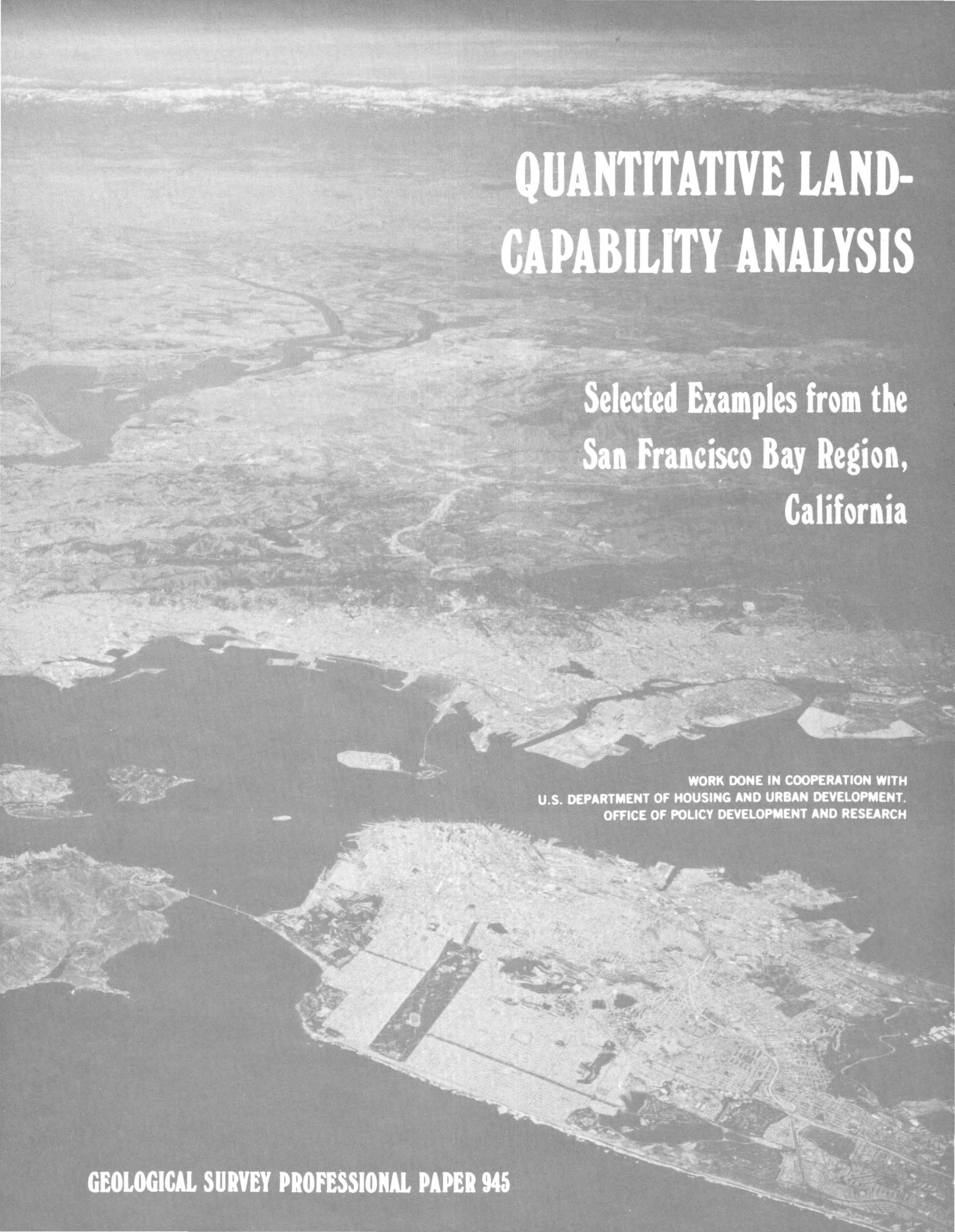

QUANTITATIVE LAND-CAPABILITY ANALYSIS

Selected Examples from the San Francisco Bay Region, California

WORK DONE IN COOPERATION WITH
U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT.
OFFICE OF POLICY DEVELOPMENT AND RESEARCH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 945

Quantitative Land-Capability Analysis

By RAYMOND T. LAIRD, JEANNE B. PERKINS, DAVID A. BAINBRIDGE,
JAMES B. BAKER, ROBERT T. BOYD, DANIEL HUNTSMAN, PAUL E. STAUB,
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FOREWORD

This report is a product of the San Francisco Bay Region Environment and Resources Planning Study, an experimental program that was designed to facilitate the use of earth-science information in regional planning and decisionmaking. The study, conducted from 1970 to 1976, was jointly supported by the U.S. Geological Survey, Department of the Interior, and the Office of Policy Development and Research, Department of Housing and Urban Development. The Association of Bay Area Governments actively participated in the study and also provided liaison with other regional agencies and with local governments.

Although the study was focused on the nine-county 7,400-square-mile San Francisco Bay region, it explored a problem common to all communities: how best to plan for orderly development and growth and yet conserve our natural resource base, insure public health and safety, and minimize degradation of our natural and manmade environment. Such planning requires that we understand the natural characteristics of the land, the processes that shape it, its resource potential, and its natural hazards. These subjects are chiefly within the domain of the earth sciences—geology, geophysics, hydrology, and the soil sciences—and information from these sciences can help guide growth and development. But the mere existence of information does not assure its effective use. Relatively few planners, elected officials, or citizens have the training or experience needed to recognize the significance of basic earth-science information, and many of the conventional methods of presenting earth-science information are ill-suited to their needs.

The San Francisco Bay Region Study has aided planners and decisionmakers by (1) identifying important geologic and hydrologic problems that are related to growth and development, (2) providing the earth-science information that is needed to solve these problems, (3) interpreting and publishing findings in forms understandable to and usable by nonscientists, (4) establishing avenues of communication between scientists and users, and (5) exploring different ways of applying earth-science information in planning and decisionmaking. More than 100 reports and maps have been produced. These products cover a wide range of topics, such as flood and earthquake hazards, unstable slopes, engineering characteristics of hillside and lowland areas, mineral and water resources, solid- and liquid-waste disposal, erosion and sedimentation, and bay-water circulation patterns.

"Quantitative Land-Capability Analysis" is one of the final reports in the San Francisco Bay Region Study. It describes a method of evaluating land-use proposals by estimating the costs that are related to geologic and hydrologic characteristics. These costs may be immediate or long delayed. They may result from mitigative measures, from the probability of future damage, or from lost opportunities. But, because all can be expressed in current dollars, cost provides a common basis for evaluating and comparing different land uses and different geologic hazards, constraints, and resources.

The method described is new and is just beginning to be used in the San Francisco Bay region. Although it is still being tested, it appears to be flexible enough to be adapted to other regions where geologic and hydrologic problems are important in land-use decisions. The report is published both to share the results with others who may be able to use the method and to encourage testing and further refinement of the method. Many who read this report may find it helpful to examine carefully not only the method, but also the basic data, engineering practices, and public policies that demonstrate how the method is used. New scientific information, new engineering methods, and changing public attitudes will not greatly affect the basic method of analysis, but they will affect the results. This method of analyzing land capability will be most successful when both data and assumptions are continually revised to keep pace with current knowledge and practice.

Robert D. Brown, Jr.
Project Director,
San Francisco Bay Region Study

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ABSTRACT

The method of analyzing land capability described in this report estimates the costs of land utilization related to geologic characteristics and processes when existing use is converted to housing, commerce, and transportation. These costs are the total attributable to geologic conditions, regardless of who pays. They include damage potential from natural hazards such as floods, landslides, or earthquakes; fees for special investigations, designs, or construction practices which are necessary to mitigate natural hazards or to remedy site deficiencies; and losses of potentially valuable natural resources such as sand and gravel. These costs are independent of any equity issues, and they are derived by assuming risk neutrality on the part of decisionmakers. Loss of life is probable for some natural hazards, but because costs attributable to life loss are difficult to evaluate, they are not considered in this analysis. Lower costs indicate a greater capability; that is, the land is relatively adaptable to the proposed new use.

Estimating cost, as a measure of capability, aids in planning, decisionmaking, and defining future research needs. This method of analyzing land capability makes it easy to compare the costs related to geologic constraints and compels the user to recognize and state his assumptions and to identify the information needed to define costs. The method is flexible so that, as more or better information becomes available, better estimates can be made. The method can also be extended to include other development costs, such as those for transportation and utility services.

Assessing capability begins by selecting the geologic processes or properties thought to influence costs for different activities on land. The geologic processes and properties that are judged most important in the part of the San Francisco Bay region analyzed here are grouped into resources (mineral, energy, water, or soil) and constraints. The most important constraints are flooding, erosion and sedimentation, and a variety of problems that are related to earthquakes, slope stability, and unsatisfactory foundation conditions. Information is collected and interpreted to describe and evaluate the relative importance of these processes and properties. Relative importance is expressed as the approximate cost related to each of eight representative land uses: (1) rural or agricultural, (2) semirural residential, (3) single-family residential, (4) multifamily residential, (5) regional shopping centers, (6) downtown commercial, (7) industrial, and (8) freeways. Because constraints and opportunities can be related in a common unit of measure (cost in dollars), the effects of different geologic processes and properties may be combined and summed. The total costs associated with all geologic problems for a specific use and a given area indicate the capability of that land to accommodate that use. Thus, capability maps can be produced for each land use when the sums of these costs are displayed by area on a map.

Land-capability maps of this kind do not make decisions, but they are a convenient means of displaying the data needed to evaluate alternatives and to make better decisions on land use. Together with other social and environmental information, they can be used by the planners, elected officials, and developers who share responsibility for land-use decisions, and they can provide a common basis for communication and for solving problems.

The Santa Clara valley south of San Francisco Bay is used here to demonstrate the method because the area is undergoing development and has a variety of geologic hazards, constraints, and resources. The procedures and methods of analysis used in the demonstration area are described in detail in the text and are further amplified in sections at the end of report so that planners in the San Francisco Bay region and elsewhere can modify and adapt this method of land-capability analysis to their own needs.

Many problems encountered in evaluating land capability result from information deficiencies; much of the information needed is difficult to obtain, and for some subjects more fundamental research is needed. Throughout this report many of these information needs, such as cost estimates, maps, and data on recurrence intervals of hazards, are recognized. They are potential targets for research.

INTRODUCTION

Despite their efforts in recent years to pay closer attention to geologic phenomena, planners have not been totally successful in incorporating earth-science information into the planning process. A review of the earth-science reports intended for use by planners, and of planning studies that incorporate earth-science information, suggests that the lack of effective communication between these disciplines is a major problem.

This study discusses and illustrates a method of alleviating the problem. By collecting appropriate basic earth-science information, interpreting that information accurately, comparing the hazards, constraints, and resources, and using this earth-science information together with information on other environmental and social considerations, planners can help make better decisions on land use.

LITERATURE EVALUATION—THE PROBLEMS

A review of the available literature (see section "Selected Reading") shows that much of the difficulty with using earth-science information in planning results from inadequate interpretation of the information by scientists or from its inappropriate application by planners.

Substantial progress has resulted from efforts to show individual classes of geologic and hydrologic hazards, constraints, and resources in map form. For example, maps in a report on relative slope stability (Nilsen and Wright, 1979) prepared as part of the San Francisco Bay Region Environment and Resources Planning Study (SFBRS), show the distribution of areas with slight, moderate, and severe landslide potential. But even these maps do not provide planners and others involved in land-use decisionmaking with sufficient information, because:

1. Geologic hazards, constraints, and resources cannot be easily compared to other environmental and social considerations.
2. Separate maps showing landslide potential, flood plains, and resource deposits cannot indicate the relative importance of hazards, constraints, and resources or show whether it is more costly to build on a landslide, a flood plain, or a sand and gravel deposit.
3. The importance of a hazard constraint, or resource depends on the land use; for example, slight, moderate, and severe landslide potential implies a level of cost for low-density residences different from that for high-density apartment buildings.

These problems in presenting earth-science information in a way that meets planning needs have been a barrier to effective use of the information by planners.

Because of these problems in interpreting and applying earth-science information, some planning reports simply overlook the information. Other studies quote or paraphrase past geologic studies but fail to incorporate the information into a general framework. And even when such integration is attempted, producers of planning studies may use only familiar criteria, such as percent slope,[1] as a rough indicator of all geologic hazards and constraints. Such a limited view may overlook important problems such as liquefaction, amplification of earthquake damage by ground shaking, and flooding.

Many land-capability studies, as well as other types of planning reports, tend to avoid the difficulty of considering the constraints, hazards, and resources by making a single geologic or hydrologic characteristic the most important; land-use choices are then resolved in terms of this single characteristic. The Lake Tahoe land capability report (Bailey, 1974) for the Tahoe Basin is an example. In this study, erosion and the resulting sedimentation which affects the water quality of the lake are considered the most important problems. Seismic safety and flooding are virtually ignored. As another example, the soil ratings of the Southeastern Wisconsin Regional Planning Commission (1969) and of the U.S. Soil Conservation Service (SCS) incorporate more than one constraint, but only basic data on soils are used.

[1]Expressed in percentage, the land surface rises or falls (slopes) the given number of feet in a distance of 100 feet. Thus, land with a 10 percent slope rises 10 feet in a distance of 100 feet.

Planners have tended to relate development constraints to different land uses by treating geologic constraints only as a stop-go approach to development. Thus, development is often accepted where problems are slight but not where they are severe; where problems are moderate, cautious development may be permitted. This approach allows only for a fixed view of future development and therefore a limited number of planning options. Earth-science information is more useful when interpreted for several land uses so that the constraints and opportunities of different alternatives can allow for flexibility in the public decisionmaking process.

Both planners and earth scientists have made substantial progress in recent years toward identifying inadequacies in the planning process and in earth-science information—the first step in correcting them.

LAND-CAPABILITY ANALYSIS

This report describes a method for making earth-science information more useful to planners by making it easier to incorporate into the planning process. This method, land-capability analysis, measures the ability of land to support different types of development with a given level of geologic and hydrologic costs. Total social costs are chosen to rank the relative importance of various geologic and hydrologic conditions; how these costs are distributed, or who pays them, is not of concern in the analysis. This technique enables one to relate resources and hazards, as well as current mitigation and prevention costs, to future damage. The procedure has at least two other advantages. First, various land-use types can be assessed separately. Second, the costs related to geologic or hydrologic conditions can be easily compared with most other municipal costs, such as those associated with roads, sewers, waterlines, and other parts of the urban infrastructure. Thus, the information can be used to relate geologic factors to the other environmental, social, and economic factors that can be expressed in a dollar form and that contribute to a land-development decision.

Some problems are encountered in this method: (1) the full spectrum of land uses must be reduced to generalized representative uses; (2) many of the cost implications of geologic or hydrologic information are still ill-defined; (3) some cost estimates must be based on standard or conventional practices, which may need to be defined and evaluated, even though these practices may encompass a broad range of costs; and (4) some costs are virtually impossible to evaluate accurately—for example, the probabilistic rate of occurrence of earthquakes is not known precisely and yet expected cost of earthquake-related damage depends largely on the recurrence interval.

POSSIBLE USERS OF LAND-CAPABILITY ANALYSIS

Decisionmakers.—Land-capability analyses provide decisionmakers with important information for weighing alternatives and making land-use choices in conjunction with other environmental and social information and with information for determining the economic feasibility of the project.

Planners.—Land-capability information can be used by planners, together with other information, in developing planning criteria and policies and in identifying significant geologic hazards, constraints, and resources. Land-capablility analyses can facilitate or be incorporated into development regulations, environmental reviews, and other implementation plans. Results of the analyses make it possible to establish priorities for time, effort, and funding of future research—in effect, for defining the significance or the severity of the problems.

Public-works engineers.—Land-capability analyses can be used by public-works engineers to help identify areas where special development ordinances and regulations may be needed or where special construction standards should be set.

Developers.—Land-capability information can be used by developers in evaluating site proposals before land acquisition and in determining what additional data, design, or engineering may be needed.

Architects and builders.—Land-capability analysis promotes better design by architects and builders because proper response to requirements is based on both detailed site information and a clear understanding of geologic constraints.

APPLICATION OF STUDY

The method of analysis described here avoids some of the problems of previous methods. It was designed to facilitate the use of earth-science information in local and regional planning programs. Although the method was developed in the San Francisco Bay region and uses a data base provided largely by the San Francisco Bay Region Environment and Resources Planning Study, its design is adaptable to other regions.

CAPABILITY ANALYSIS—GENERAL DESCRIPTION

The method described for assessing land capability encompasses five general steps. It begins by postulating which problems—for example, floods or landslides—might result in significant costs for characteristic land uses of a given region. This first step involves collecting earth-science information and preparing basic maps. In step 2, interpretive maps are developed for each problem, either directly from an appropriate basic map or by combining maps. The interpretive maps can then be used to identify specific problems.

In step 3, social costs (in dollars) are calculated for each type of development and each geologic condition. "Social cost," as used here, means the sum of all costs attributable to a problem regardless of who pays. There are three basic types of costs: First, study, engineering, design, and mitigation costs. These costs are usually incurred before or immediately upon construction of a project. Second, disaster or damage costs. These must be paid (usually at some future time) when damage occurs. Third, opportunity costs. These costs are the revenues or benefits that would have resulted from a type of land use and are foregone if the land is used for other purposes.

Costs that accrue at different times are made commensurable by calculating the present value of future costs, using an interest, discount rate. Costs that may occur at some unknown future time are calculated by finding the average, or expected, value of the costs.

In step 4, all the expected costs for all the conditions for each land use are totaled. This total is used as an indicator of the capability of the land to accommodate each use. Then, when the sums of these costs are displayed on a map, the result is a capability map for each land use. This is step 5 in the procedure, and the capability assessment can now be used in the planning and decisionmaking processes.

EARTH SCIENCE APPLIED TO LAND USE

Almost all human activities interact with the natural geologic and hydrologic setting. Current land-use and population inventories, therefore, are useful starting points for land-capability analysis. Common land-use types include wildland, rural or agriculture, semirural residential, single-family residential, multifamily residential, commercial, industrial, and utility. The classification chosen should reflect local needs and practices. Critical structures, such as hospitals, pipelines, high-rise buildings, bridges, and refineries warrant special treatment.

The effects of geology on land use can be divided into two broad categories: constraints and resources. In this section, some common geologic constraints and resources that affect the costs of using land in different ways are identified and discussed.

CONSTRAINTS

Constraints include hazards, such as ground shaking, and development constraints, such as shrink/swell soils. Several constraints include both, but they are not differentiated further in the text. Constraints become evident only when people are affected, and the type and intensity of land use affect their importance.

EARTHQUAKE PROBLEMS

Earthquakes result from readjustment of strain in the Earth's crust. Damage may result from ground shaking, fault rupture, or side effects of the shaking, such as liquefaction, tsunamis, and seiches.

Ground shaking

Earthquakes originating inside or outside a planning area may cause ground shaking within that area. The degree of hazard depends on the severity of the shaking and the susceptibility of the buildings to damage. Thus, local geologic conditions such as depth to bedrock and ground water, as well as building height and type and age of construction, all affect the degree of hazard.

Fault rupture

Fault rupture, or surface rupture, commonly occurs during earthquakes in California because the earthquakes originate relatively near the earth's surface. Ground on one side of the fault moves relative to ground on the other side, and any structures built across the fault trace will be deformed or destroyed. Displacement can be vertical, horizontal, or a combination of both. Displacement may be only a few inches or several feet.

Tsunamis and seiches

Both tsunamis and seiches can be caused by earthquake shaking or displacement. Tsunamis are great waves that originate in the ocean, and seiches are waves that originate in closed or semiclosed bodies of water. Either can cause extensive damage in shoreline areas.

SLOPE-STABILITY PROBLEMS

Downhill movement of materials may cause damage and loss of life. Different rates of movement involving varying types of material have different names, but the following basic categories are commonly used.

Landslides

The rapid downhill movement of soil and rock is termed a landslide. Road building, landscape-plant watering, and other activities that accompany or follow development may increase the size, number, or frequency of landslides. Earthquakes, particularly after a rainy season, may trigger landslides.

Creep

Slow, virtually imperceptible soil movement is termed creep. Even though the rate of movement is only a few inches per year, the movement may still rupture pipes, fracture foundations, and eventually destroy buildings.

Avalanches

The rapid or instantaneous downhill movement of snow or rock is termed an avalanche. Avalanches are an important development constraint in mountainous areas, especially where developments such as ski resorts are built close to steep slopes.

FLOODING

Flooding can be accentuated by development. Two of the most common problems are those associated with stream flooding and dam or dike failure.

Stream flooding

Heavy rains may cause streams to overflow their banks and inundate adjacent flood plains. Flooding is a natural, recurrent phenomenon that becomes a hazard only when human occupancy of flood plains occurs. This flooding may be aggravated by any type of urban development that increases the amount of impervious surface and causes faster and greater runoff and more frequent flooding.

Dam, levee, and dike failure

Areas may also be flooded if dams, levees, dikes, or other manmade structures retaining large bodies of water fail. Failure may be triggered by earthquakes or landslides. Sudden failure can destroy all of the buildings and kill many of the people in the immediate path of the water. Even gradual failure can result in a damaging inundation.

BEARING-MATERIAL PROBLEMS

Subsidence

Withdrawal of natural gas, oil, ground water, steam, and minerals or natural removal by dissolution or erosion of subsurface materials may cause subsidence. Damage may occur if subsidence is not uniform or if it increases susceptibility to dike or levee failure.

Liquefaction

Liquefaction is a process by which loose water-saturated sands and other granular materials suddenly lose strength when shaken during an earthquake or for other reasons. The lurching and sliding which occurs can cause severe damage to structures built upon such deposits.

SETTLEMENT

Settlement is caused by the compaction of loose materials, resulting in a lowering of the surface and possible damage to those structures located on top of the materials. It can be accelerated by the shaking accompanying earthquakes. Differential settlement, common when part of a building is on a cut natural surface and the other part is on a poorly compacted fill, can cause extensive damage to buildings because of uneven soil compaction.

SHRINK/SWELL POTENTIAL

Shrink/swell soils can be thought of as expansive soils on relatively flat ground. Expansive soils, containing clays that expand when wet and contract when dried, can cause heaving, cracking, and breakup of pavements and concrete-slab foundations. They can also displace and break sewer pipes, often causing pollution.

EROSION AND SEDIMENTATION

Erosion is the process by which weathered rock or soil is transported by gravity (downslope movement) or by moving water (slope runoff and stream transport). It can also be caused by ocean waves or strong winds. It can cause severe loss of agricultural soil, damage to structures, loss of property, and the degrading of water quality in streams. Grading and other development activities may increase erosion many times above natural levels.

The soil that is transported by gravity, water, and wind is eventually deposited elsewhere. This process is sedimentation. These resulting deposits can fill reservoirs, clog drains and gutters, and overload stream channels.

VOLCANIC ACTIVITY

Volcanic activity is the process by which magma and its associated gases rise into the crust and are extruded onto the earth's surface and into the atmosphere. Hazards to man may result from explosive eruptions, mudflows, lava flows, or ash falls.

RESOURCES

MINERALS

Economic deposits of minerals are found in only a few places, and any type of urban development that prevents mining them can be costly for society. Some minerals that are in particularly short supply in the United States and that lack inexpensive substitutes are called strategic minerals.

CONSTRUCTION MATERIALS

Sand and gravel are among the most important construction resources; these materials are essential for almost all development. Because transportation is a major component of the total cost, utilizing or protecting resources near a development site can save society money by avoiding high transportation costs. Other resources such as crushed rock and dimension stone are also important, and a substantial cost is associated with their loss as a potential resource.

ENERGY

Energy resources are essential to our society. Geothermal and hydropower sources are particularly important, because they are at least partly renewable. The principal fossil fuels—coal, natural gas, and petroleum—are currently the chief sources of energy but are nonrenewable. The use of nuclear power is increasing, and the siting of nuclear reactors is especially sensitive to geologic and hydrologic constraints because of needs for (1) stable and safe sites, (2) ample supplies of cooling water, and (3) suitable methods for disposing of heated water.

WATER

Water quality and supply depend in large part on geologic and hydrologic characteristics such as aquifer recharge areas and erosion control.

SOIL

Prime agricultural land is a limited resource and is many times more valuable than poor or marginal farmland.

SCIENTIFIC AND EDUCATIONAL SITES

Some areas may also be important because of their potential for scientific research or educational purposes. Fossil occurrences, type localities for rock units, places where folds and faults can be seen, and many other geologic features can be valuable.

Areas having unique physiographic features such as badlands, canyons, and caves, areas having historical importance, areas having archeological importance such as Indian mounds or abandoned pueblos, and areas having unique plant or animal assemblages are other examples of sites that have a potential for scientific research and educational purposes.

SUMMARY

The geological or hydrologic setting of an area can create opportunities for, or impose constraints on, development. Its importance depends on the costs arising from the specific constraints or resources that affect each type of land use. The following sections of the report explain how to estimate the costs of various types of development when hazards, constraints, and resources exist.

COLLECTING AND INTERPRETING DATA

After the geologic conditions that are significant for a given area are determined, basic earth-science information can be collected. The information collected is most useful if it helps in estimating cost. Thus, a map depicting relative slope stability is more useful than one depicting percent slope because the slope-stability categories can be more easily related to landslide costs.

The information also should be collected at a scale appropriate to its final use. Enlargement of mapped information should be attempted only if technical guidance is available to insure that the information on the original map is not misapplied.

Maps depicting geologic information can be obtained from a variety of sources, and although some rural areas have not yet been mapped, most urban regions have been. The most common sources are the U.S. Geological Survey (Department of the Interior), the U.S. Soil Conservation Service (Department of Agriculture), the U.S. Army Corps of Engineers, State geological surveys, water or utility districts, and colleges and universities.

Maps suitable for deriving costs are rarely directly available. Such maps sometimes can be produced by overlaying two or more maps. For example, a map showing landslide potential can be produced from a map of photointerpreted landslides, a geologic map, and a percent-slope map. This procedure was used by the U.S. Geological Survey to produce the relative slope-stability interpretive maps for the San Francisco Bay Region Study.

More specific information on data collection is provided in the section on "Geologic And Hydrologic Considerations."

RELATIVE IMPORTANCE OF GEOLOGIC AND HYDROLOGIC CONDITIONS AND THE USE OF DOLLAR COST

The purpose of land-capability analysis, as the term is used in this report, is to provide planners with a means of determining the effects of the geologic and hydrologic characteristics on the development potential of specific land areas. The methods described are designed to enable planners to determine the effect of geologic and hydrologic conditions on the relative capability of a given parcel of land to accommodate different types of land use.

Because several geologic hazards, constraints, and resources usually affect a given parcel of land, one must develop a method for evaluating the relative effects of seemingly incommensurable conditions (that is, factors apparently unable to be measured by a common yardstick) or to put it more simply, for comparing apples and oranges. For example, consider a parcel affected by two geologic constraints: landslides and active faults. Landslides are relatively frequent over a period of time, but movement on most active faults is infrequent. In order to make sensible land-use decisions, one must have some method of determining the relative importance of different conditions such as landslides and active faults.

Such a method is not easy to develop. Accordingly, many planning programs have attempted to avoid the problem by assigning separate standards for each geologic condition. As an example of such standards, a given parcel might be said to be capable of supporting a subdivision if the slope is less than 15 percent and if the houses are not within 100 feet of an active fault. This method allows one to make land-use decisions without the need to compare the cumulative impact of different constraints.

Two serious difficulties, however, typical of all arbitrary standards that do not attempt to quantify the relative importance of different constraints, seriously limit the effectiveness of this method. First, from a practical point of view, if commonly agreed upon criteria are used and the standards are strictly adhered to, in many areas little land is shown to be capable of development. An example from the Santa Clara Valley, the demonstration area used in this report, serves to illustrate this point. In this area, if building were not permitted on slopes over 15 percent, on 100-year flood plains, or on prime agricultural land, there would be little land left to develop. The second and more fundamental problem with such criteria is that they do not always lead to intuitively plausible decisions. For example, if parcel A is 101 feet from an active fault and is on a 14 percent slope, and parcel B is 100 miles from an active fault and on a 16 percent slope, the arbitrary standard would allow the first parcel to be developed but not the second. Common sense may call for the opposite conclusion. This difficulty is common to all systems that do not provide a quantitative means for comparing various geologic and hydrologic conditions. Calculating dollar costs associated with geologic conditions is one possible solution to this dilemma.

DOLLARS AS A UNIT OF MEASUREMENT

One approach to the problem of making comparisons is to estimate, for a given use, all the costs in dollars associated with each geologic hazard, constraint, or resource. Then, simply add up the dollar costs for all hazards, constraints, or resources. From one point of view, there is no particular problem in comparing apples and oranges. If apples cost a dime and oranges cost a nickel, an apple is worth two oranges. That is, the price of an object is thought to reflect the relative value that people place on that object. Admittedly, many forces act to distort prices so that they do not exactly reflect people's relative evaluations. Nonetheless, the general conclusion of applied economics is that, unless artificially controlled, prices usually approximate people's preferences and that prices are the only source of such information.

Further, it is generally believed that in a democracy public decisionmaking should reflect such preferences. For example, suppose that a river floods nearby agricultural land every year and destroys crops that can be valued at $200. Further, suppose that if a subdivision were built on this same tract, the yearly costs to the residents of the subdivision in terms of damaged houses, disruption of water quality, flood-control expenses, and so on, would be $9,000. Assume that there are no other hazards or constraints that affect this property. Then because $9,000 is greater than $200, it may be proposed that the land has a greater capability for agricultural use. Of course, at this point, one cannot conclude that agricultural use of this land is more desirable. Only increased costs due to geologic problems have been considered, and no attempt has been made to assess the relative benefit of each land use. A complete analysis would need to consider costs due to other factors and benefits as well.

One objection to using dollar costs for comparisons is that such estimates are often subject to great uncertainties. Thus, if even one of the cost estimates is in serious doubt, the whole procedure is of little value; therefore, one should simply use an intuitive weighting system. By using such a system, one could avoid putting dollar values on seemingly invaluable commodities and at the same time simplify the entire process. Even though the cost estimates are often subject to great uncertainties, however, two responses can be made to this sort of objection. First, when different kinds of commodities are being compared, no matter what system is used, a dollar value is implicitly being put on each, whether they be apples and oranges or tomato plants and split-level homes. For example, suppose that in an intuitive weighting system the flood hazard is rated as negligible, moderate, or severe, and suppose that in the river valley tract described earlier, the parcel is identified as having moderate flood danger for both agricultural and single-family residential land use. Then the designer of this weighting system is implicitly valuing these two uses equally, and inasmuch as they do have dollar prices, one is placing a dollar value on each.

Perhaps some of the popularity of nonquantitative systems stems from the fact that they appear not to place dollar values on different kinds of commodities, some of which are intangible. But, because the method of assigning the relative values of various factors usually is left unspecified, it is impossible to evaluate the accuracy or criticize the assumptions of such intuitive methods. By contrast, the dollar-cost approach outlined above yields two important dividends and, therefore, improves on the existing systems. First, because the assumptions are explicit, they may be criticized, and the effect of differing assumptions can be tested. Various advocacy groups can examine, criticize, and may thus improve the planning input. Second, the very fact that this method exposes many cost estimates as uncertain is in itself a benefit. The need for new data that must be developed to improve the estimates becomes readily apparent. In this way, evaluation and experiment can interact to improve the information available to planners and decisionmakers.

Another more serious objection to using dollar costs for comparisons is that many environmental factors are characterized by external effects on public goods. Thus, if one man's action at one place affects other people at other places, these effects are not mediated by any market. The textbook example of an external effect on public good is air pollution. By operating an automobile, each person imposes a cost on others in terms of lowered health and murky skies, and no institution (market or legal) requires automobile operators to compensate those affected. It is widely agreed that the absence of markets precludes any reliable estimation of the dollar costs associated with such public goods. (See Dales, 1968; Coase, 1960; and Calabresi, 1968.)

If an important component of costs associated with geologic conditions were of the public-good external-effect type, there would be little benefit to adopting the dollar-cost approach; cost estimates would be largely intuitive and subjective in any case. However, one fundamental assumption of this study is that geologic conditions do not involve public-good issues.

There are exceptions, to be sure: erosion and sedimentation, land pollution, and stream flooding are examples of geologic problems that have at least some element of external cost associated with them. Nonetheless, since most costs can be assigned to a specific location, geologic hazards and constraints are best compared by using dollars. If external effects were important, then one could only speak of total costs associated with a given pattern of development for the entire region in which the external effects occurred. For example, if air pollution is of concern, one must deal with the costs within the entire air basin. One cannot point to a particular site and say that there is a $9,000-per-acre air-pollution cost associated with the construction of apartments, because this cost will depend on the amount and kind of development elsewhere in the air basin. Thus, the land-capability method, since it assigns costs acre by acre, cannot be extended for use with environmental problems that have important external effects, such as air or water pollution.

TOTAL DOLLAR COST AS A DEFINITION OF SOCIAL COST

The method described in this report defines "social cost" as the total dollar cost attributable to geologic and hydrologic conditions, regardless of who pays. (This is the economists' definition of "social cost.") Accordingly, no attempt has been made to estimate only municipal costs, or only costs to specific individuals or groups, such as the landowners or the land developers. All these costs are treated equally; thus, equity considerations are absent. The choice to ignore the question of who pays implies several other assumptions, including the acceptance of current income distribution. The arguments surrounding these points are too involved for discussion here; discussions from varying points of view are given by Harberger (1971), Mishan (1973), and Merewitz and Sosnick (1971). One can conclude that this dollar-cost approach (or its more sophisticated relative, benefit-cost analysis) cannot be used by itself for making decisions; the political process is still necessary. Nonetheless, if the relative roles are kept in perspective, dollar-cost estimates can yield information and insight useful in both planning and politics.

INCORPORATING EFFECTS OF TIME AND UNCERTAINTY

Having decided to use dollars as a measure of social cost, one must then decide which dollar cost to use. Two important choices must be made:

1. Costs due to different geologic conditions occur at different times in the future. These costs must be summed, and an allowance must be made for differing values of money over time.
2. Many costs associated with geologic constraints are characterized by risk; that is, the amount and the timing of the cost are known only probabilistically. Thus, the question of "risk preference" must be resolved.

Both these choices are critical and affect both the cost estimates and the relative importance of the individual geologic conditions. They must be value judgments or dependent on the objective of the analysis, and there is no single correct answer. In general, the most widely accepted solution is chosen in order to proceed with the analysis.

DISCOUNTING

"Discounting" may be defined as the act of reducing the value of some future dollar amount to its present value by a given amount to cover interest. The expected value of all future costs discounted back to the present has been chosen in order to compare costs that occur at different times in the future. This way of measuring cost is conventional in benefit-cost analysis, and a discount rate of 10 percent is used—a number close to the present market rate. A lower discount rate would increase damage losses and potential resource losses, while a higher rate would decrease these costs.

RISK AND EXPECTED COST

Many of the costs analyzed in this study are related to risk; in other words, one cannot say with certainty when, if ever, the event that causes damage will occur. It can only be specified that at some future time, there is a probability that the event will occur. When a decision involves risk, a single-decision rule based on simple cost is no longer possible. Risk preference must be taken into account.

The concept of expected value should be familiar to the amateur gambler. The expected return for a decision is equal to the sum of the probability of each outcome times the return, if that outcome is realized. For example, the expected return of choosing heads in a game of matching pennies is:

$$\text{Expected return} = 1\text{¢} \times \text{probability (heads)} - 1\text{¢} \times \text{probability (tails)} = (1\text{¢} \times 1/2) - \times \tfrac{1}{2}) = 0.$$

The existence of risk preference results from the fact that quite different decisions can have the same expected return. For example, consider the choice of two bets: (1) Betting $1 on the flip of a coin, 1,000 separate times or (2) betting $1,000 on the single flip of a coin. The expected return for each game is zero, yet many people would clearly prefer one game to the other. This preference is because the chances of a big loss or a big gain are much larger for the second game.

People who prefer the first game are said to be "risk averse," those who prefer the second are said to exhibit "risk preference," and those who are indifferent are said to be "risk neutral." Most people are thought to be risk averse. (This fact is the foundation of the insurance industry.) The question of which risk preference governmental decisions ought to be based on is controversial, but, for this study, risk neutrality (that decisions can be based on the expected value of future costs) is assumed because it is the most commonly accepted choice for cost-benefit analysis.

Examining the costs related to surface rupture due to faulting demonstrates how assuming risk neutrality affects the relationship between the costs associated with various types of geologic conditions. One may choose to (1) pay the cost of a geologic site investigation and thereby avoid active fault traces (estimated expected cost of the investigation of, for example, $500 per acre) or (2) not investigate the site and take one's chance on fault movement during an earthquake (estimated expected cost of, for example, $500 per acre). In this study, because risk neutrality is assumed, both costs are the same.

Probably, most people given this information would prefer to pay for the study. This preference is not considered because of the difficulty in analyzing cost if risk aversion is assumed. For example, if one assumes that utility does not have a linear relationship to cost, one must know the function which represents the relationship in order to proceed with the analysis.

Risk aversion could be accounted for by assuming a discount rate lower than the market rate. This change makes future costs relatively more important than present costs. Because future costs are usually associated with damage, and because present costs are usually associated with mitigation, mitigation becomes relatively more worthwhile as future damage becomes more costly. This relationship can be illustrated by using the surface-rupture example. If one assumes a discount rate of 5 percent, rather than the 10 percent rate that actually is used here, the estimated expected cost associated with the study would remain $500 per acre. However, the expected cost of future damage associated with not performing the investigation would increase to $1,000 per acre.

CHOOSING THE TYPE OF DOLLAR COST

For purposes of land-capability analysis, there are three types of dollar cost that can be chosen to work with:

1. *Damage cost.*—the cost of replacing buildings and utilities, loss of income and profit, and relocation costs.
2. *Study and mitigation costs.*—the cost of studies to determine potential damage and of mitigation measures implemented to reduce this potential as estimated by the site-investigation firms.
3. *Opportunity cost.*—the cost of the lost resource potential to both the operator and the public.

Costs also may be insignificant or unknown.

The type of cost to choose for each situation depends both on the nature of the hazard, constraint, or resource, and on how society normally responds to it. The costs associated with some geologic hazards are considered as damage costs because no precautions generally are taken and the normal response is to accept the damages. For other hazards, costs are considered as study and mitigation costs because regulations, laws, or standard engineering practice lead to more costly methods of site evaluation, design, and construction that eliminate or greatly reduce the potential for future damage. Most mineral and water resources are expressed in terms of opportunity costs.

The choice of the type of standard engineering practice to use depends on the intended use of the capability analysis. In most cases, the practice assumed will be that used at the time of the study because one is interested in the relative capability of a given parcel of land to accommodate new development. However, if one intends to use the capability analysis as a means of estimating damage from a future disaster to existing construction, the appropriate practices used would be those applied at the time when the existing development occurred.

SUMMARY

The method of assessing land capability described in this report uses estimates of cost to indicate relative land capabilities on a map. These estimates enable land-capability mapping to be more accurate than a simple overlaying technique which treats all geologic hazards, constraints, and resources as if they were of equal importance. Cost can be used both to determine the relative importance of the geologic conditions and to visualize how much less costly it is to build on, for example, stable hillside materials than on areas that are susceptible to landsliding. However, in order to use estimates of expected cost and to proceed with the assessment, one must ignore equity considerations and risk preference, as well as select a discount rate.

The assignment of costs to particular land areas and the aggregation of costs in dollars per acre are made possible by the spatial nature of most geologic conditions. However, the common property problems associated with some of these conditions has made it necessary either to assign costs accruing in one area to another area that is causing those costs, or to ignore the costs.

Last, a standard response (see table 5) must be chosen and stated so that limitations in the validity of the cost estimates will be apparent to those using the study.

MAPPING AND DISPLAYING LAND-CAPABILITY DATA

After interpretive maps are compiled and costs are assessed, graphically acceptable capability maps must be produced.

MAP DEVELOPMENT

The actual process of adding the dollar costs for each parcel of land and each land use can be done by hand or by computer. Each method has its own limitations and advantages.

Much mapping and information storage is currently done by hand because it is cheap (at least in the short run), is familiar, and allows for inexpensive storage. There are, however, many drawbacks including (1) reduced accuracy (particularly where paper rather than a stable-base plastic is used), (2) difficulty in reproduction, (3) difficulty in overlaying maps, and (4) lack of flexibility (minor changes in methods or values may often necessitate complete redrafting). The lack of flexibility can particularly be a major problem in land-capability mapping of areas where change, improvement, and evolution are anticipated.

Various software packages for computer storage and processing are available now, and more are being developed and refined. They have various disadvantages and advantages depending on the skill and understanding of the programmers (Miller, 1975). Data can be collected and represented by either grid cells or polygons. Grid cells produce maps which generalize areas into boxes (fig. 1).

As is apparent, grid cells can miss small details unless the cell size is made exceedingly small, which increases the number of cells to be collected by the square of the dimension changes (that is, one-half width = 4 times as many cells). The smallest size that can be easily used is approximately one-tenth inch square. Such a cell size lends itself well to collection of mapped data as well as graphical presentation using readily available high-speed line printers.

A polygon system represents an area by a closed polygon rather than by cells (fig. 2). It can, therefore, represent curvilinear lines by a series of closely spaced points connected by short line segments. The digital address of each point along the line can be collected by hand operation of a line or point digitizer producing a card and (or) magnetic-tape record. Optical scanners can be used on appropriately formatted maps when interfaced with software packages to calculate polygon perimeters.

Although polygons are potentially much more accurate than grid cells, editing out discrepancies is a major quality-control problem. Because the perimeter of each area must be digitized separately, the boundaries between areas can become either data gaps or data overlaps. If many overlays are needed to produce the composite map, the map may become dominated by such errors. More sophisticated output devices can be employed to produce more satisfactory products, but at greater expense.

Both types of computer systems have advantages and disadvantages which are inherent to computer use. These include higher costs for initial map preparation, largely because maps must be digitized by hand, with a digitizer, or by optical scanner. The manual digitizer is the most commonly used method. Optical scanning is the least expensive if the maps are appropriately formatted. However, less contact between the human operator and the final map product increases the possibility of unseen error. The computer-output maps often must be reprocessed to make readable printing or display maps.

The ideal system would probably combine negative scribed basic maps (etched on an opaque stable base) with a computer polygon system. This system would be expensive, but it would provide excellent flexibility, accuracy, and potential for detailed, complicated analysis.

MAP SCALE

The method of producing land capability maps described in this study is applicable at any scale. For different uses, different scales are appropriate. Some commonly used mapping scales are 1 inch equals 2 miles, 1 inch equals 2,000 feet, 1 inch equals 800 feet, and 1 inch equals 50 feet.

The choice of map scale is related to the ultimate use of the material as well as the scale at which the basic information is available. When information is needed for a large area, a scale of 1:125,000, or 1 inch equals ap-

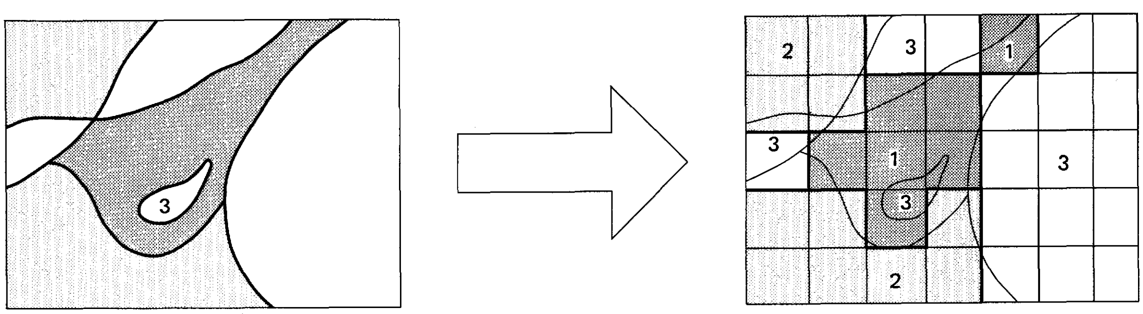


FIGURE 1.—Grid cell representation.

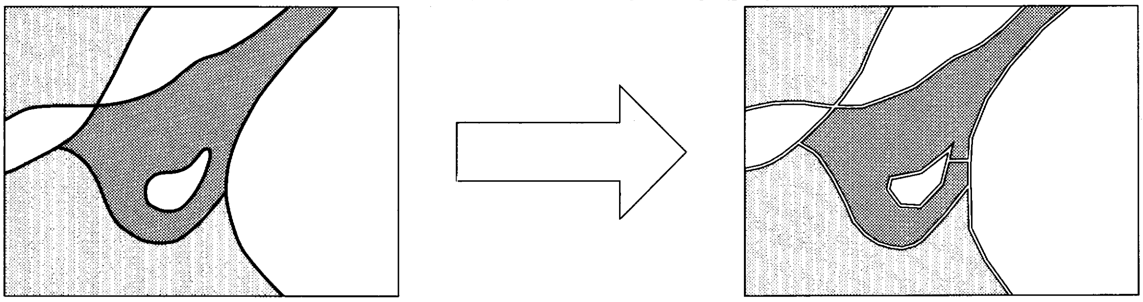


FIGURE 2.—Polygon representation.

proximately 2 miles, is convenient. Geologic and hydrologic information at or near this scale is available in most regions that are undergoing, or subject to, growth and development.

For decisions on more localized issues and as a better guide for areas where detailed site studies should be undertaken, a scale of 1:24,000 may be desirable. This scale allows use of USGS 7½-minute quadrangle sheets and begins to focus on specific areas.

For developments in areas affected by several geologic problems, a detailed site study may be needed. For this, scales of 1 inch equals 800 feet and 1 inch equals 50 feet are often useful. The layout of roads and plot of buildings can be done at 1 inch equals 800 feet, and detailed design at 1 inch equals 50 feet.

The difference in these scales is shown in figure 3. Local and site maps illustrate the differences. Confusion sometimes occurs when the assumption is made that a large-scale map shows more detail than a small-scale map. A map may easily be enlarged, but the resulting map will show no more detail than the original. The basic information must of course be available at the level of detail desired.

MAP PRESENTATION

After the basic maps are digitized and the costs are summed, the resulting information must be displayed in a manner that is easily understood by the users. Display may be done in a number of ways, each having different advantages and disadvantages. The total dollar costs can be printed directly on the map for certain uses, such as checking a test area. In most cases, however, some sort of aggregation into different categories or levels will be more useful. The exact type needed will depend on the eventual use of the study. Several different ways of categorizing the costs may be desirable to satisfy all potential users.

Then the problem becomes one of graphic display. Hand-produced maps can represent categories either with patterns or colors (fig. 4A). Many interesting methods of producing computer maps are possible, depending on the software/hardware combinations available. Line printers, square or rectangular, with simple characters or with overprinting (fig. 4B), and graphic symbols (fig. 5) can provide fairly acceptable visual separation. This visual separation can be improved by photographic reduction. As the individual characters, as well as the spaces between characters, become small, the human eye visually integrates the elements into a pattern or shade of gray. (Newspaper photographs are actually composed of various densities of black dots.) A pen plotter can be used equally well to draw perspectives (fig. 6A), produce density maps (fig. 6B), or plot contours (fig. 6C). A pen plotter can be used with a scriber to prepare negatives directly. Stable base material can be used with a pen plotter. However, this type of material cannot be used with conventional line printers.

Another display technique now available uses cathode ray tubes (CRT) either in color or black and white. These TV-type displays can be photographed to prepare copy. This type of display is particularly useful if the system is interactive and users want to test different assumptions rapidly.

Color is valuable since no more than seven categories can be represented with shades of grey on a map without loss of visual differentiation. However, shades of color are also subject to a similar category limit.

The importance of clarity and visual impact cannot be overemphasized, but the particular problems depend on use.

A summary of the capability analysis procedure is illustrated in figure 7.

SANTA CLARA VALLEY—A DEMONSTRATION

In this section, the proposed method of assessing land capability and using the land-capability analysis is illustrated in a demonstration area. The Santa Clara Valley area (from San Jose to Morgan Hill), Calif., has been selected for several reasons. It is undergoing developmental pressures, as a highly urbanized area expands into an agricultural area. The area includes a wide range of geologic and hydrologic constraints and resources and a typical variety of land uses. Adequate earth-science

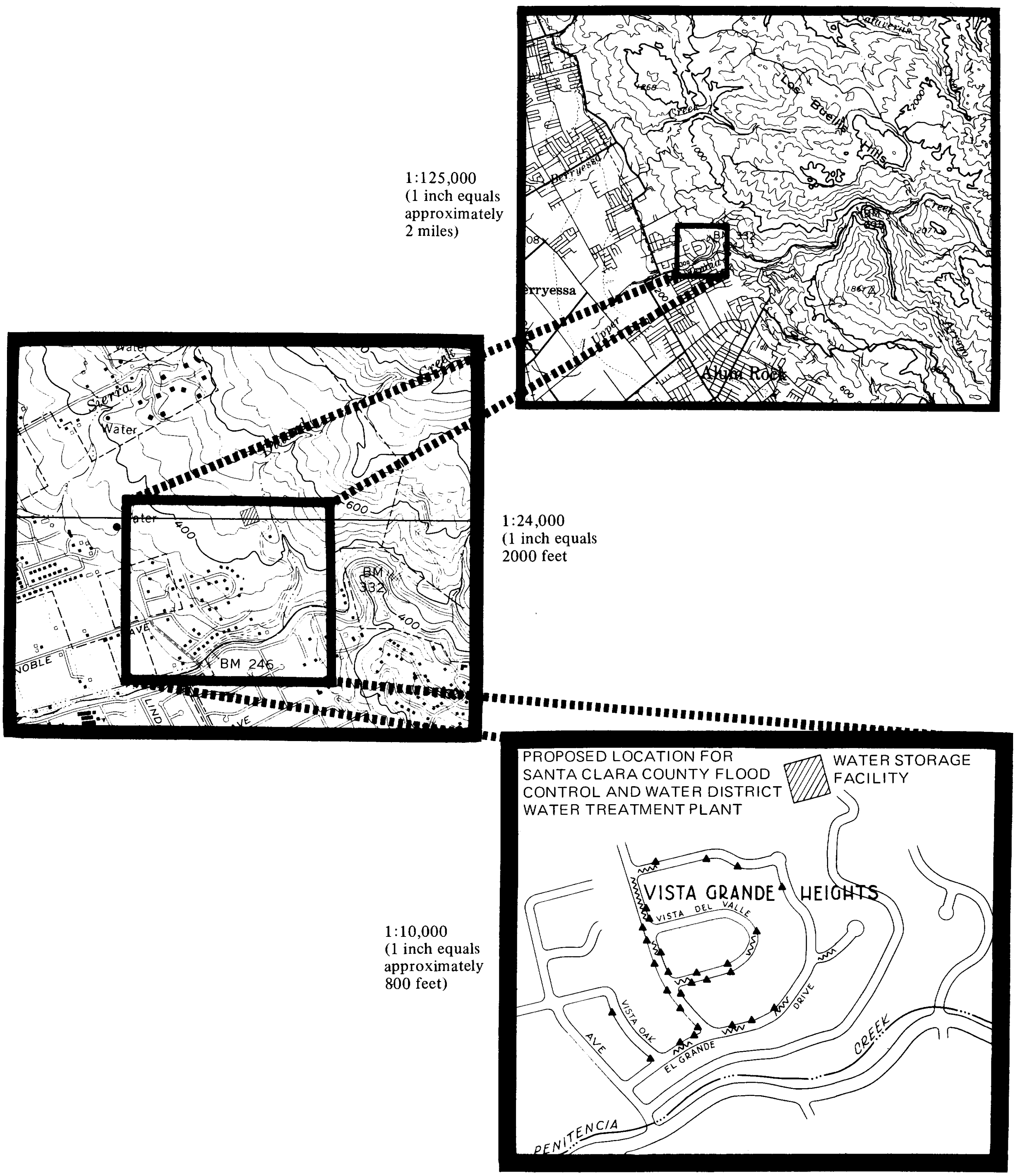


FIGURE 3.—Map scale—an illustration of detail.

