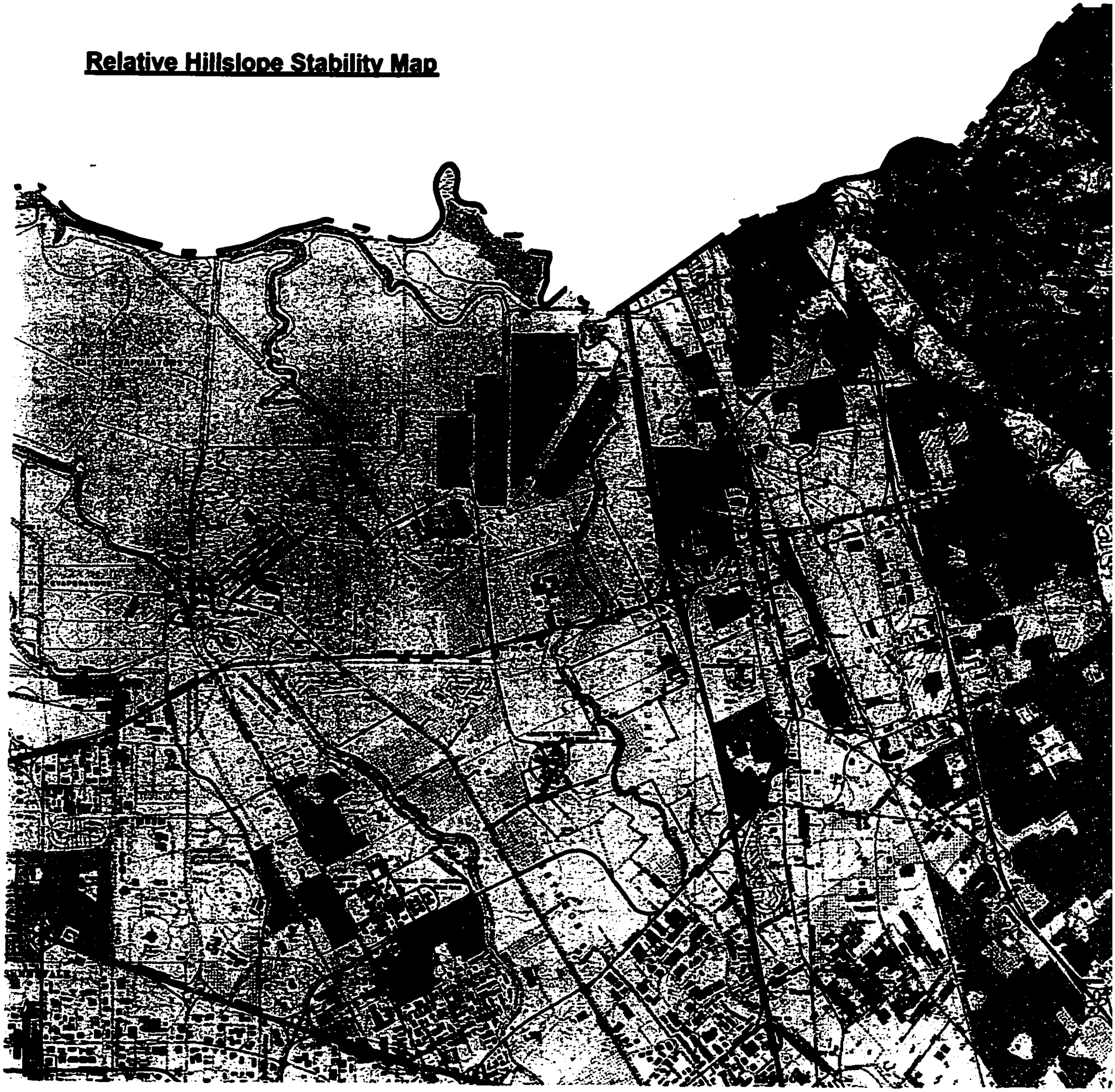
Table 3. Different combinations of stability-influencing factors, and the resulting final stability ranking.

