DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides

Chapter B. Methods and Costs for the Delineation of Susceptibility to Mud Flows and Other Landslides

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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METHODS AND COSTS FOR THE DELINEATION OF SUSCEPTIBILITY TO MUD FLOWS AND OTHER LANDSLIDES

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Introduction

Landslide risks are evaluated in the most timely, efficient, and cost-effective manner through an orderly sequence of progressively more detailed approaches. In such a sequence, the general distribution of potentially hazardous areas would be broadly defined early in the sequence, recognizing that preliminary reconnaissance studies will leave some hazardous areas unidentified and will incorrectly include some non-hazardous areas. Subsequently, more comprehensive work should be done to define and quantify the distribution of potentially hazardous processes and conditions in greater detail.

The sequence of approaches is generally intended to result in maps depicting the relative risks to different communities and the relative risks among various parts within a community. In areas where some degree of risk has been established (usually on the basis of historic damaging landslide activity), some communities have established code requirements for evaluating the stability of proposed building sites. Detailed evaluations of the stability of specific slope sites are generally undertaken only where specific new construction is contemplated, or where remedial measures are being considered as a result of landslide damage. The general purpose of landslide risk maps, therefore, is to identify areas within which prudent engineering construction practice would include further consideration of the potential for landslide damage at specific sites.

The tabulation of classification criteria and recognition factors in Plate 2 can be used to identify some of the trade-offs in cost-versus-reliability decisions for mapping landslide hazards. For example, the delineation of hillsides with steep to moderate slopes will identify nearly all of the areas in which mud flows originate, as well as areas where many other kinds of landslides are common. Slope alone, however, cannot distinguish those steep and moderate slope areas where strong earth materials or favorable geologic structure reduce susceptibility to slope failure, nor can it identify gentle slope areas that are susceptible to failure because of earthquake-induced lateral spreading or liquefaction, or areas where weak materials may fail because of construction activity. Additional information is required in and around communities in regions where these exceptions are known to be significant.

Reconnaissance interpretations of aerial photographs can generally provide a basis for recognizing the principal kinds of landslides present in a region, an approximate measure of the density of their distribution, and an approximate measure of the distribution of colluvium and similar hillside materials. Additional geological and geotechnical detail can be acquired as the needs for more precise delineation become evident. The level of detail and comprehensiveness of additional investigations in a given area will be determined by the social and economic concerns in that area. Decisions regarding the acceptability of different levels of accuracy and cost are socio political decisions. Invariably, the comprehensiveness and reliability with which the risks are identified, and the accuracy with which their distribution is depicted, must be balanced against the cost of the program for hazard delineation.

Acknowledgments

Much of the following review of methods for hazard mapping and risk evaluation is taken from USGS Circular 880 (U.S. Geological Survey, 1982), which is the report of the USGS Workshop on Ground-Failure Hazards, held in Golden, Colorado, on January 28-29, 1981. I am indebted particularly to Robert W. Fleming, who convened the conference and was responsible for editing the report for publication as a Circular, and to Earl E. Brabb, who chaired the workshop group that reviewed landslide hazard mapping and risk evaluation methods, and took a major role in editing early versions of the conference report for Open-File release. The cost estimates that have been added are preliminary approximations based on my own experience in making budget estimates for USGS research projects and programs. Over the years, I have benefited from the experiences of many other individuals in the USGS through informal conversations over a number of years. For discussions of specific costs during the preparation of this report, I am indebted to: K. Eric Anderson, Robert W. Claire, and Vincent M. Caruso, USGS National Mapping Division (digital data acquisition and computer slope calculations); to Earl E. Brabb and William E. Davies, USGS Geologic Division (reconnaissance landslide inventories); and to Gerald G. Schaber and David J. Roddy, USGS Geologic Division (slope calculations from digital terrain tapes). However, the responsibility for the way in which cost information has been compiled and used to make estimates of average unit costs remains mine. The estimates of average unit costs should not be used uncritically to constrain individual proposals for work in specific areas, because costs are likely to vary widely from one region or community to another.

Hazard Identification and Delineation: Maps

At the present time, maps are the principal format for presenting information about landslide hazards. Maps are convenient and readily understood ways to show the distribution of landslide hazards. Various physical attributes that contribute to landslide type and potential can be shown at levels of detail appropriate to their intended use. Maps are the traditional basic tools for planning and design of developments. Presentation of landslide information in map form makes it readily comparable to other mapped constraints on development. For this reason, much of the following discussion of hazards identification and delineation, and the costs of providing them, are described in a context of maps -- the kinds of maps, photographs, or images from other sensors, and their scale. Significant progress has been made during the past 10 years in preparing different types of maps of landsliding in the United States. This experience, and the results of mapping experiments from other countries, can be applied to produce the kinds of landslide and slope-stability maps necessary for loss-avoidance and mitigation. Moreover, innovative changes are in progress in both the acquisition of map data and map production. A digital cartographic revolution is under way that will undoubtedly have significant effects on the costs of acquiring landslide-hazards data, providing for continuous updating of such map data, and producing individual maps for specific areas and to unique specifications.