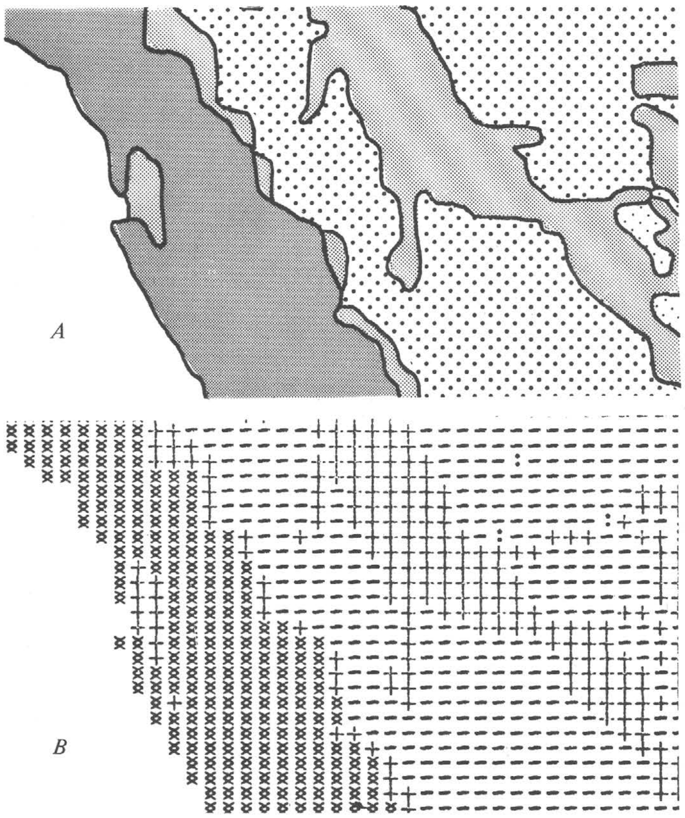


FIGURE 4.—Maps produced by hand (A) and by computer (B).

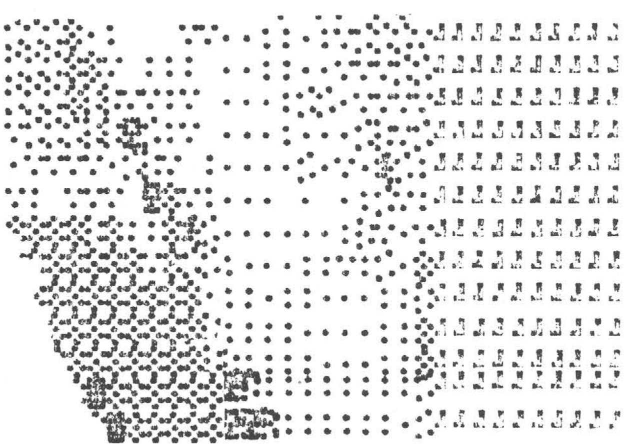


FIGURE 5.—Map using a line printer with graphic symbols.

information—work by State and Federal agencies and by private firms—is available. And the area is of concern to both regional and local planners.

The boundaries of the demonstration area (fig. 8) conform to census tract boundaries, except for part of the eastern boundary. The demonstration area maps are at a scale of 1:125,000 (1 inch equals approximately 2 miles). This scale was chosen because it is commonly used in regional and subregional studies and because most of the SFBRS products are at this scale. The area can be represented at that scale on a sheet 21 × 17½ inches. Because of the difficulties in producing such large maps in the quantities needed for this report, however, a representative part of the area has been chosen to illustrate the method and concepts of land-capability analysis. The area chosen is that part of the demonstration area in the San Jose East, Milpitas, and Calaveras Reservoir 7½-minute quadrangles (the San Jose 15-minute quadrangle). Maps of the entire area are on file at the offices of Association of Bay Area Governments (ABAG) and at the USGS library in Menlo Park. The boundaries of this area are shown on figure 8. Figure 9 shows the representative area chosen to illustrate the land-capability-analysis method in this report.

In review, the method of assessing capability used in this study involves several steps: (1) choosing the land-use types and the geologic and hydrologic hazards, constraints, and resources to be examined, (2) compiling maps of these constraints, hazards, and resources, (3) calculating costs, (4) aggregating these costs, and (5) producing land-capability maps for land-use decisions.

The following sections of the report demonstrate this process in an actual subregional area.

LAND-USE TYPES

The geology and hydrology of a site affect different land uses in different ways. The following land-use types are considered for the demonstration area:

1. Rural or agricultural (most parcels larger than 40 acres, and some specialty-crop areas of less than 40 acres).
2. Semirural or very low density residential (large lots of approximately 5 acres, much hillside land, and some recreational development).
3. Single-family residential (homes on moderate-sized lots at a density of five units per acre, neighborhood shopping centers, and schools).
4. Multifamily residential (duplexes, apartment complexes, and many housing redevelopment projects).
5. Regional shopping center (large shopping centers serving more than one jurisdiction, such as Sun Valley in Concord and Eastridge in San Jose).
6. Downtown commercial (buildings of up to five stories such as in Berkeley, not central San Francisco).
7. Light industrial (most industrial parks and large manufacturing building complexes such as IBM.)

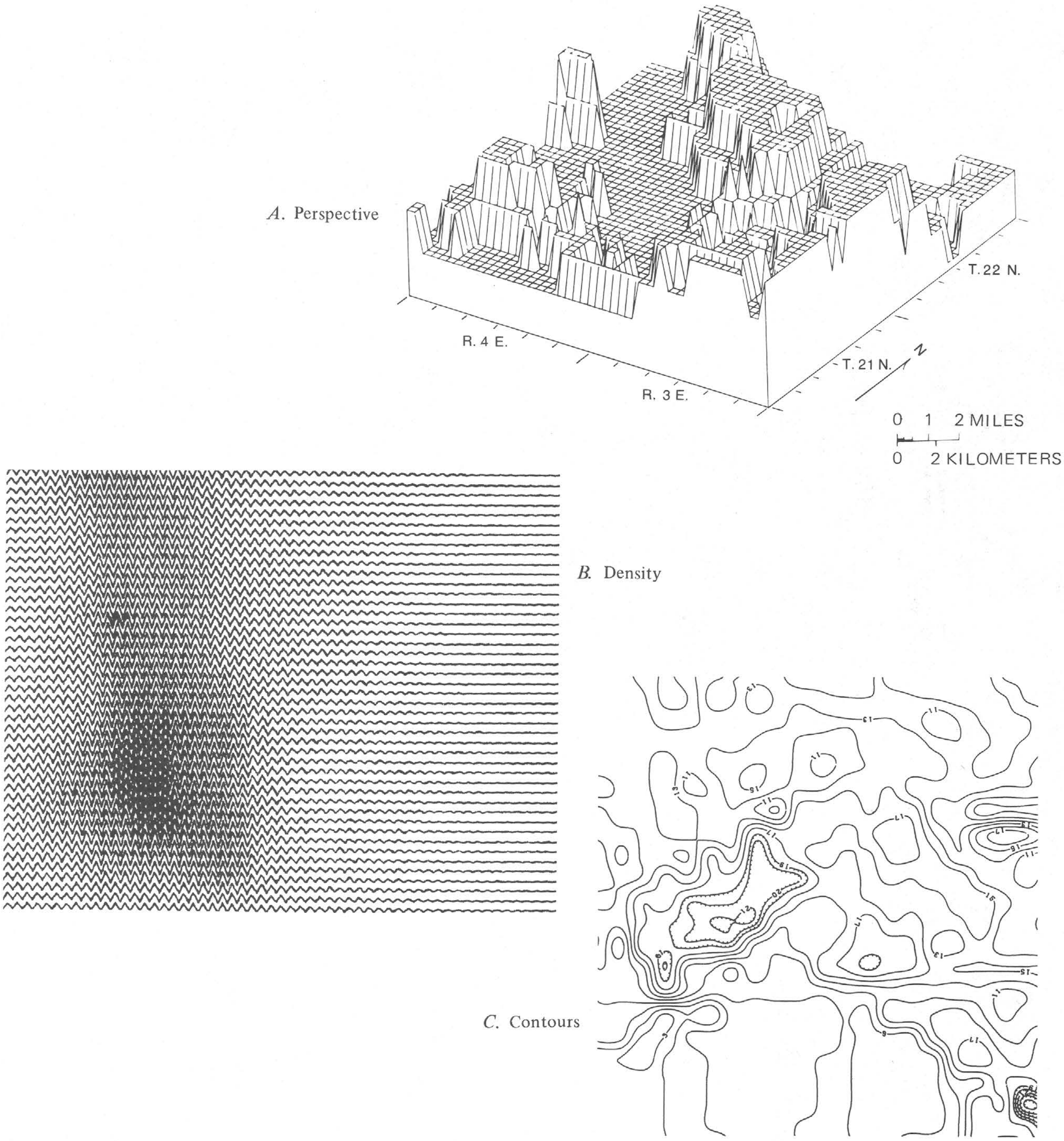


FIGURE 6.—Maps from a pen plotter. (A and C, courtesy of the Geological Society of America.)

8. Freeways (road surfaces, overpasses, and interchanges).

The list is by no means comprehensive. If the methods developed in this study were to be used in another area, other land-use categories might be added or substituted. In compiling this list, it was assumed that a regional agency is more concerned with particular land-use categories rather than with particular types of buildings.

Those land-use types selected and listed above were identified by analyzing studies conducted by ABAG and by other regional agencies. These projects are:

1. Areas of critical environmental concern (ABAG).

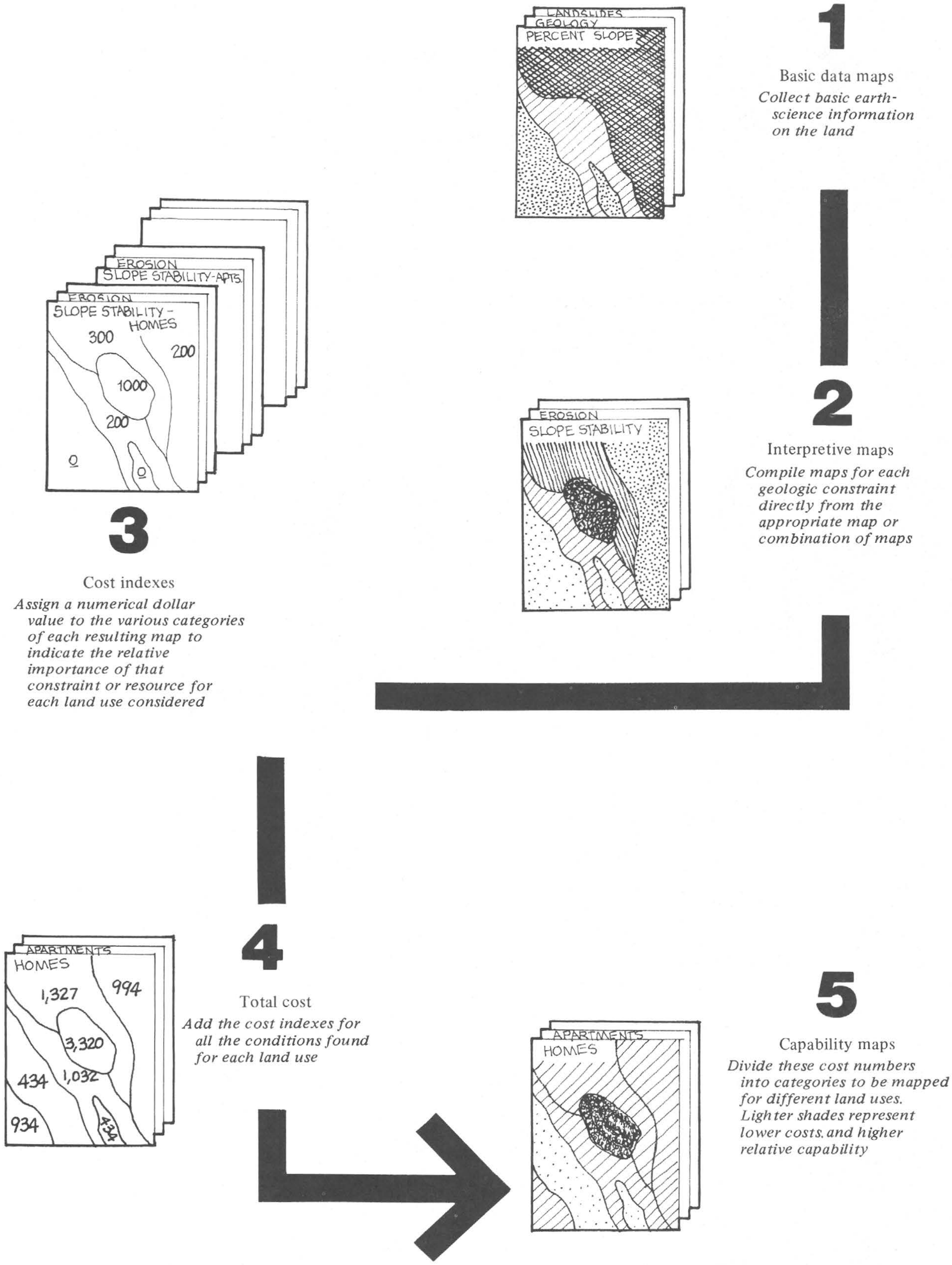


FIGURE 7.—Steps in land-capability analysis.

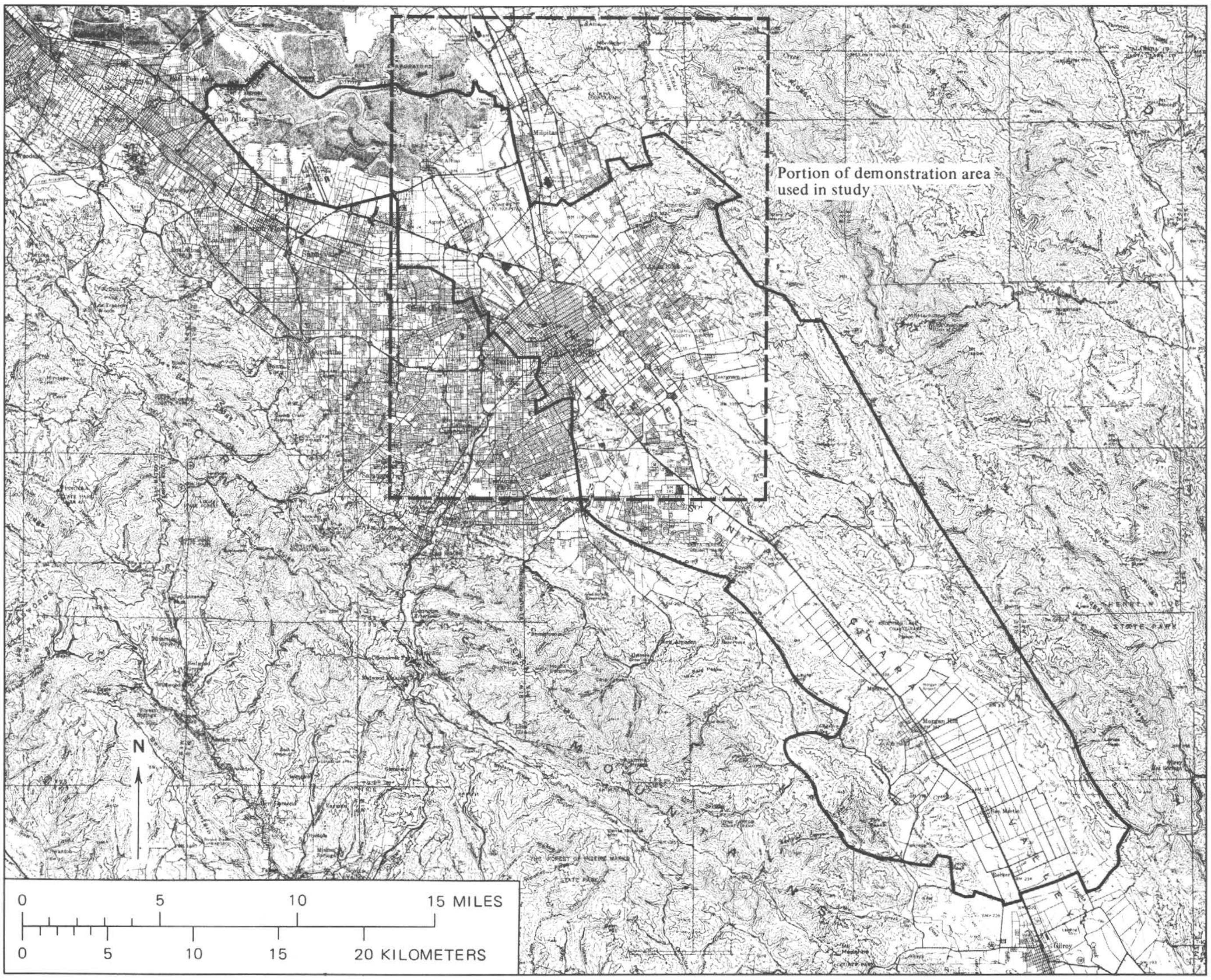
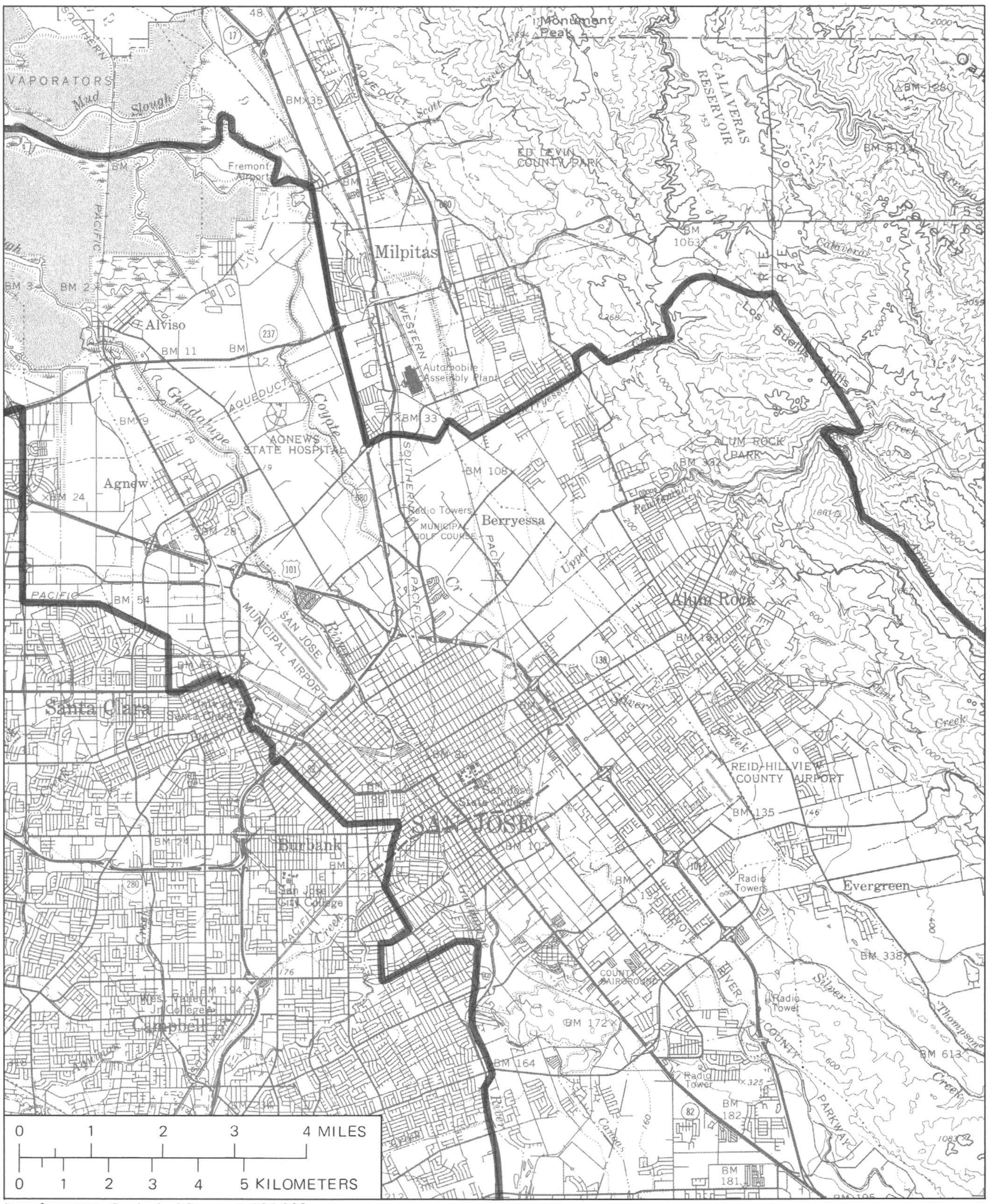


FIGURE 8.—Demonstration area for the land-capability study.

2. Threshold criteria for projects of regional significance (ABAG).
3. The San Mateo Coast Corridor evaluation (ABAG/Metropolitan Transportation Commission, or MTC).
4. The regional development "hot spots" survey (ABAG).
5. "Land Availability" and Projective Land Use Model (PLUM) Series III (ABAG).
6. The criteria for determining indirect air-pollutant—sources proposed by Environmental Protection Agency (EPA), Air Resources Board, and the Bay Area Air Pollution Control District.
7. The standards for determining metropolitan significance developed by the Metropolitan Council of the Twin Cities region, Minnesota.

All these studies deal with land-use types rather than with specific building types, but the different land-use types are characterized by distinctive and largely homogeneous building types. Corridor studies are at an even higher level of abstraction, for they deal with gen-



Base from U.S. Geological Survey 1:125,000

FIGURE 9.—Part of demonstration area used in the study.

eral growth scenarios (some city centered and some dispersed) rather than with single densities of residential development.

Each land-use type has distinctive building design, density, occupancy, and other characteristics which can be considered as typical for that land use (tables 1 and 2). Also, each land-use type can be characterized by a particular set of costs for land, improvements/utilities, buildings, and personal property and inventory (table 3).

Most high-occupancy or particularly important struc-

TABLE 1.—*Land-use characteristics*

[The physical characteristics shown in this chart are those typical of new development in the San Francisco Bay area. Although valid for much of the Bay region, they may not be applicable to other areas without revision. The information was obtained through interviews with builders and developers and through reviews of existing development. They are used to define the land-use types examined]

Physical characteristics	Land-use types							
	Agricultural or rural	Semirural residential	Single-family residential	Multi-family residential	Regional commercial	Downtown commercial	Industrial Manufacturing	Freeways
Area of typical site	⑤ 40 acres	⑤ 5 acres	⑤ 0.2 acres	⑤ 5 acres	① 66 acres	⑤ Unlimited	③ 310 acres	⑤ Unlimited
Percentage built up / Acres built up	1 percent 0.4 acre	1 percent 0.05 acre	18 percent 0.036 acre	50 percent 2.5 acre	17.5 percent 11.5 acres	64 percent —	38 percent 117.8 acres	0 percent 0 acres
Percentage paved / Acres paved	3 percent 1.2 acre	4 percent 0.20 acre	34 percent 0.068 acre	25 percent 1.8 acre	80.0 percent 52.8 acres	35 percent —	42 percent 130.2 acres	69 percent —
Percentage landscaped / Acres landscaped	2 percent 0.8 acre	5 percent 0.25 acre	48 percent 0.096 acre	25 percent 1.2 acre	2.5 percent 1.7 acres	1 percent —	20 percent 62.0 acres	31 percent —
Percentage unaltered / Acres unaltered	94 percent 37.6 acres	90 percent 4.50 acres	0 percent 0 acre	0 percent 0 acre	0 percent 0 acres	0 percent 0 acres	0 percent 0 acres	0 percent 0 acres
② Structure	② Type V-wood frame.	② Type V-wood frame.	② Type V-wood frame.	② Type V-wood frame on top of concrete block garage structure.	② Steel frame, concrete, or masonry shell, wood-frame interiors.	② Steel or concrete frame, concrete or masonry shell, wood-frame interiors.	② Concrete tilt-up buildings with wood and built-up roof.	② Asphalt or concrete roadway base and reinforced concrete structures.
Height	④ 1-3 stories.	④ 1-3 stories.	④ 1-2 stories.	④ 3 stories.	① 3 stories.	④ 10 story maximum, 3 stories typical.	③ 2 stories.	Not applicable.
Ground coverage (square feet).	House: 1,500-2,000 Barns: 2,000-10,000 Outbuildings: 50-1,000	② 1,500-4,000	② 1,500-4,000	② Approximately 100,000.	① 750,000 (17.4 acres).	② 5,000	③ 5,000-50,000	② 80-140 feed width for unlimited length.
Occupancy level.	⑤ Constant very low occupancy: 0.1 persons/acre, 4/unit.	⑤ Constant very low occupancy: 0.7 persons/acre, 3.5/unit.	⑤ Constant low occupancy: 19 persons/acre, 3.8/unit.	⑤ Constant high occupancy: 50 persons/acre, 2/unit.	① High one-half day occupancy: 90 persons/acre, maximum.	⑤ High one-half day occupancy: 100 persons/acre, maximum.	③ Medium one-half day occupancy: 25 persons/acre.	⑤ Periodic high occupancy of 50 persons/acre: Low constant occupancy, 10 persons/acre.
Site alteration required.	② Minimal: Leveling of building pad	② Minimal: Leveling of building pad	② Moderate to extensive: Streets, driveways, sidewalks, building pads, and so forth.	② Extensive.	② Extensive: Entire site must be graded, and so forth.	② Extensive: Entire site must be graded, and so forth.	② Extensive: Grading for roads, parking lots, buildings.	② Extensive: Grading, excavation, and base preparation.
④ Typical buildings mix in land-use areas.	④ Wide assortment of outbuildings: barns, sheds, garages, chicken coops, and pump and well houses.	④ Some auxiliary and outbuildings.	④ Some three-story apartment buildings as in urban residential. Some small commercial. Some planned unit developments, townhouses at slightly higher density.	④ Some commercial as in downtown commercial.	④ In close proximity to major surface transportation.	④ Some urban residential.	④ Railroad lines run onto property. Light and heavy industrial often mixed.	④ Assorted rest areas, truck stops, highway maintenance facilities, and so forth, often occur within confines of highway.
Examples					Sun Valley Shopping Center, Serramonte Center, Eastridge Center, El Cerrito Plaza.	Downtown Berkeley (Shattuck and University Ave.).	Crocker Industrial Park (Brisbane) and Orchard Industrial Park (San Jose).	Freeways, interchanges, overpasses.

① Based on average of 10 regional shopping centers typical of those likely to be found in an area that might use information from this study.
② Based on current standard design and engineering practices.
③ Based on average of typical light industrial development.
④ Based on physical inspection or research of existing examples.
⑤ Based on typical land-use models developed from information obtained from physical inspection of existing developments, plans and drawings of existing and proposed developments, and current engineering and design practices.

tures are not included because they are best evaluated through a case-by-case examination, which is beyond the scope of this study. Hospitals, schools, police and fire stations, bridges and other elevated transportation structures, such as elevated railways, and reservoirs, pipelines, and chemical plants are among those critical structures that can best be evaluated on a "site specific" basis. However, the land-capability approach can be

TABLE 2.—*Land-use development components*

[These construction actions or products characterize the land-use types defined in table 1. They indicate the relative extent of modification of the land and of interaction with the land of each use found in the San Francisco Bay area]

Development components	Land-use types							
	Agricultural or rural	Semirural residential	Single-family residential	Multifamily residential	Regional commercial	Downtown commercial	Industrial/ manufacturing	Freeways
Grading clearing, moving, stripping, trenching, backfilling).	99 percent unaltered land: Minimum.	90 percent unaltered land: Minimum (level building pad not required).	<5 percent unaltered land: Moderate to extensive.	<5 percent unaltered land: Moderate.	0 percent unaltered land land: Substantial, by virtue of size of site not slope.	0 percent unaltered land land: Moderate.	0 percent unaltered land: Substantial, by virtue of size of site rather than slope.	0 percent unaltered: Substantial.
Blasting, ripping, excavation.	Minimum.	Minimum.	Minimum.	Moderate (basement garages).	Substantial.	Moderate (some basements).	Moderate.	Substantial subsurface preparation.
Filling (compacted, uncontrolled, drainage).	Minimum.	Minimum.	Limited.	Limited.	Substantial.	Limited.	Substantial.	Substantial.
Draining (drain lines, curbs and gutters).	4 percent impervious: Natural.	5 percent impervious: Limited (open culverts if any system).	52 percent impervious: Simple (overground to storm sewers).	75 percent impervious: Extensive system required.	97½ percent impervious: Extensive system required.	99 percent impervious: Extensive system required.	80 percent impervious: Simple overground to storm sewers.	69 percent impervious: Simple overground to storm sewers.
Foundations (footings, retaining walls, trenched).	Generally spread or trenched.	Spread footing or slab.	Spread footing or slab.	Generally basement slab and retaining wall.	Reinforced concrete slab, some retaining walls.	Generally basement slab and retaining walls.	Reinforced concrete slab.	Special.
Building design (height, weight, occupancy).	2–3 story; Type V; 0.1 person/ acre; low constant occupancy level.	2–3 story; Type V; 0.7 persons/ acre; low constant occupancy level.	2 story maximum; Type V; 19 persons/acre; low constant occupancy level.	3 story typical; 50 persons/ acre; Types I–V; high constant occupancy level.	3 story typical; 90 persons/ acre; concrete and/or concrete block or street; high one-half day occupancy level.	10 story maximum; 3 story typical; 100 persons/ acre; concrete and (or) concrete block; high one-half day occupancy.	3 story maximum concrete tilt-up/steel; 25 persons/acre; one-half day medium occupancy level.	10 persons/ acre; high periodic occupancy level; low constant occupancy level.
Postconstruction activities (paving, landscaping).	Minimun paving (3 percent); minimum landscaping (2 percent).	Minimum paving (4 percent); gravel roads instead of paved, minimum landscaping (5 percent).	Moderate paving (34 percent); extensive landscaping (48 percent).	Moderate paving (15 percent); moderate (25 percent) landscaping.	Substantial paving (80 percent); minimum landscaping (2.5 percent).	Substantial paving (35 percent); minimum landscaping (1 percent).	Industrial parks: moderate paving, moderate landscaping. Others: substantial paving, minimum landscaping.	Substantial paving (69 percent); limited landscaping (31 percent).
Utilizing septic system and leach fields.	100 percent use of septic systems.	90 percent use of septic systems.	None under current regulations; up to 25 percent of existing houses use septic systems (nonconformable use).	Generally none.	None.	None.	Generally none.	None.

TABLE 3.—*Land-use costs*

[Costs presented in this table are based on typical average costs in the San Francisco Bay region in 1975 dollars and, as regionally based figures, may not be directly applicable to other regions or more specific areas without revision. These values are used in calculating the costs described in the sections which follow]

Costs	Land-use types							
	Agricultural or rural	Semirural residential	Single-family residential	Multifamily residential	Regional commercial	Downtown commercial	Industrial/ manufacturing	Freeways
Land	$200–$12,000 ($1,000 average/acre) ($40,000/lot).	$4,000/acre ($20,000/lot).	$36,250/acre ($7,250/lot).	$75,000/acre ($3,000/unit).	$100,000/acre.	$200,000/acre.	$60,000/acre.	$60,000/acre.
Improvements and utilities	$125/acre ($5,000/lot).	$1,000/acre ($5,000/lot).	$22,500/acre ($4,500/lot).	$8,750/acre ($350/unit).	$25,000/acre.	$30,000/acre.	$25,000/acre.	----------
Building(s)	$1,500/acre $60,000 for buildings/lot.	$15,000/acre ($75,000/lot).	$161,250/acre ($32,250/lot).	$700,000/acre.	$520,000/acre ($43/sq. ft.).	$780,000/acre ($65/sq. ft.).	$360,000/acre ($20/sq. ft.).	$100,000/lane mile or approximately $68,950/acre.
Personal property	$1,000/acre ($40,000/lot).	$5,000/acre ($25,000/lot).	$75,000/acre ($15,000/lot).	$250,000/acre ($10,000/ unit).	$250,000/acre.	$250,000/acre.	$250,000/acre.	----------

used to screen alternative areas for critical structures even though final decisions must incorporate site analysis.

GEOLOGIC AND HYDROLOGIC CONSIDERATIONS

The geologic and hydrologic study considers a variety of hazards, constraints to development, and resources. A comparison of this list with the constraints discussed on pages 4–6 will reveal that several categories which might be important in other areas have not been included. The categories selected are the ones that are judged to be most critical in the demonstration area but are also representative of the problems likely to be encountered elsewhere.

Concerns	*Specific hazards, constraints, and resources*
Earthquake problems	Ground-shaking potential
	Surface-rupture potential.
Flooding	Stream flooding.
	Dam-failure inundation.
	Dike-failure inundation.
Bearing material problems	Shrink/swell potential.
	Settlement potential.
	Liquefaction potential.
	Subsidence potential.
Slope stability problems	Landslide potential.
	Soil-creep potential.
Erosion and sedimentation......	Erosion and sedimentation.
Septic tank limitations	Septic-tank limitations.
Resource evaluation	Sand and gravel potential.
	Mineral-extraction potential.
	Agriculture potential.

Basic earth-science information is collected and identified for the demonstration area. Some of it can be easily related to costs, but much of it needs to be interpreted to produce maps of the cost associated with a particular geologic constraint.

The relationship between the maps of the geologic and hydrologic constraints and their sources is summarized

TABLE 4.—*Summary of maps used to describe geologic hazards, constraints, and resources*

Geologic hazards, constraints, and resources	Fault special studies zones—figure 10	Maximum earthquake intensities—figures 11–14	100-year flood plains—figure 15	Dike-failure inundation area—figure 16	Dam failure inundation area—figure 17	Relative slope stability—figure 18	Generalized soil associations—figure 19	Depth to ground water less than 10 feet—figure 20	Geologic material units—figure 21	Erosion provinces—figure 22	Mineral resources—figure 23
Surface-rupture potential	×										
Ground-shaking potential		×									
Stream-flooding potential			×								
Dike-failure inundation potential				×							
Dam-failure inundation potential					×						
Landslide potential						×					
Soil-creep potential						×	×				
Shrink/swell potential						×	×				
Liquefaction potential								×	×		
Settlement potential						×			×		
Erosion and sedimentation potential										×	
Septic-tank limitations							×				
Sand and gravel potential											×
Mercury-extraction potential											×
Agricultural potential							×				

TABLE 5.—*Standard response to geologic problems in the Santa Clara Valley, California*

[This is an average response based on a sample of practices in the demonstration area. Some individuals and some governmental bodies may respond differently, but the table is believed to represent a realistic overall summary. It shows whether damage, study and mitigation, or opportunity costs are calculated in the cost analyses used in this study. These responses may not be typical of other regions and they may change with time in the demonstration area]

Earth-science constraint or opportunity	Land-use type							
	Rural agricultural	Semirural	Single-family residential	Multifamily residential	Regional shopping centers	Downtown commercial	Industrial	Freeways
Surface rupture	B	B	A	A	A	A	A	A,B
Ground shaking	B	B	B	B	B	B	B	B,D
Stream flooding	B	B	B	B	B	B	B	D
Dike Failure	B	B	B	B	B	B	B	D
Dam failure	A,D	A,D,	A,D	A,D	A,D	A,D	A,D	A,D
Landslides	A	A	A	A	A	A	A	A
Soil creep	A	A	A	A	A	A	A	D
Shrink/swell	A	A	A	A	A	A	A	D
Liquefaction	B	B	B	B	B	B	B	D
Settlement	B	B	A	A	A	A	A	D
Erosion and sedimentation	C	C	C	C	C	C	C	C
Septic-tank limitations	D	D	D	D	D	D	D	D
Sand and gravel	D	C	C	C	C	C	C	C
Mercury extraction	D	D	D	D	D	D	D	D
Agriculture	D	C	C	C	C	C	C	C

A: Study and mitigate B: Suffer damage C: Lose resource opportunity D: No response required in table 4. The source maps are depicted on figures 10 to 23. Some of the source maps are themselves composites of other maps. The earthquake-intensity maps are based on the materials map and the fault map. The slope-stability map is based on a map showing percent of slope, a map of photointerpreted landslides, and the materials map.

Further information on the sources and the way in which the interpretive maps are compiled are presented in the sections which follow.

CALCULATIONS OF DOLLAR COST

The next step in land-capability analysis is estimating the social cost for each of these geologic hazards, constraints, or resources for each land use. Although the analysis of cost varies with the type of problem examined, some parts of the analysis are relatively constant and are discussed below.

Costs for different combinations of land use and geologic constraint result from damage, from investigative or mitigative measures, or from loss of opportunity. For

TABLE 6.—*Land-development regulations in demonstration area*

	Morgan Hill	San Jose	Santa Clara County
Soils	Analysis of soil stability is part of subdivision review process. The guide used in determining soil suitability is "Soils of Santa Clara County," by U.S. Soil Conservation Service. Studies prepared by county are also utilized.	Same as county.	Developer must submit preliminary soil report indicating existence of critically expansive soils or other soil problems which, if not corrected, would lead to structural defects. If above conditions are found to exist, report must recommend corrective action to prevent damage to each structure proposed where problems exist. Report may be waived in areas where such soil problems are known not to exist.
Flooding	Areas subject to periodic inundation by flood waters must be so indicated on subdivision map. Rights-of-way for storm drainage purposes, conforming substantially to any stream or channel shall be dedicated by developer.	Proposed development area(s) subject to flood inundation require combined geological and preliminary soil report and a preliminary grading plan. Potentially dangerous flood areas must be delineated on subdivision map.	If proposed development abuts flood control facilities as defined by Santa Clara Valley Water District, a developer may be required to dedicate a fee or easement of land for the facility to Santa Clara Valley Water District. Regarding the county hazard maps, areas subject to 25-year and less flood are in maximum hazard zone (red); areas subject to 25–100-year floods are in intermediate hazard zone (yellow); and areas above 100-year flood plan are minimum hazard (green).
Seismic zones.	Policies and criteria of Alquist-Priolo Act apply.	Development in special studies zone, as delineated by State, must submit geologic and engineering studies in sufficient detail to meet State criteria. Permit will be denied if undue hazard from surface faulting or fault creep would be created by development of subdivision.	Development on the active trace or in the currently active zone(s) of San Andreas, Hayward, or Calaveras faults must submit a geological and soil engineering report. This report must provide remedial measures that will make a safe development. County hazard maps relate seismic information as follows: maximum hazard—special studies zone; intermediate hazard—shear zones, melange; minimum hazard—unfaulted terrain.
Erosion and sedimentation.	Manufactured slopes (in hillside areas) must be planted or otherwise protected against erosion. This is made a part of the improvement bond.	Erosion control section of Uniform Building Code, Chapter 70 applicable to hillside areas (slopes above 15 percent). The faces of cut and fill slopes exposing more than 5,000 square feet must be prepared and maintained to minimize erosion, that is, protective planting, and so forth. The section further presents a time frame to coordinate planting with rainy season.	Faces of cut and fill slopes must be planted and maintained with approved ground cover. Provision must be made to prevent surface and subsurface waters from damaging an excavation or fill. Protection from surface water runoff shall be by dike or swale construction.
Grading	The city's grading policy is covered by Chapter 70 of the Uniform Building Code, 1964.	San Jose's grading ordinance essentially conforms to Chapter 70, Uniform Building Code; additions to Uniform Building Code include reference to hillside areas (see "Hillside Development"), definitions of geologic and critical geologic hazards, and a time frame for erosion-control plantings. When subdivision map is filed, an analysis of the grading plan must be submitted. This report must indicate that soil and geological conditions will not prohibit the grading plan.	Engineering geological report and soils engineering report may be required (Director of Public Works decides) before grading permit granted. Geological report must include an adequate description of the site's geology and provide conclusions and recommendations on how the geology may affect the grading. Soils report must include nature, distribution and strength of existing soils and should provide conclusions and recommendations for grading procedures and design criteria for corrective action.
Hillside development	Hillside development policy pertains to those areas above 350 feet west of Monterey Highway and above 450 feet to the east. Hillside policy discourages development in geologically unstable areas but provides no definition of, or test for, instability. Hillside policy provides for variance of codes (street widths and grades, residential clusters, etc.) to minimize grading and scarring and allow development to better fit hillside terrain.	San Jose is in the process of preparing a hillside development policy. The city defines hillsides as those areas with slopes above 15 percent. Developer must file preliminary grading plan, preliminary soil report, and a geological report (see report description just below).	Hillside development defined as one in which percent slope of the land is 10 percent or more. Areas with slopes above 10 percent may be exempt from hillside regulation if net lot areas are less than 20,000 square feet. A geological and (or) soil engineering report will be required if development is proposed for hazardous area (from county hazard maps). This report shall specify remedial measures (if necessary) that will make a safe development.
Miscellaneous references and requirements	Overall residential density in hillside areas shall be no greater than two dwelling units per gross residential acre.	The geological report must indicate the existence of any geological hazards or soil conditions which are dangerous or potentially dangerous to life, property, and so forth, owing to the movement, failure, or shifting of earth. If above conditions are found to exist, report shall recommend corrective measures to eliminate such hazards or conditions.	County hazard maps determine whether a geologic report must be submitted. The county map for relative geologic stability is organized by the stoplight system. Red: geologic report is normally required; Yellow: geologic report may be required; Green: geologic report not normally required.

Base from U.S. Geological Survey 1:125,000

FIGURE 10.—Fault special studies zones in a part of the Santa Clara Valley demonstration area.

each combination of land use and constraint the appropriate source of cost is shown by the way society normally responds to the problem. If farm buildings are routinely placed on active faults, the response is to accept future damage from faulting; but if a local regulation requires site studies and design modifications for apartment buildings located near active faults, the response is to study and mitigate. Thus, at the same site, damage costs are appropriate for rural agricultural use but study and mitigation costs are appropriate for multifamily residential use (table 5). The kind of cost to be calculated for each response in table 5 was determined by surveying current (1975) practices in the Santa Clara Valley and by reviewing land development regulations, many of which require mitigation and, hence, either eliminate or greatly reduce damage costs (table 6). The tabulated responses for the Santa Clara Valley may differ from practices elsewhere, and they may also change with time.

Where the standard practice is tolerance of damage, various social disruptions are included as part of the damage costs. These costs include relocation expenses, loss of profit, and loss of work, but they do not include all potential disruption costs. Death and injuries are not included in the cost figures because they are difficult to estimate and even more difficult to express in dollar terms.

Where the standard practice is to investigate and mitigate, costs have been estimated through interviews with experienced and knowledgeable professionals in geologic, civil engineering, and soils engineering firms, the staffs of local governments, and the building and development industries. The method used is discussed in the section "Costs Associated with Slope-Stability Problems." Because the interview results used to estimate costs for other hazards were similar, they are either not discussed or are discussed in less detail.

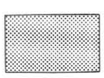
The estimates of dollar cost can be associated with specific land areas. Because acre is the common unit of area associated with land, the costs are estimated in dollars per acre. The total cost per acre due to the hazards, constraints, and resources considered for a given land use can be obtained by adding the costs associated with each land area resulting from all the geologic considerations.

Costs of land utilization can usually be directly assigned to specific land areas because most costs are associated with the land utilized. For example, landslide costs can be assigned to areas that require a study prior to development and subsequently are determined to pose a hazard that must be mitigated. Similarly, damage resulting from ground shaking can be assigned to particular buildings in the areas affected. However, costs of flooding, of erosion and sedimentation, and of land pollution can accumulate outside of the area where the development occurred that caused these costs. These common property problems can only partially be avoided.

The problem of increased development creating increased flooding downstream is not included in this analysis. The physical characteristics of the Santa Clara Valley make it less susceptible to this type of effect than most other areas. The problem of erosion costs that are borne by those downstream is avoided by assigning the sedimentation costs (estimated as the costs of dredging) equally among the number of acres of land producing the erosion contributing to that cost. It also is assumed that the land use at the site of sedimentation does not affect the cost associated with sedimentation. It is found that, at their present level of use, septic-tank systems do not cause significant land pollution. No costs have been incurred to date, so costs associated with septic-tank use have been ignored. If a greater number of septic tanks were in use, ground-water pollution might become a significant problem. However, since such pollution would be entirely an external effect, it would have to be dealt with for large areas and specified growth alternatives, much as water or air pollution. (If these types of external effects are extremely significant, the land-use capability maps can be replaced by capability maps of alternative growth scenarios.)

External effects are also associated with studies of various problems, particularly those dealing with landslides and surface rupture. The first person in an area who makes such a study will provide information that can be used to reduce cost of subsequent studies; as such, he bestows an external benefit on those who must perform subsequent studies. This type of external effect has not been included here.

EXPLANATION



SPECIAL STUDIES ZONES

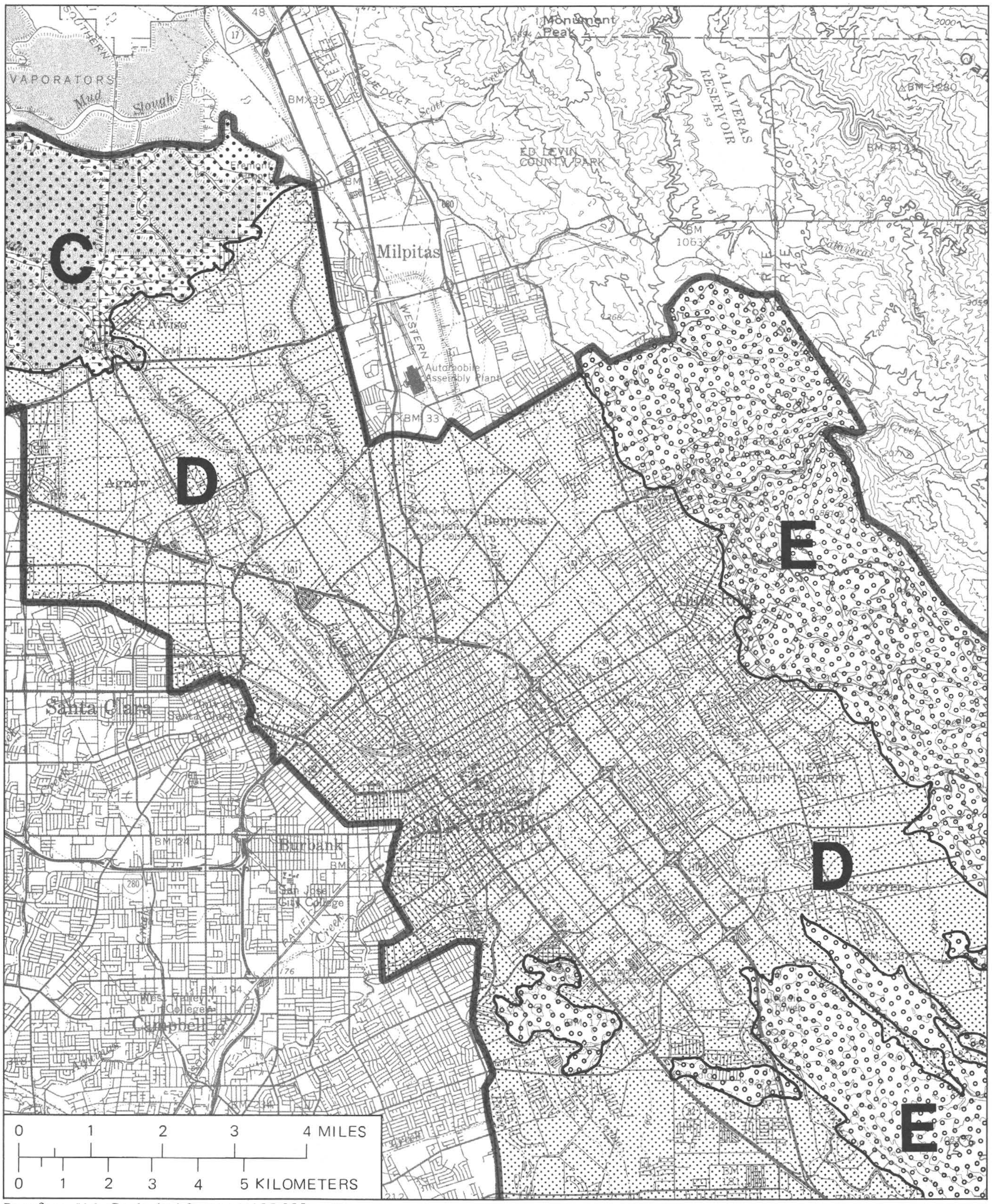
SOURCE: California Division of Mines and Geology, 1974.