Lithology	Slope	Aspect	Curvature	Multiplication	Final Value
Fm	22	206	Concave	60*60*10*10	360,000
Qhbm	1	8	Convex	5*5*7*7	1,225
H_2O	0	-1	Flat	0*-1*0	0

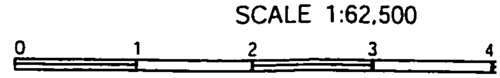
Table 3 shows two other examples of individual pixels and their corresponding final slope stability values. One pixel located within the lithologic unit Qhbm receives a final stability ranking of 1,225. Another pixel, located in an area of water, receives the most stable value possible, zero.

Forty-four unique final stability values resulted from the combination of the lithology, slope, aspect, and curvature grids. The 44 unique values of relative stability were grouped into 11 sets of relative stability, as are shown in Table 4. These groups range in stability value from zero (water) to 10 (most unstable). These eleven groups range in size from 334, 659 pixels (33.5 km^2) to 1237 pixels (0.1 km^2). As Table 4 shows, the groups of relative stability used in the Relative Hillslope Stability Map vary greatly in size, because the groupings are based on natural breaks in the distribution of the 44 final stability values. These 11 groups of relative stability are shown in Figure 27 as 11 different colors on the Relative Hillslope Stability Map.

Relative Hillslope Stability Map



SCALE 1:62,500



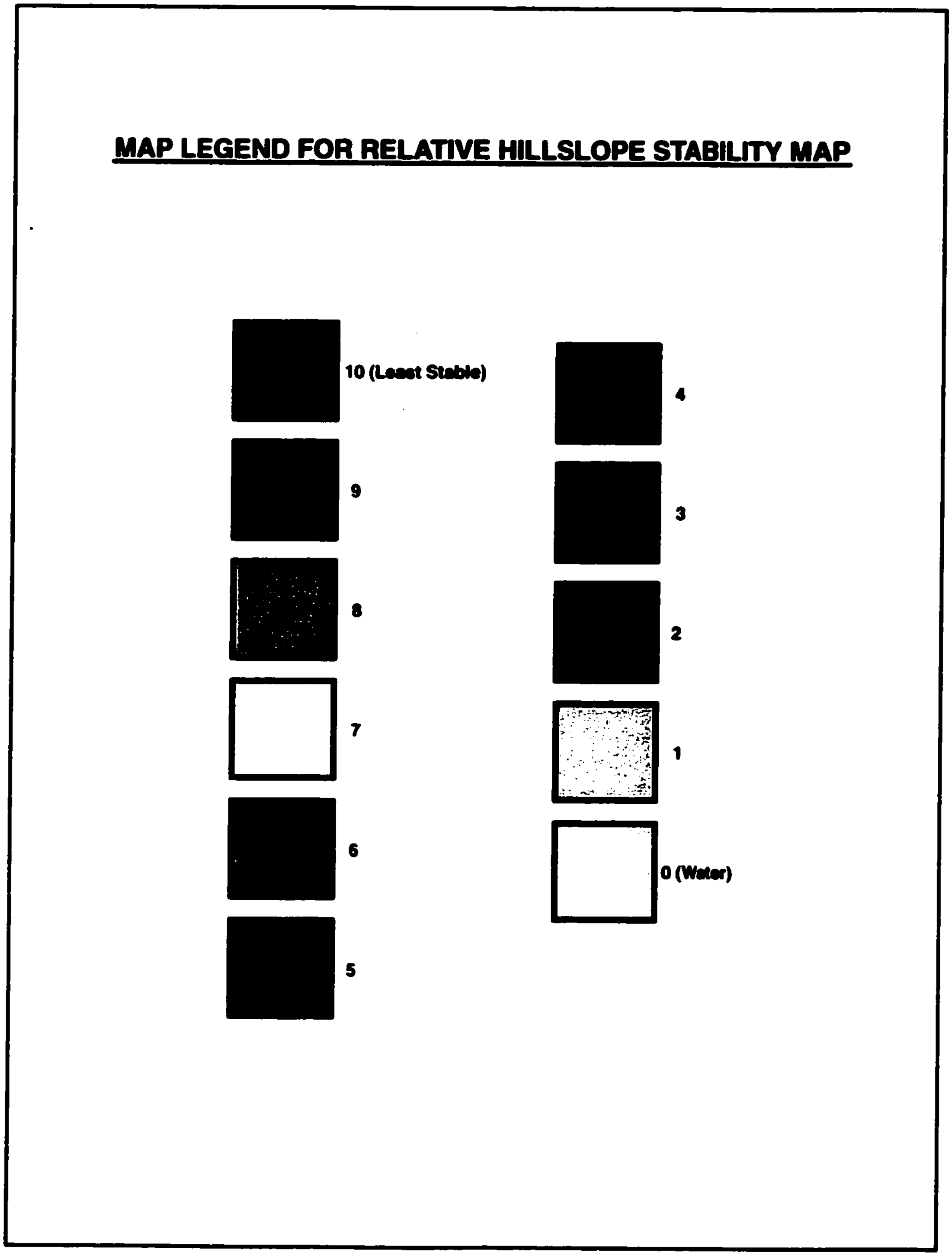


Figure 27B. Color-coded lengend to accompany Figure 27, Relative Hillslope Stability Map.

The colors range from cool, with blue representing the most stable areas, to hot, with red representing the least stable areas.

One final item of concern is how the location of previously mapped landslides should be presented on the Relative Hillslope Stability Map. Many stability models assign the highest instability ratings to areas which have failed, reasoning that areas which have slid in the past are most likely to slide again in the future (Van Horn, 1972; Brabb and others, 1972; Nilsen, 1979; Pike and others, 2001). Although this study does not automatically assign the highest instability ranking to areas of mapped landslides, it is based on the idea that areas which have slid in the past are inherently unstable. Thus, areas of mapped landslides are clearly outlined in black on the Relative Hillslope Stability Map.

Table 4. Forty-four unique values of stability were combined into 11 groups of stability rankings for use in the Relative Hillslope Stability Map.

