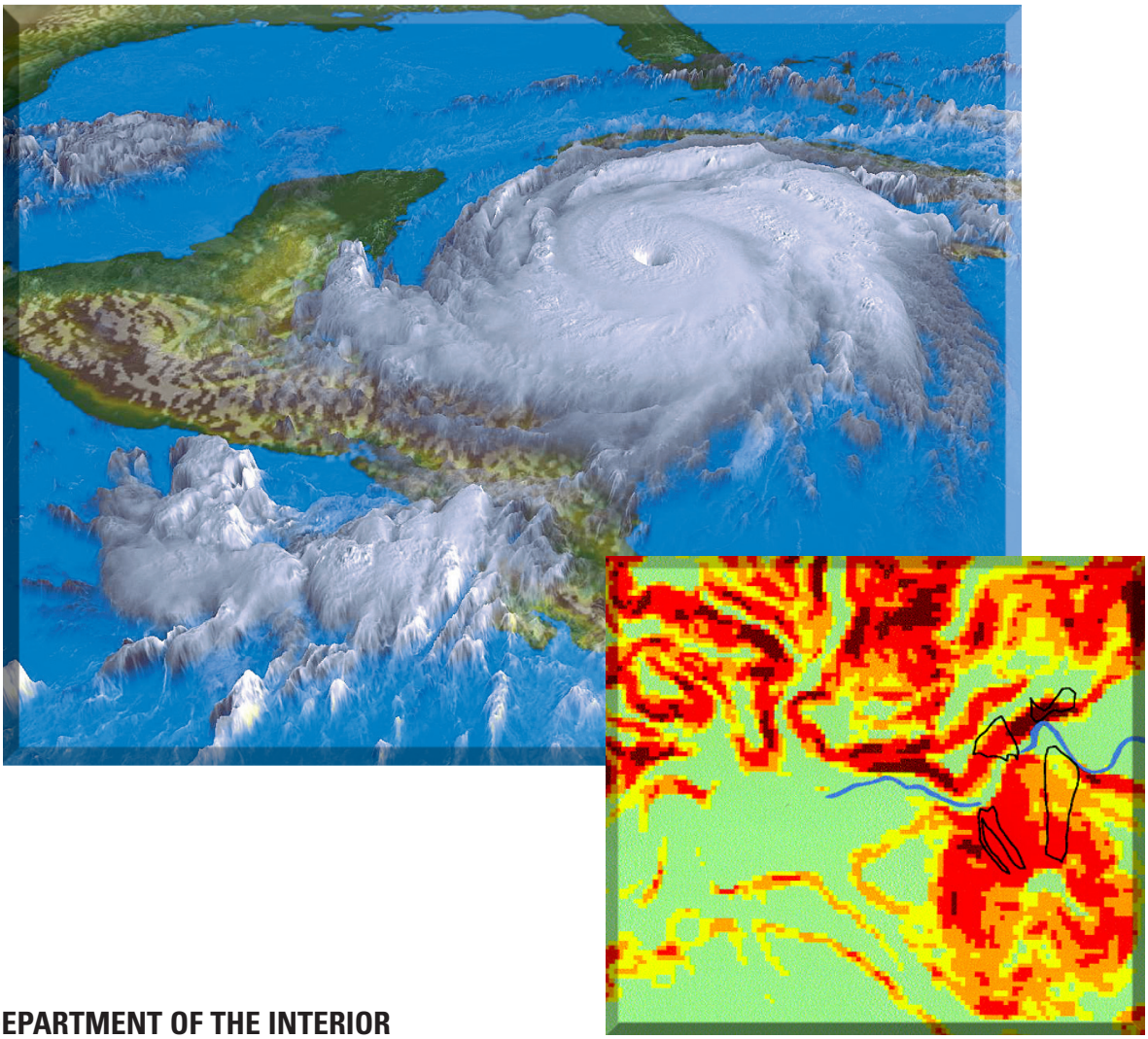
Landslide Hazard Map of Tegucigalpa, Honduras

By *Edwin L. Harp, Matthew D. Held, Mario R. Castañeda, Jonathan P. McKenna, and Randall W. Jibson*