Maps delineated in compliance with Chapter 7.5, Division 2, California Public Resources Code. The act requires mapping of 1/4-mile wide zones along active faults, special planning treatment in these zones, and geologic site investigations for most kinds of development. The zones shown here include the Calaveras, Hayward, and two shorter fault zones in the lower right corner of the map.

FIGURE 10.—Continued.

Calculation format

The general form of the calculations consists of a for-



Base from U.S. Geological Survey 1:125,000

FIGURE 11.—Maximum intensities for earthquakes on the San Andreas fault in a part of the Santa Clara Valley demonstration area.

mula in which the various components are written in prose with their units, rather than as symbols. The actual calculations are not included in the text but can be reviewed in the section at the end of the report "Derivation of Formulas and Calculations of Expected Costs." Costs are rounded off to a single significant figure to reflect uncertainty in the estimates.

It is assumed that all of the random events that determine cost, such as earthquakes, are governed by the Poisson probability distribution, in which each event is assumed to be independent of every other event and the probability of an occurrence at any time is a constant.

If the cost per acre per event is a constant, then the expected, discounted cost per acre associated with the first event is

$$\begin{pmatrix}\text{cost per}\\ \text{acre per event}\end{pmatrix} = \frac{(\text{probabilistic rate of occurrence})}{(\text{probabilistic rate of occurrence + discount rate})}$$

(If, on an average, an event occurs once every 100 years, the probabilistic rate of occurrence is 0.01 per year.)

This formula is applicable when there is no rebuilding after the event, so that no further damage occurs.

The expected discounted cost for all future events is

$$\begin{pmatrix}\text{cost per}\\ \text{acre per event}\end{pmatrix} = \frac{(\text{probabilistic rate of occurrence})}{(\text{discount rate})}$$

This formula is appropriate when rebuilding occurs. Note that if the discount rate is large compared to the probabilistic rate of occurrence, the cost for an infinite number of events is approximately equal to the cost of the first event.

Both of these formulas are derived in the section "Derivation of Formulas and Calculations of Expected Costs."

The results of these calculations are shown in a series of tables (34–41) and in corresponding pairs of maps (figs. 28–43). Each table and its accompanying pair of maps illustrates for one land use the costs that can be identified with such specific topics as surface fault rupture, stream flooding, or loss of sand and gravel resources. The methods used to estimate these costs are described more fully below, and because each geologic consideration requires somewhat specialized treatment, each is discussed separately. To help the reader understand the degree of uncertainty in the costs attributed to each consideration, the probable difference between maximum and minimum costs and the causes of these differences are discussed at the end of each section.

EXPLANATION

San Francisco Intensity Scale (see text)

Grade A – Very violent*
Grade B – Violent*
Grade C – Very strong
Grade D – Strong
Grade E – Weak

SOURCE: Borcherdt, R. D., Gibbs, J. F., and Lajoie, K. R., 1975.

Intensity is a nonlinear measure of earthquake size as determined by the effects on people, buildings, and geologic materials. Borcherdt, Gibbs, and Lajoie (1975) prepared a composite map of the maximum intensities expected from earthquakes on the San Andreas, Hayward, and Calaveras faults. In this report separate maps show intensities that result from earthquakes on each of these faults, but the method is that of Borcherdt, Gibbs, and Lajoie.

The San Andreas fault lies 12 miles southwest of central San Jose, close enough to cause much shaking and secondary effects.

*Not shown on this map.

FIGURE 11.—Continued.

COSTS ASSOCIATED WITH EARTHQUAKE PROBLEMS

GROUND SHAKING

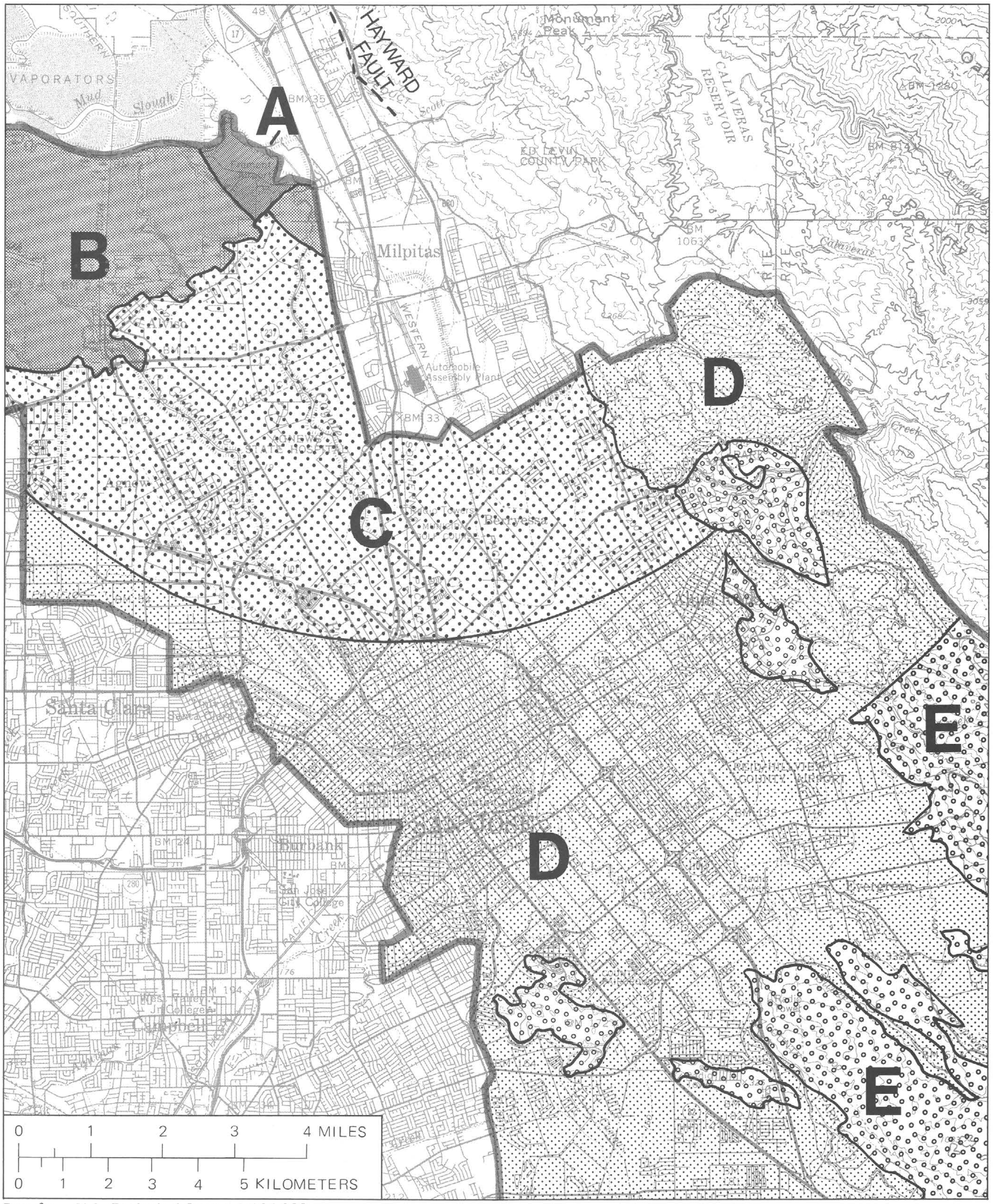
A large earthquake on any one of three faults—the Calaveras, the Hayward, or the San Andreas—could cause destructive ground shaking within the study area (fig. 24). The amount of damage at a specific site due to such an event depends on a large number of factors interacting in a complicated way. To estimate the cost per event, a simplified procedure for approximating the effect of these interactions has been developed. To compute the expected cost from all future events, further assumptions had to be made about the probabilistic rate of occurrence of events of several magnitudes on the three faults.

The current model of earthquake generation has many implications, several of which are relevant to planning:

1. Energy is released along the entire length of the segment of the fault where movement occurs. The epicenter is only the point on the surface directly above the point at which the energy release processes begin. Thus, the relevant distance for planning is the distance from the site being evaluated to the nearest point on the fault, not the distance to the epicenter.

2. The magnitude of an earthquake is directly related to the length of surface rupture (Bonilla, 1967). This has been interpreted as indicating that energy released is related to the length of the fault segment that readjusts during an earthquake.

3. Earthquake magnitude also exhibits a systematic relation to the amount of fault displacement (Bonilla, 1967). Wallace (1970) has used these and other relations to estimate the probability of occurrence of various mag-



Base from U.S. Geological Survey 1:125,000

FIGURE 12.—Maximum intensities for earthquakes on the northern part of the Hayward fault in a part of the Santa Clara Valley demonstration area.

nitudes of earthquakes on specific fault segments.

The amount of expected damage to buildings in a particular area due to a given seismic event will depend on the exact ground-motion parameters that characterize the earthquake, the distance of the area from the fault where movement occurs, the type of geologic material that underlies the site, and the structural design of the buildings. Such detailed information is not available, nor is it really appropriate for analysis at the regional level. Instead, an approximate procedure based on a qualitative measure of intensity has been used.

After the 1906 earthquake, the intensity of earthquake effects was mapped throughout San Francisco (Wood, 1908). Mapping of different levels of intensity was based on visible damage, amount of surface rupture, and personal accounts. The different levels of intensity constitute the San Francisco scale, which is divided into five categories labeled A through E in order of decreasing intensity. This scale cannot be used directly for estimating damage because building practices have changed since 1906, but by relating it to the modified Mercalli intensity scale, damages to modern wood-frame and other types of structures can be estimated (Page and others, 1975), as is done in table 7. Damage resulting from fire was excluded from the San Francisco Study by Wood (1908) and is also excluded from the estimates in this report. The approximate relationship between the two intensity scales is shown in table 8.

Thus, given the intensity (on the San Francisco scale) for a postulated earthquake, the location, and the type of construction that typifies a land use, the damage costs may be calculated. Recently, Borcherdt, Gibbs, and Lajoie (1975) have analyzed the 1906 intensity map and developed a formula to predict the intensity on the San

EXPLANATION

San Francisco Intensity Scale

Grade A – Very violent
Grade B – Violent
Grade C – Very strong
Grade D – Strong
Grade E – Weak

SOURCE: Borcherdt, R. D., Gibbs, J. F., and Lajoie, K. R., 1975.

Intensity is a nonlinear measure of earthquake size as determined by the effects on people, buildings, and geologic materials. Borcherdt, Gibbs, and Lajoie (1975) prepared a composite map of the maximum intensities expected from earthquakes on the San Andreas, Hayward, and Calaveras faults. In this report separate maps show intensities that result from earthquakes on each of these faults, but the method is that of Borcherdt, Gibbs, and Lajoie.

FIGURE 12.—Continued.

TABLE 7.—*Damage cost factors for buildings associated with selected intensities*

Modified Mercalli intensity	Estimated San Francisco intensity	Damage cost factor, in percent, for— Wood-frame dwellings	Other buildings
VI	E	0.2	1
VII	D	2	5
VIII	C	5	15
IX	—	8	35
X	B	12	50
XI–XII	A	16	65

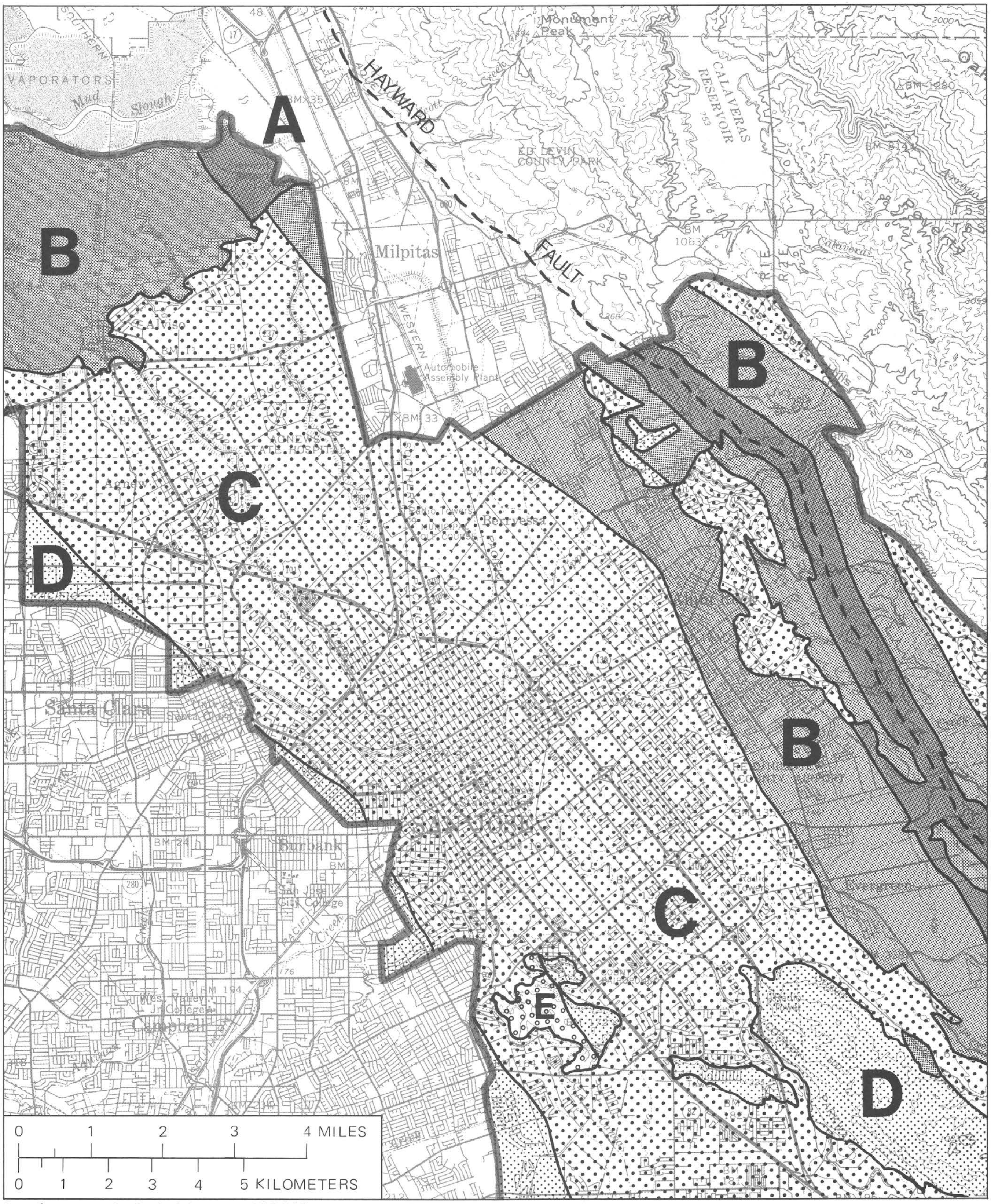
TABLE 8.—*Approximate relationships between intensity scales*
[Modified after Borcherdt, Gibbs, and Lajoie, 1975]

San Francisco scale	Modified Mercalli scale
A	XII
	XI
B	X
	IX
C	VIII
D	VII
E	VI

Francisco scale for a parcel of land underlain by the Franciscan Formation:

San Francisco Intensity = 2.69 − 1.9 log (distance in kilometers).

The San Francisco Intensity values that result from the formula are in the range from 4 to 0 and correspond to the letters A to E in the San Francisco intensity scale. The formula is based on the distance of this parcel from the fault that generates the earthquake, and it assumes an earthquake similar to that of 1906. Because intensity measures some effects of surface rupture and liquefaction as well as the more dominant effects of ground shaking, some costs may be double-counted, but the effects of this are believed to be small in terms of overall costs. Borcherdt, Gibbs, and Lajoie (1975) also described a method of predicting intensity levels for sites that are



Base from U.S. Geological Survey 1:125,000

FIGURE 13.—Maximum intensities for earthquakes on the southern part of the Hayward fault in a part of the Santa Clara Valley demonstration area.

underlain by formations other than Franciscan. Table 9 shows the intensity increments that must be added to the Franciscan intensities to estimate intensity on other geologic units.

The difficulty with this procedure is that the cost due to earthquakes of all magnitudes is required to fully evaluate land capability. To resolve the difficulty, the likelihood of the occurrence of events of several different magnitudes must be known. Assuming that there is some likelihood of smaller than 1906 type events, some method for extending the Borcherdt-Gibbs-Lajoie formula must be found.

The current model of earthquake generation makes it seem improbable that one would have both a continuing series of small events and a large event on the same section of the same fault. Thus, the occurrence of different magnitude events is not completely random. This greatly complicates the task of finding the expected cost.

For the purposes of this study, it has been assumed that the only earthquake that will occur is a "probable earthquake" for that fault. For the San Andreas, the probable earthquake has an approximate Richter magnitude of 8+, for the Hayward fault, 7.5, and for the Calaveras fault, 6.5 (Wesson and others, 1975).

The recurrence intervals for these events are taken from Wallace's (1970) calculations. The southern extension of the Hayward fault, south of the Alameda-Santa Clara County line, has had no historic major earthquake movement and has therefore been assigned a much longer recurrence interval.

To estimate damage related to the magnitude 6.5 earthquakes on the Calaveras fault, it is assumed that intensity is linearly related to magnitude. This assumption is commonly made in site analysis (see, for example, Cornell, 1968). Thus, if a magnitude 8+ earthquake produces a maximum intensity of XI at a particular site, then a 6.5 can only cause an intensity of VIII at the same site. Intensities for events of magnitude 7.5 cannot be distinguished from events of magnitude 8+. Transferring to the San Francisco scale, the maximum intensity expectable from an event on the Calaveras fault is calculated by drafting the maximum expected intensity maps as if they are based on a magnitude 8 event and then reducing each intensity by one unit. A becomes B, B becomes C, C becomes D, and D and E both become E. Such a reduction is arbitrary. It is assumed that all the residential land uses are characterized by wood-frame construction and that all commercial buildings fall in the "other" category (table 7).

EXPLANATION

San Francisco Intensity Scale

Grade A – Very violent
Grade B – Violent
Grade C – Very strong
Grade D – Strong
Grade E – Weak

SOURCE: Borcherdt, R. D., Gibbs, J. F., and Lajoie, K. R., 1975.

Intensity is a nonlinear measure of earthquake size as determined by the effects on people, buildings, and geologic materials. Borcherdt, Gibbs, and Lajoie (1975) prepared a composite map of the maximum intensities expected from earthquakes on the San Andreas, Hayward, and Calaveras faults. In this report separate maps show intensities that result from earthquakes on each of these faults, but the method is that of Borcherdt, Gibbs, and Lajoie.

FIGURE 13.—Continued.

TABLE 9.—*Statistics for intensity increments with respect to Franciscan Formation of various geologic units*

Geologic unit	Intensity increment (added to intensity for Franciscan Formation)—(1906 San Francisco scale)	
	Mean	Standard deviation
Granite	0.29	0.21
Great Valley sequence	.64	.34
Santa Clara Formation	.82	.48
Alluvium	1.34	.58
Bay mud	2.43	.58

NOTE.—Using these relations, one can construct a map of expected intensities from a 1906—magnitude earthquake on each of the three faults, and from this map the costs of earthquake damage can be calculated.

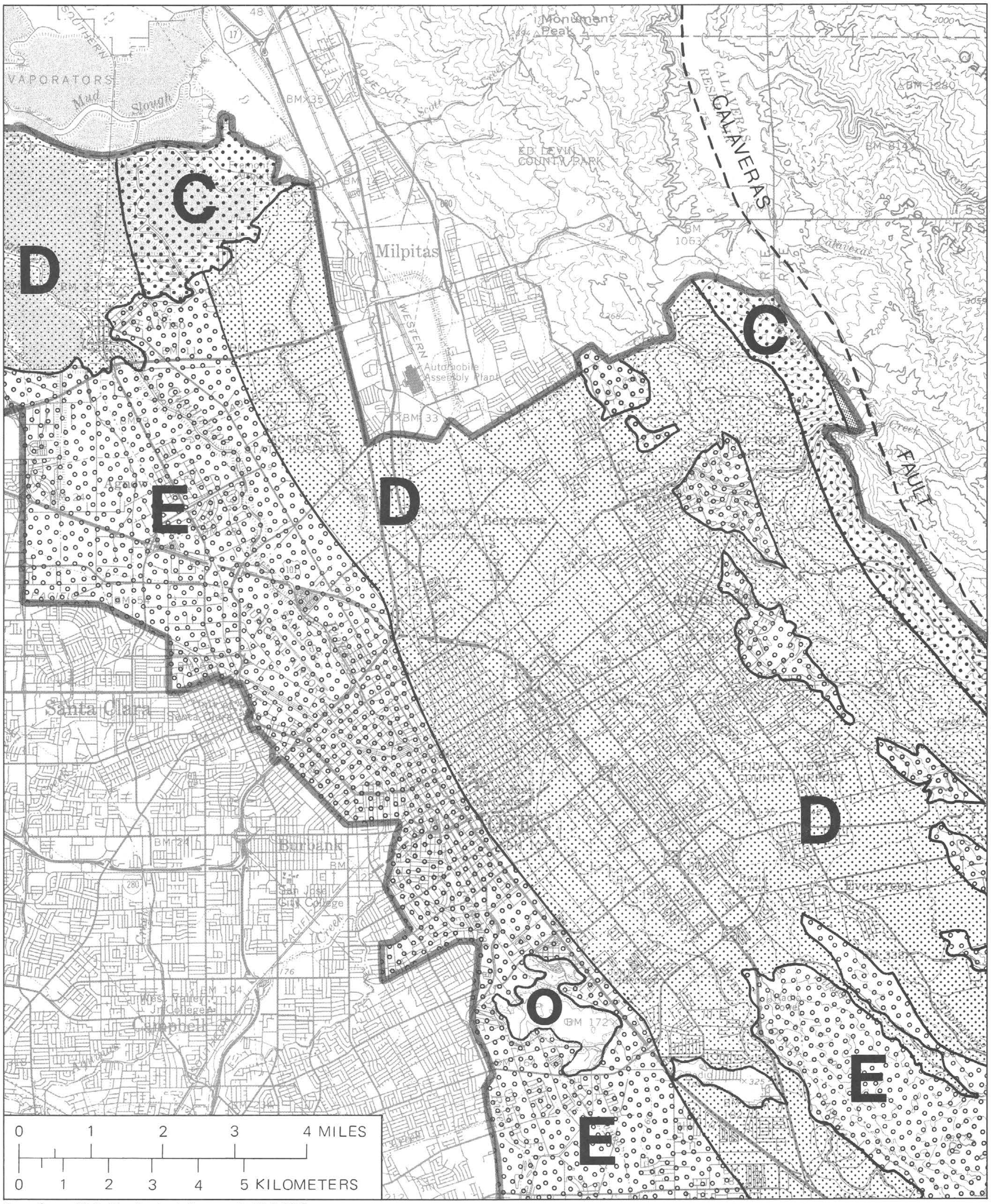
Cost information is available for damage to freeways during the 1971 San Fernando earthquake. This earthquake was characterized by a Modified Mercalli intensity of VIII–IX. It was assumed that for intensities A, B, or C, the damage to freeways will be identical to that in the San Fernando case, $123,750 per acre per event. For lower intensities, the loss will be zero.

The recurrence intervals given in table 10 are assumed.

It is also assumed that the earthquakes occur randomly in time. It should be noted that this last assumption is not conservative, since some time has elapsed since the last large event on all three faults.

Given these assumptions, the expected costs can be calculated using the following formula:

$$\begin{pmatrix}\text{expected}\\ \text{cost in}\\ \text{dollars}\\ \text{per acre}\end{pmatrix} = \frac{\begin{pmatrix}\text{value of buildings,}\\ \text{personal property,}\\ \text{utilities, and disruption}\\ \text{in dollars per acre}\\ \text{per event (table 3)}\end{pmatrix} \begin{pmatrix}\text{damage}\\ \text{cost}\\ \text{factor}\\ \text{(table 7)}\end{pmatrix} \begin{pmatrix}\text{frequency of}\\ \text{occurrence}\\ \text{in events}\\ \text{per year}\\ \text{(table 10)}\end{pmatrix}}{\text{(discount rate)}}$$



Base from U.S. Geological Survey 1:125,000

FIGURE 14.—Maximum intensities for earthquakes on the Calaveras fault in a part of the Santa Clara Valley demonstration area.

TABLE 10.—*Recurrence intervals for earthquakes on selected faults*
[Southern Hayward fault is that part south of the Alameda-Santa Clara County line]

Fault	Magnitude		Recurrence interval (years)	
	Estimate	Range	Estimate	Range
Southern Hayward	7.5	6–7.5	1,000	1,000–1,000,000
Calaveras	6.5	6–7.3	100	10–100
Hayward	7.5	6–7.5	100	10–100
San Andreas	8+	8–8.3	100	100–1,000

In calculating disruption costs, loss of work values of ($50 per day) × (30 days) × (number of employees per acre) are used. Figures of 5 employees per acre for both types of commercial and 25 employees per acre for industrial are used. Loss of profit values are calculated as 3 percent of the value of the buildings, personal property, and utilities.

Costs associated with ground shaking on the southern extension of the Hayward fault are shown in table 11.

Table 12 gives the costs associated with ground shaking on the San Andreas, Hayward, or Calaveras faults.

A change in percent for the damage factor will result in an equivalent change in percent for the expected cost. Increasing the recurrence interval on the San Andreas fault from 100 to 1,000 years would reduce the estimates in table 12 by a factor of 10. Decreasing the recurrence intervals on the Calaveras fault from 100 to 10 years would increase the estimates in table 11 by a factor of 10. Decreasing the maximum intensity expected on the Calaveras from B to C would reduce the costs to one-third of the estimates shown.

SURFACE RUPTURE

In the demonstration area costs due to potential surface rupture depend largely on the standard of predevelopment investigation and on the requirements of the

EXPLANATION

San Francisco Intensity Scale

Grade B – Violent
Grade C – Very strong
Grade D – Strong
Grade E – Weak
Grade O – Negligible

SOURCE: Borcherdt, R. D., Gibbs, J. F., and Lajoie, K. R., 1975.

Intensity is a nonlinear measure of earthquake size as determined by the effects on people, buildings, and geologic materials. Borcherdt, Gibbs, and Lajoie (1975) prepared a composite map of the maximum intensities expected from earthquakes on the San Andreas, Hayward, and Calaveras faults. In this report separate maps show intensities that result from earthquakes on each of these faults, but the method is that of Borcherdt, Gibbs, and Lajoie.

FIGURE 14.—Continued.

TABLE 11.—*Costs per acre associated with ground shaking resulting from events on the southern extension of the Hayward fault*

Land use	San Francisco intensity				
	A	B	C	D	E
Rural or agricultural	$4	$3	$1	$1	$0
Semirural residential	30	30	10	4	0
Single-family residential	400	300	100	50	5
Multifamily residential	2,000	2,000	500	200	20
Regional shopping centers	5,000	4,000	1,000	400	80
Downtown commercial	7,000	5,000	2,000	500	100
Industrial	4,000	3,000	1,000	300	70
Freeways	1,000	1,000	1,000	0	0

TABLE 12.—*Costs per acre associated with ground shaking resulting from events on the San Andreas, Hayward, or Calaveras faults*

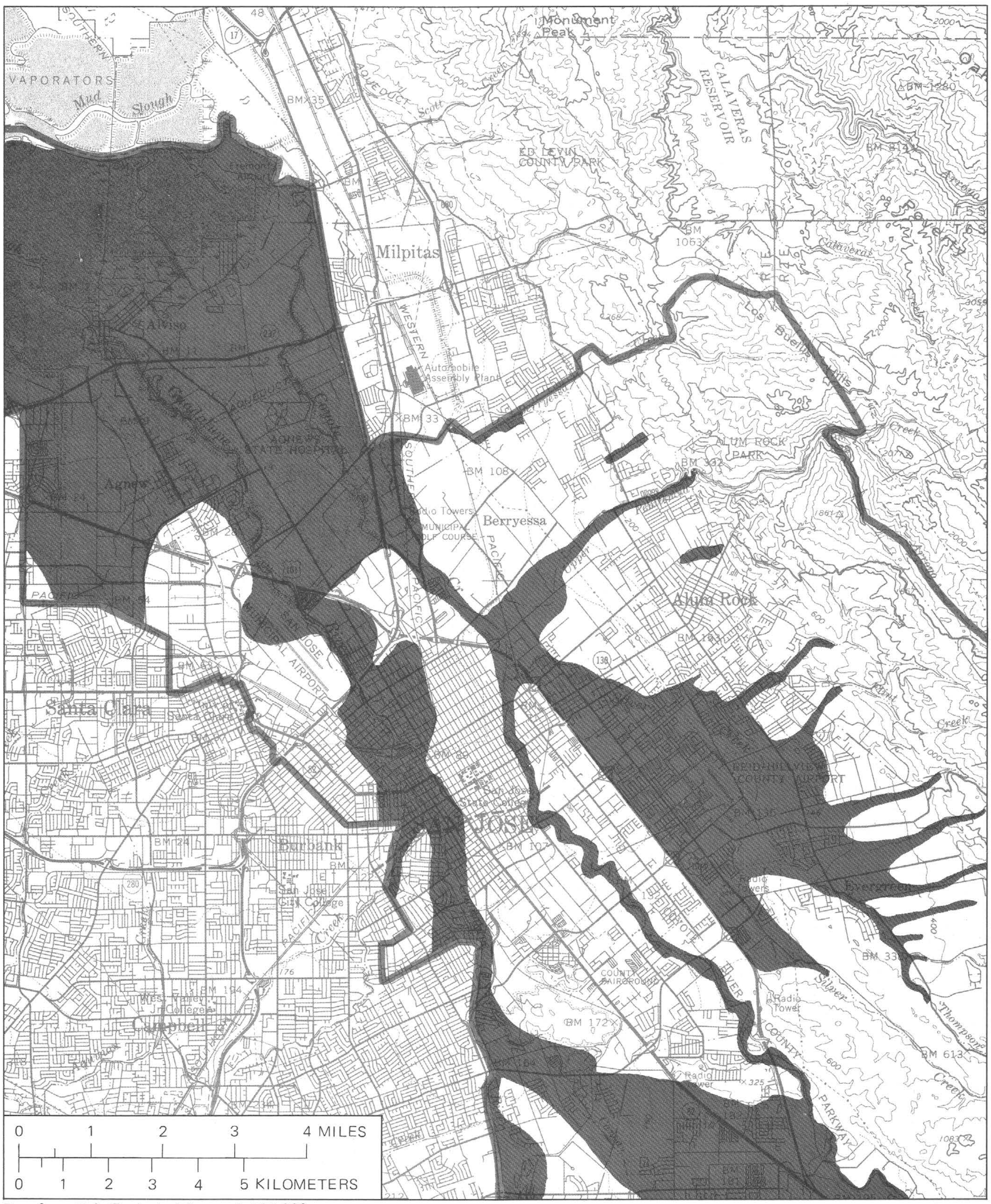
Land use	San Francisco intensity				
	[1]A	B	C	D	E
Rural or agricultural	$40	$30	$10	$5	$1
Semirural residential	300	300	100	40	4
Single-family residential	4,000	3,000	1,000	500	50
Multifamily residential	20,000	20,000	5,000	2,000	200
Regional shopping centers	50,000	40,000	10,000	4,000	800
Downtown commercial	70,000	50,000	20,000	5,000	1,000
Industrial	40,000	30,000	10,000	3,000	700
Freeways	10,000	10,000	10,000	0	0

[1] Calaveras fault excluded from this category.

Alquist-Priolo Special Studies Zones Act. This State of California act defines special studies zones one-eighth of a mile on either side of faults know to be active. It requires that before multifamily, commercial, or industrial structures are constructed, a geologic site investigation must determine if an active fault trace is on the property, and it forbids construction on or within 50 feet of the fault trace. Single-family dwellings are exempted from the State act, but in Santa Clara County, regulations extend similar requirements to subdivisions. These State and county regulations result in two different kinds of cost related to surface rupture: (1) For semirural, rural, and freeway uses, where investigation is not required, the cost will be based on damage during an earthquake and (2) for other uses (all of which, including single-family residential development, must be based on site investigation), the cost will be that of the geologic investigations required by law. Both kinds of cost will be described in turn.

The active fault zones used in this analysis are those mapped by the California State Geologist under the Alquist-Priolo Special-Studies Zones Act. These maps are readily available to jurisdictions in the bay area and are the official maps for the current State-mandated implementation program.

For each of the rural and semirural land uses, it is necessary to estimate how many structures would be damaged by surface rupture. Because accurate information on the location of fault traces is not always available and because surface rupture during future earthquakes may



Base from U.S. Geological Survey 1:125,000

FIGURE 15.—100-year flood plains in a part of the Santa Clara Valley demonstration area.

not occur along one fault trace or on existing traces, it is assumed, for the purpose of this study, that surface rupture will occur with equal likelihood throughout the Alquist-Priolo Special Studies Zones and will not occur elsewhere. Within the special studies zones, the number of houses that are built astride a fault trace will depend on the number of houses in the zone, their area, and their orientation. Thus, in general, this number will depend on the details of each development. For the purposes of this study, a simplified formula has been developed assuming square houses alined parallel to the fault. This results in the formula:

$$\left(\begin{array}{c}\text{expected fraction}\\ \text{of houses affected}\end{array}\right) = \sqrt{\frac{\text{fraction of areas covered by buildings}}{\text{number of buildings per 40 acres}}}$$

The zones are one-quarter mile wide. A segment this wide and one-quarter mile in length is a square containing 1,742,400 square feet, or 40 acres. This formula is derived in the section at the end of the report "Derivation of Formulas and Calculations of Expected Costs."

A more sophisticated analysis might assume a nonrandom distribution of building shapes and orientation controlled by roads which tend to parallel the faults. It is further assumed that any house more than 30 percent of which was astride a fault would be completely destroyed. Otherwise, the damage is assumed to be equal to half the value of the structure and contents. A relocation expense of $1,500 per residential unit affected is also included. Utility damage is assumed to be $200 per residential unit. The value of the land is assumed to drop to that of rural or agricultural use. Thus, the total cost associated with surface rupture per acre is:

The recurrence intervals used are 100 years for the Calaveras fault and 1,000 years for the southern extension of the Hayward fault and the small faults south of it (fig. 10).

For single-family, multifamily, commercial, and industrial uses, the cost of development in a special studies zone does not consist of the cost for repair of damage, but of investigation and mitigation of hazards, including:

1. *The cost of a preliminary study.*—This type of study must be performed for each parcel. A survey of geotechnical firms in the area indicates that this sort of study averaged $1,500 per parcel for multifamily, commercial, and industrial uses and $400 for a typical 1-acre single-family-home subdivision.

2. *The cost of a secondary investigation.*—If the preliminary study reveals evidence of a possible fault, then further investigations must be made. These investigations cost an average of approximately $5,000 per parcel for all uses except single-family residential, where they averaged $600. According to James O. Berkland, Santa Clara County geologist (oral commun., 1975), three-fourths of the lineations or possible faults identified in a preliminary study prove to be active on further investigation. (This estimate assumes one potentially active fault trace in that same ¼-mile-wide strip.) The number of parcels that will contain a possible fault per 40 acres and therefore require a secondary investigation is

$$\sqrt{\frac{\text{40 acres}}{\text{number of expected acres per lot}}}$$

divided by the fraction (¾) of suspicious lineations that

$$\left[\left(\begin{array}{c}\text{value of buildings}\\ \text{and personal}\\ \text{property in dollars}\\ \text{per acre}\end{array}\right)\left(\begin{array}{c}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{array}\right)\left[\left(\begin{array}{c}\text{50 percent}\\ \text{damage to 60}\\ \text{percent of the}\\ \text{buildings}\\ \text{affected}\end{array}\right)+\left(\begin{array}{c}\text{100 percent}\\ \text{damage to 40}\\ \text{percent of the}\\ \text{buildings}\\ \text{affected}\end{array}\right)\right]+\left(\begin{array}{c}\text{utility damage in}\\ \text{dollars per acre}\end{array}\right)\left(\begin{array}{c}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{array}\right)+\left(\begin{array}{c}\text{relocation}\\ \text{expense in}\\ \text{dollars per}\\ \text{acre}\end{array}\right)\right.$$

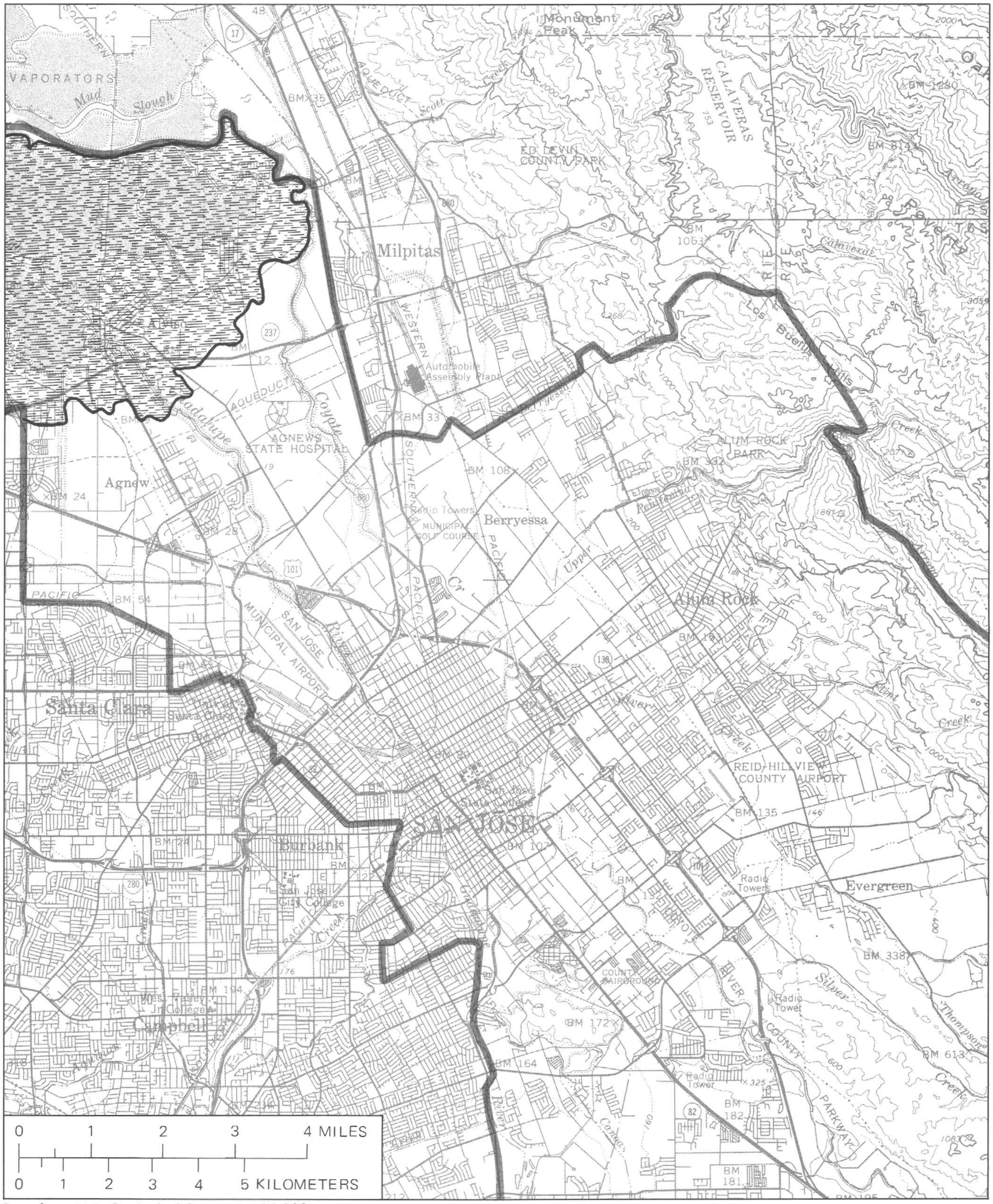
$$\left.\left(\begin{array}{c}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{array}\right)+\left(\begin{array}{c}\text{value of land for}\\ \text{current use}\end{array} - \begin{array}{c}\text{value of land}\\ \text{for rural use}\end{array}\right)\left(\begin{array}{c}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{array}\right)\right] \div \left(\text{discount rate}\right) \times \left(\begin{array}{c}\text{probability of}\\ \text{occurrence.}\end{array}\right)$$

EXPLANATION

Flood-prone areas

SOURCE: Limerinos, J. T., Lee, K. W., and Lugo, P. E., 1973.
A 100-year flood is a flood which has a 1-percent chance of occurring in any given year.

FIGURE 15.—Continued.



Base from U.S. Geological Survey 1:125,000

FIGURE 16.—Dike-failure inundation area in a part of the Santa Clara demonstration area.

prove to be active. This number cannot exceed the number of lots for which a preliminary study is performed, however. The number of expected acres per lot in the study zone is smaller than the number of acres per lot given in table 1 for lots greater than 40 acres, since it includes the smaller areas of the parts of some parcels in the zone while some other parts of those parcels are outside the zone. The expected area per lot is given as

$$\text{expected area per lot} = \frac{(\text{width of one parcel})^2\ (\text{width of fault study zone})}{(\text{width of one parcel} + \text{width of fault study zone})}$$

This formula is derived in the section "Derivation of Formulas and Calculations of Expected Costs."

3. *The cost of mitigation.*—Because the Alquist-Priolo Special Studies Zones Act forbids the placement of any building intended for human occupancy across or within 50 feet of an active fault trace, one might expect a loss of land value to be associated with the presence of an active fault. However, because the developments being considered are new and usually large, it is assumed that these setback requirements will be incorporated into the overall development plan with no loss of land value. Thus, the total cost associated with surface rupture per acre for those land uses where a study is required is

$$\frac{\begin{pmatrix}\text{cost of the}\\ \text{preliminary study}\\ \text{in dollars per}\\ \text{parcel}\end{pmatrix}\begin{pmatrix}\text{expected}\\ \text{number of}\\ \text{parcels per}\\ \text{40 acres}\end{pmatrix} + \begin{pmatrix}\text{cost of the}\\ \text{secondary}\\ \text{investigation}\\ \text{in dollars per}\\ \text{parcel}\end{pmatrix}\begin{pmatrix}\text{expected}\\ \text{number of}\\ \text{parcels}\\ \text{requiring a}\\ \text{secondary}\\ \text{investigation}\\ \text{per 40 acres}\end{pmatrix}}{\text{40 acres}}$$

For freeways, the cost associated with construction in a special studies zone is assumed to be equal to the replacement cost and the cost of a 40-acre study. If one assumes that the surface rupture is parallel to the boundaries of this zone, the length of the rupture in a 40-acre area will be one-quarter mile. If it is assumed that the freeway is equally likely to be anywhere within the area, then the cost associated with surface rupture damage per 40 acres can be approximated by calculating the replacement cost of one lane of freeway, one-quarter mile long. This cost, as given in table 3, is then divided by 40 acres and the discount rate, and multiplied by the recurrence interval to obtain a cost per acre. Note that no disruption costs are included in this calculation. The study costs are $1,500 + $5,000 divided by 40 acres.

Using these assumptions and standardizations, the expected cost can be calculated. Since surface rupture is assumed to be associated only with special studies zones, there is no cost associated with those areas outside the zones, regardless of the land use. The expected cost associated with the areas inside the zones is the cost associated with study procedures for the single-family and multifamily residential, commercial, and industrial uses. The expected costs for the rural and semirural categories are the costs associated with damage. Costs associated with freeways are of both types. The costs due to surface rupture are summarized in table 13.

A much higher cost can be obtained for semirural, rural, or freeway land uses by assuming higher damages or shorter recurrence intervals (recurrence intervals are given in the previous section in table 10). Doubling damages will double the costs. Changing recurrence intervals to half of those indicated will also double the costs. A lower cost for the other types of land uses and freeways can be obtained by assuming that study costs are lower. If the study costs were changed to one half of those used, the costs would be one-half of those shown.

EXPLANATION

Area subject to inundation from dike failure

SOURCE: Tudor Engineering Company, 1973.

FIGURE 16.—Continued.

COST ASSOCIATED WITH FLOODING

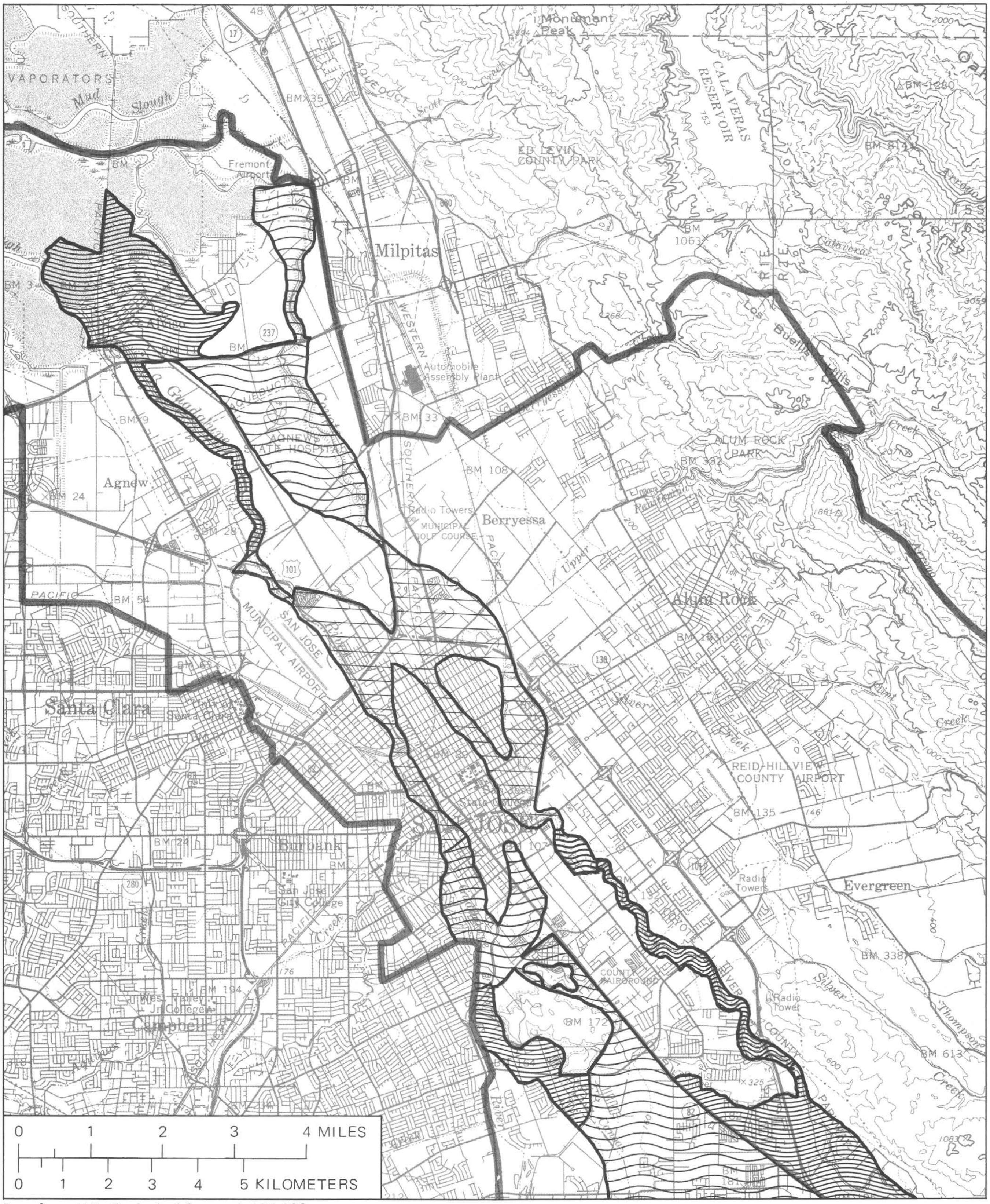
STREAM FLOODING

The categories of flood damage used in this study are designed to utilize information that is required and available for local regions to comply with the Flood Disaster Protection Act of 1973. At present, the generally accepted approach to flood-plain mapping is the designation of areas to be inundated by the 1 percent or 100-year flood. In particular, the 1 percent flood will be used by the Federal Insurance Administration to determine flood insurance rates.

The two categories, one "within the 100-year flood-prone inundation area" and the other "not within the 100-year flood-prone inundation area," are chosen to provide a simple application of readily available data

TABLE 13.—*Costs per acre associated with surface rupture*

Land-use type	Calaveras fault	All other faults in area
Rural or agricultural	$20	$2
Semirural residential	70	7
Single-family residential	500	500
Multifamily residential	800	800
Regional shopping centers	200	200
Downtown commercial	5,000	5,000
Industrial	80	80
Freeways	200	200



Base from U.S. Geological Survey 1:125,000

FIGURE 17.—Area in part of the Santa Clara Valley demonstration area subject to inundation if Anderson Dam fails.

used for flood insurance rates. These categories were taken from a U.S. Geological Survey study in the demonstration area (Limerinos and others, 1973).

Federally subsidized flood insurance is required of all areas considered subject to inundation by a 100-year flood if that area is to qualify for any Federal loans. Reliable information on depth of flooding and flow velocities was unavailable in the demonstration area, and flood insurance rates are not yet adjusted according to location within the flood plain. Thus, for this report flood-damage estimates based on depth of flooding were deemed impractical, but as detailed information on depth of flooding becomes available for flood insurance use, it can be incorporated into land-capability studies.

Regions not considered part of the 100-year flood plain in many cases still may sustain flood damages but are not assigned an expected cost, because the probability that significant flood damage will occur is very slight and because it is too difficult and arbitrary to break down the area outside the 100-year flood-prone inundation area into more than one category. The amount of flood damage exceeding the 100-year-flood level depends on the intensity of an unknown climatic event (for example a 200-year or 1,000-year flood), antecedent conditions (such as stream and reservoir stage and soil moisture), local conditions involving land use (such as degree of paving, and storm-drain facilities), and geologic conditions (such as landslides blocking channels). Furthermore, maps showing flood-inundated areas for larger magnitude events, such as a 500-year or 1,000-year flood, are not generally available.

EXPLANATION

Depth of inundation for successive reaches downstream of reservoir (depths in feet)

SOURCE: Santa Clara Valley Water District, 1973b.

Maps prepared in compliance with Chapter 780, Section 2, California Government Code (1972).

Anderson Reservoir is shown northeast of Morgan Hill in figure 8.