The detail with which features can be shown on a traditional map is limited by map scale in two general ways -- resolution of features identified in the process of data acquisition, and accuracy of portrayed position. The recognition and delineation of features on aerial photographs, for example, is limited by the image resolution obtainable from the photograph and the optical system with which it is viewed. In practice, it is generally rare for a skilled observer to be able to recognize and delineate a landslide that covers less than about 0.01 in^2 on the image being interpreted. (At an image scale of 1:24,000, 0.01 in^2 is approximately one acre on the ground.) Similarly, the accuracy with which positions are portrayed on maps is relative to the map scale. For example, a 0.005-inch-wide line drawn on a map at 1:24,000 scale, covers a width on the ground of about 10 ft. At 1:250,000 scale, the 0.005-inch line covers about 104 ft. Clearly, maps should be prepared at scales commensurate with the detail and accuracy required for their intended use. In planning a program for the delineation of landslide hazards, the requirements for detail and standards of accuracy should be carefully examined, because doubling the scale can have an order-of-magnitude effect on the cost of map preparation.

Identification and Delineation of Potential Mud Flow Areas

The needs of the National Flood Insurance Program (NFIP), seem to call for methods that might discriminate areas of potential hazard due to "mudslides" ("i.e., mudflows") comprehensively, while minimizing the effort dedicated to the identification of areas having potential hazards from other landslides. For example, if only debris flows and mud flows are to be included, factors such as shear strength and the geometric relations of bedding and slope that assist in the identification of variations in susceptibility to bedrock slides and slumps are of less overall significance to the initiation of the debris flows and mud flows than hillside steepness and the distribution of colluvial soil on the slopes. Most areas where mud flows can be initiated by soil slips during prolonged heavy rainfall are on slopes greater than 3:1 (18°) as shown in Figure A-2 (Chapter A, this report) and described by Campbell (1975, p. 10-12). The slopes of debris-flow depositional surfaces suggest that runout on slopes more gentle than 5:1 (11°) does not generally exceed about 300 feet (100 m), except where flows are confined to relatively narrow, deep channels. Consequently, even though the procedure may not identify some wet lowland areas where earthquake-triggered slumps and lateral spreads are common and mud flows can be formed as parts of such landslides, maps showing slopes within selected ranges may be satisfactory as preliminary maps of mud-flow (debris-flow) susceptibility.

In communities identified as having significant mud-flow potential as a consequence of slope relations, the further delineation of areas of mud-flow hazard will need to be supplemented by other approaches. Within areas of equal steepness, subdivision into areas of different susceptibility will require the identification and interpretation of geologic and geotechnical parameters, and geohydrologic conditions. Within areas of low slope, susceptibility to runout from debris flows and mud flows initiated on adjacent steep slopes can be evaluated by recognizing depositional and erosional features from prior events.

Information, Materials, and Costs for the Identification and Delineation of Areas Susceptible to Mud Flows and Other Landslides

Landslide-hazard delineation and risk evaluation require geologic, topographic, and other basic information. In Goals and Tasks of the Landslide Part of a Ground-Failure Hazards Reduction Program (U.S. Geological Survey, 1982, p. 20-21), an extensive list of the various kinds of information that can contribute to an improved evaluation of the distribution of landslide risk is tabulated, together with an explanation of how the information is used and an estimate of general availability. That tabulation has been modified to include information on high-altitude aerial photographs and digital elevation data, as well as preliminary estimates of unit cost (Table B-1).

Table B-1. Near Here

To clarify some of the advantages and limitations not evident in the table, additional text material has been abstracted from Circular 880 (U.S. Geological Survey, 1982) and is included here, with some additions and modifications:

Digital terrain tapes, generated by digitizing the contours on the 1:250,000 scale 1° by 2° topographic sheets, are available for the conterminous United States with relatively uniform accuracy. Their detail is limited by the scale, contour interval, and accuracy of the original maps.

Digital elevation data sets can be used to generate slope information, which can be displayed at appropriate scales. Slopes determined from these procedures can be used to discriminate among hillsides of different steepness and delineate, for example, slopes steeper than 5:1, steeper than 3:1, and steeper than 2:1, which would be of significance in delineating areas susceptible to debris flows generated during storm rainfall (see Fig. A-2). Slope information derived from this data set is limited, however, to slopes that are long enough to be defined by the contour intervals of the original topographic maps (50-ft contour intervals in relatively flat areas, to intervals of as much as 200 ft in mountainous areas). Horizontal positions have potential errors in ground position commensurate with the line widths and any positional errors on the original map. Consideration of

Table B-1.--Information, materials, availability and costs* for landslide-hazard mapping and risk evaluation