Open-File Report 02-219



U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Landslide Hazard Map of Tegucigalpa, Honduras

By *Edwin L. Harp[1], Matthew D. Held[1], Mario R. Castañeda[2], Jonathan P. McKenna[1], and Randall W. Jibson[1]*

Open-File Report 02-219

(English version; Spanish version is also available)

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

[1]USGS, Denver, Colorado
[2]Universidad Tecnologica Centroamericana (UNITEC), Honduras

Contents

Page

Introduction 1
Method of Analysis 1
    Slope Map 2
    Geologic Map 3
    Strength of Slope Materials 3
Factor-of-Safety Map 6
Hazard Categories 7
Summary 8
Acknowledgments 8
References 9

Illustrations

Figure

1 Slope map generated from the TIN of the central part of Tegucigalpa
2 Geologic units in the central part of Tegucigalpa
3 Shear-strength values for the area shown in figure 2
4 Histogram of probability (percent of landslide cells in a factor-of-safety range) versus factor of safety for landslides triggered by Hurricane Mitch in Tegucigalpa

Plates 1 and 2 [in pocket]

Cover Photo: Hurricane Mitch approaching Central America on 26 October 1998, 13:15 UTC (07:15 local time). The hurricane is over the northern half of Nicaragua at this time. The image is derived from satellite data that has been color-enhanced and processed to yield a perspective rendering of the hurricane. Modified from image produced by Hal Pierce, Laboratory for Atmospheres, NASA Goddard Space Flight Center.

Illustration: Section of Tegucigalpa landslide hazard map.

Landslide Hazard Map of Tegucigalpa, Honduras

By *Edwin L. Harp, Matthew D. Held, Mario R. Castañeda, Jonathan P. McKenna, and Randall W. Jibson*

Abstract: By comparing landslides triggered by Hurricane Mitch in the metropolitan area of Tegucigalpa, Honduras with the results of a regional GIS-based slope-stability analysis, we establish relative hazard categories for future landslide occurrence. The stability analysis employed here is the infinite-slope analysis, which uses a slope map derived from a 1:10,000-scale triangulated-irregular-network model with 10-m-cell centers, a geologic map recently modified by Japanese geologists of the Japan International Cooperation Agency (JICA), and estimated shear strengths for each of the geologic units. Fully saturated conditions were assumed for the slopes subjected to the intense rainfall during Hurricane Mitch. Slope stability in terms of factor of safety (FS) values were calculated for each cell of the map. Values near 1.0 indicate possible failure and correlate well with actual landslides triggered by the hurricane. A statistical analysis comparing the distribution of landslides with FS values allowed the grouping of FS values into landslide hazard categories.

INTRODUCTION

The intense, prolonged rainfall of October 29-31, 1998, from Hurricane Mitch triggered more than 200 landslides in and around Tegucigalpa, Honduras. Landslides triggered by Hurricane Mitch within the Tegucigalpa area are documented as a 1:10,000-scale landslide inventory map by Harp and others (2002). The landslide source areas on this map indicate the least stable slopes within the Tegucigalpa area during the rainfall conditions that existed during Hurricane Mitch. All but four landslides in this inventory were debris flows that mobilized from relatively shallow soil slides originating within colluvium or weathered bedrock. These four landslides are deep-seated slump/earth flows and debris slides and are described in Harp and others (2002).

The purpose of this report and accompanying maps is to quantitatively estimate the susceptibility and hazard of slopes within the metropolitan area of Tegucigalpa to future debris flows from an extreme event such as Hurricane Mitch. To do this, we use a Geographic Informations Systems (GIS) analysis based on a simple limit-equilibrium model of an infinite slope in materials having both frictional and cohesive strength.

METHOD OF ANALYSIS

The slope-stability model that we use for the initiation of debris flows is the infinite slope model. This model portrays the slope as a rigid friction block on an inclined plane. The ratio of the length of the block to its thickness is assumed to be infinite; thus, this analysis is appropriate for relatively thin slabs of soil such as those that form where debris flows initiate.

