Applying a GIS slope-stability model to site-specific landslide prevention in Honduras

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ABSTRACT: Conventional output of an environmental landslide model is some form of a distributed hazard index. Viability of these models has proven to be strong in tested environments, and this has encouraged modelers to apply landslide hazard models to tropical regions that generally lack advanced information systems. For steep-land farmers in the tropics, however, information on relative landslide hazard is useful but not sufficient, as knowledge of primary causes of instability is needed to develop management practices for sustained use of landslide-prone lands. Stability Index Mapping (SINMAP) is a physical slope-stability model in which relative hazard predictions are primarily governed by local slope gradient (α) and relative wetness (W). This model was applied to an agricultural region of Honduras that suffered extensive landslide damage during Hurricane Mitch, and its stability predictions were empirically evaluated. Zones of predicted instability were subsequently categorized according to α, derived from the Digital Elevation Model, and W, based on steady-state hydrology for hurricane conditions. W and α varied in a soil-specific and site-specific manner, indicating that site-specific management strategies are required for slope stabilization in the study area. Knowledge of $\alpha * W$ in potentially unstable zones allows for informed stability management practices, improving the utility of the hazard model for communities that contend with landslide risk.

Keywords: Central America, Hurricane Mitch, slope failure, spatial modeling

Steep lands (slope > 30%) comprise 34% of all land area in the tropics. These lands are susceptible to degradation by soil erosion caused by gradient, rainfall erosivity, and—in humid regions of the tropics—intense soil weathering (Lal, 1999). When natural vegetation on humid steep lands is cleared for timber harvest or for agriculture, this inherent susceptibility translates into excess soil loss and increased incidence of mass soil movement, including debris slides, mudflows, and landslides. Mass soil movement is frequently the dominant denudational process in steep

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humid areas (Iida, 1999; Nagle et al., 1999; Pla, 1997), causing catastrophic damage to lives and property (Chung et al., 1995) and contributing to progressive problems of river degradation, siltation of reservoirs, and contamination of drinking water (Cruz and Reyes, 2000; Nagle et al., 1999; Pla, 1997).

The economic cost of these problems is greatest in developed countries, but 95% of all landslide-related deaths occur in the developing world (Hansen, 1984). Even within developing nations, the human impact is unevenly distributed, as the economically or socially marginalized are forced to occupy the most hazardous slopes in rural and urban areas (Alexander, 1995). Population growth and degradation of traditional agricultural lands have intensified pressure on these fragile areas, increasing total human vulnerability to slope failure (Sheng, 1989).

Hurricane Mitch (October 1998) provided devastating evidence of human vulnerability to hillside instability. The hurricane was the largest storm to strike the Atlantic Basin in more than 10 years (Hellin and Haigh, 1999) and the deadliest in more than 200 years (McCown et al., 1998). About 11,000 people in Central America and the Caribbean lost their lives, thousands more were left homeless, and the lasting geomorphic effects of the storm have increased susceptibility to floods and landslides throughout the region (IADB, 1999).

Landslide management. Catastrophic landslides leave farmers and land managers of Central America with a considerable challenge: to manage against slope failure—and associated mudflows and inundation—at a time when pressure on fragile steep lands is at its greatest. Local and international agencies have worked on this problem in the years since Mitch, exerting considerable effort to identify management strategies that will limit surface erosion and prevent mass soil movement (e.g. World Neighbors, 2000; Cruz and Reyes, 2000). Reforestation and improved road drainage, both established slope-stabilization strategies (e.g. Bergin et al., 1995; Sidle et al., 1985; Royster, 1979), have received important attention (Cruz and Reyes, 2000; IADB, 1999), but there is still a need to identify agricultural practices that reduce vulnerability to slope failure. Given the rapid demographic expansion found in much of the Mitch-affected region, it simply won't be possible to set aside all vulnerable slopes for protection; therefore, methods for sustainable production on steep lands are required (Lal, 1994; El-Ashry, 1988).