Information or material needed	Uses	Availability	Cost
Topographic and bathymetric maps.	Provides a base for plotting landslide information. Topographic form is used to identify landslides. Provides basic data for slope maps.	Generally available from Federal agencies for most areas at scales of 1:24,000 or smaller. Large scale, more detailed mapping has been completed for some large urban areas by local agencies.	Published sheets at $2.00-$5.00 each. (For 1:24,000-scale sheets one each of the 54,000 sheets required to cover the conterminous U. S. would total $108,000, for example.)
Aerial photography	Photographs enable recognition, classification, and mapping of many past landslides in a large area in a short time. Most important mapping tool for landslides (including mud flows). Especially useful for documenting hazardous areas immediately after major triggering events such as rainstorms or earthquakes.	Aerial photography is available for the entire United States but is not consolidated in a single agency. Relatively new forms of imagery including color and infrared photography, satellite imagery, side-scan SONAR and Side-Looking Aperture Radar (SLAR) have application to landslide studies but limited availability has curtailed use.	Contact (9 in. x 9 in.) prints of USGS air photo negatives cost $5.00 each; approximately 30 needed to cover one 7 1/2 min. quadrangle. Cost to acquire new 1:24,000-scale photo coverage is approximately $7,000 to $10,000 per 7 1/2 min quadrangle.
High-altitude aerial photography program	Small-scale photographs in black and white and in color infrared provide bases for plotting landslide information. Resolution suitable for the identification, classification, and mapping of landslides from these images requires high-magnification optical systems.	Conterminous U.S. 59 percent covered in 1982; 100 percent planned for 1986, when a 6-year cyclic rephotography program begins. Usefulness for landslide identification is limited by need for special optical systems in order to achieve adequate resolution for smaller landslide features.	Cost for contact prints of existing negatives same as above; for prints enlarged to 1:24,000-scale, $35.00 each. Note: USGS plans for coverage and rephotography presently do not reflect FEMA priorities, but interagency agreement could be negotiated.
Orthophotoquads	Photographic images, produced to match U.S. Geological Survey quadrangle maps in format and scale, permit rapid and inexpensive transfer of landslide information to base maps.	Available for about 30 percent of the conterminous United States. Additional orthophotoquads may be needed in areas of high priority for inventories of landslides. The USGS has an ongoing program for eventual nationwide coverage.	Published sheets are available at cost of $2.00 per quadrangle. Although present USGS plans do not reflect FEMA priorities, interagency agreement could be negotiated to include them.
Digital base-map data	Enables automatic merger of digital topographic, geologic, seismologic, and meteorologic data to produce landslide susceptibility and risk maps at lower cost. Digital map data include digital elevation models, digital line graphs, land net, boundaries, roads, streets, etc., hydrography, census tracts, and other factors.	Base maps have been digitized for only about 1/6 th of the 1:24,000-scale sheets of the United States, most of which are U. S. public lands rather than urban or suburban areas. However, significant increases in rate of production of these data from existing maps can be expected in the near future as a result of ongoing research and development of raster scanning technology.	Costs for digital elevation data are discussed separately below. Costs for duplicating existing digital data for other factors is variable, but total costs per quadrangle probably range from $250 per 7 1/2 min sheet to about $500 per $1^{\circ} \times 2^{\circ}$ sheet. Digital data are also available from various other sources at undetermined costs.

*Many of the costs indicated in this table are preliminary approximations based on the experience of individuals in the U. S. Geological Survey. They represent estimates of average unit costs in 1983 dollars, and should not be used to constrain individual proposals for work in specific areas. Actual costs may vary widely from these estimates, and estimates for costs in specific community areas should be carefully calculated for each individual area and region.

Table B-1.--Information, materials, availability and costs* for landslide-hazard mapping and risk evaluation

Information or material needed	Uses	Availability	Cost
Digital elevation data.........	Enables rapid preparation of slope maps as well as digital mergers with geology and other data, to produce maps showing landslide susceptibility and risk at lower cost.	Two scales of data now available or being acquired: 1) From 1:250,000 $1^{o} \times 2^{o}$ topographic map sheets, entire conterminous U. S. is available; and 2) From a systematic program to acquire digital data for 1:24,000-scale 7.5' quadrangles; about 9,000 quadrangles have been completed out of a total of about 54,000 in the United States.	Existing tapes of digital terrain data at 1:250,000-scale cost \$75.00 per $1^{o} \times 1^{o}$ block per duplicate. Existing tapes of elevation data at 1:24,000-scale cost \$100.00 per duplicate. New data are being acquired for the regular USGS program at a rate of about 2,000 quadrangles per year. Cost to USGS is about \$1,300 per sheet. [1]
Slope maps	Used to prepare slope-stability maps that combine steepness, history of landsliding, and physical characteristics of different materials.	Can be prepared by hand, photomechanically, or by computer from a digitized topographic map or from digital models developed directly from air photos. Some urban communities have prepared maps showing various categories of slope, but with little uniformity from one community to another and, for the most part, with little regard for slope-stability problems.	Manual and photomechanical slope maps are expensive to produce. Use of digital elevation data and computer calculation greatly reduces time and cost of preparation in areas where digital data already exist. Capability to derive slope from existing (1:250,000-scale) digital data exists in USGS Branch of Astrogeology. USGS-National Mapping Division has capability to derive slope from 1:24,000-scale data of the ongoing NMD program. [2]

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[1] USGS plans and priorities for the ongoing program do not include consideration of factors that may be of importance to FEMA; however, interagency discussions could identify revisions of present plans and schedules that would be mutually agreeable modifications to the ongoing USGS program. In addition, an interagency agreement might be negotiatied to address priorities for areas of particular concern to FEMA on a cost-shared basis.