The limit-equilibrium equation for the static factor of safety (FS) of this infinite slope is the ratio of the resisting forces on the slope element to the driving forces:

$$FS = \frac{c'}{\gamma t \sin\alpha} + \frac{\tan\phi'}{\tan\alpha} - \frac{m\gamma_w \tan\phi'}{\gamma \tan\alpha}$$

Equation 1

where FS is the factor of safety, c' is the effective cohesion, ϕ' is the effective friction angle, α is the slope angle, γ is the material unit weight, γ_w is the unit weight of water, t is the slope-normal thickness of the slope element, and m is the proportion of the element thickness that is saturated. High values of factor of safety reflect stable slopes while low values reflect relatively unstable slopes; values less than 1.0 indicate statically unstable slopes. Using equation 1, we calculate the FS for each slope element (grid cell); ranges of FS are then colored to produce a susceptibility map.

For purposes of simplicity, the unit weight of the soils (γ) is estimated to be a constant 15.7 kN/m^3 (100 lbs/ft^3), and the slab thickness is estimated to be a constant 2.4 m, reflecting the average debris-flow thickness in the region. For conditions during Hurricane Mitch, we assume a fully saturated soil column (m=1). Evaluating this equation thus requires knowing or estimating the slope angle (α) and the shear-strength parameters, which include the effective cohesion (c') and the effective friction angle (ϕ'). Shear strengths are assigned to specific geologic units; therefore a geologic map of the area is also required.

Slope Map

A triangulated-irregular-network (TIN) model derived for the Tegucigalpa area permits calculation of the slope of the land surface. The TIN model used for our slope map is derived from a topographic map having a 2.5-m contour interval provided by the Japanese International Cooperative Agency (JICA). From this we constructed a TIN model to produce a slope map with 10-m-grid centers. Grid centers of 10 m were chosen as the optimal spacing given the scale of the topographic map from which it was derived. A slope map constructed from the TIN for this same area is shown in figure 1.