Pixel Value	Number of Pixels	Lithology Slope	Aspect	Curvature	Final Value
Group 10	1,237	3,600	10	10	360,000
Group 9	4,011	3,600	10	7	252,000
	915	3,600	7	10	252,000
	29,345	2,400	10	10	240,000
Group 8	2,996	3,600	7	7	176,400
	10,7563	2,400	10	7	168,000
	32,236	2,400	7	10	168,000
	12,077	1,600	10	10	160,000
Group 7	2,367	1,200	10	10	120,000
	11,5289	2,400	7	7	117,600
	41,749	1,600	10	7	112,000
	15,098	1,600	7	10	112,000
Group 6	8,110	1,200	10	7	84,000
	2,889	1,200	7	10	84,000
	21,343	800	10	10	80,000
	48,849	1,600	7	7	78,400
Group 5	10,366	1,200	7	7	58,800
	75,675	800	10	7	56,000
	27,754	800	7	10	56,000
Group 4	18,290	400	10	10	40,000
	95,441	800	7	7	39,200
	293	300	10	10	30,000
	20,746	400	7	10	28,000
	61,895	400	10	7	28,000
Group 3	486	300	7	10	21,000
	1,027	300	10	7	21,000
	4,454	200	10	10	20,000
	71,257	400	7	7	19,600

Pixel Value	Number of Pixels	Lithology	Slope	Aspect	Curvature	Final Value
Group 2	2,315	300		7	7	14,700
	15,154	200		10	7	14,000
	6,619	200		7	10	14,000
	21,557	100		10	10	10,000
	23,467	200		7	7	9,800
	30,825	100		7	10	7,000
	84,666	100		10	7	7,000
Group 1	175,634	100		7	7	4,900
	7,893	25		10	10	2,500
	28,539	25		7	10	1,750
	47,832	25		10	7	1,750
	74,760	25		7	7	1,225
Group 0	66,811	0		7	7	0
	1,280	0		7	10	0
	1,009	0		10	7	0
	563	0		10	10	0
Total Pixels	1,422,682					

Comparison of Relative Hillslope Stability Map with Map of Recent Landslides

Coyle mapped the geology of the southern portion of the Calaveras Reservoir 7.5-minute topographic quadrangle in 1984. This map includes not only bedrock units, but surficial units such as landslides. Because Coyle's map was created almost 10 years after the Nilsen (1975a&b) maps, it provides a good indication of recent landslide movement within the area. Coyle's map, entitled *Bedrock and Surficial Geology of the José-Milpitas Foothills Area, Santa Clara County, California*, shows that many of the more recent landslides in the area are only a fraction of the size of those mapped by Nilsen (1975a&b) from aerial photographs. A qualitative comparison of the Relative Hillslope Stability Map with Coyle's map indicates that most of dormant, static, and active landslides mapped by Coyle are within groups 5-10 (the less stable areas) on the Relative Hillslope Stability Map. This supports the conclusion that the Relative Hillslope Stability Map is a good indication of which areas are unstable relative to others within the study area.