[2] Cost estimates for deriving slope maps from these digital elevation data are included in the text discussion of a scenario for the development of a nationwide program to identify and delineate landslide hazards.

Table B-1.--Information, materials, availability and costs* for landslide-hazard mapping and risk evaluation

Information or material needed	Uses	Availability	Cost
Geologic maps of bedrock ..... and surficial materials.	Essential for understanding the causes of landslides and predicting the density, severity, and frequency of landsliding in large areas. Can be used with reconnaissance techniques to extrapolate detailed information from small areas to large regions for which no landslide information is available.	Only about 1/3 of the conterminous United States is covered by geologic maps having enough detail to prepare slope-stability maps. However, one or two carefully detailed 7 1/2 min quads. can often serve as a basis for extrapolating the causes of landslide susceptibility to many tens of surrounding quadrangles by reconnaissance methods.	Published geologic maps generally range in price from a few dollars to several tens of dollars (if photo reproduction is required). New geologic maps in urban or suburban areas commonly require from 1 to 2 1/2 years to prepare and cost from $65,000 to $200,000, exclusive of printing and distribution.[3]
Landslide-inventory maps	Important for the identification of areas where geologic conditions and triggering events have combined to produce landslides in the past. Provide guides to the expected severity of the potential landslide hazards. Essential for recognizing areas where strength of surficial and bedrock materials is more important than slope in the assessment of potential hazards, or for recognizing where the interaction of slope and geologic discontinuities controls the distribution of the potential for hazard.	Published map at scale of 1:7,5000,000 for conterminous U. S. shows generalized distribution of landslide incidence and susceptibility. Inventory maps, chiefly reconnaissance, but some detailed, exist at scales ranging from 1:24,000 to 1:500,000 for areas ranging in size from a single 7.5' quadrangle to an entire State. Approximately 1/4 of the landslide area of the conterminous U. S. is covered by some form of landslide inventory at a scale of 1:500,000 or larger; however, most inventories made prior to about 1975 do not include debris-flow fans or other evidence of mud-flow activity.	Reconnaissance-level inventories using air photos can be produced at a rate of about 25 to 35 7 1/2 min. quadrangles per man year (about $2,000 to $3,000 per quad). For a community having an area of 1,000 mi^2 (about 20 quads.), the cost might be in the range of $40,000 to $70,000, exclusive of printing and distribution. Additional costs for digitizing range from $500 to $1,500 each, partly or wholly offset by reductions in cost of printing and distribution. Costs for detailed inventories, including field verification, will be about two to ten times costs for reconnaissance.
Terrain analysis	Uses landforms recognized and classified from high-altitude photographs to identify areas having different dominant slope processes and habitats of landslides.	Not generally available. Methods are being developed, but are still being tested in Marin County area of California. Could provide rapid means for identification and delineation of landslide-hazard zones.	Requires research to determine landform-landslide associations characteristic of the terrains of different regions of the U. S. Once regional processes are established, reconnaissance extrapolation offers rapid, inexpensive means to evaluate potential hazards over larger areas.

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[3] Costs may vary widely depending on available geologic information. For example, where bedrock geology has been adequately mapped and needs for new mapping are for surficial mapping only, costs per quadrangle may be reduced to 1/4 or 1/5 of that cited for both together. However, if bedrock structure is complex and not mapped adequately for identification of bedrock controls on landslide susceptibility, costs and schedule may be several multiples of those cited.

Table B-1.--Information, materials, availability and costs* for landslide-hazard mapping and risk evaluation