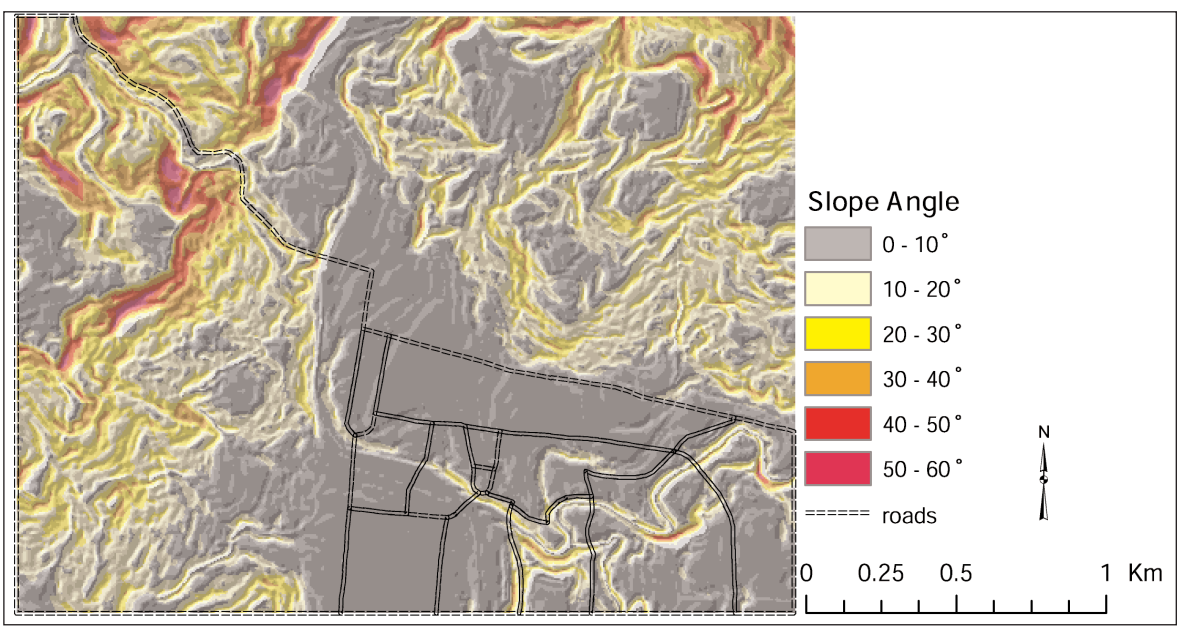


Figure 1. *Slope map generated from the TIN of the central part of Tegucigalpa.*

Geologic Map

The most recent geologic map of Tegucigalpa is that prepared by geologists of JICA (2001) at a scale of 1:10,000. This geologic map is a modification of part of a previous 1:50,000-scale geologic map of the Tegucigalpa 1:50,000-scale topographic quadrangle (Rodgers and O'Conner, 1990). The JICA map portrays the geology of the Tegucigalpa area in greater detail and subdivides some of the generalized units shown on the previous map. For the purposes of our analysis, we have used the digital files of the JICA geology in 10-m cells (figure 2).