Limitations and Uses of Investigation and Relative Hillslope Stability Map

The method by which the relative stability map was created, as well as the scales of the maps place limitations on the use of this map. These are: 1) the usable scale of the map, and 2) the Relative Hillslope Stability Map as a relative indication of hillslope stability.

The scale of the Relative Hillslope Stability Map is 1:24,000. The original landslides were mapped from 1:20,000-scale aerial photographs onto a 1:24,000-scale base map. In addition, individual geologic maps were created at a scale of 1:24,000.

Other maps used in this analysis are at a much smaller scale, such as the 1:500,000-scale precipitation map (Rantz, 1971). Furthermore, at a scale of 1:24,000, the relative stability map is slightly pixelated, due to the 10-m resolution of the grids generated from the original maps. Therefore, the scale of the Relative Hillslope Stability Map is a significant consideration in applying this map. The highest accuracy of the map is most likely at a scale of approximately 1:30,000, where the map is not pixelated. In this study, the map is provided on paper at a scale of 1:62,500, and on a compact disk with which one can zoom in or out to any desired scale.

In addition to the limitations which scale imposes on the Relative Hillslope Stability Map, much emphasis must be placed on the fact that this map presents only a relative appraisal of hillslope stability. It is not designed as an absolute indication of unstable hillslopes or future landslide locations. The focus of this study was to analyze landslide-influencing factors with the help of an ARC/INFO GIS, and therefore the Relative Hillslope Stability Map is only a visual medium through which the conclusions of the analysis can be viewed. Any use of this map for development or land-use planning should be on a regional basis, and not on a parcel-by-parcel basis. The relative stability map should be used to indicate in which locations detailed site investigations are needed before any construction is considered.

Finally, as stated previously, there are 11 categories of relative stability indicated on the map. These stability rankings, from zero, having no chance of landsliding, to 10, the most relatively unstable areas, are not exact rankings. A ranking of 2 is not twice as stable as a ranking of 4; it is only more stable. These numbers provide only a relative scale of hillslope stability.

Sources and Amount of Error

Although ARC/INFO provides a very practical method of analyzing numerous landslide-influencing factors for this study, there are several potential sources of error which should be noted when considering the accuracy of the study: error resulting from the original photointerpretive landslide maps; and error resulting from converting coverages to grids in ARC/INFO.

The original 1:24,000 scale maps of landslides and other surficial deposits were mapped from aerial photographs of 1:20,000 scale. In the course of the Nilsen (1975a&b) studies, landslides smaller than 61 meters (200 ft) in a dimension were not mapped. Therefore, many small landslides have been left outside of the scope of this study. An analysis of a more recent map of the area (Coyle, 1984) determined that many small landslides (from 30.5 to 61 meters (100-200 feet) in a dimension) are present within the study area. Although Coyle's map (1984) shows numerous active, dormant, and static landslides (more than 100) mapped within the study area, these do not account for a significant amount of area when compared to the study area as a whole.

The second source of error in this study results from converting coverages to grids in ARC/INFO. In the conversion process from a coverage to a grid, some amount of data accuracy is lost, because smooth edges of polygons are divided up into 10m x 10m pixels or cells. A pixel that falls within two or more different polygons is assigned the value of the polygon that makes up the greatest area of the pixel. In any case where a pixel falls within different polygons, some amount of information is lost. This conversion process can result in a wide range of error, varying from pixel to pixel, and therefore from grid to grid. For Example, if 99 percent of one pixel falls on a polygon with a value of fm, and only 1 percent of the pixel falls on a polygon with a value of sp, the value of the entire pixel is designated as fm. In this case, the amount of error resulting from the conversion process is one percent. However, if one pixel covers portions of multiple polygons, and the polygon with the greatest amount of area within the pixel only makes up 20 percent of the area of the pixel, the entire area of the pixel is assigned that value. In this case, the resulting error is 80 percent.