Information or material needed	Uses	Availability	Cost
Climatic data................	Data from specific events and annual and long-term climate are needed for assessments of influence for case histories and probabilistic predictions.	Data are generally available for metropolitan areas, but may be lacking in remote areas. For offshore areas, data may be adequate to estimate ocean-wave heights for tropical storms and hurricanes.	Costs to acquire available data from National Weather Service or other sources are generally small; however, reformatting for digital manipulation may be expensive. USGS researchers are currently working with these data to develop appropriate software.
Subsurface water.............	Build-up of pore-water pressures in subsurface materials is a major cause of landsliding. Knowledge of the distribution of and changes in subsurface water levels is needed for predicting the initiation of specific landslides, and, coupled with climatic information, for predicting the probability of failure.	Records are available for a few areas as case histories. Data are not available for most hillside areas in which landslides are most prevalent. Research may be required to measure and model the fluctuations in water table in key areas to identify episodic changes in landslide susceptibility.	Cost for experimental monitoring instrumentation estimated at approximately $25,000 per array to cover hillside areas ranging from about 1/4 mi^2 to 10 mi^2 in carefully selected areas.
Seismic data.................	To prepare maps of susceptibility to landsliding by earthquakes. (See, for example, Keefer and others, 1979.)	Because large earthquakes are widely scattered in time and place, the accuracy of earthquake-induced landslide mapping has not been tested. Data from previous earthquakes are sufficient to prepare experimental maps. Development of these data is part of a current USGS research project.	Probabilistic maps of expected seismic shaking are available for the cost of reproduction from the USGS at a scale of 1:500,000, prepared from digital data.
Vegetation maps	Vegetation tends to support hillslopes by means of root strength and removal of subsurface water. The role of vegetation in stabilizing slopes has been studied in only a few areas with mixed results. A clear association exists between burning of vegetation, debris floods, and some debris flows in California.	As special-purpose maps similar to slope maps, they are generally unavailable for high-priority areas. Probably they can be produced from aerial photographs in most areas.	Cost undetermined
Weathering and weathering .... products.	Processes of weathering commonly result in loss of strength. Information on thickness and kinds of weathered-rock products can be used to estimate hillslope strength and landslide susceptibility.	Not generally available.	Cost undetermined

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Table B-1.--Information, materials, availability and costs* for landslide-hazard mapping and risk evaluation

Information or material needed	Uses	Availability	Cost
Marine geophysical surveys .... and sampling.	Geophysical surveys of the ocean floor serve the same function as aerial photography of terrestrial areas. They also provide information on structural features beneath the ocean floor.	Have been obtained for landslide studies in only a few areas. Can be purchased from contractors. Much of the needed information consists of proprietary data of energy companies.	Cost undetermined
Land-use maps and socio- ..... economic data, including losses from landslides	Used to learn present and planned development for assessment of risk. Evaluating the benefits of mitigation requires information on present and expected value of property. Property-assessment data, digitized by census tract and block, have been used in research on benefit/cost studies in the Cincinnati, Ohio, area	Present (1974-1983) land use has been mapped for large parts of the United States at 1:250,000 scale. Larger scale mapping is available from State and local agencies. Socioeconomic data collected by U.S. Department of Commerce. Data on losses difficult to acquire.	Available for some areas at cost for duplicating tapes. Software for some computer uses has been developed and is available.
Chronology data	Used to determine past intensities of landsliding for comparison to climatic and human activity data. Involves use of historical records as well as various dating techniques.	Some data have been collected by the USGS National Climate Program. Other needed data should be collected in conjunction with studies in specific areas.	Cost undetermined, generally expensive at the present time. Need for research to establish more reliable, less expensive techniques.
Computerization	Data are collected, stored, and manipulated to check for sensitivity of different map parameters and to superimpose large data sets in different ways. (See, for example, Newman and others, 1978.)	Technology is well developed and can perform functions at the level needed. Large-volume use will require development of improved software.	Where programs have been developed, costs are greatly reduced and capability for merging large sets of data is enhanced.

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these limitations suggests that the usefulness of slopes derived from this digital data set should be limited to areas that are readily defined on maps having scales of 1:250,000 or smaller. Experience with the 1:250,000-scale topographic maps, however, indicates that even though some areas of short, steep slopes would not be identified, virtually all of the communities having known potential for hazards from mud flows, as well as many other kinds of landslides, will be identified.

Landslide inventories, by mapping evidence of past landsliding, provide guides to the expected severity of landslide hazards in an area. Landslide inventories may be simple inventories, made by reconnaissance methods, or they may be detailed and complex. Reconnaissance maps that show areas that appear to have failed by landslide processes commonly are prepared by interpreting aerial photographs, with a minimum of field checking. An experienced interpreter can complete a simple landslide inventory of a standard U.S. Geological Survey 7-1/2 minute topographic quadrangle (about 150 km^2) in about 7 days.

Intermediate levels of landslide inventory maps show landslide deposits and areas that appear to have failed by landslide processes. In addition, the maps distinguish active from old landslides (see, for example, U.S. Geological Survey, 1982, fig. 12), and classify them as to whether the slides are single or multiple, one type, or a combination of types. They also show and classify slope failures in manmade features such as cuts, fills, and refuse deposits. Like reconnaissance landslide inventory maps, they can be prepared by the interpretation of aerial photographs, but a limited field check of some landslides and manmade features is generally required. The inclusion of the limited field observations and additional detail in the aerial-photograph interpretations requires about 50 percent more time than for a simple inventory.

A detailed inventory map depicts each landslide classified as to type, as well as delineating scarps, limits of the zone of accumulation, and other pertinent data on depth and kinds of materials involved in sliding. Active and inactive landslides are distinguished. The age of the landslide and the rate of landslide movement should be included. A detailed inventory should also include data on slope failures associated with man's alteration of the terrain, and the locations of excavations, trenches, and boreholes used in the study of landslides should be identified on the map. Few maps of this type have been made for areas of substantial size, in part because of the great time and expense needed to obtain the information. More commonly, investigations of this detail are done for areas no larger than needed for planning a subdivision development. Some detailed information can be obtained from aerial photographs; however, much of the data must be obtained in the field by closely spaced traverses. The cost of a detailed inventory is perhaps 10 times as great as that of a simple inventory.