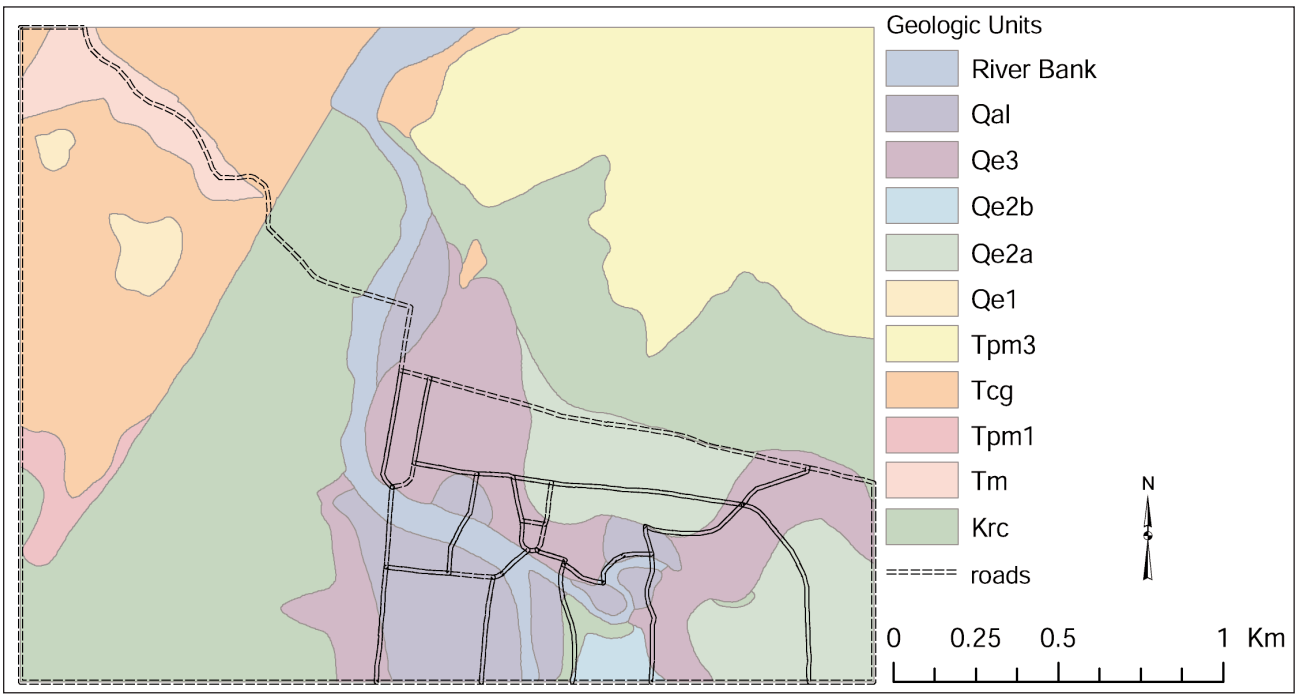


Figure 2. *Geologic units in the central part of Tegucigalpa.*

Strength of Slope Materials

The shear strength of slope materials is a combination of two parameters: effective cohesion (c') and effective angle of friction (ϕ'). We estimated representative values of shear-strength parameters for each geologic unit by examining these units in the field and comparing them with geologic units elsewhere for which ranges of shear strength are known. This was necessary because almost no geotechnical data exists for the geologic units of Honduras. A few actual shear-strength values of material from the Río Chiquito Formation and the Padre Miguel Group were available from samples taken by the U. S. Army Corps of Engineers for the analysis of the slope stability of the El Berrinche landslide in Tegucigalpa. The actual ranges of uncertainty for cohesion and friction angle are unknown. The ranges in these parameters that we have employed in our estimates result in as much as 15% difference in FS values for cohesion and as much as 20% difference in FS for friction angle. Figure 3 shows digital cohesion and friction-angle maps of the same area covered in figure 2. A list of the cohesion and angle of friction values are also listed in Table 1.

Table 1. Shear strengths of geologic units

[Conversion: 1 lb/ft^2 = 0.0479 kPa]

Geologic Unit	Description	c' (lbs/ft^2)	φ' (degrees)
Riverbank	Clay,silt, sand, cobbles.	350	34
Qal	Clay, silt, sand, cobbles, boulders.	350	34
Qe3	Terrace, sand and cobbles.	200	34
Qe2b	Terrace deposits, sand and cobbles.	300	34
Qe2a	Terrace deposits, silt, sand, and cobbles.	400	34
Qe1	Terrace sediment, sand, cobbles.	300	34
Qb	Basalt	1000	43
Qan2	Andesite	700	35
Qan1	Andesite and rhyolitic tuff, weathered.	300	25
Qdt	Debris-flow deposits	300	35
Tpm3	Padre Miguel Group, ignimbrite sequence, upper member, rhyolitic tuff.	400	30
Tep	Padre Miguel Group, tuffaceous sediments, conglomerate, sandstone, and siltstone.	500	20
Tcg	Padre Miguel Group, Cerro Grande member, weathered rhyolite and ignimbrite.	300	25
Tpm2	Padre Miguel Group, ignimbrite sequence, middle member. rhyolitic tuff.	300	20
Tpm1	Padre Miguel Group, ignimbrite sequence, lower member, rhyolitic tuff.	500	25
Tpml	Padre Miguel Group, lahar sequence, debris-flow deposits.	400	25
Ti	Intrusive rhyolite.	700	35
Tm	Matagalpa Formation, weathered tuff, tuff breccia, and andesitic flows.	600	23
Krc	Río Chiquito Formation, mudstone, siltstone, sandstone, and conglomerate.	300	20
Kvn	Villa Nueva Formation, conglomerate, sandstone, and volcanic tuff.	300	38