It is very difficult to quantify how much error this might account for within this study, because the amount of resolution loss in the conversion process varies from grid to grid. However, the following general conclusions can be made about the amount of error that this process could introduce into this study: first, the maximum amount of resolution that can be lost in this conversion process is 49 percent. However, a 49 percent error would require that every single pixel in the grid falls within two different polygons, where one polygon makes up 51 percent of the pixel, and the other makes up 49 percent. This, however, is very unlikely, because the majority of the maps included in this study are composed of very large polygons, meaning that 100 percent of most pixels are composed of 1 polygon type and result in no loss of resolution. Secondly, pixels in this study are 10m x 10m pixels. A 10m pixel is extremely small compared to the area of any of the polygons on the map. The edge length of a 10m pixel is approximately only four times as great as the width of a contact line drawn on the map. In addition, a 10m x 10m square can barely be distinguished on a 1:62,500-scale map. Therefore, it appears that the amount of error resulting from converting from coverages to grids does not have a significant effect on the outcome of the study.

GENERAL CONCLUSIONS

The landslide-influencing factors analyzed in this study are degree of slope, lithology, bedding-dip direction and topographic slope orientation, bedrock expansivity, soil expansivity, hillslope aspect, vegetation, vertical land-surface curvature, elevation, and precipitation. With the exception of vegetation data, data for all of these factors are available in digital form from the U.S. Geological Survey. These factors were analyzed both within and outside of areas mapped as landslides, with ARC/INFO, a commercial GIS program. The analysis concluded that the two factors that have a strong influence on landslides within the study area are lithology and degree of slope. Two factors which have a moderate influence on landslides within the study area are vertical land-surface curvature and hillslope aspect.

The results of the GIS analysis were used in the creation of a Relative Hillslope Stability Map, shown in Figure 27. This map divides the entire study area into 11 categories of relative hillslope stability, ranging from 0 (most stable) to 10 (least stable). These categories are each represented on the map by a different color, with the hot colors representing the least stable areas and the cold colors representing the most stable areas.

The patterns of color on the Relative Hillslope Stability Map reflect several important ideas about the creation of the Relative Hillslope Stability Map. It is very apparent that lithology played a significant role in the creation of the map. The influence of lithology is evident by the distinct swaths of color across the map. For example, the swaths of yellow and orange stand out from the rest of the colors on the map. The locations of these swaths of color are determined by the influence of lithology in the creation of the map. Similarly, the general topography of the study area is clearly seen on the map. The drainages are typically composed of warm to hot colors, indicating their relatively less stable slopes. The flatlands, in contrast, are all represented by cool colors, evidencing the important role of slope steepness in creating the map. Additionally, south-facing hillslopes tend to be more easily seen on the map than north-facing hillslopes. The south facing slopes are represented by slightly warmer colors than the north-facing slopes, reflecting the inclusion of hillslope aspect in the creation of the map. Although color patterns relating to the inclusion of land-surface curvature on the map are not as obvious as those relating to the other factors, it is still evident in some locations on the map. For example, the majority of the western portion of the study area has no curvature. This uniform flatness is shown as the purple color making up the western portion of the map.

Other observations made from the Relative Hillslope Stability Map include the fact that the entire western portion of the study area is uniformly ranked as the most stable category aside from water. In general, this area has uniform aspect, curvature, and slope, and negligible relief. In addition, it is entirely composed of lithologic units of the most stable ranking. These facts most likely explain the uniformity of stability of the valley floor, or the western portion of the study area.

One final observation from the Relative Hillslope Stability Map is that, in very general terms, the hillslope stability of the study area appears to decrease from west to east. This is most likely explained by the fact that in general, there are many more mapped landslides in the eastern portion of the study area than in the western portion. Because past landslide areas are regarded in this study as potentially unstable areas, this pattern of landsliding influences the result of the final Relative Hillslope Stability Map.

The Relative Hillslope Stability Map provides an improved indication of the relative stability across the study area. Prior to this study, only landslide inventory maps existed for the study area. The Relative Hillslope Stability Map indicates which areas have significant slope stability problems.

In addition to the Relative Hillslope Stability Map, this study provides a systematic method by which available digital data can be analyzed. A correlation of digital topographical, geological, and climatological data were analyzed with respect to locations of mapped landslides in an attempt to determine which of these factors most influence hillslope stability. Although the specific conclusions of this analysis are only applicable within the study area (i.e., lithology and degree of slope were found to be the most influential factors), the methodology of this analysis can be used in areas where digital topographical, geological, and climatological data exist.

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