FIGURE 17.—Continued.

The estimates of expected cost are based on flood insurance rates for different types of structures and their locations. Actuarial rates are based on the elevation of the first floor of a structure above (or below) the depth of the difference between the 100-year and 10-year flood at a particular location. The rates are based on a brief history of flood insurance payments of the 1970's and on other information from the Corps of Engineers and the U.S. Geological Survey.

For the demonstration area, a number of simplifying assumptions seemed reasonable. Most of the demonstration area can expect depths of less than 3½ feet for the 100-year flood and probably just a few inches for a 10-year flood. Much of the area might fall within the zone rate "sheet flooding" ("AO" in a Flood Insurance Rate study). Since this rate has not yet been determined, the study uses the "Zone A" insurance rates that are similar to "AO") and apply to: "Special Flood Hazard Areas inundated by the 100-year flood, determined by approximate methods; no base-flood elevations or flood hazard factors" (U.S. Federal Insurance Administration, 1974).

Rates are thus the same throughout the 100-year flood plain but vary significantly with different types of structures. One-story structures with no basement, such as characterize rural, semirural, and single-family residential use, will cost $0.35 per $100 of insurance for the building and $0.90 per $100 for contents. Rates for two-story commercial and multifamily residential buildings without basements are $0.50 per $100 for the building and $0.85 per $100 for contents. Rates for one-story industrial buildings without basements are $0.60 per $100 for the building and $1.35 per $100 for contents. These figures are then multiplied by the value of structure and contents per acre and then added to determine annual insurance costs per acre. This sum is then multiplied by 75 percent (S. Brugger, oral commun., 1975) to determine the approximate annual cost of flooding and divided by the standard 10 percent discount rate to determine the total cost.

A similar but more detailed method could utilize the actuarial rate tables for Special Flood Hazard Areas (Zone A1—A30). A generalized elevation of the first floor can be used, such as 12 inches average for single-family residential on a slab or on joists. For single-family residential structures (no basement) in the demonstra-

Base from U.S. Geological Survey 1:125,000

FIGURE 18.—Relative slope stability in a part of the Santa Clara Valley demonstration area.

tion area, one can assume that the Flood Hazard Zone is somewhere from A1 to A7 (6 in. to 3½ feet). If, in the absence of rate maps, an average flood depth of 2 feet is used (zones A1—A7 require the same insurance) and the elevation of the first floor is about 1 foot, a rate of $0.48 per $100 of structure value is appropriate. The residential contents rate would be $1.20 per $100. This level of detail was not used because Flood Insurance Rate Maps are not available for the demonstration area and many structures may be in zone AO (sheet floods) rather than zones A1–A7 (Special Flood Hazard Areas).

This analysis assumes that no deaths, injuries, or social disruption occur. Of course, even one flooded street causes some disruption, but the variation in possibilities and the difficulty in predicting these events make analysis impractical at the level of this study.

For agricultural land, a loss of $1,000 per acre event is included to cover flood damage to crops (University of California Agricultural Extension Office, San Jose, oral commun., 1975). This loss amounts to a cost of

$$\frac{(\$1{,}000)\ (0.01\ \text{frequency})}{(0.1\ \text{discount rate})},\quad \text{or } \$100.$$

Freeways are assumed to be above the 100-year flood level. Thus, no cost is associated with flooding for freeway use. The results of these calculations are summarized in table 14. No minimum or maximum cost estimates were calculated for flooding because there is no reliable basis for making judgments other than the Federal Insurance Administration's 100-year flood-plain insurance rates.

DAM FAILURE

Estimating the expected cost due to dam failure caused by an earthquake is perhaps the most perplexing problem encountered in attempting to apply a land-capability analysis in the study area. It is clearly an important issue; the failure of a single dam could have cost consequences greater than those of any other geologic or hydrologic hazards. The problem is that it is virtually impossible even to put limits on estimates of the rate of occurrence of dam failure. For example, the Anderson reservoir (fig. 8) is very near two active faults—the Hayward and the Calaveras. Using the relationship between magnitude and intensity described earlier in the section on ground shaking, a modified Mercalli intensity at the dam of XI from an earthquake of magnitude 7–8 on either fault is possible, and this ground shaking might cause dam failure. However, interviews with engineers of the water district indicate that they do not expect the dam to fail in any conceivable earthquake. If this is correct, then the recurrence interval would be infinite. In order to decide this question, one would need a site-specific dynamic analysis of Anderson Dam. This information is not now available; however, after the near failure of lower Van Norman Dam during the 1971 San Fernando earthquake, the State is requiring such an analysis of all dams. The results for Anderson Dam and the other dams in the study area should be available in the near future.

EXPLANATION

Slope-stability categories

1. Stable areas of 0-5 percent slope
2. Generally stable areas of 5-15 percent slope
3. Generally stable to marginally stable areas of >15 percent slope
4. Moderately unstable areas of >15 percent slope

Unstable areas underlain by, or immediately adjacent to, landslide deposits

SOURCE: Nilsen, T. H., and Wright, R. H. (1979).

FIGURE 18.—Continued

TABLE 14.—*Costs associated with stream flooding*

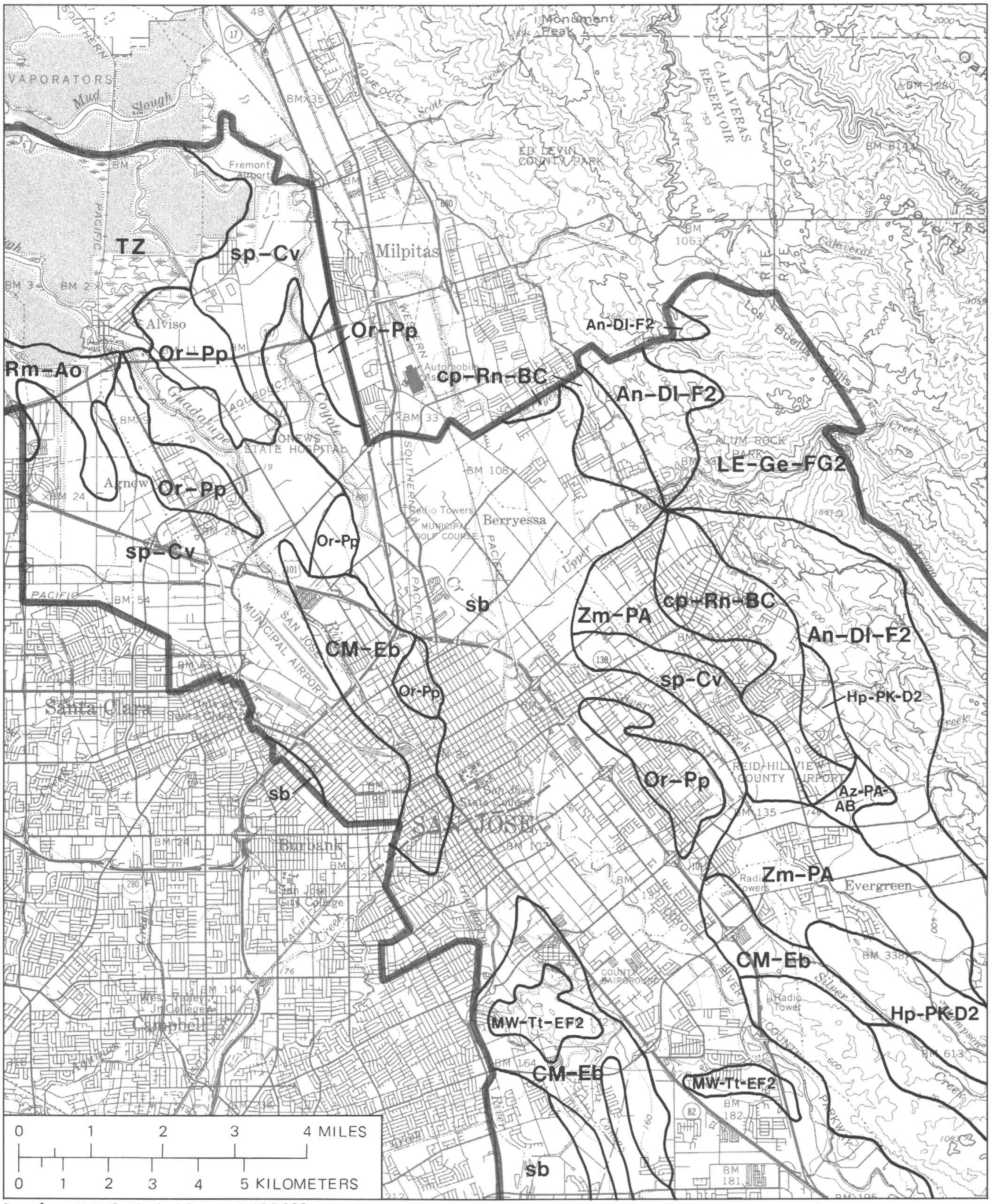
Land use	Cost per acre
Rural or agricultural	$200
Semirural residential	700
Single-family residential	9,000
Multifamily residential	40,000
Regional shopping centers	40,000
Downtown commercial	50,000
Industrial	40,000
Freeways	0

Because accurate information on dam failure is anticipated, an analysis of expected costs would be premature. For this reason, no expected cost has been associated with flooding due to dam failure.

It is possible to calculate damages per event and then discuss the variability of expected costs, depending upon the likelihood of dam failure.

The State Office of Dam Safety requires that maps of the area that would be inundated be prepared for all dams in the State. In the study area, such maps were made by the Santa Clara Valley Water District. Figure 17 illustrates depths of inundation if Anderson Dam should suffer a gradual failure. If the dam were to fail suddenly, the area inundated would be much larger. Although it is difficult to determine which failure mode is more likely in an earthquake, it would seem more conservative to assume catastrophic failure.

With this map, one can calculate the costs per event



Base from U.S. Geological Survey 1:125,000

FIGURE 19.—Generalized soil associations in a part of the Santa Clara Valley demonstration area.

in different parts of the inundation area. Based on the U.S. Federal Insurance Administration (FIA) National Flood Insurance tables (1974), the inundation area is divided into five categories:

Category 1.------------------------------0-1 foot of water
2. ------------------------------1-2 feet of water
3. ------------------------------3-5 feet of water
4. ------------------------------6-14 feet of water
5. ------------------------------14+ feet of water

Using these tables, it is possible to calculate the damage to structures and to contents for each land use. It is further assumed that everyone living in an area inundated to 10 feet or deeper would be killed (Ayyaswamy and others, 1974). Assigning a hypothetical value per life loss of, for example, $1 million, one can calculate the cost per event per acre for each of the above categories. The figures are shown in table 15.

These figures are not incorporated in the capability analysis. If they were, one would need to estimate the recurrence interval and discount the costs, as in the previous example. Even at fairly long recurrence intervals, the costs would be very high. Thus, if the probability of dam failure is 0.01 failure per year, the costs are 100 times greater than the next greatest hazard cost. On the other hand, if the probability of occurrence is 1 in 10,000, it is of the same order as the other high costs.

EXPLANATION

An-D1-F2	Altamont-Diablo-Azule association, 30-50 percent slopes, eroded
Az-PA-AB	Arbuckle-Pleasanton association, 0-5 percent slopes
CM-Eb	Clear Lake-Edenvale association, drained
cp-Rn-BC	Cropley-Rincon association, 2-9 percent slopes
Hp-PK-D2	Hillgate-Positas association, 9-15 percent slopes, eroded
LE-Ge-FG2	Los Gatos-Gaviota association, 30-70 percent slopes, eroded
MW-Tt-EF2	Montara-Toomès association, 30-50 percent slopes, eroded
Or-Pp	Orestimba-Pescadero association
Rm-Ao	Reyes-Alviso association
sb	Sorrento association
sp-Cv	Sunnyvale-Castro association
TZ	Tidal flats
Zm-PA	Zamora-Pleasanton association

Soils occurring in the demonstration area but not found in the smaller area shown in figure 19:

Hp-SZ-E2	Hillgate-Soper association, 15-30 percent slopes, eroded
Kd-Hp-BC	Keefers-Hillgate association, 2-9 percent slopes
Sm	San Ysidro association
Vc-Ge-FG2	Vallecitos-Gaviota association, 30-70 percent slopes, eroded
Yo-En-B	Yolo-Esparto association, 0-5 percent slopes

SOURCE: U.S. Soil Conservation Service and Association of Bay Area Governments, 1966.

The properties of these soil associations are discussed in later sections of this report in connection with studies of costs.

FIGURE 19.—Continued.

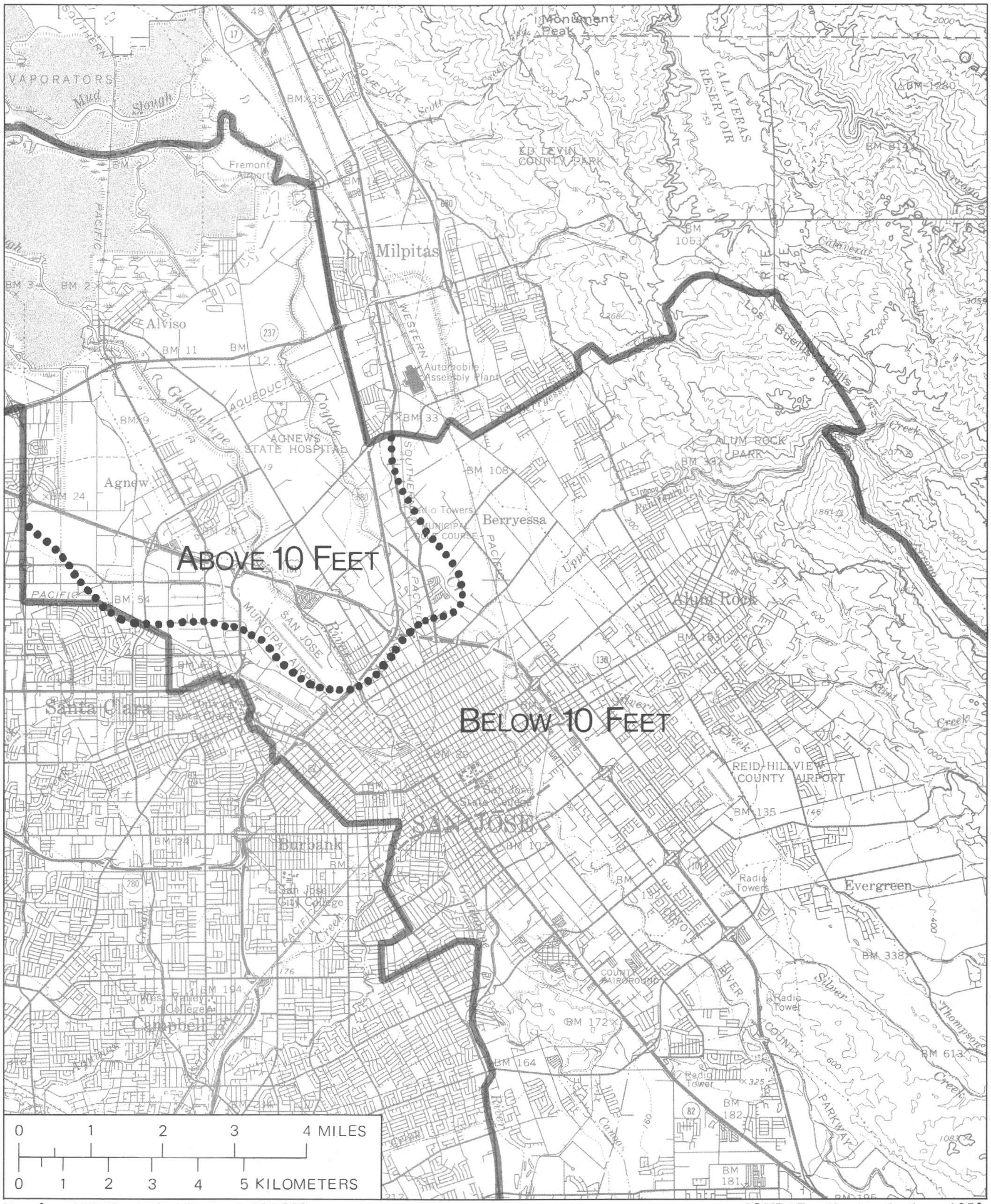
DIKE FAILURE

Dike failure would allow bay waters to flood parts of the demonstration area. The potential for property damage exists, and this makes dike failure relevant to land-capability analysis. The prediction of exact costs is very difficult, but an estimate of potential costs can be made.

The type of flooding depends on the type of failure as well as the tidal cycle. Failure might be caused by a seiche, high tides and wind, animal burrowings, ground shaking, settlement, or other structural failure. The potential dike-flooding area was delineated on the Bayland Study (Santa Clara Valley Water District, 1973). This area is lower than the 6.5-foot contour. One can expect a 6.5-foot-high tide every 6 months. Thus, if a dike fails and is not rebuilt within 6 months, one can expect this area to be inundated. The costs will vary with the type, depth, wave velocity, and duration of flooding, and because these variables cannot be predicted, they must be generalized. The dike failure is assumed to be caused by an earthquake intensity of VIII (modified Mercalli) or greater. It is likely that an earthquake of magnitude 6.5 or above on the Calaveras, Hayward, or San Andreas faults would result in a VIII intensity on this bay mud area (Borcherdt, Joyner, Warrick, and Gibbs, 1975). The recurrence interval for this intensity can be approximated by summing the probability of various magnitude

TABLE 15.—*Damage costs per acre per event from dam-failure inundation*

Depth (ft)	Semirural residential	Single-family residential	Multifamily residential	Regional shopping center	Downtown commercial	Light industrial manufacturing
0–1	$1,950	$23,831	$69,000	$66,400	$84,600	$81,225
1–3	4,000	48,525	134,500	130,200	165,300	162,300
3–6	7,025	84,019	224,500	225,450	280,050	270,600
6–14	359,975	9,619,981	25,392,500	45,403,250	50,494,250	12,892,400
14+	710,500	19,125,625	50,536,000	90,549,600	100,674,400	25,405,000



Base from U.S. Geological Survey 1:125,000 SOURCE: Youd and others, 1973.

FIGURE 20.—Depth to ground-water table in a part of the Santa Clara Valley demonstration area.

earthquakes in the area. These probabilities are estimated to be:

Magnitude	*Interval*	*Probability per year*
6.5	1 every 100 years on the Calaveras	0.01
7.5	1 every 100 years on the Hayward	.01
8+	1 every 100 years on the San Andreas	.01
	Total	.03

A 33-year recurrence is used in predicting damage, assuming that people rebuild after failure.

The flooding limit is the 6.5-foot contour, and the appropriate average depth (3 feet) is used to calculate costs from the Flood Insurance Act damage tables and the land-use-type descriptions. The floodwaters are assumed to have no wave or current velocity, because no data are available at this time. Percent damage for rural, semirural, and single-family uses are 26 and 29 percent for buildings and contents, respectively. Percent damage for multifamily and commercial uses are 24 and 33 percent, and for industrial uses are 39 and 44 percent. Freeway damage is likely to be so small that it is set here at zero. Crop damage estimates of $300 per acre are added to the cost estimated for rural or agricultural use. This crop-damage cost per event is identical to that for stream flooding damage ($1,000). Actual damage would probably be much higher. Thus:

$$\frac{\begin{pmatrix}\text{expected cost}\\ \text{in dollars}\\ \text{per acre}\end{pmatrix}\begin{pmatrix}\text{value of}\\ \text{buildings}\\ \text{in dollars}\\ \text{per acre}\end{pmatrix}\begin{pmatrix}\text{percent}\\ \text{damage}\\ \text{for}\\ \text{buildings}\end{pmatrix}+\begin{pmatrix}\text{value of}\\ \text{contents}\\ \text{in dollars}\\ \text{per acre}\end{pmatrix}\begin{pmatrix}\text{percent}\\ \text{damage}\\ \text{frequency}\\ \text{for}\\ \text{contents}\end{pmatrix}}{(\text{discount rate})}$$

These calculations lead to the estimates of expected cost in table 16.

Earthquake recurrence rates greatly affect the estimates of cost for dike failure, and slight changes in the assumed rates materially affect results. Because these recurrence rates are not yet known with certainty and because these rates differ from region to region, those assumed here may need to be changed in other analyses of this kind. To illustrate how such changes may affect results and also to show the range of uncertainty in the figures used here, two alternative recurrence rates are assumed. If a damaging earthquake generated at one of the three faults is assumed to have a recurrence rate of one earthquake per 1,000 years, instead of the one in 100-year incidence previously assumed for all three, the overall recurrence rate for damaging earthquakes becomes one in 50 years, and costs are reduced by about two-thirds of those shown in table 16. But if earthquakes generated along one of these faults are assumed to have a recurrence rate of one in 10 years, while earthquakes generated along the other two each remain at one per 100 years, the overall recurrence rate becomes one every 8 years, and costs are increased fourfold.

TABLE 16.—*Costs associated with dike failure*

Land use	Cost per acre
Rural or agricultural	$500
Semirural residential	2,000
Single-family residential	20,000
Multifamily residential	80,000
Regional shopping centers	70,000
Downtown commercial	90,000
Industrial	70,000
Freeways	0

COSTS ASSOCIATED WITH BEARING-MATERIAL PROBLEMS

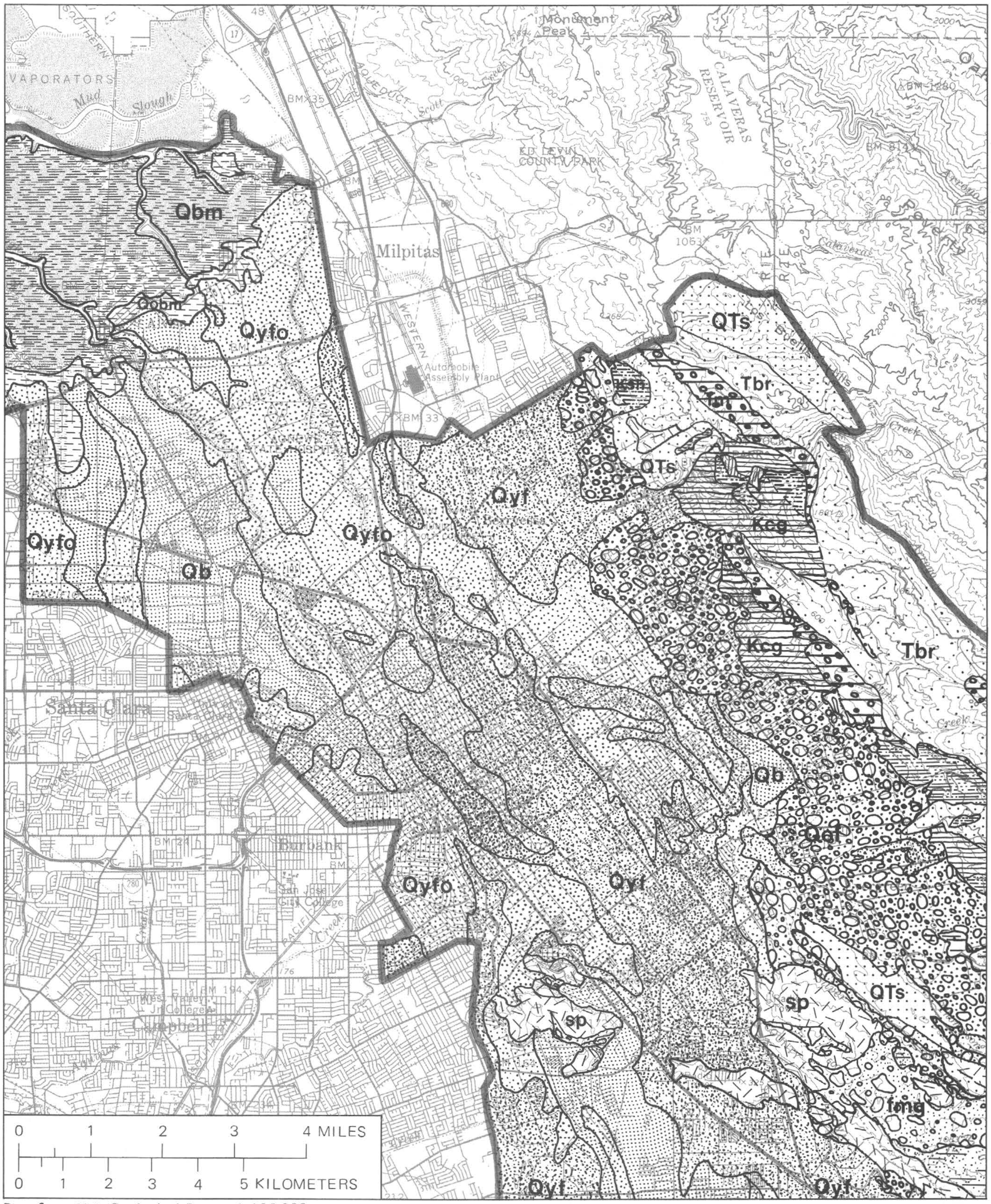
SHRINK/SWELL POTENTIAL

Shrink/swell soils cause damage because they expand when wet and shrink when dried. The Soil Conservation Service maps include information on soil expansion (U.S. Soil Conservation Service 1968; U.S. Soil Conservation Service and Association of Bay Area Governments, 1966).

Four categories of shrink/swell potential can be defined by combining information from the Soil Conservation Service maps with the U.S. Geological Survey slope maps of the San Francisco Bay region. Category 1 consists of areas of slopes greater than 5 percent. Category 2 consists of those areas of slopes less than 5 percent that have soils which are designated as having "low" shrink/swell potential by the Soil Conservation Service. No soil associations having "low" shrink/swell potential are in the demonstration area. Category 3 consists of those areas of slopes less than 5 percent that have soils which are designated as having "moderate" shrink/swell potential. These include the following soil associations:

	Association
Az–PA–AB	Arbuckle-Pleasanton.
Kd–hP–BC	Keefers-Hillgate.
LE–Ge–FG2	Los Gatos-Gaviota.
MW–Tt–EF2	Montara-Toomes.
sb	Sorrento.
Vc–Ge–FG2	Vallecitos-Gaviota.
Yo–En–B	Yolo-Esparto.
Zm–PA	Zamora-Pleasanton.

Category 4 consists of those areas of slopes less than 5 percent that have soils which are designated as having



Base from U.S. Geological Survey 1:125,000

FIGURE 21.—Geologic materials in a part of the Santa Clara Valley demonstration area.

"high" shrink/swell potential. The following soil associations have a "high" shrink/swell potential. The following soil associations have a "high" designation:

	Association
An–D1–F2	Altamont-Diablo-Azule.
CM–Eb	Clear Lake-Edenvale.
cp–Rn–Bc	Cropley-Rincon.
Hp–PK–D2	Hillgate-Positas.
Hp–SZ–E2	Hillgate-Soper.
OR–Pp	Orestimba-Pescadero.
Rm–Ao	Reyes-Alviso.
Sm	San Ysidro.
sp–Cv	Sunnyvale—Castro.
TZ	Tidal Flats.

Slope is an important factor because the nature of the problem changes if movement changes to downslope movement, or "creep". In this report swelling soils on slopes greater than 5 percent are considered under the category "soil creep potential" and are discussed later in the section 'Costs Associated with Slope-Stability Problems.'"

The Soil Conservation Service uses the Coefficient of Linear Expansion (COLE) to determine soils with "low," "moderate," and "high" shrink/swell potential. The COLE value is an index of the amount that soils swell when water is added to them or the amount they shrink when dried. The COLE values are divided into three approximately equal categories of less than 0.03, 0.03–0.06, and 0.06–0.09.

The COLE value is not proportional to the percent of the total possible cost of corrective work on foundations thought to be needed for each shrink/swell category. The predominant factor affecting cost is the depth to which the material expands. Unfortunately, Soil Conservation Service maps do not include COLE data by depth for the area. Therefore, cost estimates cannot be associated with mapped areas easily.

High shrink/swell soils have the maximum problems and thus the highest cost. The total of additional design and construction costs to avoid the problem of expansive soils is estimated as being 3 percent of the cost of the building and utilities. Category 1, soils, those on slopes steeper than 5 percent, are discussed in a later section of this report. Category 2, low shrink/swell soils on flat slopes, requires no special engineering cost. Information gathered for this study indicates that the difference in engineering cost between low and moderate shrink/swell properties is much less than that between moderate and high. Therefore, the dollar cost associated with moderate shrink/swell potential is estimated at 1 percent of the cost of the building and improvements.

Special foundation designs of freeways incorporate corrective measures, but the costs of these designs vary so widely that cost estimates for shrink/swell soil problems with freeways were not attempted for this analysis.

The calculated costs are given in table 17. Estimates of the cost of additional design ranged from a low of 0.15 percent to a high of 5–20 percent. A minimum cost estimate of one-twentieth of those given can be obtained by using the low cost estimate. A maximum cost estimate of approximately two to seven times those given can be obtained by using the high cost estimate.

EXPLANATION

Qbm	San Francisco Bay mud
Qb Qyfo Qyf	Younger alluvial fan deposits
Qobm	Older San Francisco Bay mud
Qof	Older dissected alluvial fan deposits
QTs	Poorly consolidated conglomerate, sandstone, siltstone, and claystone
Tbr	Briones Formation: light-colored massive fossiliferous sandstone
Tm Qof	Monterey Formation: light-colored siliceous shale, chert, and diatomaceous mudstone
Ksh	Shale
Kcg	Hard conglomerate, some sandstone
fmg	Melange: intensely sheared and broken rock consisting of mixed rock types
sp	Metamorphic rocks: serpentine

Materials occurring in the demonstration area but not found in the smaller area shown in figure 21:

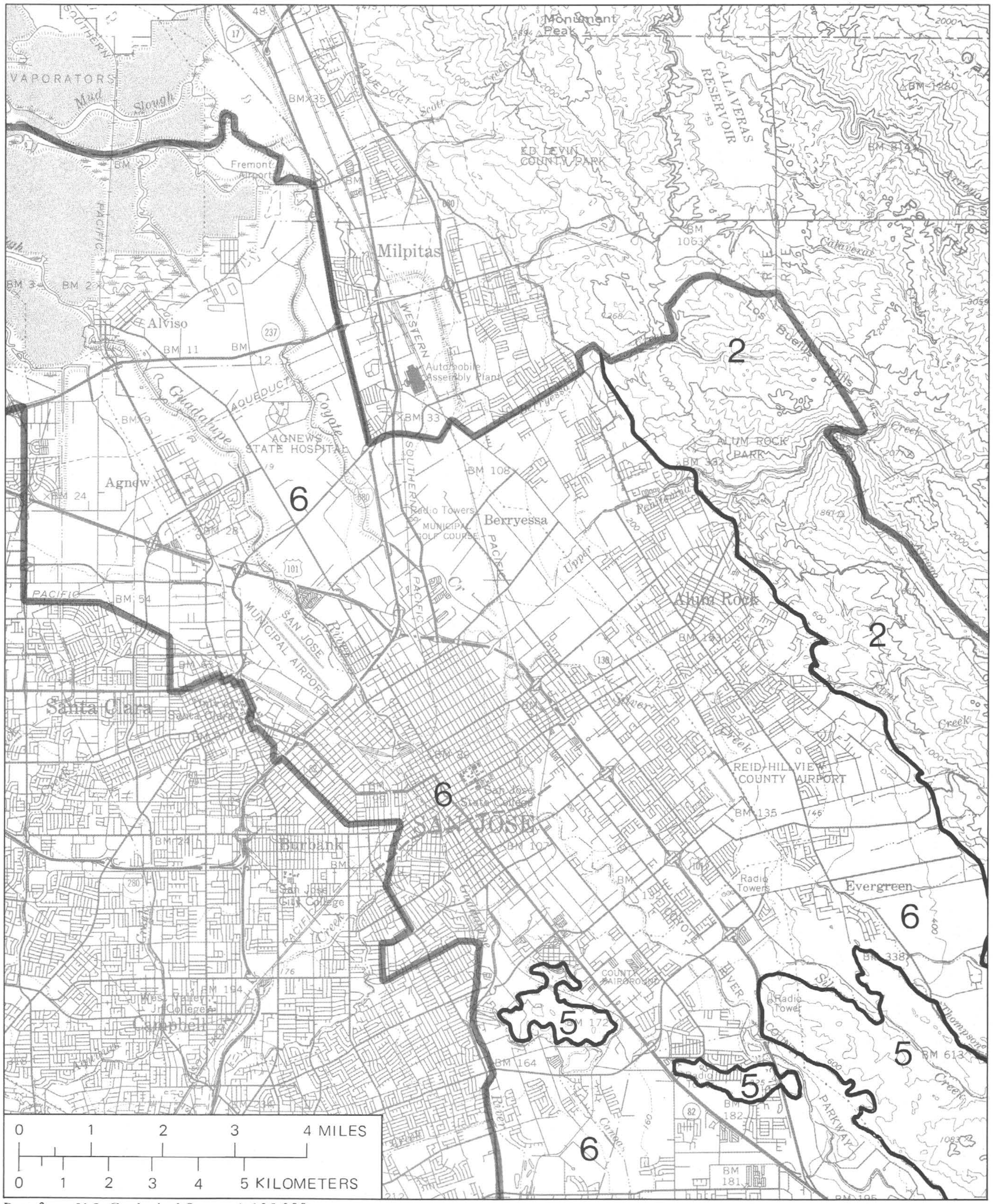
QTb	Basalt and other volcanic rocks
Tb	Volcanic rocks: massive lava flows, tuff-breccia, and tuff
Tvr	Volcanic rocks: rhyolite
JKs	Sedimentary rocks: sandstone
fu	Franciscan complex: undivided
db	Igneous rocks: diabase and gabbro, undivided

SOURCES: Helley, E. J., and Brabb, E. E., 1971. Brabb, E. E., Dibblee, T. W., Jr., Rogers, T. H., and Williams, J. W., 1974.

FIGURE 21.—Continued.

SETTLEMENT

Settlement occurs when the additional weight of a structure and (or) fill results in consolidation of the underlying materials. Variation in natural materials, or differences between areas graded and areas filled, can result in different amounts of settlement in neighboring areas. Structures undergoing prolonged differential set-



Base from U.S. Geological Survey 1:125,000

FIGURE 22.—Erosion provinces in a part of the Santa Clara Valley demonstration area.

TABLE 17.—*Costs per acre associated with shrink/swell soils*
[Although no soils in category 2 (low shrink/swell potential) are found in the demonstration area, the category is included to illustrate the range of the problem.]

Land use	Cost category			
	4. High	3. Moderate	2. Low	1. Greater than 5 percent slope
Rural or agricultural	$50	$20	$0	(See section "Soil Creep.")
Semirural residential	500	200	0	
Single-family residential	6,000	2,000	0	
Multifamily residential	20,000	7,000	0	
Regional shopping centers	20,000	5,000	0	
Downtown commercial	20,000	8,000	0	
Industrial	10,000	4,000	0	
Freeways	0	0	0	

tlement may be extensively damaged. The conventional practice is to determine subsurface conditions, conduct necessary grading, properly emplace engineered fill, and design and construct improved foundations.

The extent to which settlement may be a constraint can be delineated on the basis of categories of existing conditions:

Category 1. ----------Bay muds and marsh deposits.
2. ----------Slopes inclined at greater than 15 percent.
3. ----------Slopes of 5—15 percent inclination.
4. ----------Materials not in categories 1—3 (largely alluvial deposits).

These categories of settlement potential are derived from U.S. Geological Survey slope maps, and from a geologic map of the area (Brabb and others, 1974).

Costs cannot be related directly to these categories because the actual amount of special engineering or damage which would occur is dependent upon the highly variable distribution of materials, their different behavioral characteristics, and variations in sensitivity of structural types to different amounts and rates of settlement at different locations beneath a single building.

At the scale of this demonstration, it is possible to estimate the damage which might occur, or degree of special efforts which would be necessary, to preclude damage in different categories.

For rural-agricultural and semirural residential, it is assumed that no special efforts to minimize differential settlement damage are made at the time of construction and that subsequent damage results in costs of repairing deformation of structures at a rate of 0.15 percent of the value of the improvements/utilities annually, or 1.5 percent total cost for categories 1 and 2. Costs for categories 3 and 4 are assumed to be one-half and one-fifth of these amounts, respectively; because the results shown in table 18 are rounded, they do not precisely reflect these relations.

For single-family and multifamily residential, regional shopping, and downtown commercial uses, the measures commonly used to minimize damage are:

Category 1. (Bay muds) — extensive engineered filling operations (typical thickness of 6 feet) with costs that result from transporting fill ($30,000 per acre); for downtown commercial structures, pile foundations, and special building design, add an additional $70,000 per acre.
2. (slopes > 15 percent) — major grading operations entailing extensive cuts in natural slopes and fills composed of onsite material; costs comparable with those for category 1.
3. (5—15 percent slopes) — minor grading operations with costs averaging 60 percent of those on steeper slopes in category 2.
4. (all other areas) — conventional compaction of natural ground surface with costs about 10 percent of those in category 3.

Most industrial buildings can tolerate much more deformation than the other land-use types, and they occupy less area of a given site. Hence, the estimates of costs for engineered fill (category 1) and major grading (category 2) are substantially less.

Freeways already have extensive grading and filling costs associated with their construction regardless of locale. Such costs are extremely variable and therefore have not been included. The resulting estimates of dollar costs are shown in table 18.

The reader must be cautioned that these estimates are generalized and that special investigations, engineering,

TABLE 18.—*Costs per acre associated with settlement*

Land uses	Slope category			
	1. Bay muds	2. > 15 percent	3. 5–15 percent	4. All other areas
Rural or agricultural	$20	$20	$10	$5
Semirural residential	200	200	100	50
Single-family residential	30,000	30,000	20,000	2,000
Multifamily residential	30,000	30,000	20,000	2,000
Regional shopping centers	30,000	30,000	20,000	2,000
Downtown commercial	100,000	30,000	20,000	2,000
Industrial	10,000	10,000	6,000	700
Freeways	0	0	0	0

EXPLANATION

EROSIONAL AND DEPOSITIONAL PROVINCES

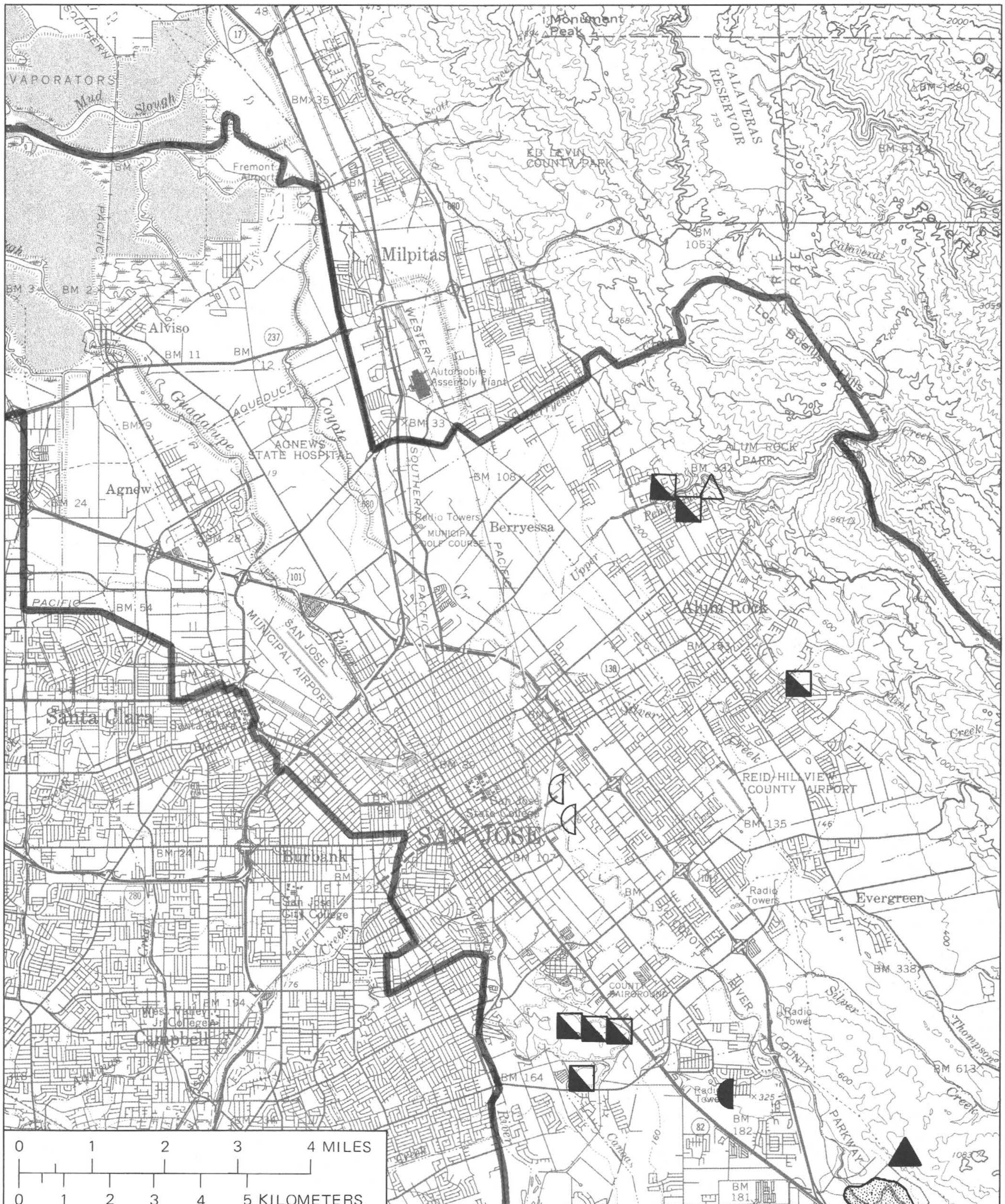
2. Diablo Range uplands

5. Foothills

6. Bay plain and alluvial valley

SOURCE: Brown W. M. III, and Jackson, L. E., Jr. 1973.
The provinces have characteristic rates of erosion and sedimentation as discussed in text.

FIGURE 22.—Continued.



Base from U.S. Geological Survey 1:125,000

FIGURE 23.—Mineral resources in a part of the Santa Clara Valley demonstration area.

and construction practices are necessary only where site-specific studies demonstrate a hazard.

LIQUEFACTION

The liquefaction-potential categories used in this analysis are those used by Youd, Nichols, Helley, and Lajoie (1973). The categories are:

Category 1. ------------------------Tertiary and older deposits.
2. ------------------------Older (Pleistocene) alluvial fan deposits.
3. ------------------------Younger (Holocene) alluvial deposits.
4. ------------------------Younger (Holocene) alluvial deposits where the water table is normally within 10 feet of the surface.
5. ------------------------Deposits underlying young bay sediments.
6. ------------------------Reference category: Liquefiable deposits within young bay sediments.

The reference category contains, in the area mapped as bay mud, those isolated pockets of materials which are especially susceptible to liquefaction. The distribution of these deposits is largely unknown, but the category is included because of its importance and because more knowledge of these deposits may become available later.

A map of liquefaction potential was prepared by combining a geologic map with one showing the depth to the ground-water table. The percent damage associated with liquefaction potential is assumed not to vary with the land use.

The potential for liquefaction is estimated from information supplied by Youd, Nichols, Helley, and Lajoie (1973) as shown in table 19.

Those materials likely to liquefy in a moderate earthquake (magnitude 6.5) are said to have a high liquefaction potential. Those sediments unlikey to liquefy in even a large event (magnitued 8.0) do not have significant liquefaction potential. Marginal liquefaction potential indicates that the materials are intermediate between high and low. It is assumed that this potential indicates that these materials could liquefy in one-half the earthquakes of magnitude 6.5 and in all magnitude 7.5 and 8 + events. It is also assumed that these earthquakes have the approximate recurrence intervals given in table 20.

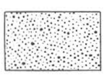
The categories also have the following characteristics regarding saturation (Youd and others, 1973).

Category 1. ------------------------Not saturated.
2. ------------------------Rarely saturated.
3. ------------------------Seasonally and locally saturated.
4-6.----------------------Saturated.

The following assumptions can be made from this saturation information:

Category 1. ------------------------Saturated 0 percent of time.
2. ------------------------Saturated 1 percent of time.
3. ------------------------Saturated 10 percent of time.
4-6.----------------------Saturated 100 percent of time.

EXPLANATION

SYMBOL	RESOURCE
	Chromite
	Clay
	Manganese
	Mercury
	Sand and gravel
	Stone, crushed and broken

Resources occurring in the demonstration area but not found in the small area shown in figure 23:

	Gemstones
	Limestone
	Cement plant
	Magnesite

SOURCE: Bailey, E. H., and Harden, D. R., 1975.

FIGURE 23.—Continued.

TABLE 19.—*Material characteristics for liquefaction potential, in percent*

	Materials loose enough for high liquefaction potential	Materials loose enough for marginal liquefaction potential	Materials not loose enough to have significant liquefaction potential
Category 1	0	0	100
Category 2	11	29	60
Category 3	22	33	45
Category 4	22	33	45
Category 5	33	28	39
Category 6 (reference)	73	21	6

TABLE 20.—*Recurrence intervals for earthquakes on selected faults*

Fault	Magnitude		Recurrence interval (years)	
	Estimate	Range	Estimate	Range
Southern Hayward	7.5	6–7.5	1,000	1,000–1,000,000
Calaveras	6.5	6–7.3	100	10–100
Hayward	7.5	6–7.5	100	10–100
San Andreas	8+	8–8.3	100	100–1,000

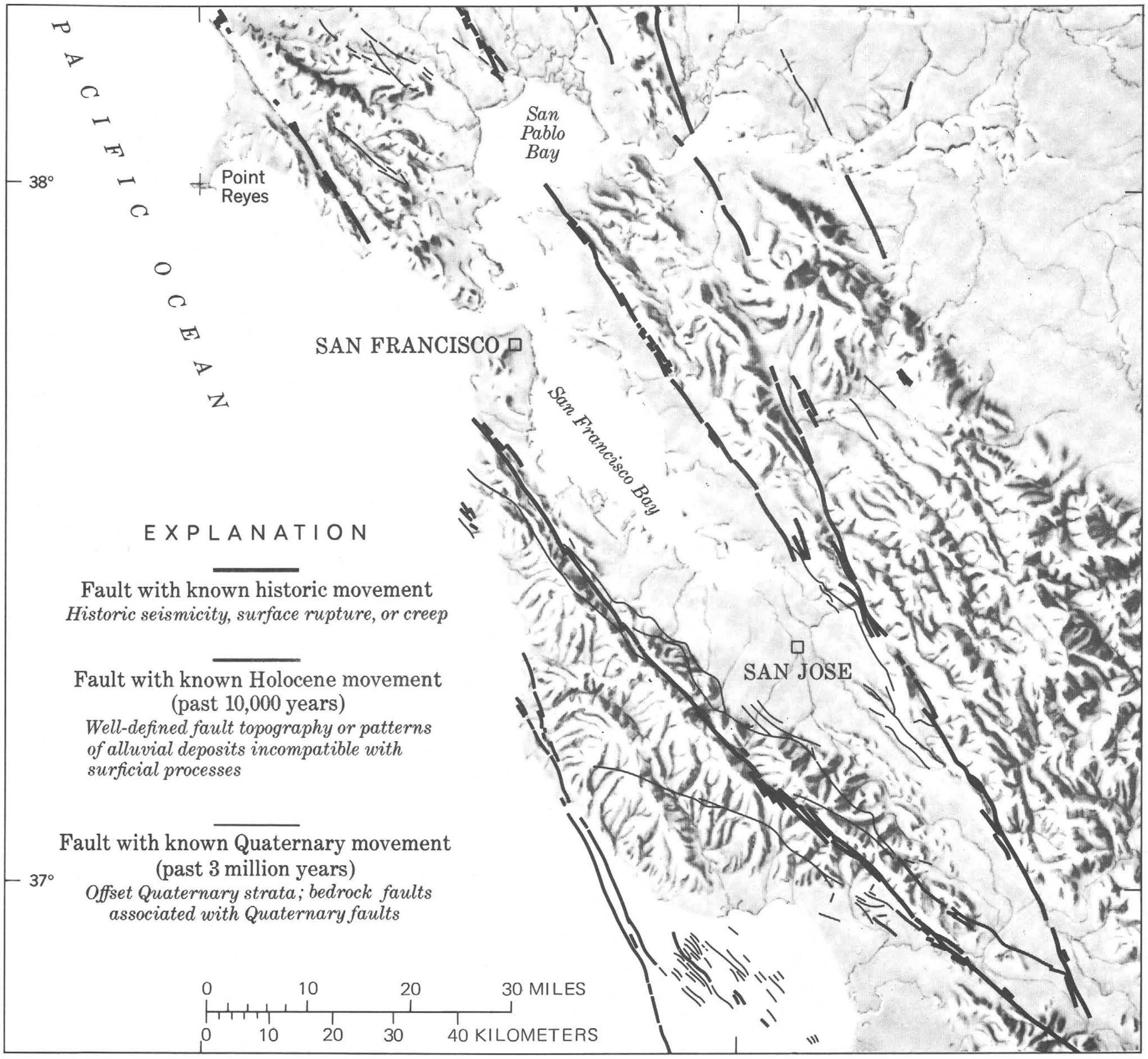


FIGURE 24.—Faults in the southern San Francisco Bay Region.