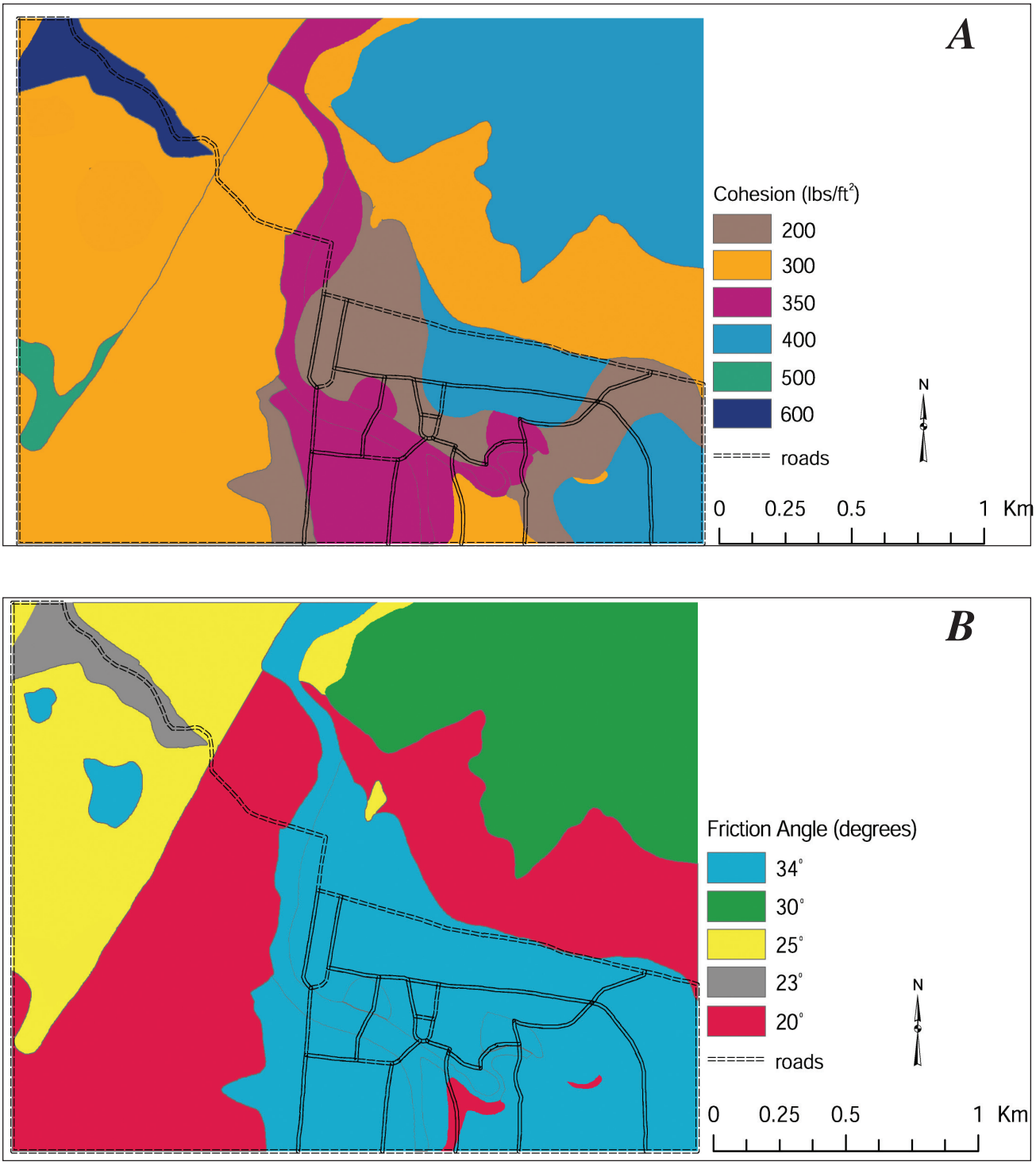


Figure 3. *Shear-strength values for the area shown in figure 2. (**A**) Cohesion. (**B**) Friction angle. See Table 1 for a list of cohesion and shear-strength values.*

FACTOR-OF-SAFETY MAP

Using equation 1, the factor of safety is calculated for each 10-m-grid cell using the shear-strength values appropriate for each geologic unit and the slope from the TIN model. The resulting map is shown on Plate 1. The various categories of factor of safety are portrayed as different colors ranging from dark red for the lowest values or least stable slopes to light green for the highest values or most stable slopes.

To evaluate the accuracy of the map in portraying the relative stability of slopes, we have also plotted the landslide inventory from Hurricane Mitch for comparison. Most of the landslide locations correspond to the lowest factors of safety. We have plotted a histogram showing, for each factor-of-safety range, the percentage of cells in that range that are in landslide source areas (figure 4).

The proportion of cells within landslide source areas shown in figure 4 decreases with increasing factor of safety. This distribution shows good agreement with the susceptibility analysis because most of the cells within landslides are located within the lowest factors of safety. Ideally, all of the landslide source areas should be located in areas having factors of safety less than 1.0; however, analyses of this type are regional approximations and contain generalized estimates of both slope values and material-strength properties such that the clustering of cells within landslide source areas within the lower factor-of-safety values shown in figure 4 is a good validation of the analysis results.