It should be noted that past geologic mapping practice has been to include many debris deposits in stream canyons and on fans with "alluvium" map units. In addition, most landslide inventory maps made prior to 1975 do not delineate the distribution of debris-flow deposits, not because they are more difficult to recognize than other kinds of landslide deposits, but because their landslide origins had not been widely recognized.

Terrain analysis techniques are used to recognize and classify the distinctive landform textures formed as the aggregate product of various geomorphic processes, including landsliding, on the earth materials of an area. These techniques can be used to interpret the slope stability of the natural landscape by identifying appropriate terrain units, which can then be recognized and delineated on small-scale (high-altitude) aerial photographs. Slope processes in individual terrain units are determined by field mapping in small areas representative of each terrain unit at sufficient detail to characterize the landslide associations of that unit. The result is a map of terrain units, each of which has a topographic expression that represents a common set of active erosive processes; an explanation for each unit describes the kinds of landslides and their specific habitats. (U.S. Geological Survey, 1982, fig. 13.)

Slope-stability maps distinguish areas that have different potentials for landsliding. The maps predict where new landslides are likely to occur by a ranking of relative stability of slopes. A simple form of slope-stability map can be made in areas where only a single geologic unit produces landslides. In such situations, a map showing the distribution of that unit shows the area of potential landsliding as well. Other simple slope-stability maps can be made of large areas in a short time by determining from the literature and (or) experience which mappable geologic units are landslide prone, and then using a geologic map to delineate slope-stability units (U.S. Geological Survey, 1982, fig. 14). Addition of other attributes, such as slope inclination and aspect, can improve the assessment of relative stability within specific geologic units.

More reliable (and more complex) slope-stability maps are constructed by a variety of means. One method simply combines a landslide inventory with a geologic map. The combination shows which of the geologic units are most likely to fail by landsliding and where these units are located. If the landslide inventory is a map that distinguishes types of landslides, then complex slope-stability maps showing likelihood of different types of landslide can be constructed. Large areas, such as counties, States, and even countries can be mapped in a short time using reconnaissance inventories in areas where reliable geologic maps are available. The use of more detailed data permits the compilation of better and more reliable slope-stability maps. The reliability of slope-stability maps depends to a large extent on how well known are the factors that control the initiation of landslides in the map area, and how they are distributed over the map area.

Landslide-hazard (zoning) maps are probably the most sophisticated type of landslide map that can be obtained with existing technology. These maps contain detailed information on the probable type of landslide, the extent of slope subject to failure, the probable maximum extent of ground movement, and the probable frequency of slope failure. Important in the classification of landslide type are data on velocity and mass of moving material. With this information, the risk can be estimated of varying degrees of injury to people and animals and damage to structures and real property that the landslide processes are capable of inflicting. Few such maps have been produced, and procurement of data, especially in regard to probability, requires extensive studies.

Risk maps show the potential impact of landslide hazards on people or structures. Thus, evaluation of risk requires a knowledge of the structures or lives that can be affected by a given hazard, in combination with knowledge of the hazard itself. Techniques for preparing risk maps have not been significantly developed in the United States. However, such maps can be prepared if the necessary demographic and property-value data can be compiled and made available.

Options and Costs for Nationwide Identification and Delineation of Susceptibility to Mud Flows and Other Landslides

Any program for the nationwide delineation of mud-flow and other landslide hazards should be designed in a context of technical, economic, and socio-political considerations. Clearly, the cost of mapping will vary widely depending on scale and detail, and only the user can judge the appropriate balance between cost and technical accuracy. Because of past confusion regarding regulatory inclusion or exclusion of various kinds of landslides within the scope of the NFIP and disaster-assistance programs, FEMA has not yet defined its needs for landslide mapping in a way that can be used to determine appropriate standards of detail, accuracy, comprehensiveness, and reliability. Therefore, to provide some preliminary estimates for the range of costs to be expected, the following scenario describes a sequence of progressively more detailed studies. The scenario is not intended to provide a definitive program design nor a specific proposal, but simply to provide a general example of the kind of program that is technically feasible and of the range of costs that might be expected. Publication and distribution costs are not included in the estimates.

I. Comprehensive Nationwide Reconnaissance: To acquire a preliminary nationwide overview for the identification of communities that should be examined in greater detail before insurance rates or code requirements are established, prepare a State-by-State evaluation of landslide susceptibility at 1:500,000-scale using slope (as derived from existing digital elevation data) and any existing data on landslide occurrence and distribution. (Slope is selected as the primary factor for discrimination because of its importance in the initiation of debris flows/mud flows.) Note that the development of statewide digital elevation data bases would also make possible the addition of other digital data such as population and property value by census tract, rainfall distribution, expected earthquake shaking, etc., at minimum cost and with optimum capability for updating and production of individual components or of various combinations.