Last, it is assumed that 10 percent of those sands that can potentially liquefy will liquefy in a given event. Of those structures that are built over material that actually liquefies, it is assumed that 10 percent will be undamaged, 80 percent will be damaged to 15 percent of their value, and 10 percent will be totally destroyed. These damage figures result in a total expected damage factor per event of 22 percent on sands which liquefy; thus:

$$\begin{pmatrix}\text{damage}\\ \text{cost}\\ \text{per event}\end{pmatrix} = \begin{pmatrix}\text{22 percent damage}\\ \text{per event}\end{pmatrix} \begin{pmatrix}\text{10 percent liquefy}\\ \text{per event}\end{pmatrix} \begin{pmatrix}\text{value of buildings, improvements,}\\ \text{personal property,}\\ \text{and disruption}\end{pmatrix}.$$

Loss of work and loss of profit values are included for the industrial and commercial uses. Loss of work values of ($50 per day) (30 days) (0.022 loss) (number of employees per acre) are used. Figures of 5 employees per acre for both types of commercial and 25 employees per acre for industrial are used. Loss of profit values are calculated as 3 percent of the 0.022 loss times the value of the buildings, personal property, and utilities. In addition, a disruption value of $1,500 is added to the building and improvements values for damage calculations to cover costs of relocation. Again, no attempt is made to evaluate the social disruption which occurs when transportation facilities are not operating. The expected cost associated with each map category is

$$\left(\frac{\text{damage cost}}{\text{discount rate of 0.10}}\right)\left(\begin{array}{c}\text{fraction}\\ \text{of time}\\ \text{the ma-}\\ \text{terial is}\\ \text{saturated}\end{array}\right)\left[\left(\begin{array}{c}\text{percentage of material}\\ \text{of high lique-}\\ \text{faction po-}\\ \text{tential}\end{array}\right)\left(\begin{array}{c}\text{frequency}\\ \text{it can}\\ \text{liquefy:}\\ 0.03\end{array}\right)+\left(\begin{array}{c}\text{percentage of material}\\ \text{of moderate}\\ \text{liquefaction}\\ \text{potential}\end{array}\right)\left(\begin{array}{c}\text{frequency}\\ \text{it can}\\ \text{liquefy:}\\ 0.02\end{array}\right)\right]$$

This formula is used to determine the expected costs tabulated in table 21.

These numbers depend on correctly evaluating data regarding earthquake recurrence intervals, percentage of time the materials are saturated, the lack of dependence of liquefaction on type of construction, and the proportion of occurrence of loose saturated materials to damage occurrence. Uncertainties in the range in recurrence intervals alone can result in cost estimates of approximately two-thirds to seven times those used. Better information on all these variables could narrow the range of uncertainty; also site studies can provide a much more reliable assessment for specific projects.

SUBSIDENCE

Subsidence is the decrease in surface elevation which results when subsurface materials compact. This process can result from withdrawal of ground water, from infiltration of water into materials which collapse when exposed to impounded water, from the violent shaking during a large earthquake, or from other causes. A potential for subsidence exists whenever unconsolidated granular deposits, such as valley alluvium, can be consolidated.

The costs associated with potential subsidence can be either preventive or related to damage. An example of a preventive cost is that related to directing or importing surface waters to balance withdrawal by pumping, thereby inhibiting subsidence and reducing damage. Damage-related costs result chiefly from changes in surface elevation.

For many years between 1914 and 1965, the amount of ground water pumped from confined aquifers in the Santa Clara Valley exceeded the amount re-entering the system in recharge areas, causing subsidence of the ground surface. In 1965 the Santa Clara Valley Water District began artificially recharging the ground water by impounding imported water in percolation basins. Monitoring of surface elevations reveals that no subsidence has occurred since 1969 when ground-water levels rose above their previous low. Figure 25 shows this increase in water level and cessation of subsidence (Santa Clara Valley Water District, 1974).

It is assumed that the continuing operations of the Santa Clara Valley Water District will preclude the overpumping of ground water and that no additional subsidence will occur. Thus, no future cost is assigned to subsidence.

TABLE 21.—*Costs per acre associated with liquefaction potential*

Land uses	Cost category 6	5	4	3	2	1
Rural or agricultural	$20	$10	$9	$1	$0	$0
Semirural residential	100	80	70	7	0	0
Single-family residential	2,000	$1,000	900	90	6	0
Multifamily residential	6,000	4,000	3,000	300	20	0
Regional shopping centers	5,000	3,000	3,000	300	20	0
Downtown commercial	7,000	4,000	4,000	400	30	0
Industrial	4,000	3,000	2,000	200	20	0
Freeways	0	0	0	0	0	0

COSTS ASSOCIATED WITH SLOPE-STABILITY PROBLEMS

LANDSLIDES

In the study area, landslide potential has been evaluated in terms of relative slope stability (Nilsen and Wright, 1979). Five categories, ranging from 1 for stable to 5 for unstable, are mapped and used to identify increasing landslide potential. The categories are derived from percent slope, relative stability of geologic units, and extent of landslide deposits as identified on aerial photographs:

Category 1 ---------- Slopes less than 5 percent.
2 ---------- Slopes between 5 percent and 15 percent.
3 ---------- Slopes greater than 15 percent and underlain by stable materials.
4 ---------- Slopes greater than 15 percent and underlain by unstable materials.
5 ---------- Landslide areas, regardless of percent slope or materials.

The costs of building in areas with landslide potential depend, in part, on the extent of the geotechnical investigation required and on the special engineering and construction practices necessary to prevent damage from slope failure. It is presently the conventional engineering practice in the study area to perform site investigations and design special foundations in most hillside areas. In estimating these costs, therefore, it is assumed that unstable areas will be recognized and avoided and that no damage will occur. This assumption may not be valid in other hillside regions; for example, where hillside development proceeds without any evaluation of slope-stability problems, damage and damage-related costs are the major elements of cost.

STUDY COSTS

The cost of investigations was determined by interviewing professionals representing 13 geotechnical firms that operate in the study area (see list that follows). The following hypothetical situation was used as a basis for cost estimates:

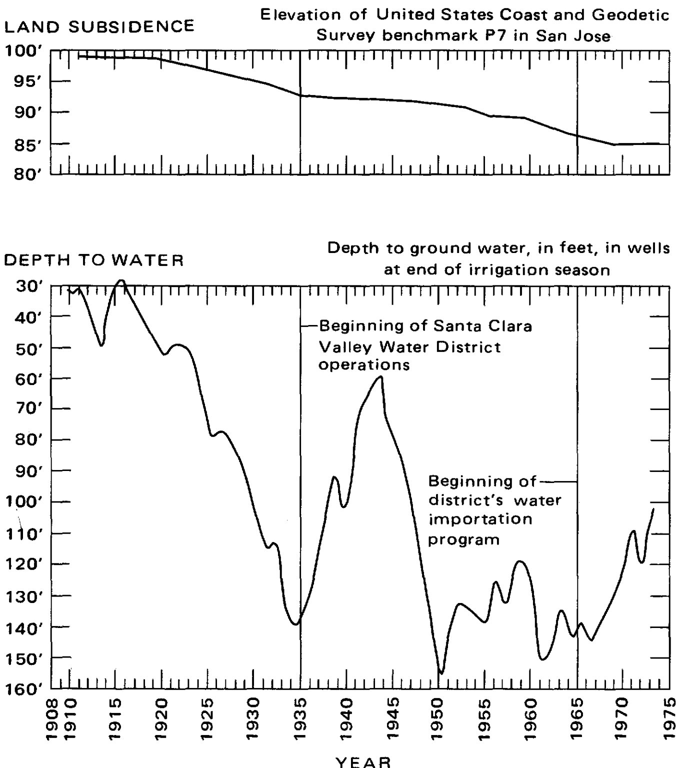


FIGURE 25.—Subsidence and ground-water levels in the Santa Clara Valley from 1910 to 1974.

The owner of 25 acres in a hillside area has applied for a subdivision permit and has been informed that a geotechnical report is required. This person is now approaching your firm requesting information on the range of cost he can expect to incur for a landslide investigation.

The results of the interviews are summarized in table 22. The great variability in the costs of level 1 and 2 investigations shown in the table are due to the costs being based on costs per parcel and being shown as costs per acre.

TABLE 22.—*Cost estimates for slope-stability studies*

Level	Type of investigation	Cost
1	Preliminary geologic report: Literature search, aerial-photograph interpretation, surface mapping, few geophysical profiles.	$300–2,000 (avg = $1,000)
2	Subsurface reconnaissance: Drilling and trenching, samples and laboratory testing, preliminary slope-stability, analysis.	$1,500–10,000 (avg = $5,000)
3	Detailed geotechnical investigation: Borings, soil mapping and testing, grading and construction specifications, foundation design.	$2,500–5,000 ($10,000 maximum for larger structures)

Contacts and interviewees for costs of geotechnical investigations

Cooper, Clark and Associations, Mr. Bob Cooper
International Engineering Co., Mr. Joe Long
Terratech, Inc., Mr. Dennis Eckels
United Soil Engineering, Mr. Max Gahrahmat
Woodward-Lundgren & Associates, Mr. George Hervert
Applied Soil Mechanics, Inc., Mr. Greenly
Percell, Rhodes, and Associates, Mr. Daniel Rhodes
Hallenbeck, McKay & Associates, Mr. Ted Timmons
Western Geological Consultants, Mr. Harry Short
Berlogour, Long and Associates, Mr. Frank Berlogour
Richard E. Rowland
Peter Kaldveer, Associates, Mr. Peter Kaldveer
Terrasearch, Inc.

Although these ranges of study costs have been determined only for single-family residential subdivisions, they can be applied to other land uses by assuming the following:

- Rural-agricultural (40-acre site) requires level 1 (preliminary report) only.
- Semirural residential (5-acre site) requires level 1 with level 2 (subsurface reconnaissance in categories 4 and 5).
- Single-family residential (5 units per acre) requires levels 1, 2, and 3 (detailed investigation) and some special engineering.
- Multifamily residential
- Regional shopping centers
- Downtown commercial
- Industrial
- Freeways

} Require all levels of investigation and special engineering.

On the basis of these data and assumptions and the densities assumed for each land use, one can compute the study costs. These study costs are shown in table 23–25.

MITIGATION COSTS

Most persons interviewed agree that if site conditions necessitated a level 3 investigation, special engineering recommendations would certainly result, and additional costs would be incurred for special construction. Estimates of the added cost of special mitigating measures ranged from 1 to 50 percent of the total cost of constructing the structure. The actual cost would depend on the specific site conditions and the findings of the detailed investigation. A range of costs can be estimated for each category and each land use (fig. 26). Many interviewees noted that the results of the first two levels of investigation might negate the economic feasibility of the proposed development.

For purposes of this study, an average percent of building cost is assumed for each landslide potential category. These percentages correspond to the points on figure 26 and are for category 1, 0 percent; for category 2, 1 percent; for category 3, 5 percent; for category 4, 15 percent; and for category 5, 25 percent.

OTHER COSTS

In addition to the costs described above, most persons interviewed agree that it would not be possible to develop the property at the originally intended density (structures per acre) in the higher-potential categories. However, for this study, it is assumed that this effectively lost area would be financially compensated for by increasing densities in localized areas or by increasing the price of the units. The latter appears to be common practice, perhaps because hillside areas are esthetically more attractive. Therefore no special costs are included.

TOTAL COST

The total cost for landslides is calculated by using the following formula:

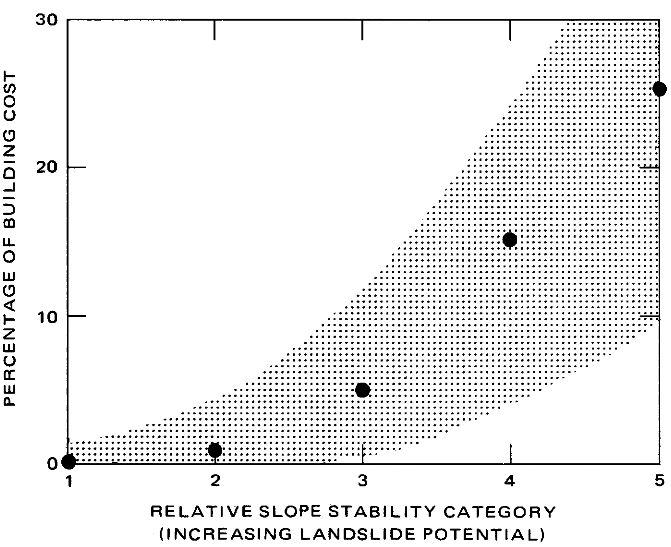


FIGURE 26.—Cost of special engineering and construction as a function of landslide potential. The shaded area represents the range of possible additional cost based on experience as determined by interviews; the points represent the numbers assumed for this study.

$$\begin{pmatrix}\text{cost}\\ \text{in dollars per}\\ \text{acre}\end{pmatrix} = \begin{pmatrix}\text{cost of levels}\\ \text{1,2, and 3 investi-}\\ \text{gations per acre}\end{pmatrix} + \begin{pmatrix}\text{cost of special}\\ \text{engineering measures}\\ \text{in dollars per acre}\end{pmatrix}$$

where

$$\begin{pmatrix}\text{cost of special}\\ \text{engineering measures}\end{pmatrix} =$$

$$\left(\text{percentage of building cost}\right) \begin{pmatrix}\text{value of buildings in}\\ \text{dollars per acre}\end{pmatrix}$$

These costs for each land use are listed in table 26.

TABLE 23.—*Level 1: Approximate investigation costs per acre for landslide hazards*
[See text for explanation of categories 1–5.]

Land use	Cost category 1	2	3	4	5
Rural or agricultural	$0	$12	$20	$25	$38
Semirural residential	0	100	160	200	300
Single-family residential	0	40	60	72	80
Multifamily residential	0	1,000	1,500	1,800	2,000
Regional shopping centers	0	15	22	27	30
Downtown commercial	0	1,000	1,500	1,800	2,000
Industrial	0	1,000	1,500	1,800	2,000
Freeway	0	100	150	180	200

TABLE 24.—*Level 2: Approximate investigation costs per acre for landslide hazards*
[See text for explanation of categories 1–5.]

Land use	Cost category 1	2	3	4	5
Semirural residential	$0	$0	$0	$500	$1,000
Single-family residential	0	200	240	280	320
Multifamily residential	0	5,000	7,000	9,000	10,000
Regional shopping centers	0	75	106	136	151
Downtown commercial	0	5,000	7,000	9,000	10,000
Industrial	0	5,000	7,000	9,000	10,000
Freeways	0	500	700	900	1,000

TABLE 25.—*Level 3: Approximate investigation costs per acre for landslide hazards*
[See text for explanation of categories 1–5.]

Land use	Cost category 1	2	3	4	5
Single-family residential	$0	$100	$120	$160	$200
Multifamily residential	0	2,500	3,000	4,000	5,000
Regional shopping centers	0	2,500	3,000	4,000	5,000
Downtown commercial	0	2,500	3,000	4,000	5,000
Industrial	0	2,500	3,000	4,000	5,000
Freeways	0	2,500	3,000	4,000	5,000

TABLE 26.—*Costs per acre associated with landslide potential*

Land use	Cost category 5	4	3	2	1
Rural or agricultural	$40	$30	$20	$10	$0
Semirural residential	1,000	700	200	100	0
Single-family residential	40,000	20,000	8,000	2,000	0
Multifamily residential	200,000	100,000	50,000	9,000	0
Regional shopping centers	$100,000	80,000	30,000	8,000	0
Downtown commercial	200,000	100,000	50,000	20,000	0
Industrial	100,000	70,000	30,000	10,000	0
Freeways	20,000	20,000	7,000	4,000	0

A maximum value of dollar cost can be calculated by doubling the costs of the investigations and mitigation measures which doubles the value of expected cost. A minimum value can be estimated by cutting these cost figures by 50 percent.

SOIL CREEP

Soil creep, as defined in this study, is the slow downslope movement of soils and is assumed to be associated with soils having shrink/swell potential. While there can be other causes, shrink/swell soils are the most common cause of this problem.

The Soil Conservation Service has mapped soils in the demonstration area and determined their shrink/swell potential (U.S. Soil Conservation Service, 1968; U.S. Soil Conservation Service and Association of Bay Area Governments, 1966). Four categories can be defined by combining this map with the percent slope information from U.S. Geological Survey slope maps.

Category 1 ------------------------Slopes of less than 5 percent.
2 ------------------------Slopes greater than 5 percent with "low" shrink/swell soils.
3 ------------------------Slopes greater than 5 percent with "moderate" shrink/swell soils.
4 ------------------------Slopes greater than 5 percent with "high" shrink/swell soils.

The soil associations in the three shrink/swell categories are listed in the section "Shrink/Swell Potential." The relationships between the percent costs associated with soils having creep potential (categories 2–4) are assumed to be the same as those for shrink/swell soils because creep categories are derived from the map of shrink/swell potential.

The depth of soil which is creeping affects costs. Since the depth to which creep extends is not generally mapped, costs associated with soil creep are difficult to estimate.

It is assumed that the total costs of additional design due to creeping soils in category 4 (high shrink/swell soils on slopes greater than 5 percent) would be 6 percent of the total improvement costs. (A survey of soils engineering firms disclosed that costs ranged from 5 to 20 percent of the total value of the buildings and improvements with the most usual costs somewhere at the lower end of the range. The 6 percent value is estimated as the average). The total costs for creeping soils in the moderate category is assumed to be 2 percent. No cost is assumed to be associated with soils characterized by low creep potential; these soils are not found in the demonstration area, but they are found in other parts of the San Francisco Bay region. The calculated values of cost are given in table 27.

TABLE 27.—*Costs associated with soils with creep potential*
[Although no soils in category 2 (slight shrink/swell potential) are found in the demonstration area, the category is included to illustrate the range of the problem.]

Land uses	Cost category			
	4. High	3. Moderate	2. Low	1. Less than 5-percent slope
Rural or agricultural	$100	$30	$0	
Semirural residential	1,000	300	0	
Single-family residential	10,000	4,000	0	
Multifamily residential	40,000	10,000	0	
Regional shopping centers	30,000	10,000	0	(See shrink/swell soils, table 17.)
Downtown commercial	50,000	20,000	0	
Industrial	20,000	8,000	0	
Freeways	0	0	0	

The range of costs estimated by the soils engineering firms can be used to calculate minimum and maximum costs. If a cost increase of 5 percent is used, a minimum value of five-sixths of the values given above can be obtained. If a cost increase of 20 percent is used, a maximum value 3⅓ times the values given can be obtained.

For a further description of soil creep, refer to the preceding section "Shrink/Swell Potential."

COSTS ASSOCIATED WITH EROSION AND SEDIMENTATION

In previous studies of the south and central San Francisco Bay region by Brown and Jackson (1973), six erosion and depositional provinces were identified:

1. Santa Cruz Mountains uplands.
2. Diablo Range uplands.
3. Bay Hills.
4. Upland valleys and ridgetop terrain.
5. Foothills.
6. Bay plain and alluvial valley.

The Diablo Range uplands (2), Foothills (5), and Bay plain and alluvial valley (6) provinces are present in the part of the Santa Clara Valley demonstration area shown in figure 22.

Information on soils from the U.S. Soil Conservation Service could have been used if Brown and Jackson's study had not been available.

Stream sediment may be generated in a number of different ways, including sheet wash, gullying, and landslides. It is difficult to trace such sediment to its source. Most landslide costs are described in the preceding section, but the cost of erosion and sedimentation caused by or related to landsliding is different and was not considered in the previous discussion of landslides. The primary costs of erosion and sedimentation are assumed to be due to loss of agricultural soil and to the need to eventually remove sediment from stream channels. Other costs, such as the costs of loss of water quality, the damage from increasing flood frequency due to reduced channel and storage capacity, engineering mitigation measures, and the loss of spawning grounds, are not specifically analyzed but are partly reflected in dredging costs to remove sediment.

Thus, there are two basic problems to be solved: first, the volume of sediment yield per acre for each land use must be determined and, second, the costs associated with dredging this amount of sediment must be assessed. The solution found for each of these problems will be discussed in turn.

For one erosion province, the bay hills, sediment-yield data exist for four land uses (Knott, 1973). These land uses and yields are given in table 28.

Unfortunately, only the sediment yields in open-space areas are known for the other erosion provinces. It is assumed, therefore, that the ratio of sediment yield for any developed land use to the sediment yield for open space is constant for all erosion provinces. Thus, one may calculate the sediment yield per acre for land use x and erosion province y with the formula:

$$\left(\begin{array}{c}\text{sediment yield}\\ \text{in tons per acre}\\ \text{for use } x \text{ and erosion}\\ \text{province } y\end{array}\right) = \frac{\left(\begin{array}{c}\text{sediment yield in}\\ \text{tons per acre for}\\ \text{use } x \text{ for bay hills}\\ \text{province}\end{array}\right)}{\left(\begin{array}{c}\text{sediment yield in}\\ \text{tons per acre for}\\ \text{open space for bay}\\ \text{hills province}\end{array}\right)} \left(\begin{array}{c}\text{sediment yield in}\\ \text{tons per acre for}\\ \text{open space for}\\ \text{erosion province } y\end{array}\right)$$

The open-space sediment yields (Brown and Jackson, 1973) for the other erosion provinces are given in table 29.

The appropriate erosion costs to associate with development are the additional dredging expenditures caused by development, that is, the expenditures necessary to dredge the sediment yield over and above the open-space yield. Thus, the relevant sediment yield for cost calculations is given by:

$$\left(\begin{array}{c}\text{incremental sediment}\\ \text{yield per acre for}\\ \text{land use } y \text{ and erosion}\\ \text{province } y\end{array}\right) = \left(\begin{array}{c}\text{gross sediment}\\ \text{yield in tons}\\ \text{per acre per year}\\ \text{for land use } y\\ \text{and erosion}\\ \text{province } y\end{array}\right) - \left(\begin{array}{c}\text{gross sediment yield}\\ \text{in tons per acre per}\\ \text{year for open space and}\\ \text{erosion province } y\end{array}\right)$$

An assumption is made that all sediment accumulated for a 20-year period will have to be dredged to maintain present channel capacities. For 1969–70 Colma Creek conditions, about 60 percent of the sediment is sand and 40 percent is silt and clay. It is assumed that 75 percent of this total annual sediment load will eventually be dredged to maintain present channel conditions. Most of the sand fraction and some of the finer materials will be deposited in channels and never get far into the bay. This crude assumption is one way of quantifying the number of tons of measured sediment yield that will be involved in sedimentation costs.

TABLE 28.—*Average annual sediment yield for Colma Creek, in tons per square mile per year*

Land use	Yield
Open space	310
Agricultural	21,000
Urban	760
Construction	26,000

TABLE 29.—*Average annual sediment yield for open space, in tons per square mile per year*

[The gaging stations are outside the demonstration area, but the sediment yields are considered typical for similar provinces throughout the San Francisco Bay region. Table 29 is based on data from Brown and Jackson (1973). Provinces in a part of the demonstration area are shown in fig. 22.]

Province	Gaging station	Yield
Bay hills	Colma Creek	310
Santa Cruz Mountains	Upper Crystal Springs Reservoir	2,300
Foothills	San Francisquito Creek	140
Diablo Range Uplands	Alameda Creek	140
Valley floor	(estimated)	almost 0

Dredging costs are estimated from costs of recent dredging on Alameda Creek at $2 per ton (B. Mazyck, oral commun., 1975). Dredging operations are calculated as a single event after 20 years. This is an arbitrary but reasonable figure. The frequency or timing of dredging operations is difficult to forecast because it depends on such unpredictable variables as basin-wide land uses (rather than the per acre land use) and long-term climatic effects.

The total cost for the agricultural land use for each province may now be calculated using the following formula:

$$(\text{cost in dollars per acre}) = \frac{\left(\begin{array}{c}\text{sediment}\\ \text{yield in tons}\\ \text{per acre per}\\ \text{year for}\\ \text{“agriculture”}\end{array} - \begin{array}{c}\text{sediment}\\ \text{yield in}\\ \text{tons}\\ \text{per acre}\\ \text{per year}\\ \text{for “open}\\ \text{space”}\end{array}\right)\left(\begin{array}{c}\text{fraction}\\ \text{dredged}\end{array}\right)\left(\begin{array}{c}\text{dredging}\\ \text{cost in}\\ \text{dollars}\\ \text{per}\\ \text{ton}\end{array}\right)}{(\text{discount rate})}$$

Land value loss is not included in the calculated cost figures for agricultural use because Assessor's Office figures revealed very low land values of $100 to $120 per acre, and little of this value would be lost even if the land were severely eroded. (This figure is for hillside lands covered by the Williamson Act and therefore is the value of the land for grazing.)

Cost for urbanized land-use types has been calculated with the knowledge that the rate of erosion returns to near open-space values after a very high peak during actual construction (Brown and Jackson, 1973). The construction is assumed to be completed in 1 year, with dredging every 20 years at random as other construction takes place in the area. The standard discount rate of 10 percent is used. Thus, for calculating the expected cost for all other uses, the following formulas are used:

$$\left(\begin{array}{c}\text{cost}\\ \text{in dollars per}\\ \text{acre}\end{array}\right) = \left(\begin{array}{c}\text{cost}\\ \text{for ``urban''}\\ \text{in dollars}\\ \text{per acre}\end{array}\right) + \left(\begin{array}{c}\text{cost}\\ \text{for ``construction''}\\ \text{in dollars per acre}\end{array}\right)$$

where

(cost for "urban" in dollars per acre) =

$$\frac{\left(\begin{array}{c}\text{sediment}\\ \text{yield for}\\ \text{``urban'' in}\\ \text{tons per}\\ \text{acre per}\\ \text{year}\end{array} - \begin{array}{c}\text{sediment}\\ \text{yield for}\\ \text{``open}\\ \text{space''}\\ \text{in tons}\\ \text{per acre}\\ \text{per year}\end{array}\right)\left(\begin{array}{c}\text{fractions}\\ \text{dredged}\end{array}\right)\left(\begin{array}{c}\text{dredging}\\ \text{cost in}\\ \text{dollars}\\ \text{per year}\end{array}\right)}{(\text{discount rate})}$$

and where

(cost for "construction" in dollars per acre) =

$$\frac{\left(\begin{array}{c}\text{sediment}\\ \text{yield}\\ \text{for}\\ \text{``construction''}\\ \text{in tons}\\ \text{per acre}\\ \text{per year}\end{array} - \begin{array}{c}\text{sediment}\\ \text{yield}\\ \text{for}\\ \text{``open}\\ \text{space''}\\ \text{in tons}\\ \text{per acre}\\ \text{per year}\end{array}\right)\left(\begin{array}{c}\text{fraction}\\ \text{dredged}\end{array}\right)\left(\begin{array}{c}\text{dredging}\\ \text{cost in}\\ \text{dollars}\\ \text{per ton}\end{array}\right)\left(\begin{array}{c}\text{frequency}\\ \text{of}\\ \text{dredging}\end{array}\right)}{(\text{discount rate} + \text{frequency of dredging})}$$

The costs can be estimated using this information and are given in table 30.

A minimum estimate can be obtained by assuming that the percentage of material dredged is reduced to 25 percent, reducing the cost figures to one-third of those given in table 30. To obtain a maximum value, the cost of dredging can be increased to as high as $7 per ton. This change yields cost figures 3½ times larger than those used. Higher values of expected cost can also be obtained by using figures for annual sediment yield obtained from years of above-average rainfall. If figures from one such year, 1967, are used, the costs would increase approximately five times.

TABLE 30.—*Costs per acre associated with erosion and sedimentation*

Land use	Santa Cruz Mountains	Bay hills	Foothills and Diablo Range	Uplands and valley
Rural or agricultural	$4,000	$500	$200	$0
Semirural residential	200	30	10	0
Single-family residential	200	30	10	0
Multifamily residential	200	30	10	0
Regional shopping centers	200	30	10	0
Downtown commercial	200	30	10	0
Industrial	200	30	10	0
Freeways	200	30	10	0

COSTS ASSOCIATED WITH SEPTIC-TANK LIMITATIONS

The U.S. Soil Conservation Service assigns ratings of "slight," "moderate," and "severe" septic-tank limitations to the soil associations it maps (U.S. Soil Conservation Service, 1968). The Arbuckle-Pleasanton soils (Az-PA-AB) have "slight" limitations. The Sorrento soils (sb) and the Yolo-Esparto soils (Yo-En-b) have "moderate" limitations. All other soils in the demonstration area have "severe" limitations (U.S. Soil Conservation Service and Association of Bay Area Governments, 1966).

The costs resulting from septic-tank limitations are of two types. The first is that associated with ground-water pollution. This cost is the sum of the cost of the preventive measures taken by both the private and the public sector and the pollution cost (including the cost of importing water and the value of any loss in public welfare). No significant costs from any of these sources have been incurred to date (F. Roettger, oral commun. 1975; T. I. Iwamura, oral commun., 1975; D. DeMattei, oral commun., 1975).

A second type of cost resulting from soil limitations is the cost associated with increased failure of the systems and therefore the cost of more frequent replacement. Information on failure rates of septic systems is incomplete (D. DeMattei, oral commun., 1975) and is inadequate for the kind of cost analysis made in this report. For the above reasons, the costs associated with soil limitations for septic-tank systems have not been incorporated in this study.

COSTS ASSOCIATED WITH RESOURCES

SAND AND GRAVEL

For land-capability analysis, the important costs associated with sand and gravel deposits are "opportunity costs," that is, the benefits lost if the deposits are not exploited. Sand and gravel exploitation is compatible with only rural land use. Thus, if the land is used for some other purpose such as, for example, single-family residences, the resource value is lost. The amount of loss can be estimated by adding the loss of revenue to the sand and gravel operator and the higher transportation costs that users will have to pay. The transportation costs are higher because sand and gravel is a high-bulk/low-value commodity. At distances of more than 20 miles, such costs may exceed those related to production.

The uncertainty of future use patterns and costs makes it difficult to estimate the costs associated with the loss of sand and gravel.

Bishko and Wallace (1970) devised a planning simulation model to help evaluate zoning decisions that affect sources of construction materials, but in this report a simpler method is used because it is more compatible with other parts of the capability study. The method used here relies on the relatively good information (fig. 23) regarding the sand and gravel deposits in the demonstration area. The area of sand and gravel deposits is 3,950 acres, and the amount of recoverable material is estimated by Burnett and Barneyback (1975) and Goldman (1964) at about 50,000 tons per acre, for a total of 200 million tons.

Most sources estimate the normal per capita use of sand and gravel at about 9 tons per capita per year (San Diego County Environmental Development Agency, 1972; Evans, 1973; and Withington, 1969). However, the Santa Clara Valley deposits contain reactive minerals that make them inappropriate for use in concrete. Because about one-third of the sand and gravel used is in concrete (J. Rapp, Calif. Div. Mines and Geology, oral commun., 1975), a per capita use of 6 tons per year of local sand and gravel is appropriate.

Return on sales for sand and gravel operations is reported to be about 15 percent or 30¢ per ton. This figure will be correct for some operations, high or low for others, depending on efficiency of operation and management (J. Rapp, oral commun., 1975).

Transportation rates are a significant portion of total sand and gravel costs. Rates vary between routes but average about 10¢ per ton per mile (J. Rapp, oral commun., 1975; J. Cedarblade, Association of Sand and Gravel Production, oral commun., 1975). A detailed investigation could use the Public Utilities Commission rate book for more accurate calculations. The population of users closer to the Santa Clara Valley deposits than to the Livermore deposits, the nearest alternate source, is approximately 500,000 people. The average user is 30 miles closer to the Santa Clara Valley deposits. The transportation savings are, therefore, $3.00 per ton.

Rehabilitation of sand and gravel quarries is or will soon be required. It is also required for most future uses of quarry areas. Cost for rehabilitation of sand and gravel quarry sites in Sonoma County are averaging about $10,000 per acre when rehabilitated for use as vineyards (D. W. Keane, oral commun., 1975).

Only one important sand and gravel deposit is recognized in the Santa Clara Valley, and no costs are computed for any other deposits.

The costs associated with the sand and gravel deposit are estimated as follows:

$$\frac{\dfrac{\left(\begin{matrix}\text{dollars}\\\text{per}\\\text{ton from}\\\text{both}\\\text{profit}\\\text{and}\\\text{transpor-}\\\text{tation}\end{matrix}\right)\left(\begin{matrix}\text{tons}\\\text{per}\\\text{acre}\end{matrix}\right) - \left(\begin{matrix}\text{dollars per}\\\text{acre for}\\\text{rehabilitation}\end{matrix}\right)}{\text{acres in deposit}}}{(\text{tons per capita per year})\,(\text{people})\,(\text{acres per ton})} = \begin{matrix}\text{(dollars per}\\\text{acre per year)}\end{matrix}$$

or

$$\frac{\dfrac{(3.30)(5\times 10^4) - 10^4}{3{,}950}}{(6)(5\times 10^5)(2\times 10^{-5})} = \$2{,}354 \text{ per acre per year}$$

Discounting for the life of the reserve (essentially forever) results in an expected value of:

$$\frac{\$2{,}354 \text{ per acre}}{0.10} = \begin{matrix}\$23{,}540 \text{ per acre, or approximately}\\ \$20{,}000 \text{ per acre using one significant}\\ \text{figure.}\end{matrix}$$

This value is to the producer and to society, but mostly to society.

The costs for all uses except rural are the same, as the opportunity for resource extraction is lost.

Because most rural land use is compatible with development of sand and gravel deposits, there is no cost associated with sand and gravel loss for that use. The estimated costs that result from loss of sand and gravel resources are tabulated in table 31.

Uncertainty in the cost estimate results largely from unknown patterns of future use. The per capita use figure is particularly sensitive and can appropriately be used only to provide minimum and maximum estimates.

If building construction slows down further and road construction remains depressed, a per capita use figure of 2 tons per capita per year might occur. This figure would reduce the cost estimate to $8,300 per acre.

If the lower grade sand and gravel deposit west of Cupertino is utilized as an alternative source instead of the Livermore deposits, the transportation costs would be reduced to $1.00 per ton and the cost estimate would become $8,000 per acre.

A maximum value can be calculated by using higher estimates of per capita use. An expected use of 24 tons per capita (U.S. Army Corps of Engineers, 1964) would increase the cost estimate to $100,000 per acre.

MINERALS

Mercury is the only mineral commodity that has been produced in the area, but small deposits of other minerals also occur there. The location of former mercury mining operations has been reported by Bailey and Harden (1975).

Determining the expected costs associated with mineral resources is extremely difficult because of the complexity of mineral economics and distribution. The global nature of supply and demand introduces both theoretical and practical difficulties in the valuation of the deposits. Ideally, estimates would be made with information on the different uses and deposits both here and elsewhere, applicable mining and refining technology and costs, substitutability, and long-run demand projections for each mineral that exists in the study area. None of this information is readily available. Therefore, many assumptions have been made to determine an expected value.

TABLE 31.—*Costs per acre associated with loss of sand and gravel*

Land uses	Cost per acre
Rural or agricultural	$0
Semirural residential	20,000
Single-family residential	20,000
Multifamily residential	20,000
Regional shopping centers	20,000
Downtown commercial	20,000
Industrial	20,000
Freeways	20,000

None of the surveyed mineral deposits in the study area is likely to be exploited in the near future. Thus, in one sense, the deposits have very little value, and the opportunity costs associated with noncompatible land uses in these areas are similarly very low. However, as has been demonstrated by petroleum resources, cartel formation and geopolitical maneuvering can radically alter market conditions and thus radically change the value of mineral deposits.

Some specific minerals, often called strategic, seem likely to be more valuable in the future. These minerals have two characteristics: they have few substitutes, and they exist in only limited amounts within the United States. Some mineral deposits occur in the demonstration area. Of these, mercury, chromite, and manganese are in limited supply in the United States and might be considered strategic (Meadows and others, 1972).

The California Division of Mines and Geology is just beginning an evaluation of chromite and manganese resources. As of 1975, the deposits in the demonstration area are classified as small and usable only if prices are high (Bailey and Harden, 1975).

Mercury is mentioned here for demonstration purposes because considerable literature is available and because the New Almaden mine just outside demonstration area is the fourth largest producer in world history (Bailey and Everhart, 1964) and therefore is conceivably large enough to be of national importance.

The potential importance of the mercury deposits can be estimated by examining what the price of mercury was when the mines were operated. During World War II, the price of mercury reached $196 per flask (U.S. Bureau of Mines, 1965). A flask is 76 pounds of mercury. Although it was equivalent to about $1,000 per flask in 1975 dollars, the World War II price stimulated only minor activity, chiefly the reworking of old tailings (Bailey, 1951). Activity resumed in 1956–61 when prices reached close to $800 per flask in 1975 dollars. It was again largely confined to bulldozer stripping and trenching (Bailey and Everhart, 1964).

In recent years, the cost of hard-rock mining has increased rapidly under rising pressure for environmental protection and increased safety requirements. Thus, a value of over $1,000 per flask would probably be the absolute minimum required to activate mercury mining. Other mercury resources in the United States are likely to become economic before this price is reached.

Growing environmental concern has reduced the use of mercury, and substitutes for many uses have been found (U.S. Bureau of Mines, 1974). The price has dropped to about $140 per flask but may rise because a new mercury cartel has recently been formed. In previous years, the price increased under cartel control in mercury supply (U.S. Bureau of Mines, 1965). A consideration of these factors leads to an estimate of expected cost of zero, for the mercury deposits in or near the demonstration area, because the deposits have no current dollar value.

To calculate maximum value, some assumptions can be made. A price of $1,000 per flask may be assumed for 1980 and production (with 20 percent return) that would then begin immediately. Potential production is assumed to be 20,000 flasks per year. This production rate is approximately the average during the period of maximum production in 1850–70 (Bailey, 1951). This assumption yields a revenue of $4 million per year for the New Almaden mine, a holding of about 4,000 acres. This value is equivalent to $1,000 per acre per year.

The present value of production can be calculated using a discount rate and production period of 20 years. The value, because of discounting, would not be much different if production continued for a longer period.

Two other assumptions also have to be made to obtain this estimate of maximum cost: All identified mercury deposits have the same potential as the New Almaden, and mercury will not be found elsewhere in the study area.

The calculation of the maximum cost is demonstrated below:

$$\text{Value the first year (1980)} = \frac{(2 \times 10^4 \text{ flasks per year})(0.2 \text{ profit})(10^3 \text{ dollars})}{(4 \times 10^3 \text{ acres in area})}$$

$$= 10^3 \text{ dollars per acre per year.}$$

To compute the present value under the assumptions described above, the following integral must be computed:

$$(10^3 \text{ dollars per acre per year}) \int_5^{25} e^{-rt}dt,$$

where r is the discount rate. The present value of future production, and thus the maximum expected cost associated with mercury, is approximately $5,000 per acre.

Given these assumptions, the cost associated with all identified deposits is $5,000 per acre, and with all other areas, zero.

AGRICULTURE POTENTIAL

The U.S. Soil Conservation Service classifies land into several agricultural categories but considers both Class I and Class II to be "prime" for agricultural production (U.S. Soil Conservation Service, 1968). Their maps are used for categorizing estimates of cost (U.S. Soil Conservation Service and Association of Bay Area Governments, 1966). The following soil associations are considered prime agricultural land:

	Association
Az-PA-AB	Arbuckle-Pleasanton.
CM-Eb	Clear Lake-Edenvale.
cp-Rn-BC	Cropley-Rincon.
sb	Sorrento.
Yo-En-B	Yolo-Esparto.
Zm-PA	Zamora-Pleasanton.

The Williamson Act in California stipulates that agricultural land placed in the program may not be developed for specific periods of time. This restriction causes such parcels to have value only as agricultural land because any other use is precluded. Therefore, land that is under the Williamson Act should fairly accurately reflect the value of the land itself.

According to the Santa Clara County assessor's office (oral commun., 1975), property under the Williamson Act ranges in assessed value from $1,200 to $1,500 per acre, which is 25 percent of the market value. An estimate of full value, $5,400 per acre, can be calculated using the average value, $1,350 per acre assessed. Because this value is current, no discounting is needed. The results of these calculations are summarized in table 32. Also, a minimum cost can be calculated from the minimum assessed value and is $4,800 per acre.

Additional assumptions can be made to calculate a maximum cost. Starting with the maximum assessed value of $1,500 per acre, or a market value of $6,000 per acre, a maximum value can be estimated by postulating a 3 percent per year growth rate in value (equivalent to world population growth). This leads to a cost associated with the resource loss of:

$$\$6,000 \times {}^{10}/_{7} = \$8,570 \text{ per acre.}$$

AGGREGATING AND DISPLAYING RESULTS OF THE COST ANALYSIS

An electronic computer is used to produce maps of development costs. This method has advantages in the speed of computing, flexibility of varying input, and automatic graphics which are relatively inexpensive.

TABLE 32.—*Costs per acre associated with loss of prime agricultural land*

Land uses	Cost per acre
Rural or agricultural	$0
Semirural residential	5,000
Single-family residential	5,000
Multifamily residential	5,000
Regional shopping centers	5,000
Downtown commercial	5,000
Industrial	5,000
Freeways	5,000

The process of automatically mapping capability involves four major steps: (1) digitizing data maps, (2) creating a master file of these maps and other maps created by combining maps, (3) totaling costs, and (4) displaying these dollar amounts in map form. This section of the report describes the way in which each of these steps has been performed for the demonstration area by using the existing land-use mapping programs at the University of California, Davis. The results of this process are shown in a series of capability maps for the eight land-use types.

DATA COLLECTION

Before utilizing any automated system, it is necessary to put data into a machine-readable form. Many techniques are available, and some have been discussed in the section "Mapping and Displaying Land-Capability Data."

For this demonstration, a uniform grid was used for data collection. Because of difficulties in collecting data by hand, a grid cell of no smaller than one-tenth of an inch on a side could be justified. On the 1:125,000-scale maps used for this demonstration, one such grid cell measures approximately 1,042 feet on a side and contains approximately 1 million square feet, or 24.9 acres. Because of the grid size, areas smaller than the cell may be overlooked, but the grid is suitable for this level of study.

Gridded transparent overlays of translucent film, frosted on one side, were pin-registered to each of the basic data maps. Registry was carefully checked to insure that cells were correctly matched on each map.

Data were collected by using the gridlines to approximate boundaries between mapped units, a process which is referred to as "rectilinearization." When all boundaries were converted to grid lines, a number of polygonal shapes resulted, each of which approximated a corresponding unit defined by curvilinear boundaries on the original data map.

Keypunch coding forms were prepared with the demonstration boundary drawn and line number written directly on them. These forms helped orient the person transposing the data from the map and overlay to coding form. The coding-form space correspoding to each cell was determined, and a single letter or number was written in the space. The letter-number code was preestablished for all units on each map.

The forms then were keypunched, and the resulting cards were listed. These listings were checked against the gridded overlays to verify that the correct character has been punched. The cards were then processed in an ABAG computer program that translates the character in each cell into a corresponding integer value and writes it on magnetic tape.

Some 64 different units could be so coded for each map. This limitation is acceptable because it accommodated the data (maximum number of units needed was 26 for soils).

The computer program stores the map data on a magnetic tape, and the tape can be fed to a map-generating program at the University of California, Davis (Johnston and others, 1975).

TRANSLATION OF DATA TO LAND-USE MAPPING PROGRAM (LUMP)

A program designated Modified LUMP/MERGE takes the data from the ABAG program on 14 basic data maps and an area map (figs. 8—23) and places it into a master file where each cell is assigned 14 variables, one for each map.

Five additional data maps are created by combining some of the original maps, and these maps are added to the master file as five additional variables for each cell. The additional maps created are for soil creep, shrink/swell soils, liquefaction potential, settlement potential, and prime agricultural land. These maps have not been printed but are on tape.

LAND-CAPABILITY CALCULATION

Calculating land capability involves only simple addition. The reasons for using the computer are the speed with which it performs the calculations for the large number of cells, the ease with which minor changes can be made and calculations rerun, and the ease and speed with which maps are produced.

A program designated LUMP/WEIGHTER uses a table of costs to obtain a value of total cost associated with the category of each constraint or resource for each cell and adds the cost determined for each problem or resource to the cost sum for that cell.

The resulting number in each cell is the dollar cost per acre expected to be incurred by developing that cell with that land use. These values are stored in an array for further processing.

DISPLAY

Once values have been calculated for each cell, there are many ways to display them. The program LUMP/MAPPER provides for producing two types of maps on a time-share terminal.

Both sets of maps make use of overprinted symbols. The density or darkness of the symbols has been chosen so that the maps show higher costs in darker shades of gray. Because of the need to distinguish between gray shades, all of the maps are limited to the six shades of gray shown in figure 27.

The program provides for a first set of maps, series A, which have designated cost ranges that are the same for all eight land uses; any tone means the same interval of costs on each map. For the series A maps, a geometric progression of 10 was used because it encompassed all values possible while providing for some change in tone for even the lowest range in the rural or agricultural land use (table 33).

Other cost increments can be selected and displayed as needed. This aspect of computer graphic display makes it very flexible. If the first run produces a visually unacceptable rendition, the values are adjusted into different ranges and a second run is made. To illustrate this flexibility, this report contains second-run, series B maps, which display all of the eight land uses, using limits defined by the square, cube, or fourth root of 10.

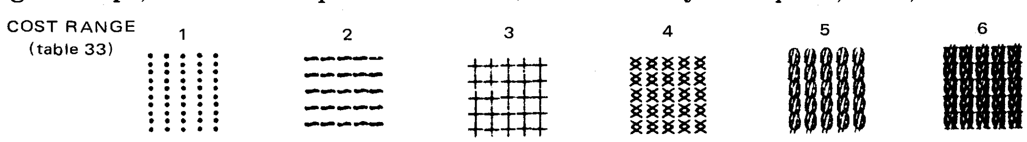


FIGURE 27.—Shade-of-gray scale.

TABLE 33.—*Cost ranges per acre for first set of capability maps (series A)*

Cost category	
1	$0 - $10
2	10.01- 100
3	100.01- 1,000
4	1,000.01- 10,000
5	10,000.01- 100,000
6	100,000.01-1,000,000

The explanation printed with each map displays the symbols, the range of total dollar cost, the number of cells in each increment, and the shade of gray used for that increment.

The total cost in each cell is also written on magnetic tape and can be used to generate statistical analyses or other forms of graphic display employing pen plotters, electrostatic plotters, or cathode ray tube screens.

RESULTS

The land-capability maps for the eight land-use types are included as figures 28–43. Summary tables of the costs on which these maps are based are included as tables 34–41.

The cost tables and the series A capability maps show how costs per acre increase as residential density increases. Area variation in the geologic constraints and resources is also apparent. Thus, the maps, and the costs that they are derived from, reemphasize that no one variable—for example the amount of slope—can adequately represent the scope or effect of geologic problems. Moreover, the large difference between cost categories—each is 10 times more costly than the next—shows the limits of such subjective statements as slight, moderate, or severe constraints.

Erosion, landslides, soil creep, flooding, and loss of sand and gravel reserves have the highest costs, but the magnitude of most of these costs differs for each land use.

Rural or agricultural land use, as the capability maps show, is extremely sensitive to erosion. The hills on the east side of the valley have by far the highest costs associated with them, but areas subject to dike failure also have significant costs associated with them.

For semirural residential use, loss of sand and gravel reserves and of prime agricultural land are most important, but slope-stability problems and potential flooding from dike failure also are responsible for high costs. Isolated areas of low slope outside of the flood plains have the lowest costs associated with geologic considerations. Even though the total costs for this kind of land use never exceed approximately $30,000 per acre, these costs are equivalent to a cost per residential unit (on 5-acre lots) of almost $150,000. These costs are extremely large, especially when compared with the maximum costs per unit for single-family residential use of approximately $20,000 and for multifamily residential use of approximately $1,000.

For single-family residential use, settlement is an important concern, as are sand and gravel resources, dike failure, and slope instability. The total costs approach $100,000 per acre in several areas, equivalent to a per unit cost of $20,000.

The costs per acre associated with multifamily residential use are high, regardless of the area. The costs per unit are not as high as for single-family residential, however. (The costs only approach $1,000 per unit.) Ground shaking, stream flooding, dike failure, landslides, and soil creep are the most significant constraints. Again, the areas outside the flood plains and not on the hillsides have the least costs associated with them. The unstable hillside areas on the east side of the valley and the bay mud areas are most susceptible to geologic problems.

As with multifamily residential use, the costs associated with both types of commercial development are high, regardless of the area. The costs per acre are only about half that of the high-density residential use, however. Even though the capability maps for the two types of commercial use are extremely similar, the costs for downtown commercial use are consistently as large or larger than those for regional shopping-center use. The totals of these costs are about one-third larger for downtown commercial use than regional shopping-center use. For both uses, ground shaking, stream flooding, dike failure, landslides, and soil creep are the most significant constraints.

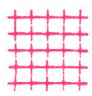
The capability maps for industrial use again illustrate that relatively high costs are associated with this type of development. The total costs are, in general, lower than those for regional shopping-center use but are attributed to the same geologic constraints: ground shaking, stream flooding, dike failure, landslides, and soil creep.

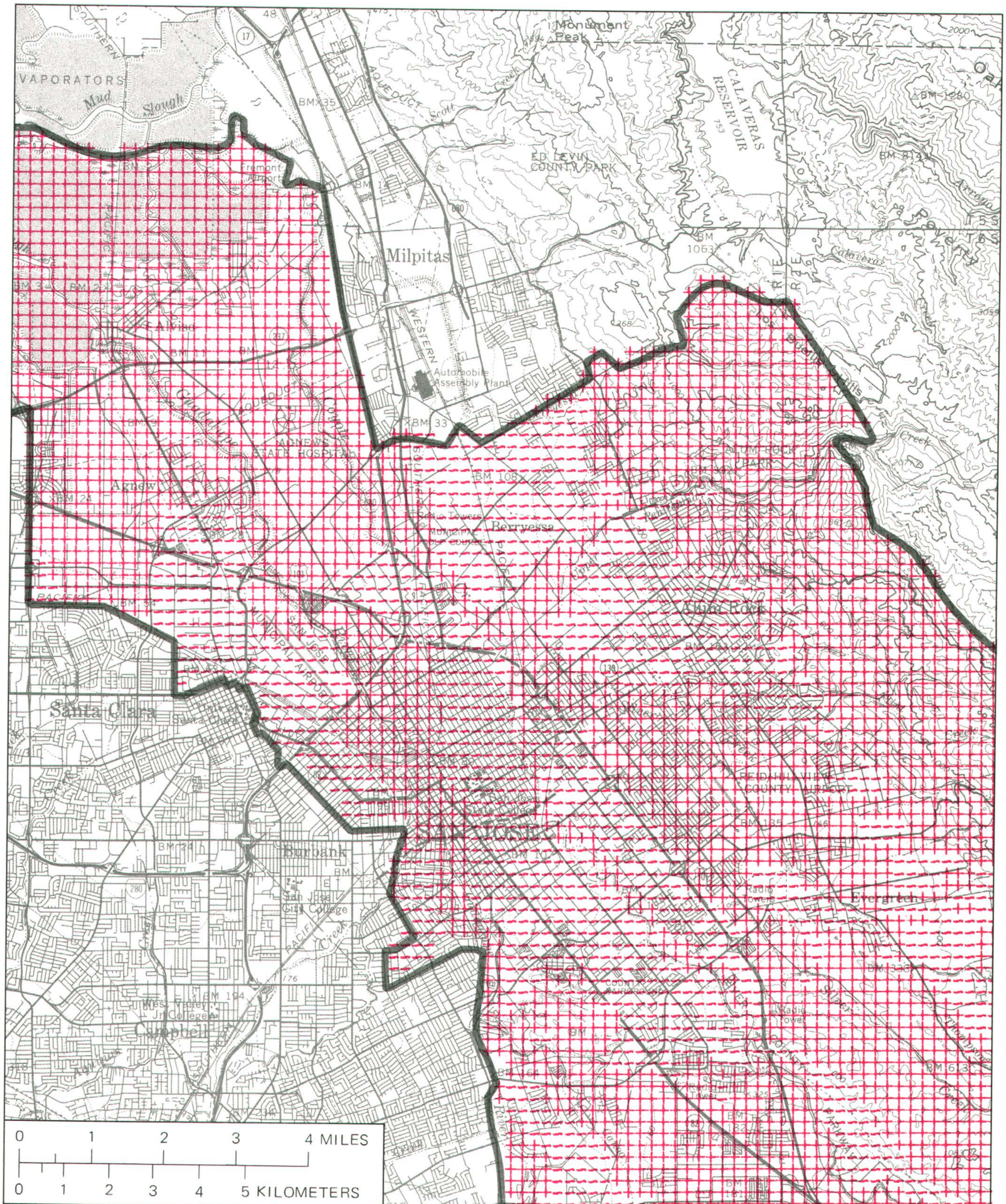
The costs associated with geologic constraints and resources for freeway use are extremely variable. Loss of sand and gravel resources and of prime agricultural land, landslides, ground shaking, and erosion are the most important geologic constraints for freeway use, but much of the demonstration area has relatively low costs associated with this type of development. Most of the areas of low costs, however, do not extend for a long distance in any single direction. Use of the map by itself for locating freeways to avoid geologic constraints could be extremely misleading, however, because freeways encourage development that may have relatively higher costs in these areas. The capability maps illustrate this type of problem by showing that although freeways are relatively unaffected by flood damage, most other uses are greatly affected by it.