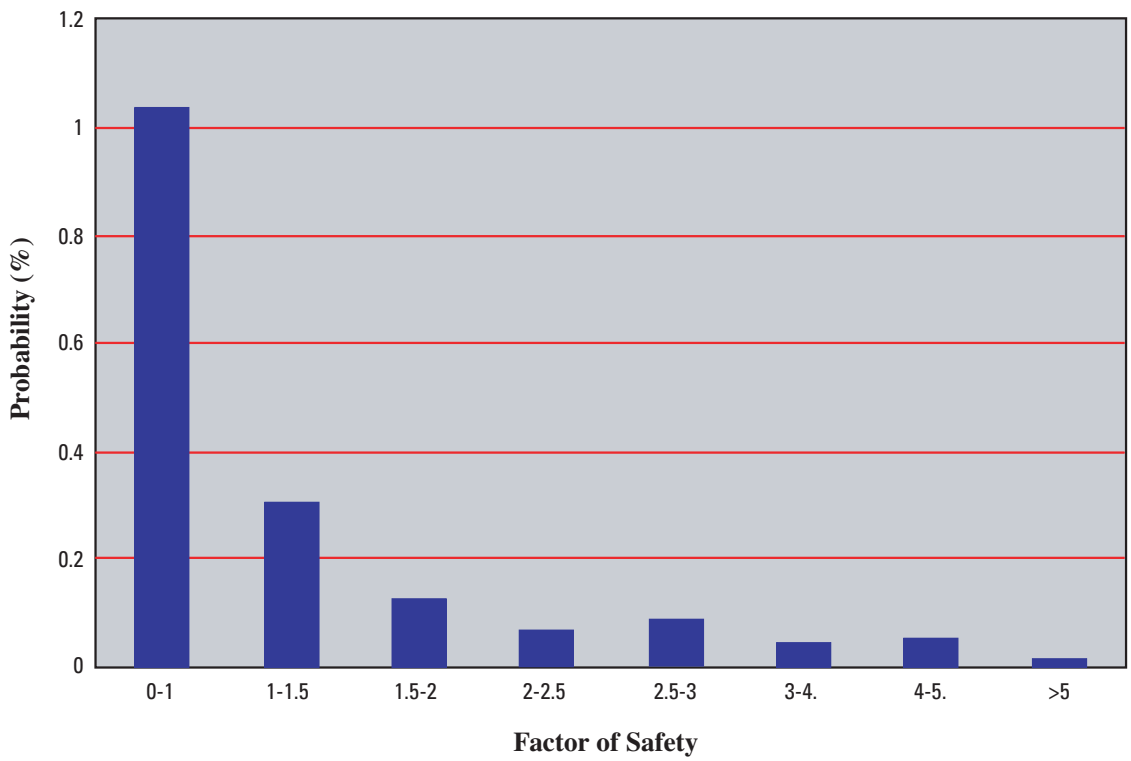


Figure 4. *Histogram of probability (percent of landslide cells in a factor-of-safety range) versus factor of safety for landslides triggered by Hurricane Mitch in Tegucigalpa.*

HAZARD CATEGORIES

To provide a tool for future land-use planning and emergency preparedness, the factor-of-safety (susceptibility map) has been modified to highlight the hazard levels within five different ranges of factor of safety. The basis for this modification is the observed landslide distribution within each of these factor-of-safety ranges (see figure 4). In accordance with this distribution, factor-of-safety values of less than 1.0 are categorized as "very high", 1.0-1.5 as " high", 1.5-2.0 as "moderately high", 2.0-3.0 as "moderate", and >3.0 as "low". The corresponding probabilities for each of the categories are: "very high"-1.03%, "high'-0.31%, "moderately high"-0.13%, "moderate"-0.07%, and "low"-0.03% (see Table 2). These probability estimates are calculated by dividing the number of map cells within landslide-source areas in a given factor-of-safety range corresponding to a landslide hazard category by the total number of map cells within that factor-of-safety range. For example, there are 383 map cells within landslide-source areas in the factor-of-safety range of 0.0-1.0 corresponding to the category "very high". There are 37,067 total cells within this factor-of-safety range. Dividing 383 by 37,067 yields approximately 1.03% or the probability that a given map cell within this hazard category will experience a landslide under saturated slope conditions produced by a rainfall event similar to that created by Hurricane Mitch. The landslide-hazard categories are depicted on Plate 2 as the landslide-hazard map of Tegucigalpa.