Capability: The USGS Branch of Astrogeology in Flagstaff, Arizona, has demonstrated a capability for merging and manipulating the existing Defense Mapping Agency (DMA) digital elevation data from the $1^{\circ} \times 1^{\circ}$

blocks that cover the conterminous United States. The available data and capability are suitable for the production of State maps showing appropriate slope zones at 1:500,000 scale.

Schedule: Existing personnel and facilities could produce 1:500,000-scale maps showing slope categories for major slope-dominated landslide processes, for each of the 48 conterminous States in about three years.

Cost: Approximately $330,000 per year (1983 dollars) would be required over the 3-year period, for a total of approximately $1 million.

II. Community Susceptibility: For the communities identified in I., Comprehensive Nationwide Reconnaissance, as subject to hazard from mud-flow and other landslide hazards, prepare more detailed maps at 1:24,000 scale. A sequence of maps of increasing comprehensiveness and detail can be prepared at this scale, with incremental increases in cost, providing options from which a selection can be made as the most vulnerable parts of communities become better delineated. The use of digital format for the incremental input of new information would enhance the capability for analytical synthesis, updating, and preparation of revised landslide susceptibility maps.

A. Prepare preliminary susceptibility maps at 1:24,000-scale based on slope and existing geologic map information. Slope data should be derived from topographic sources at 1:24,000-scale or larger. Where available, digital elevation data at 1:24,000-scale detail should be used. Where digital data of that quality are unavailable, they should be acquired or provision made for updating the susceptibility maps as new data become available. In many communities, it may be possible to acquire new digital elevation models (DEMs) through the cost-sharing program of the USGS National Mapping Division (NMD).

Capability: USGS NMD is acquiring digital elevation data at this scale systematically as a part of ongoing topographic mapping programs. NMD researchers have demonstrated capability to process the digital data to produce slope information for the Cincinnati, Ohio, area. USGS Offices of Earthquakes, Volcanoes, and Engineering (OEVE) and Regional Geology (ORG) include personnel experienced in the acquisition and evaluation of existing geologic map information for the development of landslide-susceptibility maps. In addition, appropriate expertise also exists in some State geological surveys and local agencies, as well as in some university geology departments and consultants in the private sector.

Schedule: At the present rate of 2,000 7-1/2 min. quadrangles per year, more than 20 years will be required to provide complete DEM coverage for the entire conterminous United States However, areas of key communities could be completed much sooner if interagency agreements on priorities can be reached, so that critical areas identified in the Nationwide Reconnaissance (I) are given high priority.

Cost: The cost of preparing detailed slope data from the DEM for one 7-1/2 min quadrangle is expected to range from $350 to $2,100, depending on the availability of the digital elevation data (exclusive of publication and distribution). Communities range in area from less than one quadrangle to the equivalent of a few hundred quadrangles. For example, Hamilton County, Ohio (Cincinnati), is contained within 17 quadrangles, for several of which digital elevation data are available; therefore, the cost for coverage of that community would range from about $5,500 to about $20,000, and could be prepared in one to two years. On the other hand, the southern California urban area that stretches from Santa Barbara to San Diego, includes more than 500 quadrangles, most of which have not yet been digitized; therefore, the cost of acquiring new DEMs and processing them for slope coverage of the area could be as much as $600,000 to $1 million.

B. Prepare improved community susceptibility maps by adding data on past landslide activity to the information base of option II. A. Where not previously available, landslide inventories should be prepared. These inventories identify areas where geologic conditions and triggering events have combined to produce landslides in the past. The inventories provide guides to the expected severity of future landslide hazards, identify areas where strength of surficial and bedrock materials is more important than slope in the assessment of landslide potential, and identify where interactitons of slope and geologic discontinuities enhance landslide susceptibility. Unfortunately, most landslide inventories made prior to 1975 do not include debris-flow deposits or other evidence of past mud flows. However, debris fans and other features that indicate a past history of mud-flow activity are commonly recognizable on aerial photographs at 1:24,000-scale, and including these features in reconnaissance inventories made by photointerpretation is expected to add only a small fraction to the time (and cost) of preparation.

Capability: Several Branches in the U. S. Geological Survey, particularly in OEVE and ORG, include personnel experienced at the recognition and delineation of landslides. In addition, many State geological surveys, university geology departments, and private-sector consultants could contribute to the necessary expertise.

Nationwide standards for nomenclature and recognition criteria should be established by some nationally-recognized scientific organization, and monitored by appropriate means, to keep confusion to a minimum.

Schedule: The rate of inventory mapping depends on the size of the community being inventoried, the number and expertise of the individuals doing the work, and the difficulty of the interpretations required. Completion of a reconnaissance inventory for a community of about 1,000 mi^2 each (roughly equivalent to 20 7-1/2 min quads) would probably take a year. The range in time required for preparing inventories is large, and the rate of mapping could be less than 10 quadrangles per year in difficult terrain.