TABLE 34.—*Summary of costs for rural or agricultural use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$20	$2	$0	—	—
Ground shaking—San Andreas, Hayward	40	30	10	$ 5	$1
Ground shaking—Southern Hayward	4	3	1	1	0
Ground shaking—Calaveras	30	10	5	1	—
Stream flooding	200	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	500	0	—	—	—
Shrink/swell soils	50	20	0	0	—
Settlement	20	20	10	5	—
Liquefaction	10	9	1	0	0
Subsidence	0	—	—	—	—
Landslides	40	30	20	10	0
Soil creep	100	30	0	0	—
Erosion and sedimentation	4,000	500	200	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	0	—	—	—	—
Mercury	0	—	—	—	—
Agricultural land	0	—	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



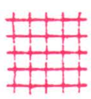
Base from U.S. Geological Survey 1:125,000

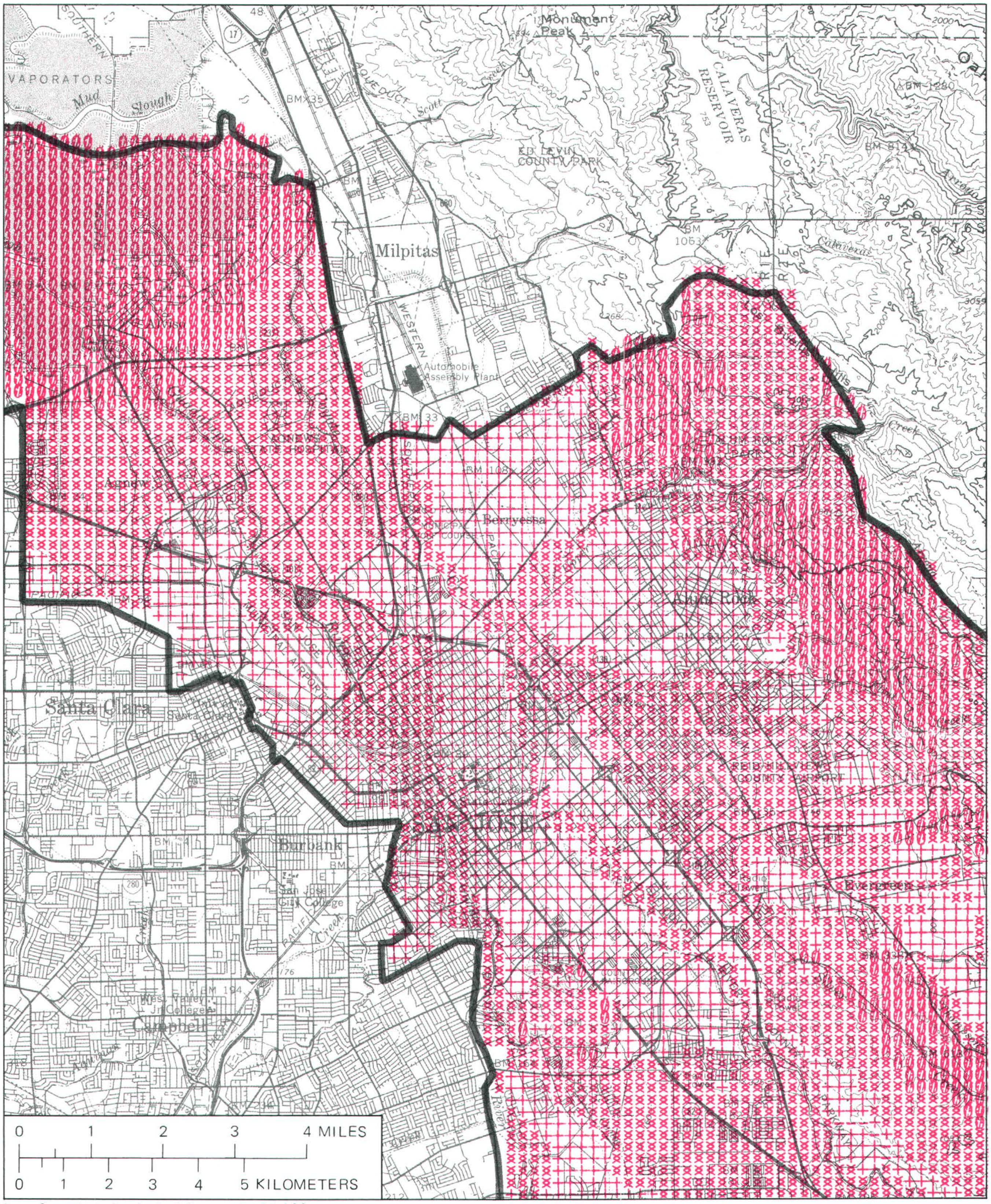
FIGURE 28.—Land-capability map for rural or agricultural use—series A.

TABLE 34.—*Summary of costs for rural or agricultural use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$20	$2	$0	—	—
Ground shaking—San Andreas, Hayward	40	30	10	$ 5	$1
Ground shaking—Southern Hayward	4	3	1	1	0
Ground shaking—Calaveras	30	10	5	1	—
Stream flooding	200	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	500	0	—	—	—
Shrink/swell soils	50	20	0	0	—
Settlement	20	20	10	5	—
Liquefaction	10	9	1	0	0
Subsidence	0	—	—	—	—
Landslides	40	30	20	10	0
Soil creep	100	30	0	0	—
Erosion and sedimentation	4,000	500	200	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	0	—	—	—	—
Mercury	0	—	—	—	—
Agricultural land	0	—	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	31.60
3		31.61	100.00
4		100.01	316.00
5		316.01	1,000.00
6		1,000.01	10,000.00



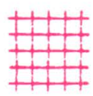
Base from U.S. Geological Survey 1:125,000

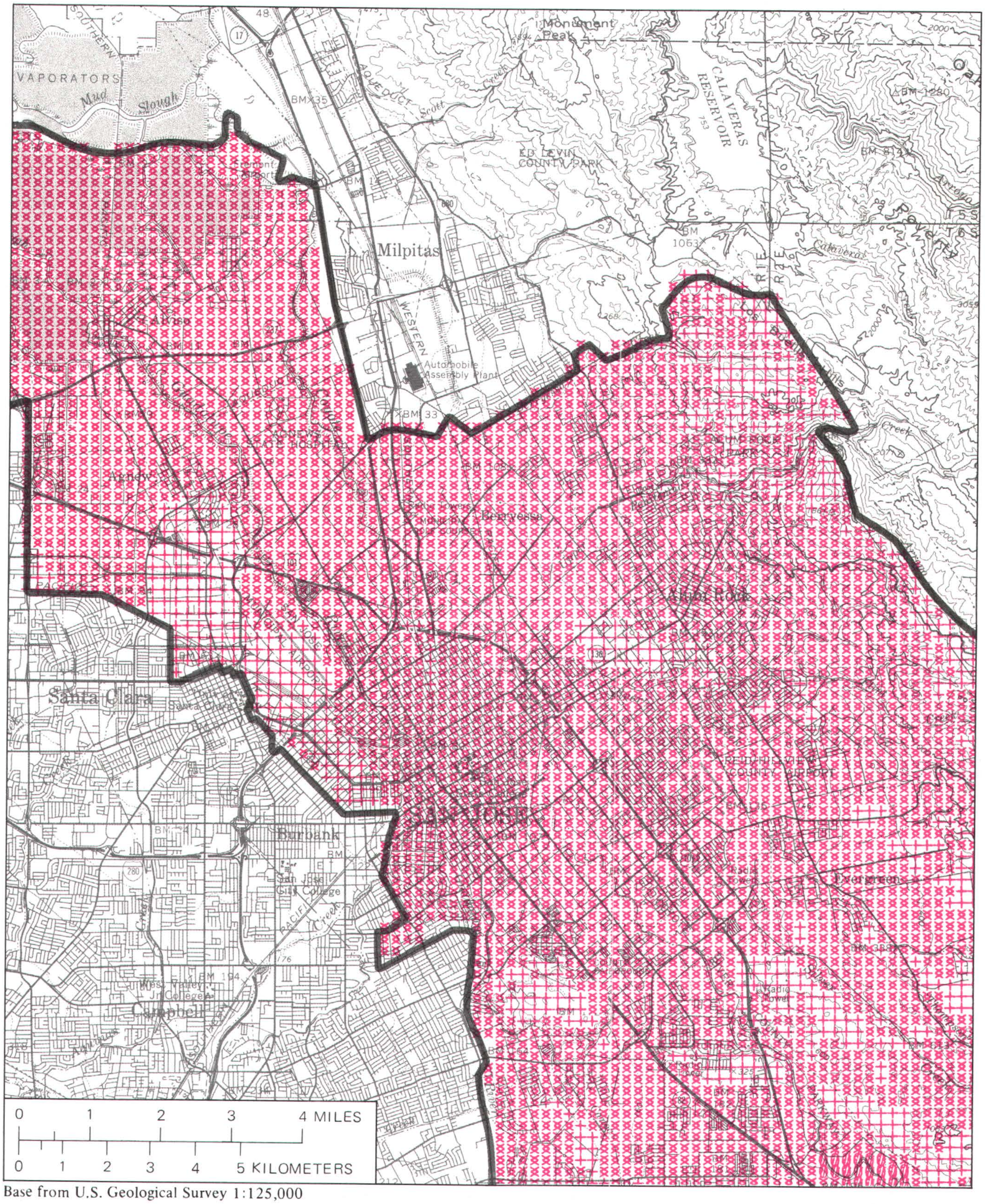
FIGURE 29.—Land-capability map for rural or agricultural use—series B.

TABLE 35.—*Summary of costs for semirural residential use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$70	$7	$0	—	—
Ground shaking—San Andreas, Hayward	300	300	100	$ 40	$4
Ground shaking—Southern Hayward	30	30	10	4	0
Ground shaking—Calaveras	300	100	40	4	—
Stream flooding	700	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	2,000	0	—	—	—
Shrink/swell soils	500	200	0	0	—
Settlement	200	200	100	50	—
Liquefaction	80	70	7	0	0
Subsidence	0	—	—	—	—
Landslides	1,000	700	200	100	0
Soil creep	1,000	300	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



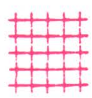
Base from U.S. Geological Survey 1:125,000

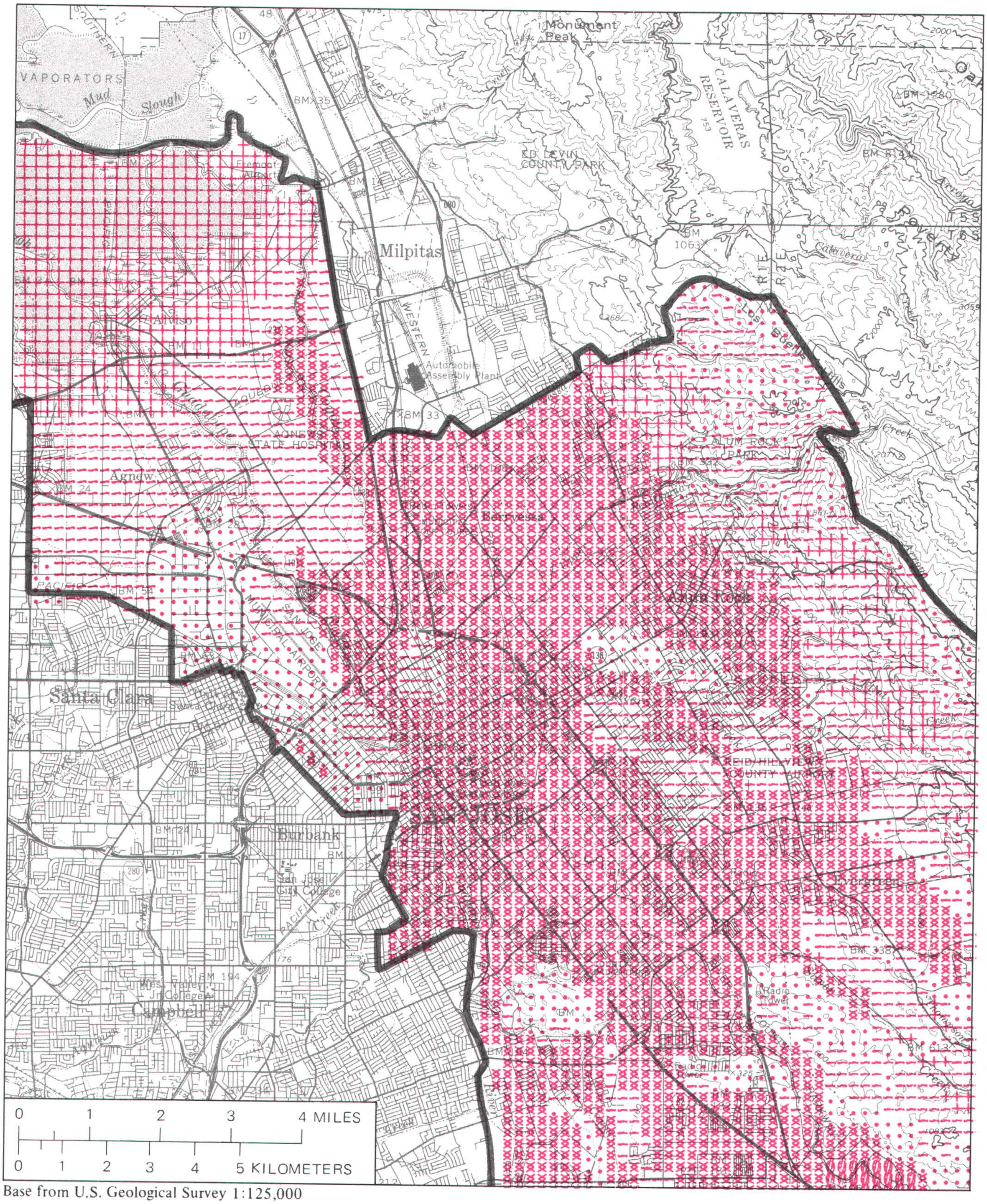
FIGURE 30.—Land-capability map for semirural residential use—series A.

TABLE 35.—*Summary of costs for semirural residential use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$70	$7	$0	—	—
Ground shaking—San Andreas, Hayward	300	300	100	$ 40	$4
Ground shaking—Southern Hayward	30	30	10	4	0
Ground shaking—Calaveras	300	100	40	4	—
Stream flooding	700	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	2,000	0	—	—	—
Shrink/swell soils	500	200	0	0	—
Settlement	200	200	100	50	—
Liquefaction	80	70	7	0	0
Subsidence	0	—	—	—	—
Landslides	1,000	700	200	100	0
Soil creep	1,000	300	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	1,000.00
2		1,000.01	2,153.00
3		2,153.01	4,634.00
4		4,634.01	10,000.00
5		10,000.01	31,623.00
6		31,623.01	100,000.00



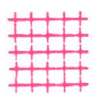
Base from U.S. Geological Survey 1:125,000

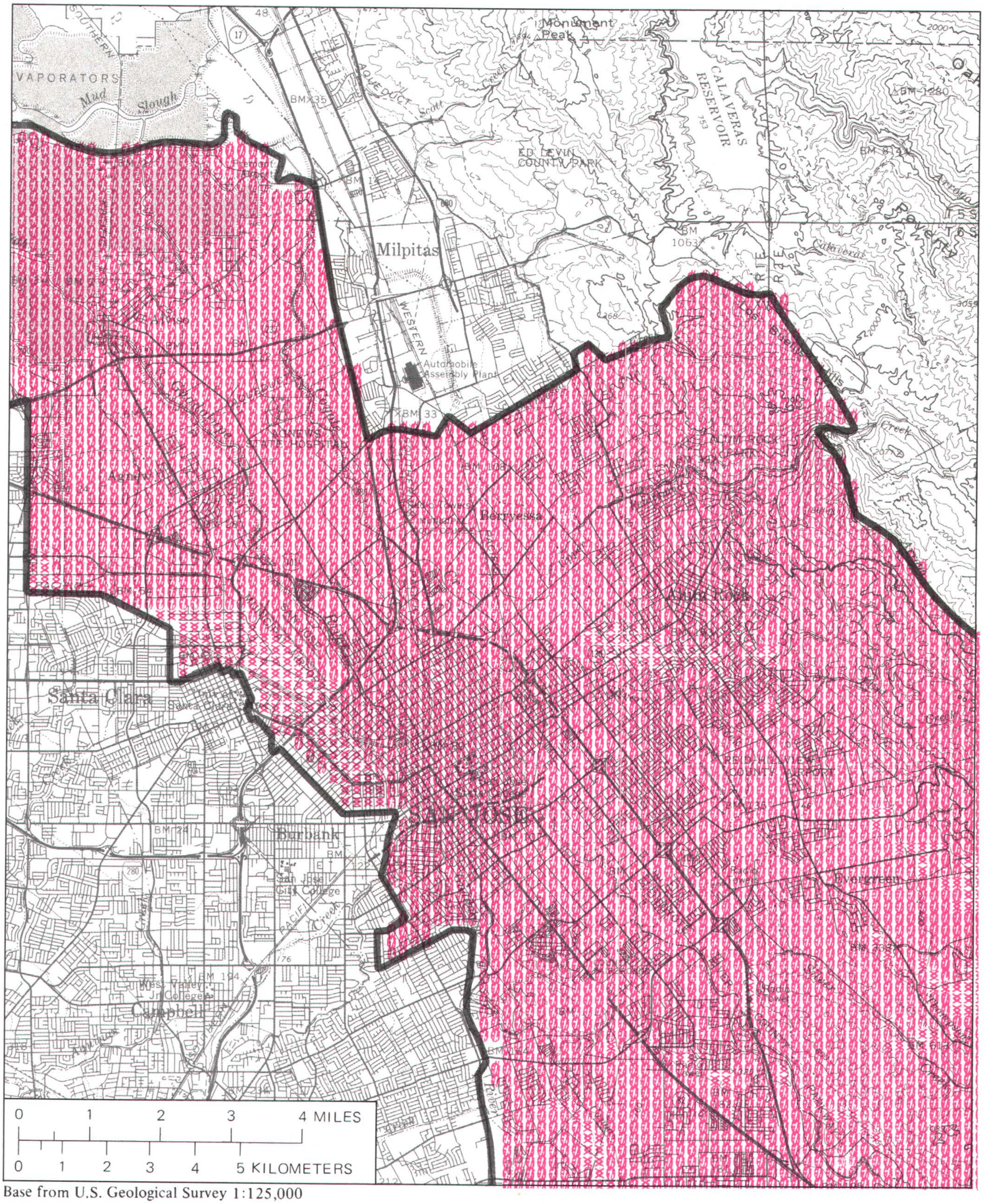
FIGURE 31.—Land-capability map for semirural residential use—series B.

TABLE 36.—*Summary of costs for single-family residential use, in dollars per acre*

Hazard, constraint, or resource	Severe ⟵				⟶ Slight
Surface rupture	$500	$500	$0	—	—
Ground shaking—San Andreas, Hayward	4,000	3,000	1,000	$ 500	$50
Ground shaking—Southern Hayward	400	300	100	50	5
Ground shaking—Calaveras	3,000	1,000	500	50	—
Stream flooding	9,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	20,000	0	—	—	—
Shrink/swell soils	$ 6,000	2,000	0	0	—
Settlement	30,000	30,000	20,000	2,000	—
Liquefaction	1,000	900	90	6	0
Subsidence	0	—	—	—	—
Landslides	40,000	20,000	8,000	2,000	0
Soil creep	10,000	4,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



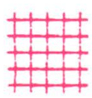
Base from U.S. Geological Survey 1:125,000

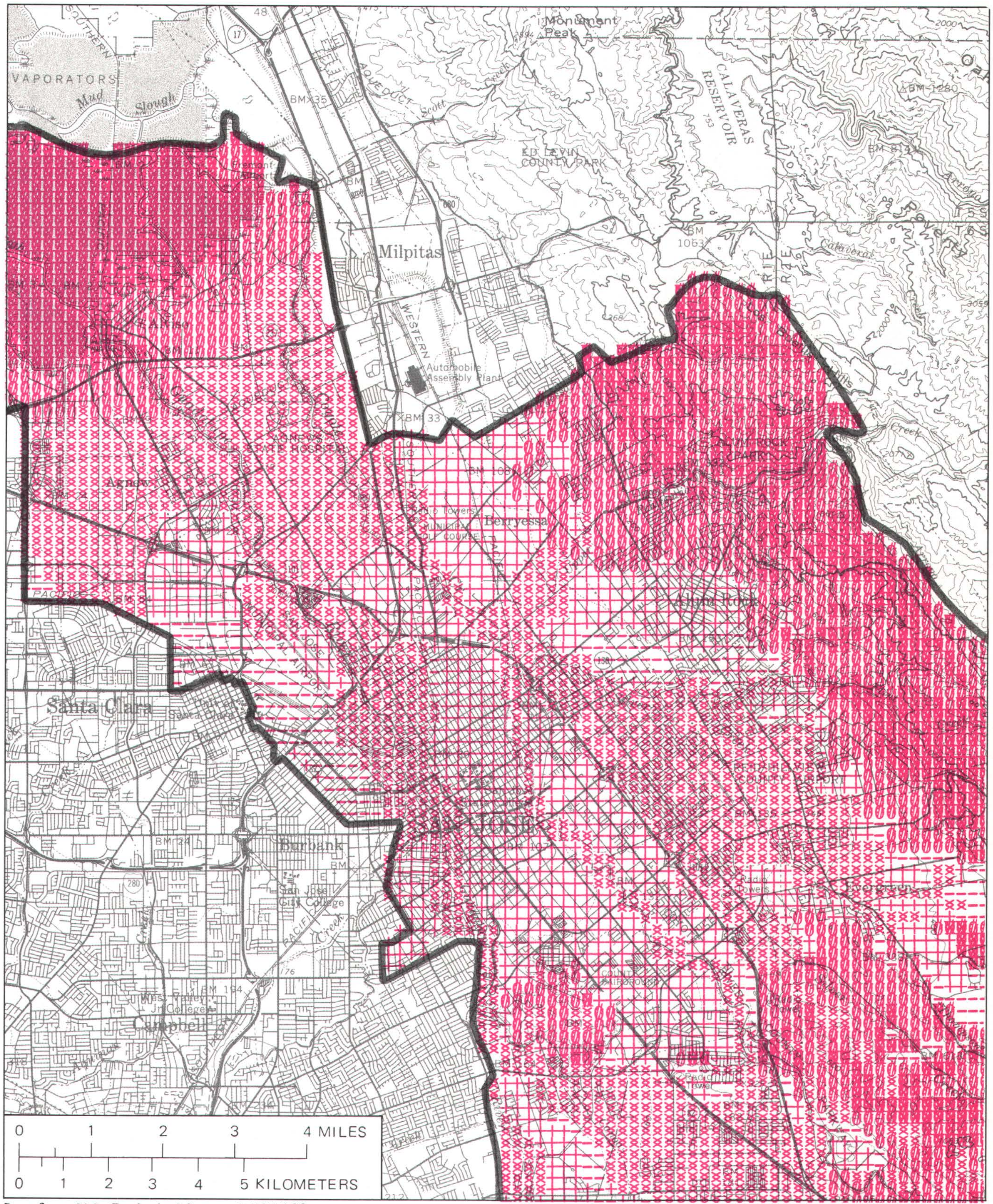
FIGURE 32.—Land-capability map for single-family residential use—series A.

TABLE 36.—*Summary of costs for single-family residential use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$500	$500	$0	—	—
Ground shaking—San Andreas, Hayward	4,000	3,000	1,000	$ 500	$50
Ground shaking—Southern Hayward	400	300	100	50	5
Ground shaking—Calaveras	3,000	1,000	500	50	—
Stream flooding	9,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	20,000	0	—	—	—
Shrink/swell soils	$ 6,000	2,000	0	0	—
Settlement	30,000	30,000	20,000	2,000	—
Liquefaction	1,000	900	90	6	0
Subsidence	0	—	—	—	—
Landslides	40,000	20,000	8,000	2,000	0
Soil creep	10,000	4,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	3,162.00
2		3,162.01	10,000.00
3		10,000.01	17,783.00
4		17,783.01	31,623.00
5		31,623.01	56,234.00
6		56,234.01	100,000.00



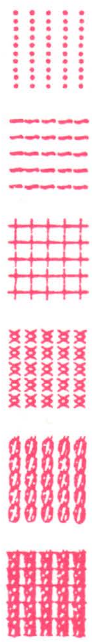
Base from U.S. Geological Survey 1:125,000

FIGURE 33.—Land-capability map for single-family residential use—series B.

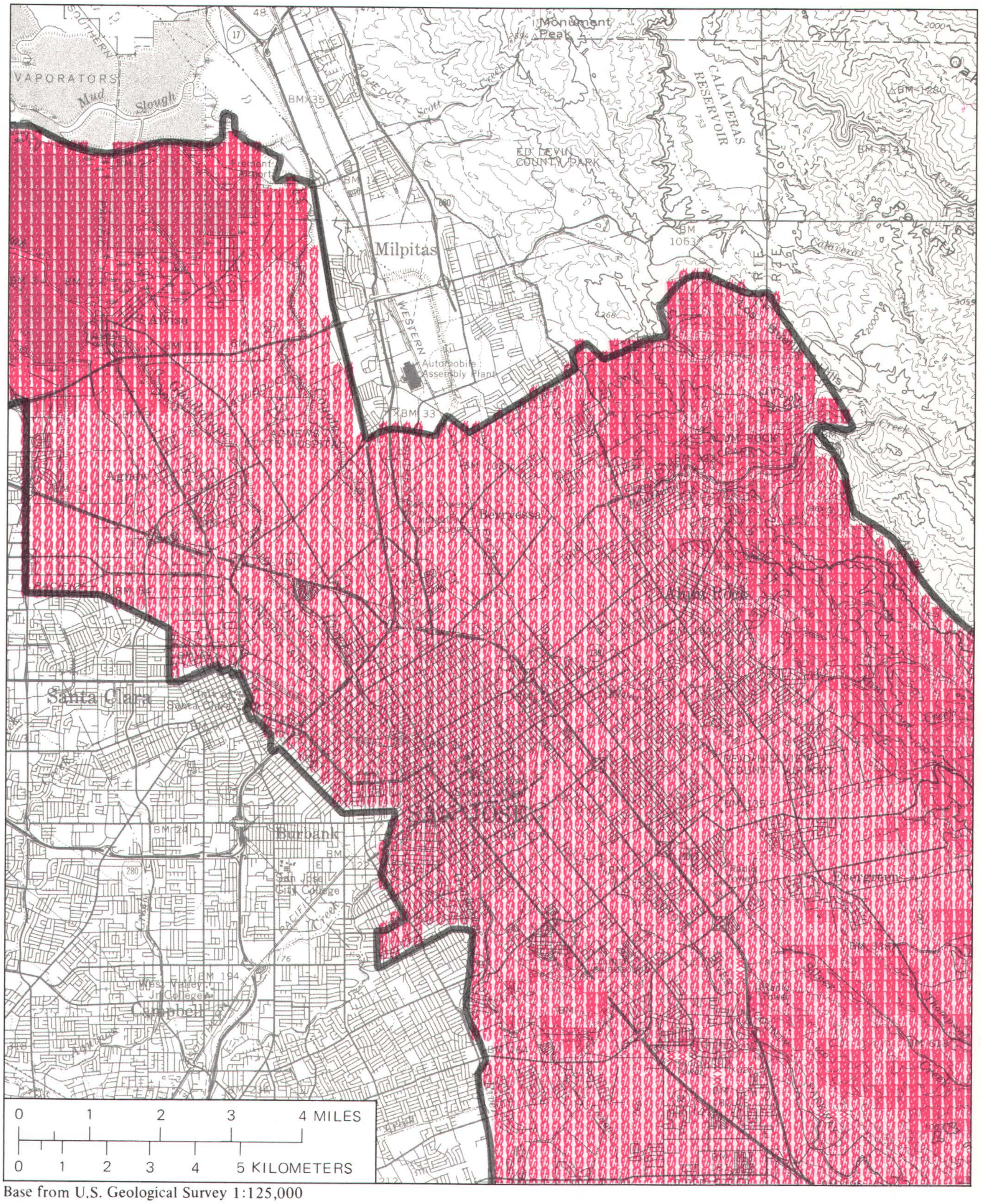
TABLE 37.—*Summary of costs for multifamily residential use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface ruputre	$800	$800	$0	—	—
Ground shaking—San Andreas, Hayward	20,000	20,000	5,000	$2,000	$200
Ground shaking—Southern Hayward	2,000	2,000	500	200	20
Ground shaking—Calaveras	20,000	5,000	2,000	200	—
Stream flooding	40,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	80,000	0	—	—	—
Shrink/swell soils	20,000	7,000	0	0	—
Settlement	30,000	30,000	20,000	2,000	—
Liquefaction	4,000	3,000	300	20	0
Subsidence	0	—	—	—	—
Landslides	200,000	100,000	50,000	9,000	0
Soil creep	40,000	40,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION



Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



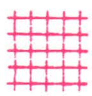
Base from U.S. Geological Survey 1:125,000

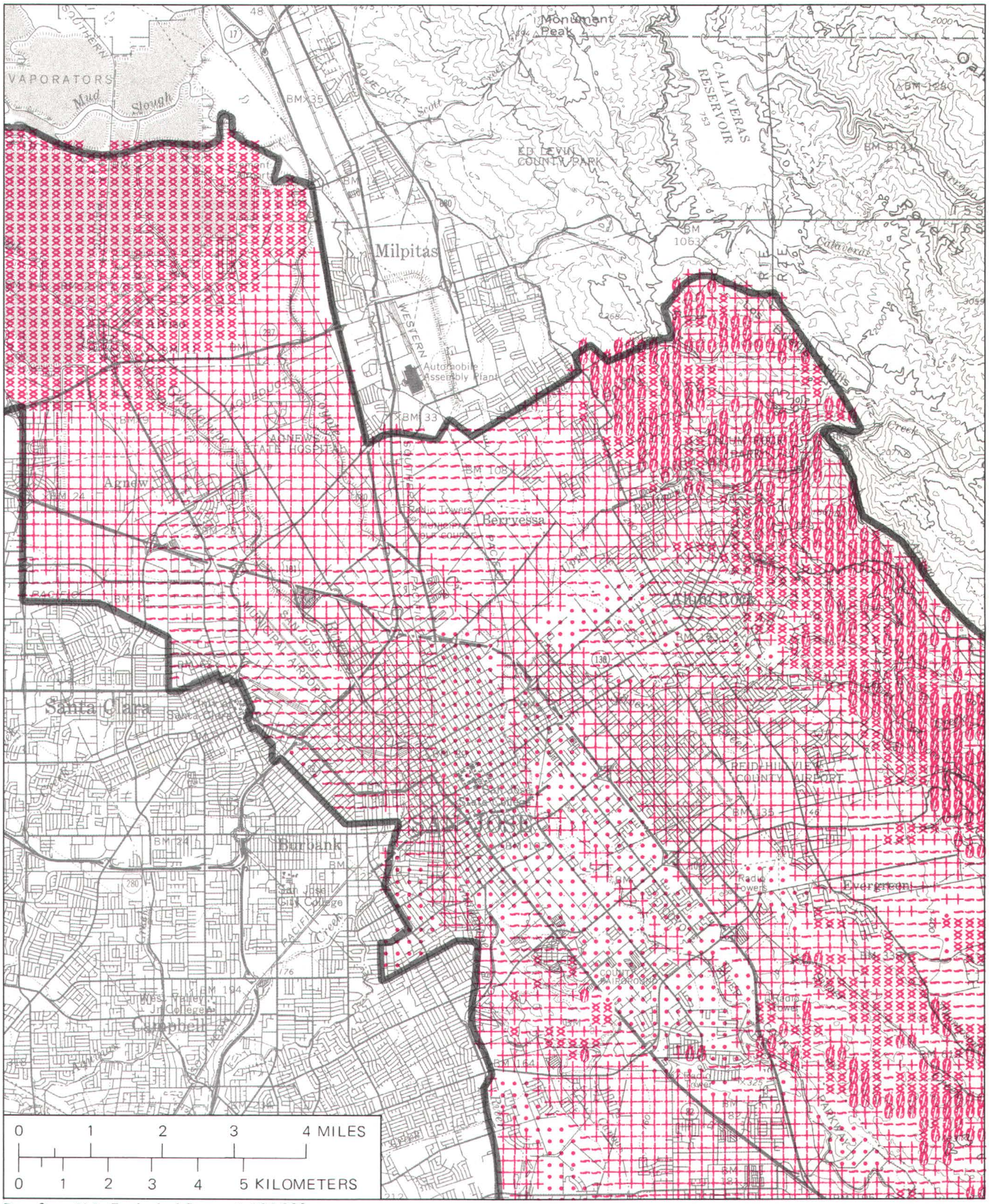
FIGURE 34.—Land-capability map for multifamily residential use—series A.

TABLE 37.—*Summary of costs for multifamily residential use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄		────		► Slight
Surface ruputre	$800	$800	$0	—	—
Ground shaking—San Andreas, Hayward	20,000	20,000	5,000	$2,000	$200
Ground shaking—Southern Hayward	2,000	2,000	500	200	20
Ground shaking—Calaveras	20,000	5,000	2,000	200	—
Stream flooding	40,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	80,000	0	—	—	—
Shrink/swell soils	20,000	7,000	0	0	—
Settlement	30,000	30,000	20,000	2,000	—
Liquefaction	4,000	3,000	300	20	0
Subsidence	0	—	—	—	—
Landslides	200,000	100,000	50,000	9,000	0
Soil creep	40,000	40,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	21,500.00
2		21,500.01	46,300.00
3		46,300.01	100,000.00
4		100,000.01	215,000.00
5		215,000.01	463,000.00
6		463,000.01	1,000,000.00



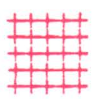
Base from U.S. Geological Survey 1:125,000

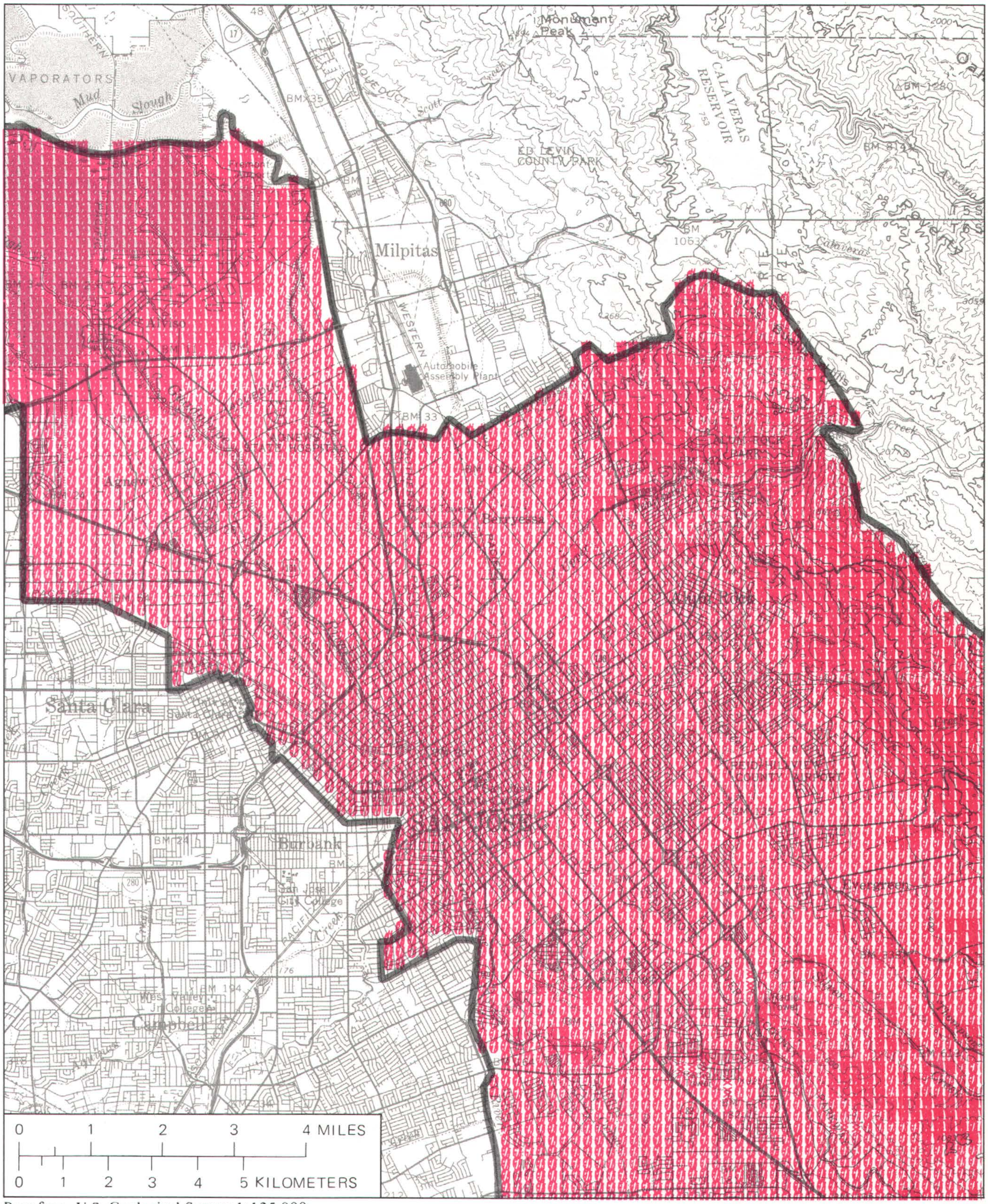
FIGURE 35.—Land-capability map for multifamily residential use—series B.

TABLE 38.—*Summary of costs for regional shopping-center use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄		———	►	Slight
Surface rupture	$200	$200	$0	—	—
Ground shaking—San Andreas, Hayward	50,000	40,000	10,000	$4,000	$800
Ground shaking—Southern Hayward	5,000	4,000	1,000	400	80
Ground shaking—Calaveras	40,000	10,000	4,000	800	—
Stream flooding	40,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	70,000	0	—	—	—
Shrink/swell soils	20,000	5,000	0	0	—
Settlement	30,000	30,000	20,000	2,000	—
Liquefaction	3,000	3,000	300	20	0
Subsidence	0	—	—	—	—
Landslides	100,000	80,000	30,000	8,000	0
Soil creep	30,000	10,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



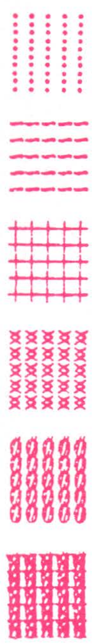
Base from U.S. Geological Survey 1:125,000

FIGURE 36.—Land-capability map for regional shopping-center use—series A.

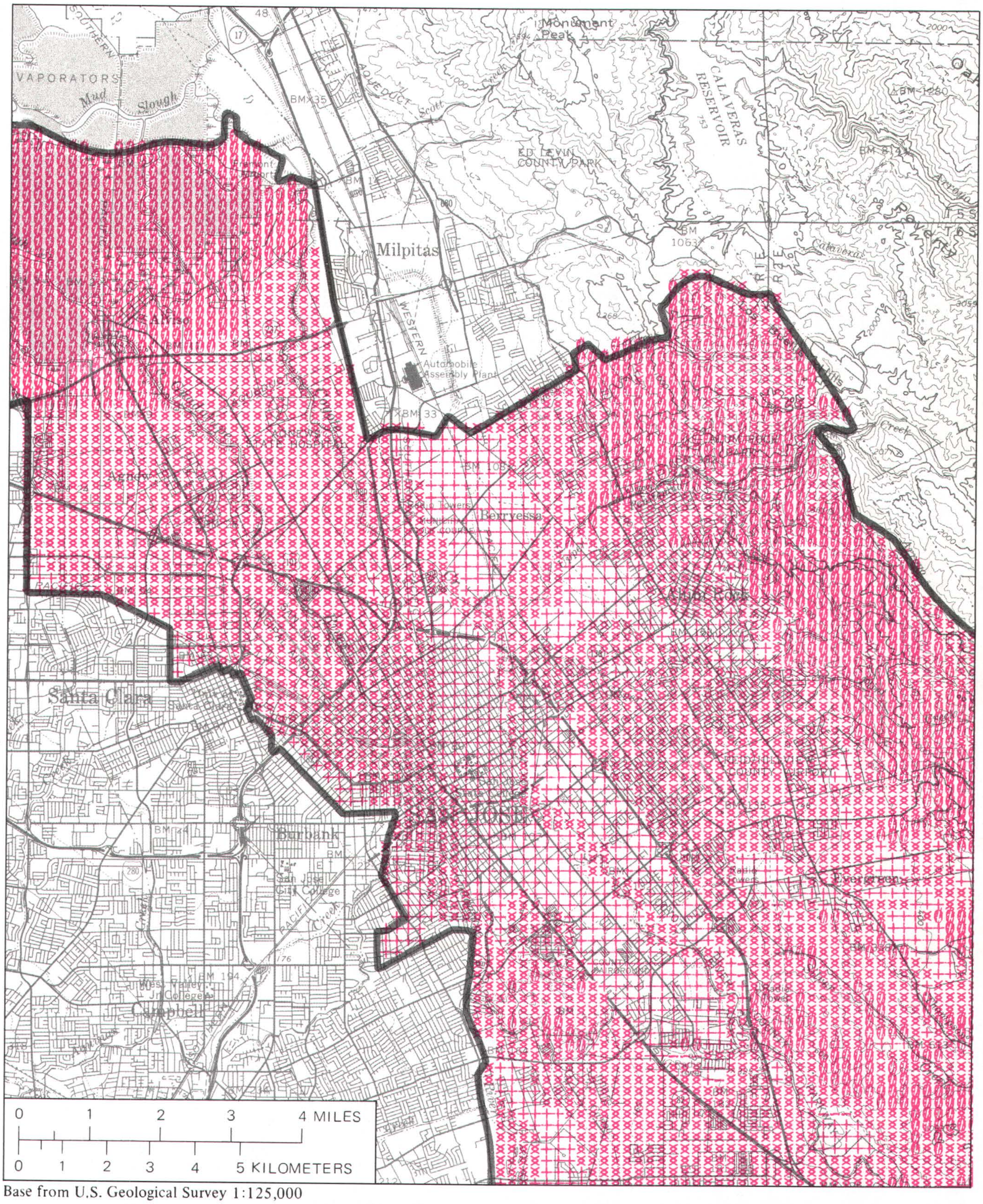
TABLE 38.—*Summary of costs for regional shopping-center use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$200	$200	$0	—	—
Ground shaking—San Andreas, Hayward	50,000	40,000	10,000	$4,000	$800
Ground shaking—Southern Hayward	5,000	4,000	1,000	400	80
Ground shaking—Calaveras	40,000	10,000	4,000	800	—
Stream flooding	40,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	70,000	0	—	—	—
Shrink/swell soils	20,000	5,000	0	0	—
Settlement	30,000	30,000	20,000	2,000	—
Liquefaction	3,000	3,000	300	20	0
Subsidence	0	—	—	—	—
Landslides	100,000	80,000	30,000	8,000	0
Soil creep	30,000	10,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION



Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	21,528.00
2		21,528.01	46,451.00
3		46,451.01	100,000.00
4		100,000.01	215,278.00
5		215,278.01	464,515.00
6		464,515.01	1,000,000.00



Base from U.S. Geological Survey 1:125,000

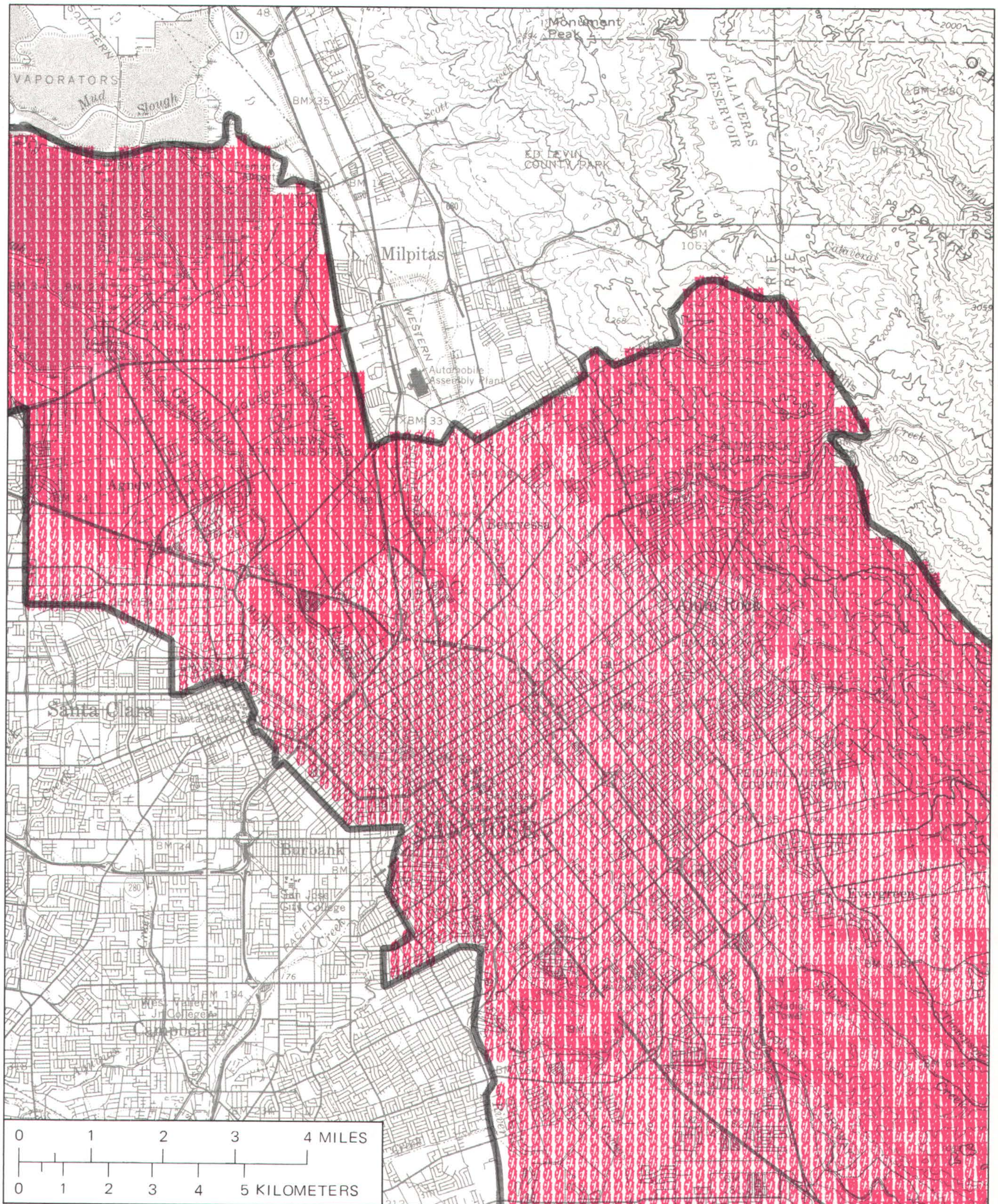
FIGURE 37.—Land-capability map for regional shopping-center use—series B.