It should be noted that the hazard categories displayed on Plate 2 refer to source areas only. As debris flows are triggered, they commonly travel into map areas depicted as having lower hazard. Although models of debris-flow runout exist, it is difficult to accurately predict average runout distances for a given storm event or suite of geologic materials. A more accurate sense of the range of runout distances and the hazard due to debris-flow movement is obtained by inspection of the debris-flow outlines, which are plotted on Plate 2.

The utility of having these landslide-hazard categories is to forecast what is likely to happen in future climatic events that trigger landslides (debris flows) in the Tegucigalpa area. The probabilities listed above and depicted on Plate 2 are valid for extreme events similar to Hurricane Mitch, for which an assumption of fully saturated soil conditions is reasonable. For less extreme rainfall events, fewer landslides will likely be triggered than the numbers produced by Hurricane Mitch. However, the distribution of triggered landslides for any storm scenario (notwithstanding possible local rainfall variability) is likely to be similar and therefore conform to the hazard categories estimated using the Hurricane Mitch inventory.

Table 2. Hazard categories for landslides in the Tegucigalpa area

Hazard Category	Factor of Safety	Landslide Probability (%)
Very High	0-1.0	1.03
High	1.0-1.5	0.31
Moderately High	1.5-2.0	0.13
Moderate	2.0-3.0	0.07
Low	> 3.0	0.03

SUMMARY

Using a slope map prepared from 1:10,000-scale topographic data supplied by the Japan International Cooperative Agency (JICA) and shear-strength values estimated for the geologic units on a recent 1:10,000-scale geologic map produced by JICA, we have conducted a GIS-based susceptibility analysis that estimates the factor of safety of each 10-m cell based on an infinite-slope model (Plate 1). Then, using the inventory of landslides triggered by Hurricane Mitch in Tegucigalpa of Harp and others (2002), a hazard map was constructed (Plate 2) by comparing the number of landslide source areas with the factor-of-safety values.

The hazard map constructed for debris flows in the Tegucigalpa area has five categories: very high, high, moderately high, moderate, and low to describe the relative hazard within the respective areas from future rainfall events. The categories could easily be redefined to include more or fewer categories of hazard as desired. Hazard maps depicting 3 to 5 levels of hazard are commonly used throughout the United States and Europe for many different types of natural hazards. We anticipate that this map will be useful as a land-use planning tool and for emergency response within the city of Tegucigalpa for making future decisions. We realize that there are few areas within the urban area that are available for massive relocations of people or for great changes in land use in short time periods. However, with the use of the map, long-term targets can be set to achieve a safer and more reasonable distribution of people and property as growth continues.

Acknowledgments

The authors would like to acknowledge the assistance of the U.S. Agency for International Development (USAID) and several key individuals whose efforts made the fieldwork, data gathering, and this final report possible. These individuals include: Jeff Phillips of the USGS on temporary duty to USAID as a liaison officer to track all of the USGS effort in Honduras; Adrian Oviedo of USAID who arranged meetings, contacts, and travel for our fieldwork and seminars; and Sherry Thorn, professor of Biology at the University of Honduras who provided translation service, detailed knowledge of all field areas visited in Honduras as well as access to local individuals with eyewitness knowledge of the Hurricane Mitch event, and knowledge of the local customs and practices that proved invaluable for our safety and effectiveness in performing field studies.

We greatly appreciate the graphics and layout design by Eleanor M. Omdahl.

REFERENCES

Harp, E.L., Castañeda, M.R., and Held, M.D., 2002, Landslides triggered by Hurricane Mitch in Tegucigalpa, Honduras: U.S. Geological Survey Open-File Report 02-33, 11 p., 1 plate.

Rodgers, R.D., and O'Conner, E A., 1990, Geologic map of the Tegucigalpa quadrangle, Honduras: Instituto Geográfico Nacional Geologic Quadrangle Map, scale 1:50,000.

Japanese International Cooperative Agency, 2001, The study on flood control and landslide prevention in the Tegucigalpa metropolitan area of the Republic of Honduras: Japan International Cooperation Agency (JICA) Interim Report, 148 p.