Cost: As indicated in Table B-1, the cost for new reconnaissance-level inventories, where none existed previously, can be expected to be in the range of $40,000 to $70,000 for each 1,000 mi^2. The upper limit, however, may be greater, for particularly difficult terrain. Costs for intermediate and detailed inventories can be expected to be as much as ten times the costs for reconnaissance surveys.

C. Prepare improved community susceptibility maps by adding data on bedrock and surficial geology to the information base of II. B., with emphasis on engineering aspects of the earth materials, geologic structures and discontinuities. The kinds of examinations that are required to make a good 1:24,000-scale engineering-geologic map yield information on the causes and mechanisms of landslides that can be used to predict the severity, density, and frequency of landsliding. The basic geologic data are important to the development of terrain characterizations of dominant landslide processes that can be used to extrapolate susceptibility evaluations to large regions.

Because comprehensive geologic mapping is the most expensive and time-consuming of the procedures in this scenario, the areas where it is undertaken should be carefully chosen. For example, small areas representative of much larger areas, should be mapped so that general conclusions can be extrapolated by less expensive methods. It may be generally satisfactory to cover only 1/10 th of a region (or a community) with comprehensive geologic mapping, and considerably smaller fractions may be appropriate for many areas.

Capability: USGS-OEVE and USGS-ORG have demonstrated comprehensive expertise and support capabilities of the sort that are needed to evaluate the geology of an area in this level of detail. Some State geological surveys and some university geology departments include personnel with appropriate expertise. Landslide-prone areas with extreme stratigraphic variations and complex geologic structure require more expertise for the interpretation of field evidence than do areas with relatively few stratigraphic units and broad open structure. Many good geologic maps exist, some in key regions, and more are being prepared under ongoing mapping programs. New geologic mapping should be undertaken only after careful evaluation of existing maps.

Schedule: As indicated in Table B-1, new geologic maps in urban or suburban areas commonly require from 1 to 2-1/2 years to complete, exclusive of drafting and other preparation for publication. Where bedrock mapping is adequate, but there are needs for refinement of information on surficial, unconsolidated deposits, the time for completion may be significantly reduced. However, where physical exploration and sampling for laboratory analysis are intrinsic parts of the investigation, additional time will be required.

Cost: Costs for comprehensive geologic mapping range widely depending on available geologic information from prior surveys, the complexity of the bedrock and surficial geology, the accessibility of key parts of the area, and the needs for exploration, sampling and laboratory analyses. New geologic quadrangle maps in urban and suburban areas commonly range from about $65,000 to more than $200,000 to complete, exclusive of printing and distribution. (For comparison, using these unit costs, complete coverage of the conterminous U. S. would take several tens of years and cost about $8.1 billion.)

The foregoing scenario describes discrete steps in a sequence. However, a practical approach could provide for overlapping parts of the several steps, in a sustained effort over a period of 10 to 15 years. The comprehensive design of such a program is beyond the scope of the present study; however, the present data indicate the feasibility of designing a program that would meet FEMA's minimum requirements in six major metropolitan areas within a period of about 15 years at a sustained level of approximately $1.5 million per year, exclusive of publication and distribution costs. The schedule probably could be accelerated to completion in approximately 10 years at a sustained rate of about $2.5 million to $3.0 million per year.

An aggregate of approximate unit costs suggests that, for community unit areas of about 1,000 mi^2, the cost for minimum (option II. A.) landslide-susceptibility identification and delineation could be expected to range from about $125,000 to about $350,000, and to require from 1-1/2 to 4 years for completion. Consequently, a program sustained at a level of $1.5 million per year for 15 years could be expected to complete State-by-State overviews at 1:500,000-scale for each State (option I.), and complete 1:24,000-scale (option II. A.) studies of approximately 90 "community units". (Together, six major metropolitan areas of the United States -- Boston-Washington, southern California, San Francisco Bay area, Puget Sound area, Salt Lake City-Ogden-Provo, and Denver-Boulder -- include 80 to 90 community units of 1,000 mi^2 each. The land area of the conterminous United States includes a total of about 3,000 units of the same size.)

At optimum utilization of existing facilities and earth science expertise, which would be achieved with a funding rate of about $7 million to $10 million per year, approximately 25 to 40 community units should be completed each year, following a start-up period of 2-1/2 to 3 years. A maximum utilization of facilities and earth sciences expertise would be reached at an approximate funding rate of $20 million per year; a level of effort which would be expected to complete the entire area of the conterminous United States within about 35 years. Higher funding rates might shorten the schedule for completion, but costs would probably rise as a result of competition with mineral- and energy-resources programs and from other natural hazards programs for competently trained personnel.

The experience of the USGS Ground Failure Hazards Research Program indicates that many State geological surveys would participate in landslide-susceptibility identification on a cost-shared basis. Provided that a means of satisfactory coordination can be developed, the USGS and other Federal, State, and local agencies having research or regulatory concerns regarding landslides and other ground failures, could make significant contributions toward the acquisition of the information and materials that address FEMA's concerns for insurance, disaster response, and planning for mitigation. Cooperative efforts could significantly reduce the direct cost to FEMA for the acquisition of mud-flow and other landslide susceptibility information.

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