TABLE 39.—*Summary of costs for downtown commercial use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄		─────		► Slight
Surface rupture	$5,000	$5,000	$0	—	—
Ground shaking—San Andreas, Hayward	70,000	50,000	20,000	$ 5,000	$1,000
Ground shaking—Southern Hayward	7,000	5,000	2,000	500	100
Ground shaking—Calaveras	50,000	20,000	5,000	1,000	—
Stream flooding	50,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	90,000	0	—	—	—
Shrink/swell soils	20,000	8,000	0	0	—
Settlement	100,000	30,000	20,000	2,000	—
Liquefaction	4,000	4,000	400	30	0
Subsidence	0	—	—	—	—
Landslides	200,000	100,000	50,000	20,000	0
Soil creep	50,000	20,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



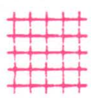
Base from U.S. Geological Survey 1:125,000

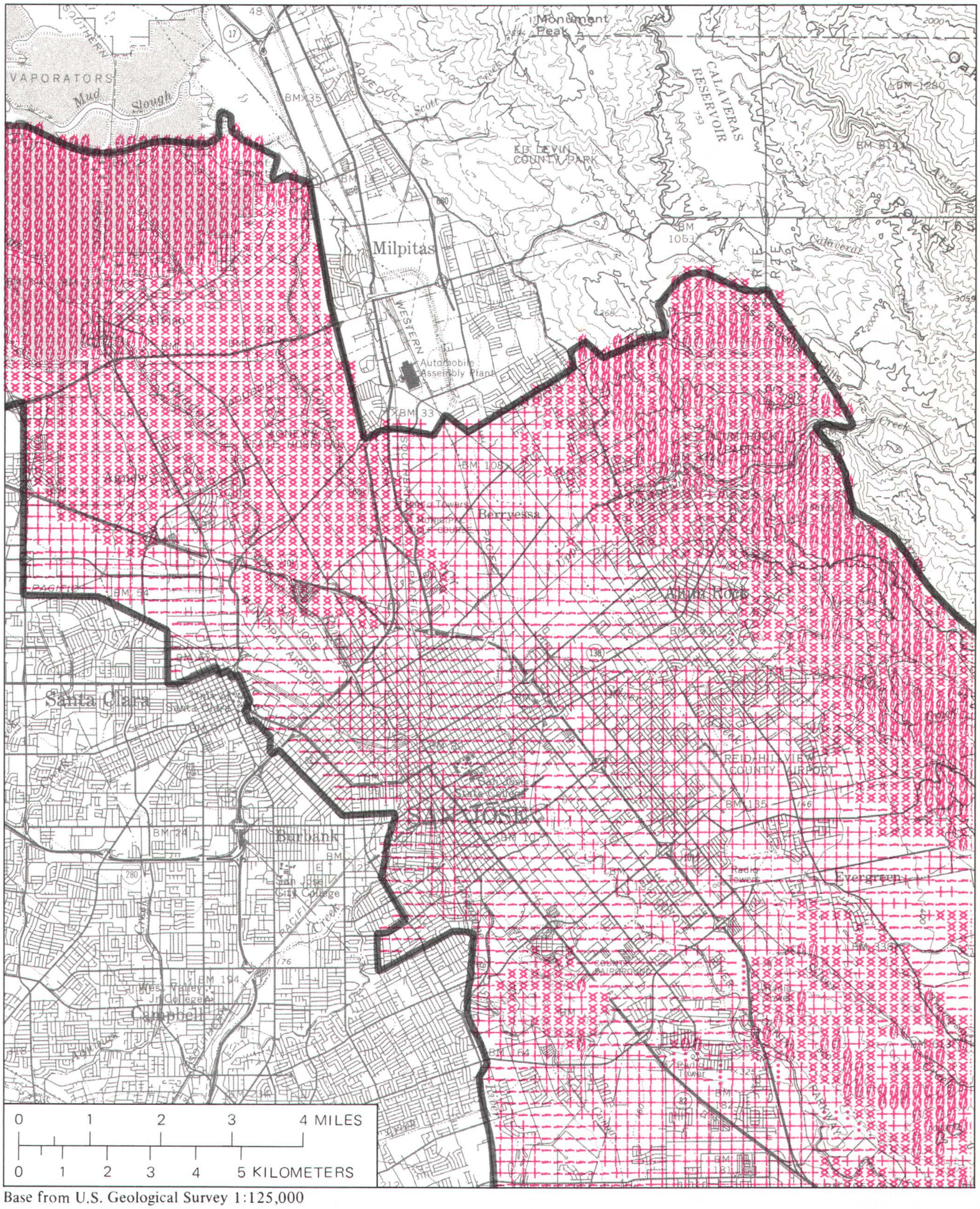
FIGURE 38.—Land-capability map for downtown commercial use—series A.

TABLE 39.—*Summary of costs for downtown commercial use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$5,000	$5,000	$0	—	—
Ground shaking—San Andreas, Hayward	70,000	50,000	20,000	$ 5,000	$1,000
Ground shaking—Southern Hayward	7,000	5,000	2,000	500	100
Ground shaking—Calaveras	50,000	20,000	5,000	1,000	—
Stream flooding	50,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	90,000	0	—	—	—
Shrink/swell soils	20,000	8,000	0	0	—
Settlement	100,000	30,000	20,000	2,000	—
Liquefaction	4,000	4,000	400	30	0
Subsidence	0	—	—	—	—
Landslides	200,000	100,000	50,000	20,000	0
Soil creep	50,000	20,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	3,162.00
2		3,162.01	10,000.00
3		10,000.01	31,623.00
4		31,623.01	100,000.00
5		100,000.01	316,227.00
6		316,227.01	1,000,000.00



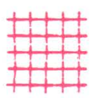
Base from U.S. Geological Survey 1:125,000

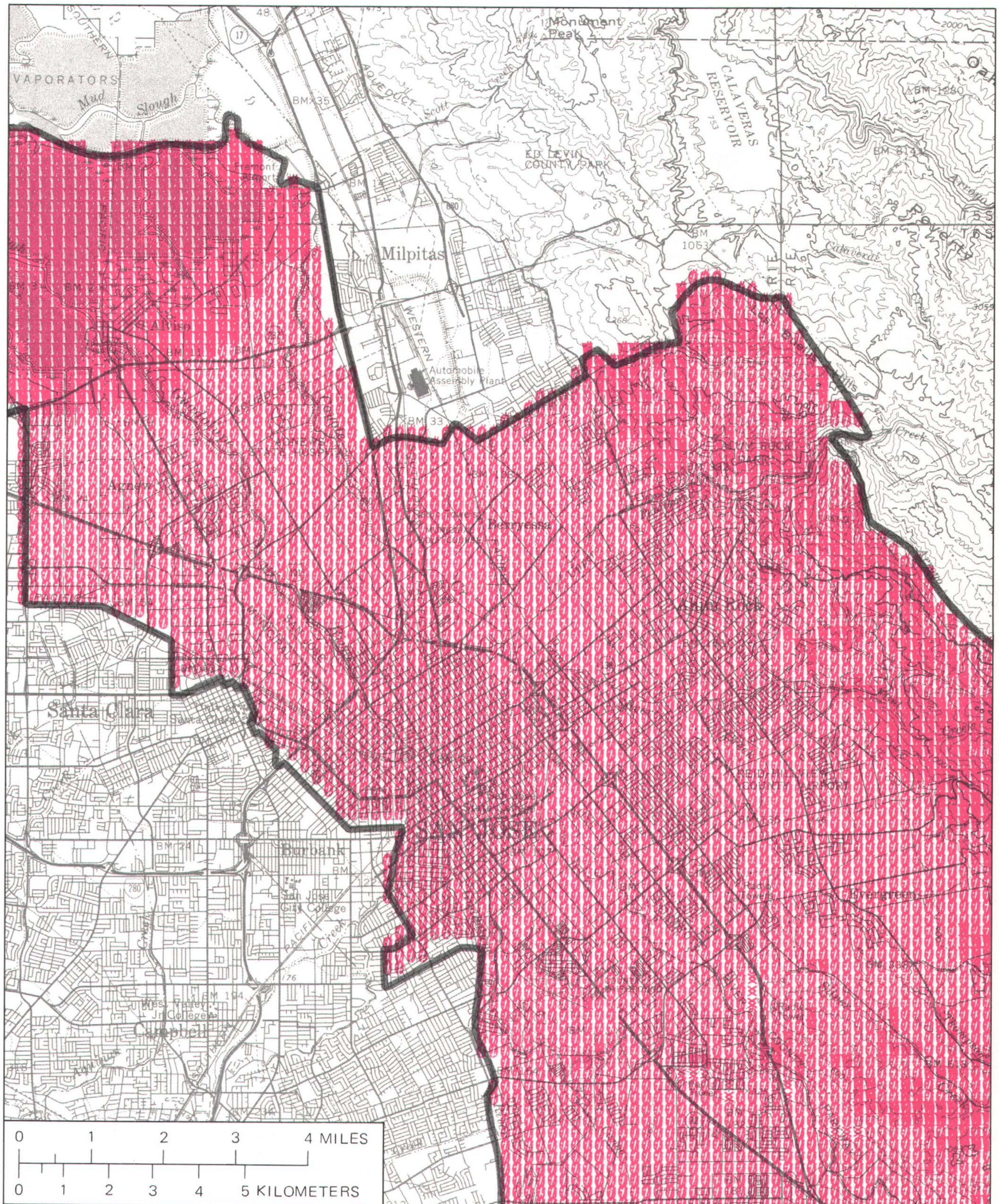
FIGURE 39.—Land-capability map for downtown commercial use—series B.

TABLE 40.—*Summary of costs for industrial use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$80	$80	$0	—	—
Ground shaking—San Andreas, Hayward	40,000	30,000	10,000	$ 3,000	$700
Ground shaking—Southern Hayward	4,000	3,000	1,000	300	70
Ground shaking—Calaveras	30,000	10,000	3,000	700	—
Stream flooding	40,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	70,000	0	—	—	—
Shrink/swell soils	10,000	4,000	0	0	—
Settlement	10,000	10,000	6,000	700	—
Liquefaction	3,000	2,000	200	20	0
Subsidence	0	—	—	—	—
Landslides	100,000	70,000	30,000	10,000	0
Soil creep	20,000	8,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



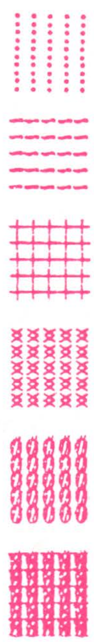
Base from U.S. Geological Survey 1:125,000

FIGURE 40.—Land-capability map for industrial use—series A.

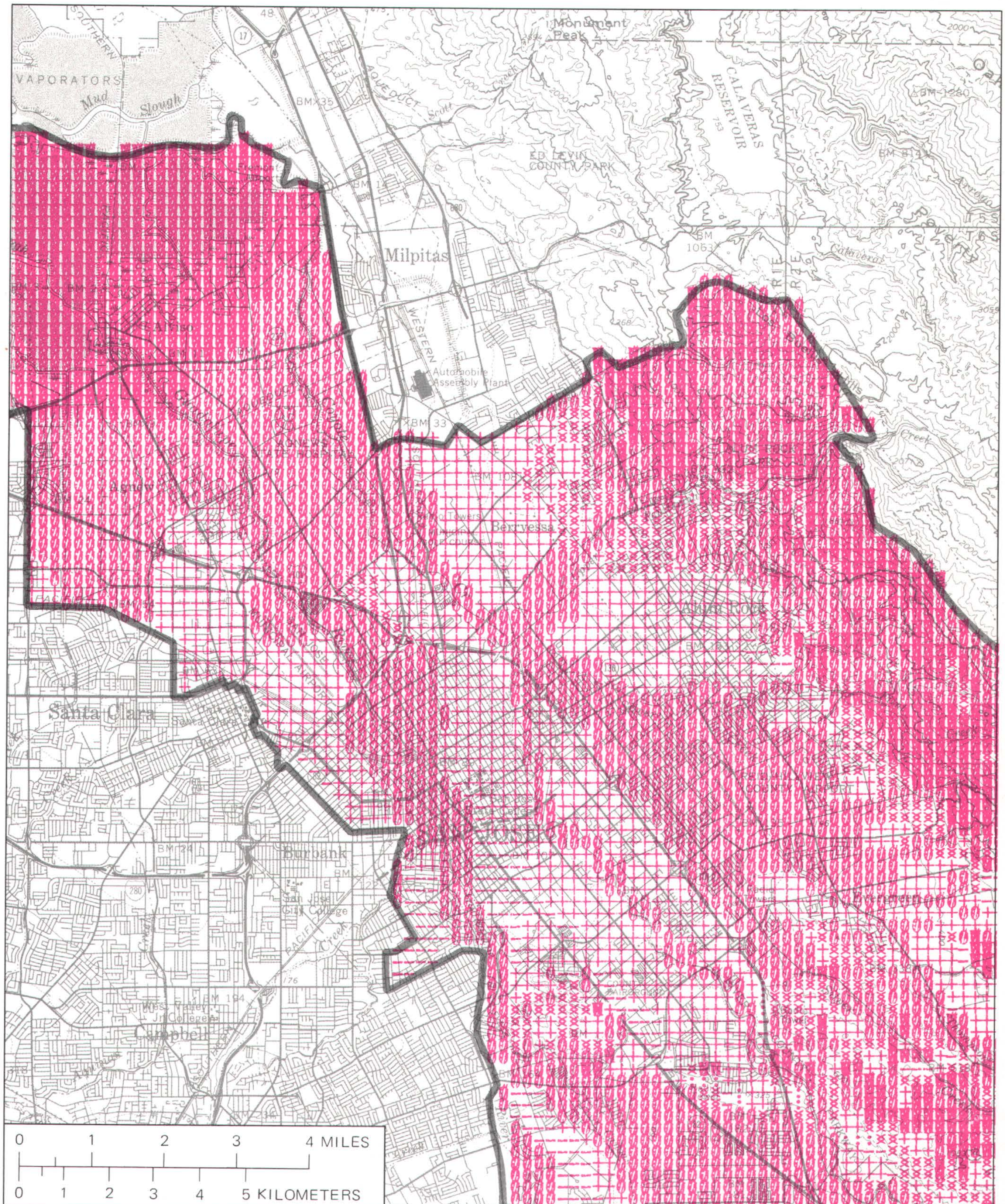
TABLE 40.—*Summary of costs for industrial use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$80	$80	$0	—	—
Ground shaking—San Andreas, Hayward	40,000	30,000	10,000	$ 3,000	$700
Ground shaking—Southern Hayward	4,000	3,000	1,000	300	70
Ground shaking—Calaveras	30,000	10,000	3,000	700	—
Stream flooding	40,000	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	70,000	0	—	—	—
Shrink/swell soils	10,000	4,000	0	0	—
Settlement	10,000	10,000	6,000	700	—
Liquefaction	3,000	2,000	200	20	0
Subsidence	0	—	—	—	—
Landslides	100,000	70,000	30,000	10,000	0
Soil creep	20,000	8,000	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION



Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10,000.00
2		10,000.01	17,783.00
3		17,783.01	31,623.00
4		31,623.01	56,234.00
5		56,234.01	100,000.00
6		100,000.01	215,278.00



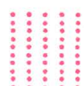
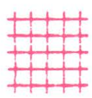
Base from U.S. Geological Survey 1:125,000

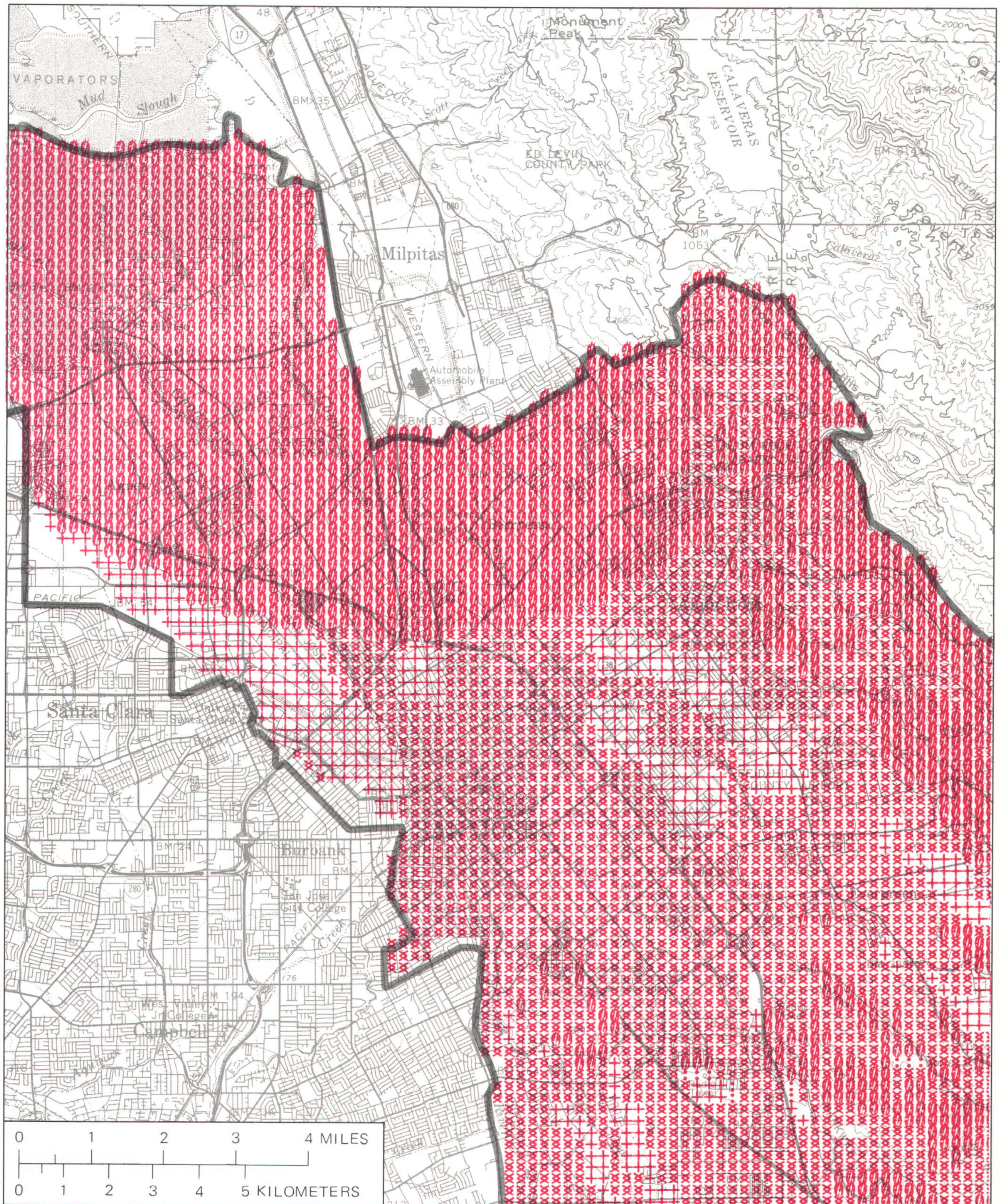
FIGURE 41.—Land-capability map for industrial use—series B.

TABLE 41.—*Summary of costs for freeway use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄				► Slight
Surface rupture	$200	$200	$0	—	—
Ground shaking—San Andreas, Hayward	10,000	10,000	10,000	$ 0	$0
Ground shaking—Southern Hayward	1,000	1,000	1,000	0	0
Ground shaking—Calaveras	10,000	10,000	0	0	—
Stream flooding	0	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	0	0	—	—	—
Shrink/swell soils	0	0	0	0	—
Settlement	0	0	0	0	—
Liquefaction	0	0	0	0	0
Subsidence	0	—	—	—	—
Landslides	20,000	20,000	7,000	4,000	0
Soil creep	0	0	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	10.00
2		10.01	100.00
3		100.01	1,000.00
4		1,000.01	10,000.00
5		10,000.01	100,000.00
6		100,000.01	1,000,000.00



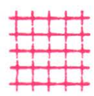
Base from U.S. Geological Survey 1:125,000

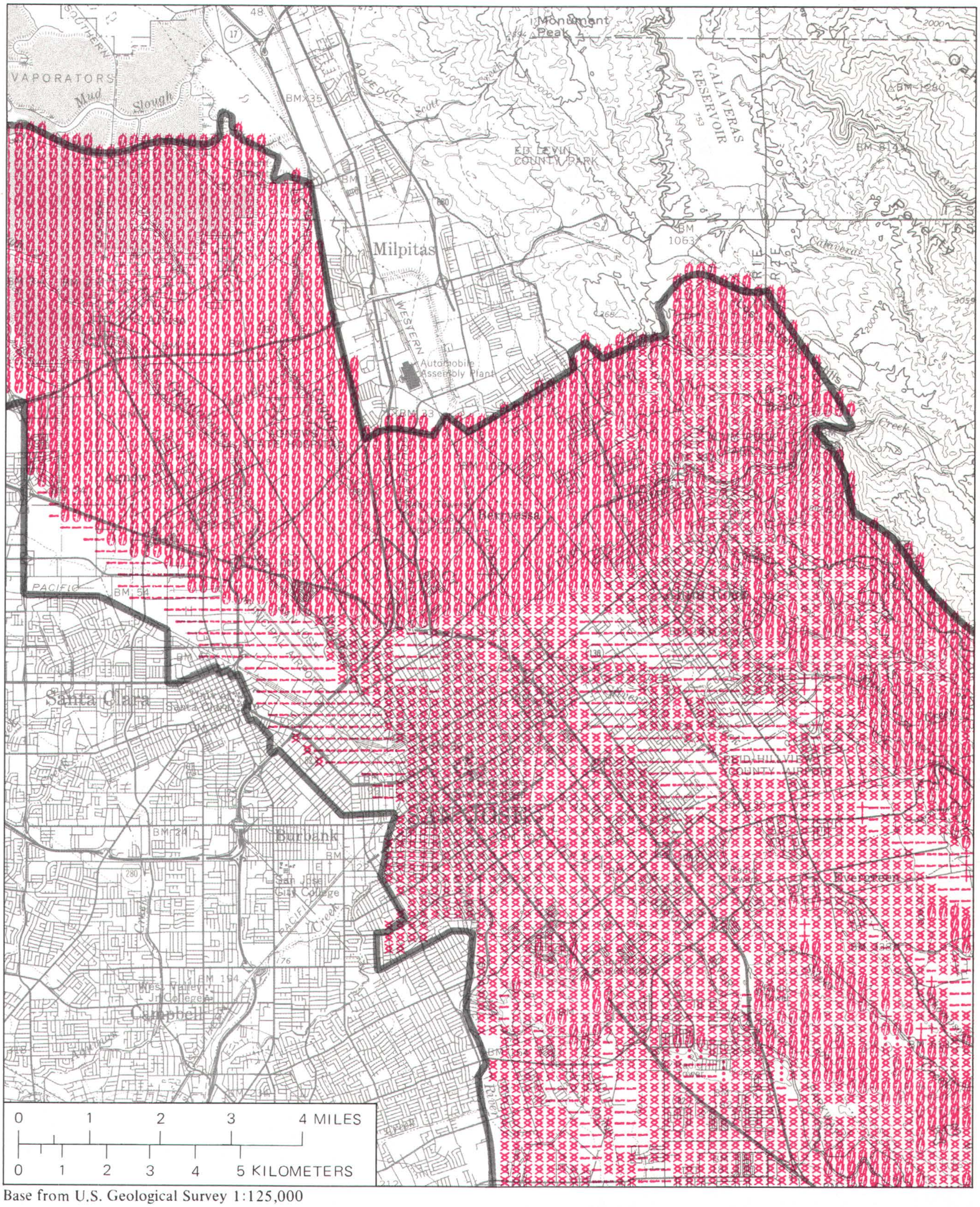
FIGURE 42.—Land-capability map for freeway use—series A.

TABLE 41.—*Summary of costs for freeway use, in dollars per acre*

Hazard, constraint, or resource	Severe ◄		───		► Slight
Surface rupture	$200	$200	$0	—	—
Ground shaking—San Andreas, Hayward	10,000	10,000	10,000	$ 0	$0
Ground shaking—Southern Hayward	1,000	1,000	1,000	0	0
Ground shaking—Calaveras	10,000	10,000	0	0	—
Stream flooding	0	0	—	—	—
Dam failure	0	—	—	—	—
Dike failure	0	0	—	—	—
Shrink/swell soils	0	0	0	0	—
Settlement	0	0	0	0	—
Liquefaction	0	0	0	0	0
Subsidence	0	—	—	—	—
Landslides	20,000	20,000	7,000	4,000	0
Soil creep	0	0	0	0	—
Erosion and sedimentation	200	30	10	0	—
Septic tanks	0	—	—	—	—
Sand and gravel	20,000	0	—	—	—
Mercury	0	—	—	—	—
Agricultural land	5,000	0	—	—	—

EXPLANATION

Level	Symbol	Total cost range (in dollars per acre)	
1		0.01	100.00
2		100.01	1,000.00
3		1,000.01	3,162.00
4		3,162.01	10,000.00
5		10,000.01	31,623.00
6		31,623.01	100,000.00



Base from U.S. Geological Survey 1:125,000

FIGURE 43.—Land-capability map for freeway use—series B.

USES OF LAND-CAPABILITY ANALYSIS

Rarely is earth-science information completely and systematically incorporated into land-use decisions. Buyers, sellers, and developers of land often have difficulty in obtaining such information and therefore do not incorporate it in their market decisions. Earth-science information is more readily available to local planners because it can be obtained more efficiently by them. However, it is difficult for planners to use such information unless they have some feeling for its importance and unless earth scientists have presented the information in a way that they can understand.

This land-capability study is designned to help incorporate earth-science information into land-use decisions. When planners in local government have adequate information, they then can insure that it is made available to those who are involved in the land market and can also employ it to improve both plans and implementation procedures regarding land use. This type of capability analysis also points out information gaps and helps to direct further work into study areas where needed.

FORMULATION OF POLICIES AND STANDARDS

Any type of development can be allowed anywhere as long as people accept the costs. The point at which the costs become unacceptable depends on the individual or group making the decision, the people who pay the costs, and the other social and environmental benefits and costs which affect the development. Policies and standards for development cannot be specified without a thorough knowledge of these other considerations.

If land-capability information is available, policies and standards can be more refined than they were previously. For example, the concept of land capability does not imply that development should be prohibited on steep slopes or on flood plains. People can, and do, build in these areas without incurring unacceptable costs. But policies can be developed that are more sensitive to actual developmental constraints.

Although other costs and benefits must be considered for most decisions regarding land use, geologic constraints may sometimes be dominant. For example, the results of this analysis could be used to argue that in the Santa Clara Valley semirural development should be discouraged on areas of sand and gravel deposits and that this land should be either retained in agricultural use or converted to some higher density use. The key points of this argument are (1) the high per-unit cost associated with placing semirural residential use in these areas ($100,000) and (2) the wide availability of other sites with much lower costs associated with semirural residences. Thus, semirural residential land use on sand and gravel deposits would be most inefficient. Note that this reasoning leads to a more specific policy than one that merely seeks to reserve sand and gravel deposits for subsequent extraction.

Tables and maps that show land-capability costs can also be used directly by local governments in preparing or refining the criteria and standards for general plans or the specific elements of such plans.

By providing information on the relative cost of geologic constraints for selected growth alternatives, this type of analysis also can help evaluate special-purpose plans, such as those for transportation corridors, and regional plans which involve several different jurisdictions.

Where alternative growth scenarios are being examined, different uses can be assigned to parcels of land, and the costs for each scenario can be averaged. The relative costs of, for example, a specified "city-centered" development as opposed to "semirural dispersed" development can be determined and the results can be used, together with other social and environmental information, for growth-policy decisions. For example, two simple scenarios could be developed for the Santa Clara Valley area. In the first scenario, development would occur only within the urban service area boundaries of the cities of San Jose and of Morgan Hill, and a number of new single-family homes would be built. In the second scenario, the same number of homes would be built, but they would be on 5-acre parcels (of semirural use) and would be built throughout the demonstration area. The average cost associated with each home in the first scenario is $*A* and in the second scenario is $*B*. Thus, assuming that all other considerations are equal (which they are not), the less costly scenario would be most efficient. Policies could be developed which would encourage the more efficient pattern.

The land-capability cost information can be used when the goals, policies, and standards of an existing general plan are reviewed for their compatibility with earth-science information. Any areas of high or low cost can be noted and evaluated against development trends which would be likely under existing plan policy. If current policies are unresponsive to such new cost information, the plan may need to be amended. In order to illustrate this use of land-capability information, one can compare the general plan of the City of San Jose, which is currently being revised (City of San Jose, 1971), to the current areas of development as reflected by the street patterns on the topographic base map. The areas designated as single-family residential on the general plan map correspond very closely to those areas with least geologic costs associated with them. The existing pattern of development, however, typically shows many single-family homes that are located on the flood plains; this is especially evident in the flood-prone area bordering and to the northeast of Highway 101.

The pattern may reflect more an avoidance of prime agricultural land than a preference for flood plains because the value of prime agricultural land had been incorporated into the land market whereas the costs associated with building on flood plains had not until the initiation of National Flood Insurance. If the National Flood Insurance program did not exist, the city might have considered adopting policies which discouraged residential development on flood plains.

PLAN IMPLEMENTATION

Land-capability analyses and the resulting maps can be used in many different ways to pursue goals and to help set policies and standards. Because the extent of most geologic and hydrologic problems is confined to specific areas, the implementation function usually is the responsibility of a local government. One goal of planning law concerns the regulation of activity to protect the health, safety, and welfare of the community: "Regulations to minimize threats to public health and safety enjoy almost a special presumption of constitutionality" (Association of Bay Area Governments, 1973).

Although the Santa Clara Valley area maps at a scale of 1 inch equals 2 miles lack the detail necessary for local decisions, on specific sites the same cost assessment and mapping procedures can be used at larger scales and with more detailed information. Most readers will recognize that the level of detail and degree of specificity must be tailored to the nature of the problem; for some kinds of problems, the method used here will need to be modified for more detailed data.

DESIGNING AN IMPLEMENTATION PROGRAM

Land-capability information can be used by local governments to develop methods for directing, taxing, subsidizing, regulating, or reviewing the use of parcels of land. The wide applicability of land-capability information permits the flexibility needed to design an implementation program for a particular problem and end result. The intent of the implementation program could be to lessen the costs associated with land-development constraints. It also might incorporate cost information into the land market, as is done when insurance requirements are imposed.

The range of options that can utilize land-capability information is illustrated by examining the potential land-use conflicts that result from sand and gravel deposits in the Santa Clara Valley. First, the area may be zoned for uses other than semirural residential; this action might reflect the view that benefits from other types of development except semirural residential use exceeded the opportunity costs. Second, those who build on the sand and gravel deposits, before removal of those materials and rehabilitation of the surface, could be charged a dollar amount per acre—an amount that is related to the cost to the public of such an opportunity loss; this action permits the land market to assess the benefits of development and determine the use of the land. Third, the sand and gravel operators could be subsidized by providing them with tax incentives while development is discouraged. Fourth, development could be limited to mobile homes that can be easily moved to allow for eventual removal of the sand and gravel deposits. Fifth, the land could be purchased and used as a park until the underlying resource is needed. And sixth, the local government might choose to have a resource-conservation ordinance which prohibits urban development on the deposits before removal of the materials and rehabilitation of the surface. Such an ordinance would indicate that any benefits associated with immediate development in that area were felt to be outweighed by the opportunity cost. The technique chosen will depend on the goals and policies of the jurisdiction and should be the result of the public decisionmaking process.

EVALUATING ALTERNATIVE IMPLEMENTATION PROGRAMS

The methods of assessing costs described in this report are useful in determining the relative cost of alternative implementation programs. A simple example is the hazard of surface rupture along an active fault. Two methods of dealing with this problem are (1) perform an investigation, find the fault, and avoid it or (2) take a chance and build randomly within the zone of hazard. The ways in which both of these costs can be calculated are described in the section "Costs Associated with Earthquake Problems." The results, in terms of costs for these two actions in the Santa Clara Valley demonstration area, are tabulated in table 42. These costs do not include loss of life.

The savings realized by requiring investigations for most development along the Calaveras fault are appar-

TABLE 42.—*Costs per acre associated with surface rupture for two alternative actions*

[(1) Locate the fault and plan and design for movement on it or (2) ignore the problem and accept the damage at some later time. These costs apply only to that portion of Santa Clara County, Calif., examined]

Land-use type	1. Study	2a. Damage for Calaveras	2b. Damage for all other faults in area
Rural or agricultural	$10	$20	$2
Semirural residential	80	70	7
Single-family residential	500	600	60
Multifamily residential	800	20,000	2,000
Regional shopping centers	200	20,000	2,000
Downtown commercial	5,000	9,000	900
Industrial	80	7,000	700

ent. Even along minor faults, the study costs are lower for much high-density development. In addition, because the study costs become a part of the land market and the damage costs do not, the study requirement automatically makes surface rupture a part of land-use decisions without any use directives, such as zoning, being necessary.

Before deciding to require such studies, one must remember the limitations of the use of dollars as a measure of social cost. The numbers do not take into account any equity issues. This issue is not significant in this instance because the landowner is both the one who pays for the study indirectly by paying more for the property and the one who probably must fix any damage. The numbers also do not reflect risk preference, which in this case would make the study alternative even more appealing. Last, the numbers do not reflect any life loss. Such losses are likely in high-density development.

ENVIRONMENTAL IMPACT REVIEW

The capability-assessment procedure can be used in the environmental review process to determine rapidly the magnitude of geologic constraints on development. Land-capability information can affect both the decision on whether or not to file a negative declaration and the decision as to the adequacy of environmental impact reports or statements. To illustrate, a recent project reviewed by ABAG called for a variety of land uses, but most of the land was allocated to single-family residences. The capability of the project area, shown in table 43, is derived from data and methods used in this study.

The highest estimated costs are in the slope-stability and settlement categories, but these problems were only examined superficially in the proposal and the environmental impact report although surface rupture, for which zero cost is estimated, is given extensive consideration. The reports were judged inadequate because they did not consider the correct geologic problems.

IDENTIFICATION OF FUTURE INFORMATION NEEDS

Because of their quantitative and explicit content and because they incorporate input from different disciplines, land-capability analyses of the kind described here are useful in identifying information gaps. Equally important, such analyses are uniquely suited to help planners and decisionmakers establish priorities for time, effort, and funding among future study topics. This second asset is equivalent to defining the significance or severity of a problem—a part of the planning process.

First, a rough ranking of research needs can be achieved by examining the effect of different variables on the cost estimates. A larger effect indicates that the variable is more critical and that, therefore, the data needed to accurately evaluate it are more important. Table 44 lists most of the research needs which were identified in the analysis of the demonstration area.

Second, after the costs have been approximated, work can be focused preferentially on those geologic hazards, constraints, and resources that have large costs associated with them. The land-capability analysis for the Santa Clara Valley indicates that dike failure, settlement, landslides, soil creep, and loss of sand and gravel reserves are associated with large costs for single-family use. This relationship indicates that these topics probably deserve more consideration for funding where single-family use will occur in the Santa Clara Valley than topics with lower costs, such as liquefaction, surface rupture, and erosion.

This tendency to identify information needs and to focus research also encourages the feedback of new information that is necessary to update land-capability analyses.

MAIN FUNCTIONS OF ANALYSES

The main function of a land-capability analysis is to help elected officials, planners, and others in the land-use planning process make better use of earth-science information as a step toward better decisions. Neither the analysis nor the maps can make land-use decisions, but because they are expressed in the economic terms of other land-related information, they help reduce technical problems to a more understandable base.

PROBLEMS ENCOUNTERED

During the course of this study, many problems were encountered; a brief review of these should prove useful to those who plan to undertake similar studies. Many of the problems resulted from the pioneering approach and

TABLE 43.—*Land-capability project analysis*

Condition	Category	Cost (in dollars per acre)
Surface rupture	Not in an Alquist-Priolo special studies zone	$0
Ground shaking	Intensity E for all faults	300
Stream flooding	Not in a flood-prone area	0
Dam failure	Not in an inundation area	0
Dike failure	do	0
Landslides	Slopes of unstable materials and slight slopes	14,000
Soil creep	"High"	10,000
Shrink/swell	Hillside ground	0
Liquefaction	do	0
Settlement	Cut/fill in parts; slight settlement in others	16,000
Erosion	Moderate to high	200
Septic tanks	Not applicable	0
Sand and gravel	"Out" of area	0
Mercury	do	0
Agriculture	do	0
Approximate total cost		40,000

TABLE 44.—*List of research topics for which further effort is needed to improve the accuracy of cost estimates*

Earthquake problems

1. Ground-shaking potential categories that do not include the effects of both surface rupture and liquefaction, thus eliminating the double counting of these two problems associated with ground shaking.
2. Percent damage expected for surface rupture.

Flooding

1. Improved dike-failure recurrence interval.
2. Dam-failure recurrence intervals based on current dynamic analysis and studies of dams.
3. Costs attributable to flooding freeways and resulting traffic disruption.
4. Data on depth, velocity, and resulting damage.

Bearing-material problems

1. Map depicting depth of expansive soils.
2. Costs due to settlement.
3. Percent damage expected for liquefaction.

Slope-stability problems

1. Costs of landslide mitigation.
2. The expected damage due to landslides which occur even though a study has been performed and the mitigation measures are undertaken before development.
3. Analysis of the relationship between creep and expansive soils.

Erosion and sedimentation

1. Identification of costs due to erosion, other than that of dredging.

Septic-tank limitations

1. Costs associated with septic-tank use and failure.

Resource loss

1. Better estimate of population that would use the Santa Clara Valley sand and gravel deposits rather than the deposits in the Livermore Valley or west of Cupertino.
2. The average difference in miles required for transporting sand and gravel to the side of use.
3. Reliable estimates of the effect of loss of prime agricultural land on local, State, and national needs for food and fiber.

are common to most research projects. Because future studies of this type will be able to draw upon the work described in this report, some of these problems should not be as great, and some may be avoided. To aid those preparing similar studies, we have attempted to catalog the assumptions and facts used to obtain the resulting costs.

SELECTION OF CONSTRAINTS AND RESOURCES

The final decision on which geologic constraints and resources to include was postponed until late in the progress of the study. Septic-tank limitations, subsidence, and dam failure were all added, revised, and omitted several times before the decision was made to include these sections in their present form. These three topics, along with mercury extraction, have estimated costs that are so small that they were eliminated at one time. However, slight changes in the data result in very large changes in the costs calculated. For example, if the valley again subsides, or the dams fail, or the natural ability of the ground to absorb septic-tank wastes is about to be reached, the costs will obviously be incurred. Elimination of these constraints from consideration would conceal possible future problems, however. Thus, these sections were included.

Sand and gravel were originally the only resources considered. However, concern that the report was emphasizing damage-oriented development constraints led to the sections on minerals, using mercury as an example, and on prime agricultural land. Last, erosion and sedimentation were originally included as separate topics. However, because of the common property problems involved, they were eventually combined to make the calculations of the costs simpler.

CHOICE OF LAND-USE TYPES

The final choice of land-use types was also not fixed until near the end of the study. Originally, only six uses were to be considered: rural, semirural residential, single-family residential, multi-family residential, commercial, and industrial. Commercial and industrial uses were later divided into two categories each, and two types of freeway use were added. The differences between regional shopping centers and downtown commercial development, as well as between light and heavy industrial uses, proved to be large enough that valid generalizations about the characteristics of these uses were impractical. Two transportation uses, freeways and transportation structures, were included because of ABAG's work with the Metropolitan Transportation Commission. But as the cost estimates were being derived, transportation structures (such as bridges and elevated railways) and heavy industrial uses were both eliminated from the study because accurate cost information was not available.

USE OF RATES AND WEIGHTS

The method that is adopted here, to combine the hazards, constraints, and resources to obtain a land-capability map, was finally decided about two-thirds of the way through the study. Before that time, the cost information was expressed as a combination of a weight and a rate (see section at end of report "Rates and Weight Factors for Relating Mapped Information"). The product of these two factors was the cost. This procedure originally was used to emphasize the fact that the cost figures could provide information on both the relationships between the categories on a single map, such as liquefaction, and the relative importance of the various constraints and resources. Because it hid the economic basis of the figures and was difficult to explain to people, the procedure was abandoned and replaced by the dollar-cost approach in which the total costs were reduced to present-worth basis.

RISK AVERSION AND THE DISCOUNT RATE

An unanticipated problem arose when the discount rate was chosen. In most cases, choosing a discount rate lower than that of the market will favor advocates of resource conservation, and choosing a higher discount rate will favor those who are averse to risk. (People who are averse to risk, in general, would prefer having their money now rather than in the future because the future is, by nature, uncertain.) These two trends then can be assumed to cancel, and the market rate can be used. However, people who are risk-averse will prefer a lower discount rate for geologic constraints because present money is associated with study costs to avoid future damage, and these people would prefer to do the study. Thus, both trends favor a discount rate lower than the market. The authors decided to use the 10-percent rate because of problems with determining how much lower the rate should be to account for these preferences.

SENSITIVITY OF COST ESTIMATES TO ASSUMPTIONS

The final costs depend critically on the data and assumptions used in the analysis. Several methods of showing this dependence were examined. The most appropriate appears to be the method used—describing the maximum and minimum values of a probable range of costs.

JUDGMENTS INVOLVING DOLLARS

A major problem in estimating costs is to obtain accurate information on investigations, designs, and special construction practices because these costs involve estimates by a number of professional disciplines as well as by government employees. Many of these estimates depend on a wide range of variables and must be greatly generalized. Because of the complexity of these estimates and their degree of generalization, the dollar amounts cited throughout the report represent our synthesis of estimates from many different sources.

COMPUTER MAPPING

Originally, the computer programming needed to aggregate and map the cost information was to be done by the ABAG staff. However, the programming needed to produce rectified maps of the thousands of grid cells required unanticipated technical expertise. Fortunately, the Division of Environmental Studies of the University of California, Davis, was able to provide the needed programs and produce the maps. The programming required is not nearly as simple as one initially might expect, and the mapping effort was the largest obstacle encountered during the study. Therefore, the mapping should be planned as soon as one has an idea of the final product needed.

CONCLUSION

The method presented for assessing land capability is designed to help apply earth-science information to land-use planning. It has both strengths and weaknesses, but it clearly shows both the need for gathering and interpreting earth-science information that can be applied in land-use planning and the need for more effective use of the available information.

One strength of the land-capability method is that it is rational. Assumptions and reasoning must be explicit and stated, rather than hidden and obscure. Geologic and hydrologic constraints and resources are compared quantitatively with a common yardstick, cost. Land-capability assessment also helps to identify information needs, and consequently it helps set priorities for future research. Moreover, the method can readily incorporate the results of new research and provide a simple objective mechanism for modifying capability ratings when new data make this necessary.

Among its weaknesses is the initial expense of the method. It is expensive because considerable time and money must be spent in assigning dollar costs to the constraints and resources and in testing and perfecting the method. A second problem is that those who use the land-capability method must compare subjects that in many cases are poorly understood. This lack of understanding of the subjects, combined with the inherent credibility of anything that has been quantified, may result in misuse of the results. Finally, the subjects compared by the method must still be related to others for which the method cannot be easily applied; some evaluation must be determined subjectively through the political process.

On balance, however, the potential for improving decisions that are a based wholly or in part on earth-science information makes this method of assessing capability appear promising.

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SUPPLEMENTAL INFORMATION

ANALYSIS OF SIGNIFICANT PLANNING STUDIES THAT UTILIZE EARTH-SCIENCE INFORMATION

TABULAR ANALYSIS

[Explanation: no= technique not used; unQ= technique used, information unquantified or subjective; Q= technique used, information quantified or objective]

Planning study titles	Hazard and resource mapping	General land-use implications statement	Matrix identifying "impacts"	System to weight relative importance of different mapped information	Capability mapping for land-use types by—		Recommendations:	
					Computer shading	Stop-light color method	General policies	Specific program alternatives
Santa Barbara County, Calif., Seismic Safety Element.	limited Q	unQ	no	semi-Q	Q	no	unQ	unQ
Santa Cruz Mountains, Calif., Early Warning System.	limited unQ	unQ	unQ	unQ	Q	no	unQ	no
Soils Development Guide, Southeastern Wisconsin Regional Planning Commission.	limited Q	unQ	Q	no	no	unQ	unQ	semi-Q
Connecticut Valley Urban Area Project.	Q	unQ	no	no	no	no	no	no
Percolation Rates in Western Whatcom County, Wash.	limited Q	Q	no	no	no	semi-Q	Q	Q
Geology and Groundwater in the Eagle River, Chugiak Area, Alaska.	unQ	unQ	no	no	no	no	no	no
Environmental Geologic Atlas of the Texas Coastal Zone.	limited unQ	unQ	unQ	no	no	no	unQ	no
Approaches to Environmental Geology (Texas).	Q	unQ	unQ	no	no	no	no	no
Geology in Land-Use Planning (the Puget Lowland, Wash.).	Q	unQ	no	no	no	no	no	no
The Seismic Safety Study for the General Plan, Tri-Cities, California, Seismic Safety and Environmental Resources Study.	limited unQ	unQ	unQ	no	no	no	unQ	no
Land-Capability Classification of the Lake Tahoe Basin, California-Nev.	limited unQ	unQ	unQ	no	no	unQ	unQ	Q
Bucks County, Pa., Natural Resources Plan, Phases I and II.	Q	unQ	unQ	unQ	Q	no	unQ	unQ
Urban Geology Master Plan for California, Phases I and II.	Q	unQ	Q	Q	no	no	Q	no
The Genesee/Finger Lakes Region, New York, Technical Study Reports 10 and 11.	no	unQ	unQ	unQ	Q	no	unQ	unQ
Hayward, Calif. Earthquake Study.	limited Q	unQ	no	no	no	no	unQ	Q
Geology for Planning in McHenry County, Ill.	Q	unQ	no	no	no	unQ	unQ	no
Geology for Planning in Lake County, Ill.	Q	unQ	no	no	no	unQ	unQ	no
Palo Alto, Calif., Foothills Environmental Design Study.	no	unQ	no	Q	Q	no	unQ	unQ

CATEGORIZATION OF FINDINGS ON PLANNING-STUDY METHODS

Category	Examples
Limited earth-science topics	Santa Barbara County, Calif., Seismic Safety Element. Santa Cruz Mountains, Calif., Early Warning System. Southeastern Wisconsin Regional Planning Commission, Soils Development Guide. Percolation Rates in Western Whatcom County, Wash. Environmental Geologic Atlas of the Texas Coastal Zone. Tri-Cities, California, Seismic Safety Study. Land Capability Classification for the Lake Tahoe Basin. Hayward, Calif., Earthquake Study.

Category	Examples
Lacked combined land capability information.	Connecticut Valley Urban Area Project. Geology and Groundwater in the Eagle River-Chugiak Area, Alaska. Environmental Geologic Atlas of the Texas Coastal Zone. Approaches to Environmental Geology, University of Texas. Geology in Land Use Planning (the Puget Lowland). Tri-Cities, California, Seismic Safety Study. Hayward, Calif., Earthquake Study.
Developed maps without appropriate information on land capability.	The Genessee/Finger Lakes Region, New York, Technical Study Reports 10 and 11. Palo Alto, Calif., Foothills Environmental Design Study. Parts of the Santa Cruz Mountains, Calif., Early Warning System.

Category	Examples
No specific planning policy recommendations.	Tri-Cities, California, Seismic Safety Study. Urban Geology Master Plan for California. Geology for Planning in McHenry County, Ill. Geology for Planning in Lake County, Ill. Santa Cruz Mountains, Calif., Early Warning System. Connecticut Valley Urban Area Project. Geology and Groundwater in the Eagle River-Chugiak Area, Alaska. Environmental Geologic Atlas of the Texas Coastal Zone. Approaches to Environmental Geology (Texas). Geology in Land-Use Planning (the Puget Lowlands, Washington).

SAMPLE ANALYSIS FORM

[Similar forms are available for all those studies examined in this report at the offices of both ABAG and USGS, Menlo Park, Calif.]

TITLE: The Seismic Safety Study for the General Plan AUTHOR: Dean Armstrong, Project Director (Tri-Cities Citizen Advisory Committee) PAGES: 199	INFORMATION TYPE: Planning Study SCALE: Maps not included@1:24,000 DATE: September 1, 1973 TOPIC(S) : Earthquake, dam failure, bearing material problems, slope stability AREA Cities of El Cerrito, Richmond, and San Pablo.

BASIC DATA USED:

The basic data used includes maps of generalized surface geology, active faults, and active and recently active landslides.

ASSUMPTIONS MADE REGARDING THAT DATA, INCLUDING INTERPRETED DATA

The report includes interpreted maps of high, medium, and low landslide risk areas, of relative ground response, of liquefaction potential, and of fill overlying mud.

CONCLUSIONS USEFUL FOR LAND-USE PLANNING APPLICATIONS, INCLUDING CAPABILITY INFORMATION OR POLICY AND PROGRAM RECOMMENDATIONS:

The report includes a general discussion of risk analysis. It also includes recommendations for a disaster preparedness program, a Geologic Hazards Review Board, and Geologic Hazards Special Management Areas.

DERIVATION OF FORMULAS AND CALCULATIONS OF EXPECTED COSTS

POISSON PROCESSES

In the main part of this report, it was assumed that the probabalistic rate of occurrence of several different geologic events, for example earthquakes, is constant in time. That is, the probability that n events occur in a given time interval, at Δt, is governed by the Poisson probability distribution:

$$\begin{pmatrix}\text{the probability that}\\ n \text{ events occur in a}\\ \text{time interval } \Delta t\end{pmatrix} = \frac{(\lambda \Delta t)}{n!} e^{-\lambda \Delta t}$$

where $\lambda =$ the instantaneous rate of occurrence.

It can be shown that if the number of events in time interval t is governed by the Poisson distribution, then the probability that the next event will occur t units of time from now is determined by the exponential distribution:

$$\begin{pmatrix}\text{probability that}\\ \text{one must wait}\\ \text{until } t \text{ for an}\\ \text{event}\end{pmatrix} = \lambda e^{-\lambda t}.$$

The term "recurrence interval" is often used. The expected time until the next event is one interpretation that can be made of the intuitive term, recurrence interval:

$$\begin{pmatrix}\text{the expected time}\\ \text{until the next}\\ \text{occurrence}\end{pmatrix} = \int_0^\infty \lambda t \, e^{-\lambda t}$$
$$= -t \, e^{-\lambda t}\Big|_0^\infty + \int_0^\infty e^{-\lambda t} dt$$
$$= \frac{1}{\lambda}.$$

Thus an estimate of the recurrence interval can be used to estimate the parameter λ.

In all the expected cost calculations, it was assumed that the cost per event was constant except for discounting. If this is true, the expected cost due to the first occurrence can be easily calculated.

Let

X = the cost per event in dollars at time t.

Then

$$Xe^{-rt} = \begin{pmatrix}\text{the discounted cost}\\ \text{in present dollars}\\ \text{of an event at time } t\end{pmatrix}$$

where r is the discount rate.

The expected cost due to the first (next) event is given by the sum over the cost of the event at time t times the probability that the event occurs at the time:

$$\begin{pmatrix}\text{expected cost}\\ \text{due to the}\\ \text{next event}\end{pmatrix} = \int_0^\infty (Xe^{-rt}) \lambda e^{-\lambda t} dt$$
$$= \int_0^\infty \lambda X e^{-(\lambda + r)t} dt$$
$$= \frac{\lambda}{\lambda + r} X.$$

For some kinds of events, the damage can occur repeatedly, for example, if rebuilding occurs after an earthquake. For these events, it would be of interest to calculate the expected cost due to all future events.

First, one calculates the probability that one must wait a time t_1 for the first event and t_2 for the second event:

$$\begin{pmatrix}\text{the probability that the}\\ \text{second event occurs at}\\ \text{time } t_2 \text{ given that the}\\ \text{first event occurs at } t_1\end{pmatrix} = \lambda e^{-\lambda(t_2 - t_1)}.$$

Now the theory of conditional probabilities tells one:

$$\begin{pmatrix}\text{probability}\\ \text{that the}\\ \text{second}\\ \text{event}\\ \text{occurs at}\\ \text{time } t_2\\ \text{and that}\\ \text{first event}\\ \text{occurs at}\\ t_1\end{pmatrix} = \begin{pmatrix}\text{probability}\\ \text{that the}\\ \text{second}\\ \text{event}\\ \text{occurs at}\\ \text{time } t_2\\ \text{given that the}\\ \text{first event}\\ \text{occurs at}\\ t_1\end{pmatrix}\begin{pmatrix}\text{probability}\\ \text{that the}\\ \text{first event}\\ \text{occurs}\\ \text{at } t_1\end{pmatrix}$$

$$= \lambda e^{-\lambda(t_2 - t_1)} \lambda e^{-\lambda t_1}$$
$$= \lambda^2 e^{-\lambda t_2}.$$

From this it is easy to show by induction that:

$$\begin{pmatrix}\text{probability that the}\\ n\text{th event occurs at}\\ t_n \text{ and the n–1 event}\\ \text{at } t_{n-1} \ldots \text{ and the}\\ \text{first event at } t_1\end{pmatrix} = \lambda^n e^{-\lambda t_n}.$$

From this one can calculate the expected cost due to the first n events:

$$\begin{pmatrix}\text{expected cost}\\ \text{due to the}\\ \text{first } n \text{ events}\end{pmatrix} = X\int_0^\infty \int_{t_{n-1}}^\infty \cdots \int_{t_1}^\infty \lambda n\, e^{-\lambda t_n} \sum_{i=1}^{n} e^{rti}\, dt_1 \ldots dt_n$$

$$= X\lambda^n \sum_{i=1}^{n} \int_0^\infty \int_{t_{n-1}}^\infty \cdots \int_{t_1}^\infty e^{-\lambda t_n - rt_i}\, dt_1 \ldots dt_n$$

$$= X \sum_{i=1}^{n} \frac{\lambda^i}{(\lambda+r)i} .$$

The expected cost for all future events is given by:

$$\begin{pmatrix}\text{the expected}\\ \text{cost for all fu-}\\ \text{ture events}\end{pmatrix} = \sum_{i=1}^{n} \begin{pmatrix}\text{the probability}\\ \text{there are } n\\ \text{events}\end{pmatrix} \begin{pmatrix}\text{the expected}\\ \text{cost associated}\\ \text{with } n \text{ events}\end{pmatrix}$$

but for all future time, n infinite number of events will occur with probability equal to one. Thus

$$\begin{pmatrix}\text{the expected}\\ \text{cost for all}\\ \text{future events}\end{pmatrix} = \lim X \sum_{i=1}^{n} \frac{\lambda^i}{(\lambda+r)i}$$

$$= \frac{\lambda}{r} X .$$

DERIVATION OF FORMULAS FOR COSTS RELATED TO SURFACE RUPTURE ON AN ACTIVE FAULT

Two types of calculations were made to estimate the expected cost due to surface rupture. For rural and semirural land–use types, it was assumed that preconstruction geologic studies were not made, that active faults are not precisely located, and that for these land uses the costs are those that will result from damage. For the rest of the land–use types, except freeways, it was assumed that, in accordance with the Alquist–Priolo Act, a preconstruction geologic study will locate faults so that damage is avoided. Thus, costs are those associated with performing the study. In order to calculate the first type of cost, it was necessary to estimate the expected number of structures that lie astride an active fault. For the second type of cost, it was necessary to estimate the number and cost of studies that need be performed. This section details some of the analyses made to obtain these numbers.

CASE 1: COST DUE TO DAMAGE

Rural and semirural land–use types are characterized by a certain number of structures per acre, each with an average square footage in area. It was necessary to use this information to derive the expected width of the house perpendicular to the fault trace. Assume that houses are rectangular. Then figure 44 shows the relationship of the house to the fault trace.

The angle ϕ gives the orientation of the house relative to the fault and l and w are respectively the length and width of the house. The width of the house perpendicular to the fault trace is given by

$$\ell \sin\phi + w\cos\phi .$$

If it is assumed that ϕ is uniformly distributed between 0 and $\phi/2$, then the expected value of the width perpendicular to the fault trace is given by:

$$\frac{1}{\pi/2}\int_0^{\pi/2} \ell \sin\phi\, d\phi \;\; \frac{1}{\pi/2}\int_0^{\pi/2} w\cos\phi\, d\phi = \frac{2}{\pi}(\ell + w) .$$

Next, the effect of different values of l/w with the average area per house A held constant is considered:

$$w = \frac{A}{\ell}.$$

Thus, the expected width of the house perpendicular to the fault trace is given by

$$\frac{2}{\pi}(\ell + A/\ell).$$

Now, if one supposes that the shapes of houses are uniformly distributed between square houses ($l = \sqrt{A}$) and houses where the ratio of the length to the width is equal to α, that is,

$$\alpha = \frac{\ell}{w} => \begin{cases}\ell = \sqrt{\alpha A}\\ w = \sqrt{\dfrac{A}{\alpha}}\end{cases} ,$$

then the expected value of the width of the house perpendicular to the fault trace (with variations in building shape taken into account) is given by

$$\frac{1}{\sqrt{\alpha A} - \sqrt{A}} \int_{\sqrt{A}}^{\sqrt{\alpha A}} \frac{2}{\pi}(\ell + A/\ell)\, d\ell = \frac{\sqrt{A}}{\pi}\; \frac{a - 1 + 1na}{\sqrt{a} - 1} ,$$

which for a reasonable range of values of α, that is, $2 < a < 4$,

$$\approx \frac{4}{\pi}\sqrt{A} .$$

Another calculation assuming square houses all alined with the fault yields the results, $\sqrt{A}$. Because this formula was developed first and used extensively before the one derived above and because the result seems relatively insensitive to assumptions about orientation and shape, it was decided to use the formula

$$\begin{pmatrix}\text{width of a house}\\ \text{with area } A\\ \text{perpendicular to}\\ \text{the fault trace}\end{pmatrix} = \sqrt{A}\,.$$

This result will now be used to calculate the expected number of houses per acre that lie astride the fault trace. Consider a square section of an Alquist–Priolo special studies zone (fig. 45).

It is assumed that the fault trace is parallel to the boundaries of the special studies zone; it is further assumed that the fault trace can be anywhere in that zone. Assume that there are n houses, each with an identical area A. If the center point of the width of these houses perpendicular to the fault lies in the shaded area in figure 45, then the house will sit astride the fault. The object, then, is to calculate the expected number of houses for which this is true. This will be done for two cases.

Case 1: Assume that the houses are uniformly distributed over the square. Then the number of houses in the area is distributed according to the Poisson distribution:

$$\mu = \frac{L\,A}{L^2}\;n = \frac{n\,A}{L}\,.$$

It is well known that the expected value of the Poisson distribution is μ thus:

$$\begin{pmatrix}\text{expected number of}\\ \text{houses astride}\\ \text{fault in a ¼ × ¼}\\ \text{mile square}\end{pmatrix} = \mu = \frac{L\sqrt{A}}{L^2}\;n = \frac{n\sqrt{A}}{L}\,.$$

It is convenient to express this in terms of n, and F is defined as the fraction of the total area in the square section of the special studies zone:

Thus,

$$F = \frac{An}{L^2}\,.$$

$$\mu = \sqrt{Fn}\,,$$

or expressed as number of houses per acre,

$$\begin{pmatrix}\text{expected number of}\\ \text{houses per acre in}\\ \text{the special studies}\\ \text{zone astride the}\\ \text{full trace}\end{pmatrix} = \frac{\sqrt{Fn}}{40}$$

and

$$\begin{pmatrix}\text{expected fraction}\\ \text{of houses affected}\end{pmatrix} = \frac{\sqrt{Fn}}{n} \text{ or } \frac{\sqrt{F}}{n}\,.$$

Case 2: In this case it is assumed that the houses are arranged in a more or less ordered array (fig. 46). Divide the square zone into $\sqrt{n}$ strips perpendicular to the fault trace. Then in each strip, assume there are exactly $\sqrt{n}$ houses.

CASE 2: COST DUE TO STUDY

To calculate the cost for other land uses, it is necessary to estimate the number of studies that need to be performed. For single–family and multifamily land–use types, this calculation is very simple. Since the lots are small relative to the width of the special studies zone, edge effects can be ignored. Thus, assuming the lots are square, the number of studies is given by:

$$\begin{pmatrix}\text{number of}\\ \text{studies per}\\ \text{one–quarter–mile square}\\ \text{of special}\\ \text{studies zone}\end{pmatrix} = \frac{1}{40}\left(\frac{40}{a}\right)^{1/2}$$

where a is the area per lot.

For larger lots, the problem is slightly more difficult since a significant proportion of the parcel of property may be out of the special studies zone; thus, edge effects become important for commercial and industrial land uses.

If one assumes there is no overlap, then the probability that a house lies astride the fault in any strip is:

$$\begin{pmatrix}\text{probability that one house lies astride}\\ \text{the fault in a strip}\end{pmatrix} = \frac{\sqrt{n}\,\sqrt{A}}{L}\,.$$

The number of houses in the square that lie across the strip is distributed binomially with parameters $\sqrt{n}$ and $\sqrt{n}\sqrt{A/L}$. Thus, the expected number of houses in the quarter–mile–square section of the study zone is:

$$\begin{pmatrix}\text{expected number of houses astride the}\\ \text{fault}\end{pmatrix} = \frac{n\,\sqrt{A}}{L}\,,$$

which is exactly the same result that was arrived at in case 1. (It should be noted that only the expected values are identical; the variances, for example, are different.) It is interesting, though, that quite different assumptions result in the same answer.

Consider two ways in which a large commercial or industrial parcel might lie astride a special studies zone (fig. 47). Obviously, the number of studies done per acre will depend on the amount of overlap of the parcels relative to the fault. The expected value of the fraction of an arbitrary parcel within the special studies zone, given the size of the parcels, is needed. Let x and y be defined as they are shown in figure 47. Then the expected area of the parcel in the study zone $E[A]$ is given by

$$E[A] = \int_{\alpha}^{\ell} \frac{x \cdot y}{\ell + y}\, dx + \int_{\ell}^{y} \frac{\ell y}{\ell + y}\, dx + \int_{y}^{\ell + y} \frac{(\ell + y - x)}{(\ell + y)}\, y\, dy = \frac{y^2\, \ell}{\ell + y}.$$

Thus:

$$\frac{E[A]}{40 \text{ acres}} = \frac{1}{(\text{number of parcels per one–quarter–mile section of the special studies zone})}$$

and expected cost is given by

(number of lots) × (dollars per study).

SAMPLE CALCULATIONS FOR COSTS OF DAMAGE DUE TO GROUND SHAKING DURING AN EARTHQUAKE

$$\begin{pmatrix}\text{expected cost}\\ \text{in dollars per}\\ \text{acre}\end{pmatrix} = \frac{\begin{pmatrix}\text{value of buildings,}\\ \text{personal property,}\\ \text{utilities, and}\\ \text{disruption in}\\ \text{dollars per acre per}\\ \text{event}\end{pmatrix}\begin{pmatrix}\text{damage cost}\\ \text{factor}\end{pmatrix}\begin{pmatrix}\text{frequency of}\\ \text{occurrence in}\\ \text{events per}\\ \text{year}\end{pmatrix}}{(\text{discount rate})}.$$

Obtain the values for the first term from table 3. Obtain the damage factors by combining tables 7 and 8.

San Francisco intensity	*Modified–Mercali intensity*	*Damage cost factor, in percent*	
		Wood	*Other*
A	XI–XII	16	65
B	X	12	50
C	VIII	5	15
D	VII	2	5
E	VI	.2	1

Earthquakes have a recurrence frequency of 0.01 events per year on the Hayward, San Andreas, and Calaveras faults. Thus, ground shaking resulting from events on these faults yields the following expected costs for single–family residential land use:

A: not utilized

B: not utilized

C:

$$\frac{\begin{pmatrix}\$161{,}250/\text{acre buildings} + \$75{,}000/\text{acre personal property} + \$22{,}500/\text{acre utilities} + \$7{,}500/\text{acre } (\$1{,}500/\text{unit}) \text{ relocation}\end{pmatrix}\begin{pmatrix}0.05\\ \text{damage}\end{pmatrix}\begin{pmatrix}0.01\\ \text{frequencies}\end{pmatrix}}{(0.1 \text{ discount})}$$

$$= \frac{(\$266{,}250/\text{acre})(0.02)(0.01)}{(0.1)} = \$1{,}331.25/\text{acre} \approx \$1{,}000/\text{acre}$$

D: $$\frac{(\$266{,}250/\text{acre})(0.02)(0.01)}{(0.1)} = \$533/\text{acre} \approx \$500/\text{acre}$$

E: $$\frac{(\$266{,}250/\text{acre})(0.002)(0.01)}{(0.1)} = \$53.25/\text{acre} \approx \$50/\text{acre}$$

Events occur once every 1,000 years (0.001 events per year) on the southern Hayward fault. Thus, ground shaking resulting from events on that fault yields the following expected costs for single–family residential land use:

A: $$\frac{(\$266{,}250/\text{acre})(0.16 \text{ damage})(0.001 \text{ frequency})}{(0.1 \text{ discount})}$$

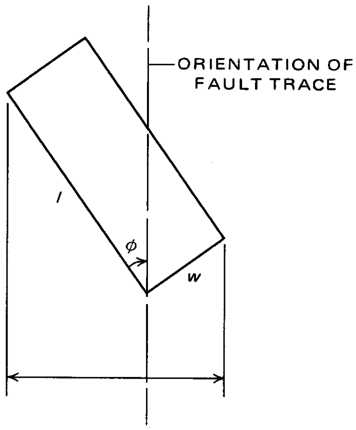
$$= \$426/\text{acre} \approx \$400/\text{acre}$$

B: $$\frac{(\$266{,}250/\text{acre})(0.12)(0.001)}{(0.1)} = \$319/\text{acre} \approx \$300/\text{acre}$$

C: $$\frac{(\$266{,}250/\text{acre})(0.05)(0.001)}{(0.1)} = \$133.13/\text{acre} \approx \$100/\text{acre}$$

D: $$\frac{(\$266{,}250/\text{acre})(0.02)(0.001)}{(0.1)} = \$53.25/\text{acre} \approx \$50/\text{acre}$$

E: $$\frac{(\$266{,}250/\text{acre})(0.002)(0.001)}{(0.1)} = \$5.32/\text{acre} \approx \$5/\text{acre}$$



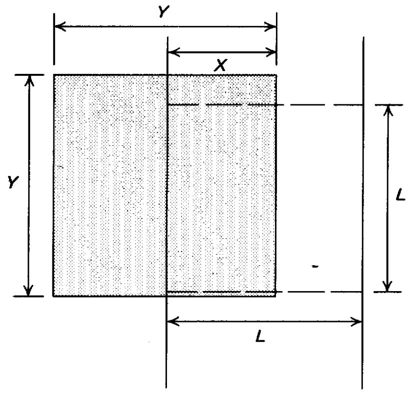


FIGURE 44.—Relationship of house to fault trace.

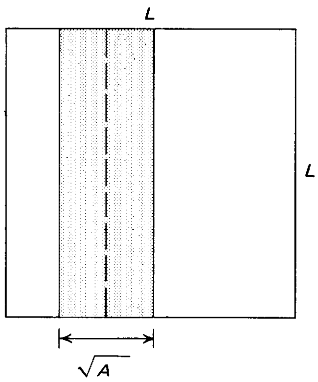


FIGURE 45.—Square segment of one of the special studies zones designated by the Alquist-Priolo Act.

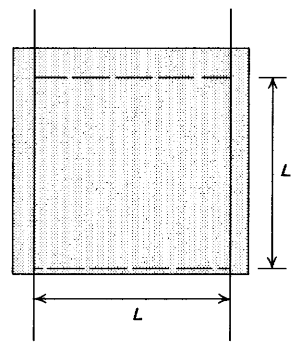


FIGURE 47.—Orientation of a large parcel in a special studies zone.

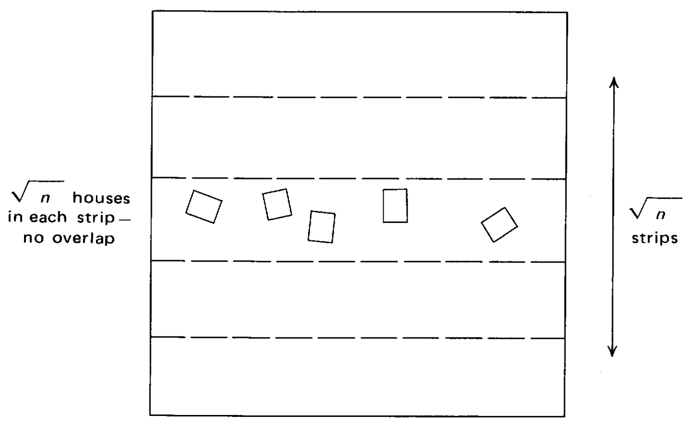


FIGURE 46.—Study zone with ordered houses.

SAMPLE CALCULATIONS FOR COSTS OF DAMAGE DUE TO SURFACE RUPTURE ALONG AN ACTIVE FAULT OR FOR COSTS OF SITE STUDIES TO AVOID DAMAGE

For calculating damage in an Alquist–Priolo special studies zone:

$$\Bigg\{ \begin{pmatrix}\text{value of build-}\\ \text{ings and per-}\\ \text{sonal property}\\ \text{in dollars per}\\ \text{acre}\end{pmatrix} \begin{pmatrix}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{pmatrix} \left[\begin{pmatrix}\text{50 percent}\\ \text{damage to}\\ \text{60 percent of}\\ \text{the buildings}\\ \text{affected}\end{pmatrix} + (\text{100 percent damage to 40 percent of the buildings affected}) \right]$$

$$+ \begin{pmatrix}\text{utility damage}\\ \text{in dollars per}\\ \text{acre}\end{pmatrix} \begin{pmatrix}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{pmatrix} + \begin{pmatrix}\text{relocation ex-}\\ \text{pense in dol-}\\ \text{lars per acre}\end{pmatrix} \begin{pmatrix}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{pmatrix}$$

$$+ \left(\begin{matrix}\text{value of}\\ \text{land for}\\ \text{current}\\ \text{use}\end{matrix} - \begin{matrix}\text{value of}\\ \text{land for}\\ \text{rural use}\end{matrix} \right) \begin{pmatrix}\text{fraction of}\\ \text{buildings}\\ \text{affected}\end{pmatrix} \Bigg\} \div \begin{pmatrix}\text{discount}\\ \text{rate}\end{pmatrix} \times$$

(frequency of occurrence of 0.01).

Obtain the values for the first term from table 3:

$$\begin{matrix}\text{fraction of buildings}\\ \text{affected}\end{matrix} = \sqrt{\frac{\text{fraction of area covered by buildings}}{\text{number of buildings per 40 acres}}} \; .$$

Using the example of single-family residential land use,

$$\begin{matrix}\text{fraction of buildings}\\ \text{affected}\end{matrix} = \sqrt{\frac{0.18}{200}} = 0.03 \; .$$

$$\text{Total cost} = \left[\begin{pmatrix}\text{\$161,250/acre}\\ \text{buildings}\end{pmatrix} + \begin{pmatrix}\text{\$75,000/acre}\\ \text{personal property}\end{pmatrix} (0.03) \right.$$

$$[(0.30) + (0.40)] + \begin{pmatrix}\text{\$200/unit} \times \text{five units/acre}\\ \text{utility damage}\end{pmatrix} (0.03) +$$

$$\begin{pmatrix}\text{\$1,500/unit} \times \text{five units/acre}\\ \text{relocation}\end{pmatrix} (0.03) + \begin{pmatrix}\text{\$36,250/acre}\\ \text{single–family}\end{pmatrix} -$$

$$\left. \begin{pmatrix}\text{\$1,000/acre}\\ \text{rural}\end{pmatrix} (0.03) \right] \div \; (\text{0.1 discount}) \times (\text{0.01 frequency})$$

$$= \frac{(4{,}961.25 + 30 + 225 + 2{,}057.50)(0.01)}{(0.1)}$$

$$= \text{\$627.33/acre} \approx \text{\$600/acre.}$$

For calculating study costs:

$$\frac{\begin{pmatrix}\text{cost of the}\\ \text{preliminary}\\ \text{study in dol-}\\ \text{lars per}\\ \text{parcel}\end{pmatrix} \begin{pmatrix}\text{expected}\\ \text{number of}\\ \text{parcels per}\\ \text{40 acres}\end{pmatrix} + \begin{pmatrix}\text{cost of the}\\ \text{secondary}\\ \text{investigation}\\ \text{in dollars per}\\ \text{parcel}\end{pmatrix} \begin{pmatrix}\text{expected}\\ \text{number of}\\ \text{parcels re-}\\ \text{quiring sec-}\\ \text{ondary in-}\\ \text{vestigation}\\ \text{per 40 acres}\end{pmatrix}}{\text{40 acres}}$$

$$= \frac{(\$400)\left(\dfrac{\text{40 acres}}{\text{1 acre/parcel}}\right) + (\$600)\sqrt{\dfrac{\text{40 acres}}{\text{1 acre/parcel}}}\left(\dfrac{4}{3}\right)}{\text{40 acres}}$$

$$= \frac{16{,}000 + (600)\,(6.32)\left(\dfrac{4}{3}\right)}{40} = \text{\$526/acre} \approx \text{\$500/acre} \; .$$

If the acres per parcel were larger than the 40 acres, such as with regional shopping centers or industrial use, the expected acres per parcel are:

$$\frac{(\text{width of the parcel})^2(\text{width of the study zone})}{(\text{width of the parcel}) + (\text{width of the study zone})}$$

SAMPLE CALCULATION TO DETERMINE COSTS ATTRIBUTABLE TO STREAM FLOODING

$$\frac{\left[\begin{pmatrix}\dfrac{\text{value of buildings per acre}}{\$100}\end{pmatrix} \begin{pmatrix}\text{rate for}\\ \text{buildings}\\ \text{per \$100}\end{pmatrix} + \begin{pmatrix}\dfrac{\text{value of contents per acre}}{\$100}\end{pmatrix} \begin{pmatrix}\text{rate for}\\ \text{contents}\\ \text{per \$100}\end{pmatrix} \right] \begin{pmatrix}\text{75percent of}\\ \text{rate is}\\ \text{actual}\\ \text{cost}\end{pmatrix}}{(\text{0.1 discount rate})}$$

Using the values and rates for single–family use yields

$$\frac{\left[\left(\dfrac{\$161{,}250}{\$100}\right)(0.35) + \left(\dfrac{\$75{,}000}{\$100}\right)(0.90) \right](0.75)}{(0.1)}$$

$$= \frac{(\$564.38 + \$675)(0.75)}{(0.1)} = \text{\$9,295.35/acre} \approx \text{\$9,000/acre.}$$

SAMPLE CALCULATION TO DETERMINE COSTS ATTRIBUTABLE TO DIKE FAILURE

$$\frac{\left[\begin{pmatrix}\text{value of}\\\text{buildings in}\\\text{dollars}\\\text{per acre}\end{pmatrix}\begin{pmatrix}\text{percent}\\\text{damage for}\\\text{buildings per}\\\text{event}\end{pmatrix}+\begin{pmatrix}\text{value of}\\\text{contents in}\\\text{dollars}\\\text{per acre}\end{pmatrix}\begin{pmatrix}\text{percent}\\\text{damage}\\\text{for contents}\\\text{per event}\end{pmatrix}\right]\begin{pmatrix}\text{frequency}\\\text{in events}\\\text{per year}\end{pmatrix}}{(\text{discount rate})}$$

Using the values and rates for single–family use yields

$$\frac{[(\$161{,}250)(0.26)+(\$75{,}000)(0.29)]\ (0.03)}{(0.1)}$$

$$=\frac{(\$41{,}925+\$21{,}750)(0.03)}{(0.1)}$$

$$=\$19{,}108.50/\text{acre}\approx\$20{,}000/\text{acre}.$$

SAMPLE CALCULATIONS TO DETERMINE COSTS ATTRIBUTABLE TO SHRINK/SWELL SOILS

$$\begin{pmatrix}\text{cost in dollars per}\\\text{acre}\end{pmatrix}=\begin{pmatrix}\text{value of buildings}\\\text{and improvements}\\\text{in dollars per acre}\end{pmatrix}\begin{pmatrix}\text{percent}\\\text{construction costs}\end{pmatrix}$$

Construction costs are 3 percent for severe, 1 percent for moderate, and 0 percent for slight.

Using the values in table 3 for single–family use yields:

Severe: $\begin{pmatrix}\$161{,}250\\\text{buildings}\end{pmatrix}+\begin{pmatrix}\$22{,}500\\\text{improvements}\end{pmatrix}(0.03)$

$=(\$183{,}750/\text{acre})(0.03)=\$5{,}512.50/\text{acre}\approx\$6{,}000/\text{acre}.$

Moderate:

$(\$183{,}750/\text{acre})(0.01)=\$1837.50/\text{acre}\approx\$2{,}000/\text{acre}.$

Slight:

$0/acre.

SAMPLE CALCULATIONS TO DETERMINE COSTS OF DAMAGE ATTRIBUTABLE TO LIQUEFACTION

$$\begin{pmatrix}\text{expected cost in}\\\text{dollars per acre}\end{pmatrix}=\left(\frac{\text{damage cost}}{\text{discount rate}}\right)\begin{pmatrix}\text{fraction of time the}\\\text{material is}\\\text{saturated}\end{pmatrix}$$

$$\left[\begin{pmatrix}\text{percentage of}\\\text{material in}\\\text{“high” category}\end{pmatrix}\begin{pmatrix}\text{frequency of}\\0.05\end{pmatrix}+\begin{pmatrix}\text{percentage of}\\\text{material in}\\\text{“moderate”}\\\text{category}\end{pmatrix}\begin{pmatrix}\text{frequency of}\\0.025\end{pmatrix}\right]$$

$$\text{damage cost}=(\text{damage factor})\ (0.10\text{ liquefy})\begin{pmatrix}\text{value of buildings,}\\\text{improvements, and}\\\text{personal property}\end{pmatrix}$$

$$\begin{aligned}\text{damage factor}=\ &10\text{ percent}\times 0\text{ percent damage}=0\\+\ &80\text{ percent}\times 15\text{ percent damage}=0.12\\+\ &10\text{ percent}\times 100\text{ percent damage}=\underline{0.10}\\&\qquad\qquad 0.22\end{aligned}$$

Value of buildings, improvements, and personal property have been summed in the calculations for ground shaking. The discount rate is 10 percent. For single–family use:

$$\left[\frac{(0.22)(0.1)(\$266{,}250)}{(0.1)}\right]=\$58{,}575\ .$$

Category 6:

$(58{,}575)(1)\ [(0.73)(0.03)+(0.21)(0.025)]$
$=(58{,}575)(1)(0.0272)=\$1{,}593/\text{acre}\approx\$2{,}000/\text{acre}\ .$

Category 5:

$(58{,}575)(1)\ [(0.33)(0.03)+(0.28)(0.025)]$
$=(58{,}575)(1)(0.0169)=\$990/\text{acre}\approx\$1{,}000/\text{acre}\ .$

Category 4:

$(58{,}575)(1)\ [(0.22)(0.03)+(0.33)(0.025)]$
$=(58{,}575)(1)(0.0149)=\$873/\text{acre}\approx\$900/\text{acre}\ .$

Category 3:

$(58{,}575)(.1)\ [(0.22)(0.03)+(0.33)(0.025)]$
$=(58{,}575)(0.1)(0.0149)=\$87/\text{acre}\approx\$90/\text{acre}\ .$

Category 2:

$(58{,}575)(0.01)\ [(0.11)(0.03)+(0.29)(0.025)]$
$=(58{,}575)(0.01)(0.0106)=\$6.21/\text{acre}\approx\$6/\text{acre}\ .$

Category 1:

$0/acre .

SAMPLE CALCULATIONS FOR COSTS ATTRIBUTABLE TO LANDSLIDES

$$\begin{pmatrix}\text{costs in dol-}\\\text{lars per acre}\end{pmatrix} = \begin{pmatrix}\text{cost of levels 1, 2,}\\\text{and 3 investigations}\\\text{in dollars per acre}\end{pmatrix} + \begin{pmatrix}\text{cost of special}\\\text{engineering in}\\\text{dollars per acre,}\end{pmatrix}$$

where

$$\begin{pmatrix}\text{cost of special}\\\text{engineering}\end{pmatrix} = \begin{pmatrix}\text{percent of build-}\\\text{ing cost}\end{pmatrix}\begin{pmatrix}\text{value of buildings in}\\\text{dollars per acre}\end{pmatrix}$$

For single–family use:

Category 1:

total cost = (\$0 for level 1 + \$0 for level 2 + \$0 for level 3)+ (\$0 for special engineering) = \$0/acre.

Category 2:

total cost = (\$40/acre for level 1 + \$200/acre for level 2 + \$100/acre for level 3) + (0.01) (\$161,250/acre) = \$340/acre + \$1,612/acre = \$1,952/acre ≈ \$2,000/acre.

Category 3:

total cost = (\$60/acre for level 1 + \$240/acre for level 2 + \$120/acre for level 3) + (0.5) (\$161,250/acre) = \$420/acre + \$8,063/acre = \$8,483/acre ≈ \$8,000/acre.

Category 4:

total cost = (\$72 for level 1 + \$280/acre for level 2 + \$160/acre for level 3) + (0.15) (\$161,250/acre) = \$512 + \$24,187 = \$24,699/acre ≈ \$20,000/acre.

Category 5:

total cost = (\$80 for level 1 + \$320 for level 2 + \$200 for level 3) + (0.25) (\$161,250/acre) = \$600 + \$40,313 = \$40,913/acre ≈ \$40,000/acre.

SAMPLE CALCULATIONS FOR COSTS ATTRIBUTABLE TO SOIL CREEP

$$\begin{pmatrix}\text{cost in dollars}\\\text{per acre}\end{pmatrix} = \begin{pmatrix}\text{value of buildings}\\\text{and improvements}\\\text{in dollars per acre}\end{pmatrix}\begin{pmatrix}\text{percent con-}\\\text{struction costs}\end{pmatrix}$$

Percent construction costs are 6 percent for severe, 2 percent for moderate, and 0 percent for slight.

Using the values in table 3 for single–family use yields

Severe:

(\$161,250 buildings + \$22,500 improvements)(0.06) = (\$183,750/acre) (0.06) = \$11,025/acre ≈ \$10,000/acre.

Moderate:

(\$183,750/acre) (0.02) = \$3,675/acre ≈ \$4,000/acre.

Slight:

\$0/acre.

SAMPLE CALCULATIONS FOR COSTS ATTRIBUTABLE TO EROSION

First, one must calculate:

$$\begin{pmatrix}\text{sediment yield}\\\text{in tons per acre}\\\text{for use } x \text{ and}\\\text{erosion province}\\y\end{pmatrix} = \frac{\begin{pmatrix}\text{sediment yield}\\\text{in tons per acre}\\\text{for use } x \text{ for}\\\text{bay hills}\\\text{province}\end{pmatrix}}{\begin{pmatrix}\text{sediment yield}\\\text{in tons per acre}\\\text{for open space}\\\text{for bay hills}\\\text{province}\end{pmatrix}}\begin{pmatrix}\text{sediment yield}\\\text{in tons per acre}\\\text{for open space}\\\text{for erosion}\\\text{province } y\end{pmatrix}$$

For open–space use:

sediment yield for bay hills province $= \dfrac{310 \text{ tons/square mile/year}}{640 \text{ acres/square mile}}$

$= 0.4844$ tons/acre/year

sediment yield for foothills and Diablo Range $= \dfrac{140}{640} = 0.2188$ tons/acre/year

sediment yield for Santa Cruz Mountains $= \dfrac{2300}{640} = 3.5938$ tons/acre/year

For agricultural use:

sediment yield for bay hills province $= \dfrac{21{,}000}{640} = 32.8125$ tons/acre/year

sediment yield for foothills and Diablo Range $= \dfrac{21{,}000 \text{ tons/square mile/year}}{310 \text{ tons/square mile/year}}$

$\left(\dfrac{140}{640} \text{ tons/acre/year}\right)$

$= 14.8185$ tons/acre/year

sediment yield for Santa Cruz Mountains $= \frac{21{,}000}{310}\left(\frac{2{,}300}{640}\text{ tons/acre/year}\right)$

$= 243.4476$ tons/acre/year

For urban use:

sediment yield for bay hills province $= \frac{760}{640} = 1.1875$ tons/acre/year

sediment yield for foothills and Diablo Range $= \frac{760}{310}\left(\frac{140}{640}\text{ tons/acre/year}\right)$

$= 0.5363$ tons/acre/year

sediment yield for Santa Cruz Mountains $= \frac{760}{310}\left(\frac{2{,}300}{640}\text{ tons/acre/year}\right)$

$= 8.8105$ tons/acre/year

For construction use:

sediment yield for bay hills province $= \frac{26{,}000}{640} = 40.625$ tons/acre/year

sediment yield for foothills and Diablo Range $= \frac{26{,}000}{310}\left(\frac{140}{640}\text{ tons/acre/year}\right)$

$= 18.3468$ tons/acre/year

sediment yield for Santa Cruz Mountains $= \frac{26{,}000}{310}\left(\frac{2{,}300}{640}\text{ tons/acre/year}\right)$

$= 301.4113$ tons/acre/year

Then, one can calculate the costs associated with rural or agricultural use:

$$\left(\begin{array}{c}\text{cost in dollars per acre}\\ \text{for rural or}\\ \text{agricultural use}\end{array}\right) = \frac{\left[\left(\begin{array}{c}\text{sediment yield in}\\ \text{tons per acre per}\\ \text{year for "agriculture"}\end{array}\right) - \left(\begin{array}{c}\text{sediment yield in}\\ \text{tons per acre per}\\ \text{year for "open space"}\end{array}\right)\right]\left(\begin{array}{c}\text{fraction}\\ \text{dredged}\end{array}\right)\left(\begin{array}{c}\text{dredging cost in}\\ \text{dollars per ton}\end{array}\right)}{(\text{discount rate})}$$

bay hills province:

$$\frac{(32.8125 - 0.4844)(0.75)(2)}{(0.1)} = \frac{(32.3281)(1.5)}{0.1}$$

$$= \$484.92/\text{acre} \approx \$500/\text{acre}$$

foothills and Diablo Range:

$$\frac{(14.8185 - .2188)(.75)(2)}{(0.1)} = \frac{(14.5997)(1.5)}{(0.1)}$$

$$= \$219.00/\text{acre} \approx \$200/\text{acre}$$

Santa Cruz Mountains:

$$\frac{(243.4476 - 3.5938)(0.75)(2)}{(0.1)} = \frac{(239.8538)(0.75)(2)}{(0.1)}$$

$$= \$3{,}597.81 \approx \$4{,}000/\text{acre}$$

One can calculate the costs for all other land uses:

$$\left(\begin{array}{c}\text{cost in dollars per}\\ \text{acre for all other}\\ \text{uses}\end{array}\right) = \left(\begin{array}{c}\text{cost in dollars per}\\ \text{acre for "urban"}\end{array}\right) + \left(\begin{array}{c}\text{cost in dollars per}\\ \text{acre for}\\ \text{"construction"}\end{array}\right)$$

where

(cost in dollars per acre for "urban") =

$$\frac{\left[\left(\begin{array}{c}\text{sediment yield for}\\ \text{urban in tons}\\ \text{per acre per year}\end{array}\right) - \left(\begin{array}{c}\text{sediment yield for}\\ \text{"open space" in}\\ \text{tons per acre per year}\end{array}\right)\right]\left(\begin{array}{c}\text{fraction}\\ \text{dredged}\end{array}\right)\left(\begin{array}{c}\text{dredging cost in}\\ \text{dollars per ton}\end{array}\right)}{(\text{discount rate})}$$

and where

(cost in dollars per acre for "construction") =

$$\frac{\left[\left(\begin{array}{c}\text{sediment yield for}\\ \text{"construction" in tons}\\ \text{per acre per year}\end{array}\right) - \left(\begin{array}{c}\text{sediment yield for}\\ \text{"open space" in}\\ \text{tons per acre per year}\end{array}\right)\right]\left(\begin{array}{c}\text{fraction}\\ \text{dredged}\end{array}\right)\left(\begin{array}{c}\text{dredging cost in}\\ \text{dollars per ton}\end{array}\right)\left(\begin{array}{c}\text{frequency of}\\ \text{dredging}\end{array}\right)}{(\text{discount rate + frequency of dredging})}$$

Bay hills province:

$$\frac{(1.1875-0.4844)(0.75)(2)}{(0.1)}+$$

$$\frac{(40.6250-0.4844)(0.75)(2)(0.05)}{(0.1+0.05)}=\frac{(0.7031)(1.5)}{(0.1)}+$$

$$\frac{(40.1406)(1.5)(0.05)}{(0.15)}=10.5465+$$

$$20.0703=\$30.62/\text{acre}\approx\$30/\text{acre}$$

Foothills and Diablo Range:

$$\frac{(0.5363-0.2188)(0.75)(2)}{(0.1)}+$$

$$\frac{(18.3468-0.2188)(0.75)(2)(0.05)}{(0.1+0.05)}$$

$$=\frac{(0.3175)(1.5)}{(0.1)}+\frac{(18.1280)(1.5)(0.05)}{(0.15)}$$

$$=4.7625+9.0640=\$13.83/\text{acre}\approx\$10/\text{acre}$$

Santa Cruz Mountains:

$$\frac{(8.8105-3.5938)(0.75)(2)}{(0.1)}+$$

$$\frac{(301.4113-3.5938)(0.75)(2)(0.05)}{(0.1+0.05)}$$

$$=\frac{(5.2167)(1.5)}{(0.1)}+\frac{(297.8175)(1.5)(0.05)}{(0.15)}$$

$$=78.2505+148.9088=\$227.16\approx\$200/\text{acre}$$

RATE AND WEIGHT FACTORS FOR RELATING MAPPED INFORMATION

If dollar–cost information is difficult or virtually impossible to obtain, a system of rate and weight factors can be used to aid in estimating and quantifying the relative importance of selected developmental considerations.

In such a system, the rate factor quantifies the relative severity of each geologic constraint as it applies to a single land use; for example, the range from a low to a high potential for soil creep may be expressed on a rating scale of 0 to 10. The weight factor ranks different constraints, such as soil creep or ground shaking, in terms of their impact on a single use. The product of the two factors yields a numerical score, and when all relevant scores for a particular parcel of land and a particular land use are summed, the sum expresses capability.

The expected costs for erosion and sedimentation calculated for the demonstration area are listed in table 45. These values can be converted to rate and weight factors by normalizing the values for each land use to a scale of 0 to 10 and then choosing a weight factor such that the product of the weight and rate will yield the dollar cost. The rate and weight factors for erosion and sedimentation calculated for the demonstration area are listed in table 46.

With this type of information, one can visualize the relative susceptibility to erosion of the various erosion provinces and the relative significance of erosion to rural or agricultural use as opposed to the urban uses.

The rates are approximately identical for all the land uses for this constraint, but this is not always the case.

Because the dollar–cost numbers calculated for the study can be expected to be used in combination with land–use categories without dollar units, the expected costs have been translated into rate and weight factors, where the dollar units have been ignored in tables 47–54. These tables are the equivalent of tables 34–41 in the main text. Occasionally, the rate times the weight does not round off to the dollar cost given. These discrepancies are due to the use of the original (nonrounded) costs in the calculation of the rates. The use of a single significant figure inevitably results in losses of information which these discrepancies represent.

TABLE 45.—*Costs per acre associated with erosion and sedimentation*

Land use	Santa Cruz Mountains	Bay hills	Foothills and Diablo Range	Uplands and valley
Rural or agricultural	$4,000	$500	$200	$0
Semirural residential	200	30	10	0
Single-family residential	200	30	10	0
Multifamily residential	200	30	10	0
Regional shopping centers	200	30	10	0
Downtown commercial	200	30	10	0
Industrial	200	30	10	0
Freeways	200	30	10	0

TABLE 46.—*Rate and weight factors associated with erosion and sedimentation*

Land use	Weight	Rates: Santa Cruz Mountains	Rates: Bay hills	Rates: Foothills and Diablo Range	Rates: Uplands and valley
Rural or agricultural	400	10	1.25	0.5	0
Semirural residential	20	10	1.50	.5	0
Single-family residential	20	10	1.50	.5	0
Multifamily residential	20	10	1.50	.5	0
Regional shopping centers	20	10	1.50	.5	0
Downtown commercial	20	10	1.50	.5	0
Industrial	20	10	1.50	.5	0
Freeways	20	10	1.50	.5	0

TABLE 47.—*Summary of rate and weight factors for rural or agricultural use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	2	10	1	0	—	—
Ground shaking—San Andreas, Hayward	4	10	8	3	1	0
Ground shaking—Southern Hayward	1	10	8	3	1	0
Ground shaking—Calaveras	3	10	5	2	0	—
Stream flooding	20	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	50	10	0	—	—	—
Shrink/swell soils	5	10	3	0	0	—
Settlement	2	10	10	5	2	—
Liquefaction	1	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	4	10	7	5	3	0
Soil creep	10	10	3	0	0	—
Erosion and sedimentation	400	10	1	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	0	—	—	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	0	—	—	—	—	—

TABLE 48—*Summary of rate and weight factors for semirural residential use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	7	10	1	0	—	—
Ground shaking—San Andreas, Hayward	30	10	8	3	1	0
Ground shaking—Southern Hayward	3	10	8	3	1	0
Ground shaking—Calaveras	30	10	4	2	0	—
Stream flooding	70	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	200	10	0	—	—	—
Shrink/swell soils	50	10	3	0	0	—
Settlement	20	10	10	5	2	—
Liquefaction	8	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	100	10	5	1	1	0
Soil creep	100	10	3	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—

TABLE 49.—*Summary of rate and weight factors for single-family residential use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	50	10	10	0	—	—
Ground shaking—San Andreas, Hayward	400	10	8	3	1	0
Ground shaking—Southern Hayward	40	10	8	3	1	0
Ground shaking—Calaveras	300	10	4	2	0	—
Stream flooding	900	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	2,000	10	10	0	—	—
Shrink/swell soils	600	10	3	0	0	—
Settlement	3,000	10	10	7	1	—
Liquefaction	100	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	4,000	10	6	2	0	0
Soil creep	1,000	10	3	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—

TABLE 50.—*Summary of rate and weight factors for multifamily residential use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	80	10	10	0	—	—
Ground shaking—San Andreas, Hayward	2,000	10	8	3	1	0
Ground shaking—Southern Hayward	200	10	8	3	1	0
Ground shaking—Calaveras	1,000	10	4	2	0	—
Stream flooding	4,000	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	8,000	10	0	—	—	—
Shrink/swell soils	2,000	10	3	0	0	—
Settlement	3,000	10	10	7	1	—
Liquefaction	400	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	20,000	10	6	2	0	0
Soil creep	4,000	10	3	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—

TABLE 51.—*Summary of rate and weight factors for regional shopping-center use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	20	10	10	0	—	—
Ground shaking—San Andreas, Hayward	5,000	10	8	2	1	0
Ground shaking—Southern Hayward	500	10	8	2	1	0
Ground shaking—Calaveras	4,000	10	3	1	0	—
Stream flooding	4,000	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	7,000	10	0	—	—	—
Shrink/swell soils	2,000	10	3	0	0	—
Settlement	3,000	10	10	7	1	—
Liquefaction	300	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	10,000	10	6	2	1	0
Soil creep	3,000	10	3	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—

TABLE 52.—*Summary of rate and weight factors for downtown commercial use*

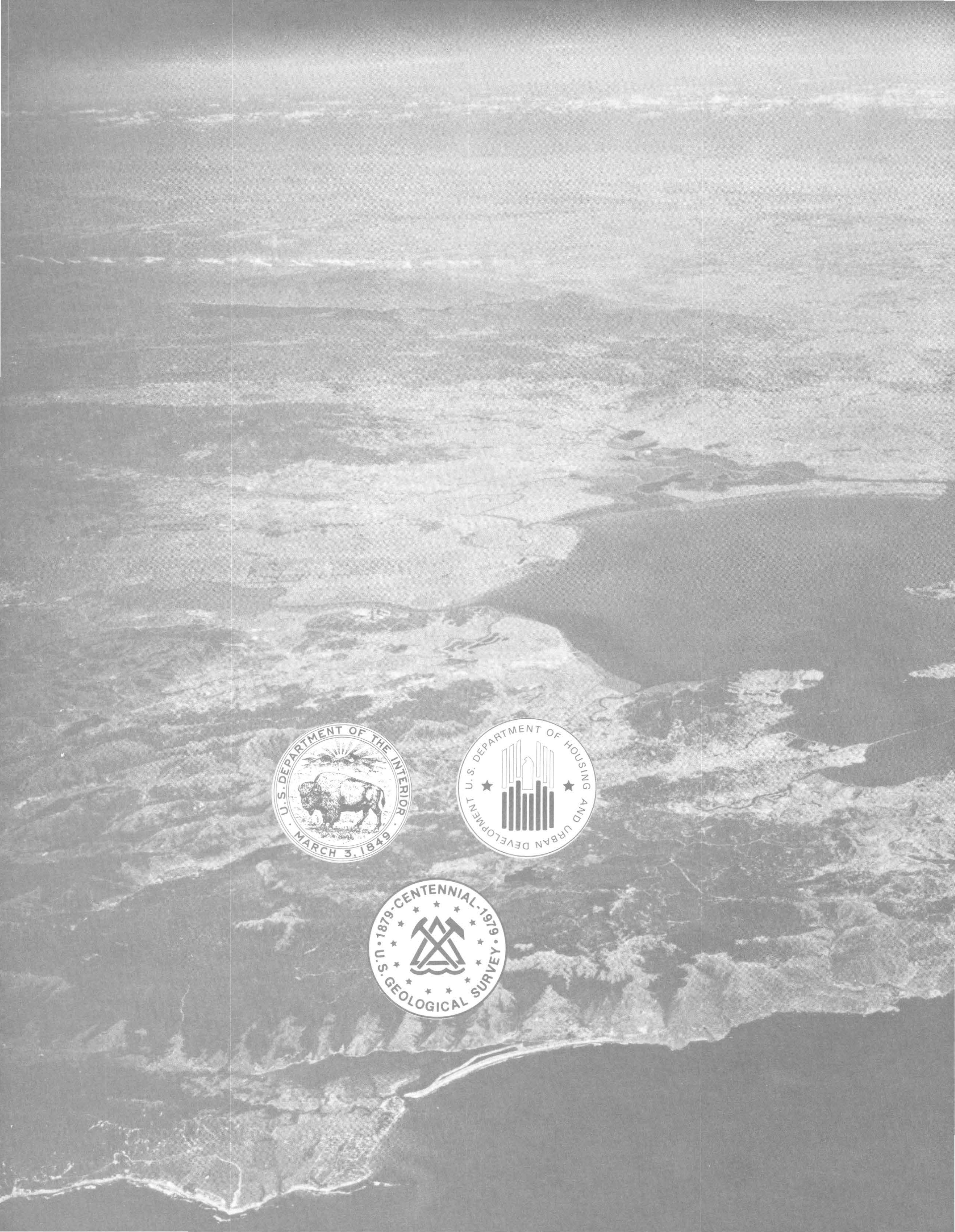
Constraint or oportunity	Weight factor	Rate factors				
Surface rupture	500	10	10	0	—	—
Ground shaking—San Andreas, Hayward	7,000	10	8	2	1	0
Ground shaking—Southern Hayward	700	10	8	2	1	0
Ground shaking—Calaveras	5,000	10	3	1	0	—
Stream flooding	5,000	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	9,000	10	0	—	—	—
Shrink/swell soils	2,000	10	3	0	0	—
Settlement	10,000	10	3	2	0	—
Liquefaction	400	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	20,000	10	6	2	1	0
Soil creep	5,000	10	3	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—

TABLE 53.—*Summary of rate and weight factors for industrial use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	8	10	10	0	—	—
Ground shaking—San Andreas, Hayward	4,000	10	8	2	1	0
Ground shaking—Southern Hayward	400	10	8	2	1	0
Ground shaking—Calaveras	3,000	10	3	1	0	—
Stream flooding	4,000	10	0	—	—	—
Dam failure	0	—	—	—	—	—
Dike failure	7,000	10	0	—	—	—
Shrink/swell soils	1,000	10	3	0	0	—
Settlement	1,000	10	10	6	1	—
Liquefaction	300	10	9	1	0	0
Subsidence	0	—	—	—	—	—
Landslides	10,000	10	6	3	1	0
Soil creep	2,000	10	3	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—

TABLE 54.—*Summary of rate and weight factors for freeway use*

Constraint or opportunity	Weight factor	Rate factors				
Surface rupture	20	10	7	0	—	—
Ground shaking—San Andreas, Hayward	1,000	10	10	10	0	0
Ground shaking—Southern Hayward	100	10	10	10	0	0
Ground shaking—Calaveras	1,000	10	10	0	0	—
Stream flooding	0	0	0	0	—	—
Dam failure	0	—	—	—	—	—
Dike failure	0	0	0	—	—	—
Shrink/swell soils	0	0	0	0	0	—
Settlement	0	0	0	0	0	—
Liquefaction	0	0	0	0	0	0
Subsidence	0	—	—	—	—	—
Landslides	2,000	10	7	3	2	0
Soil creep	0	0	0	0	0	—
Erosion and sedimentation	20	10	2	0	0	—
Septic tanks	0	—	—	—	—	—
Sand and gravel	2,000	10	0	—	—	—
Mercury	0	—	—	—	—	—
Agricultural land	500	10	0	—	—	—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