A soil conservation survey conducted in Honduras, Nicaragua, and Guatemala in the wake of Hurricane Mitch failed to find any beneficial effect of "agroecological" farming on landslide resistance during the storm (World Neighbors, 2000). Use of agroforestry, contour cropping, physical and vegetative erosion barriers, or integrated weed management was found to reduce soil degradation and surface erosion on farms affected by Mitch, but these techniques did not correlate with a reduction in landslides. While it is possible that soil conservation farming truly has no effect on slope stability, the experience of geotechnical engineers and landslide modelers indicates that land management targeted to soil or site-specific conditions can reduce the probability of slope failure (Montgomery et al., 2000; Collison et al., 1995; Royster, 1979).

Unfortunately, the biophysical complexities of the problem are nearly as great as the social and economic. Surface erosion of soil is influenced by slope form (length, shape, and topography), rainfall (intensity, duration, and frequency), soil properties (granulometry, structure, aggregate stability, and strength), hydrology (antecedent water content, hydraulic conductivity, and slope drainage), and vegetation characteristics (density, height, and management). Slope stability is influenced by the same factors and also depends on subsurface pore pressures, the distribution and strength of roots, localized weathering of surficial bedrock, and hillside geohydrology. The number of variables involved makes it difficult to characterize the influence of land management on landslide susceptibility and even more difficult to predict how changes in management will impact the current state (El-Swaify and Fownes, 1992). It is hardly surprising that efforts to conserve soil on tropical steep lands have often failed because of recommendation of inappropriate practices (Shaxson, 1988).

In recent years, the field of physical landslide modeling has made excellent progress in dealing with the complexities of slope failure. Applications of simplified slope-stability models have proved effective as descriptive and predictive tools in temperate zones, allowing for rapid stability assessment over a wide area (e.g. Miles et al., 2000; Pack et al., 1998; Wu and Sidle, 1995; Montgomery and Dietrich, 1994; Jibson, 1993). Few models have been developed expressly for stability analysis in the tropics, but applications of simplified slope-stability models have performed reasonably well (Divakarla and Macari, 1998; Terlien et al., 1995) despite the influence of localized weathering and subsurface flow on tropical slope stability (Simon et al., 1990). It is rare, however, for landslide prediction models to be fully utilized as prescriptive tools for land management. Most provide the end user with a spatially distributed stability index but offer no indication of the relative significance of modeled processes that drive the calculation. Knowledge of a stability index alone may be useful for planning timber harvests (e.g. Montgomery et al., 2000) or for citing infrastructure (e.g. Carrara et al., 1995), but it is not helpful for steep-land farmers for whom non-use and relocation are not viable options. If physical landslide models are to contribute to slope stabilization in tropical, agricultural watersheds, then a driving *cause* for instability must be identified, along with the *probability* that a slope will fail.

Importance of causal information is born out by physical slope-stability models that do consider the influence of dynamic hydrology and plant growth. These models are computationally intensive and, to our knowledge, have only been applied to engineered or "characteristic" slope formations (Pla, 1997; Duncan, 1996; Collison et al., 1995; Anderson et al., 1988). Nonetheless, results of these modeling exercises are relevant to field-level management. Collison et al. (1995) found that planting trees on an engineered embankment only enhances the embankment's stability if soil hydraulic conductivity is relatively high. For deep-soiled embankments with low hydraulic conductivity, planting trees was, in fact, detrimental to stability. Macropore flow along tree roots increased permeability, leading to elevated pore pressures in and below the rooting zone, while roots themselves did not penetrate deeply enough to anchor against deep-seated slope failure. Under such conditions, it is preferable to vegetate the embankment with grass, or some similar shallow-rooted ground cover, that sheds water off the saturated portion of the slope. Pla (1997), modeling a slope characteristic of the Western Andes of Venezuela, found that simple reforestation of a degraded pasture was not sufficient to prevent landslides—hydraulic conductivity was so low in the argillic horizon of Ultisols that drainage ditches were required to prevent saturation-induced translational failure. Both these studies indicate that tree planting is not the solution to slope instability in all cases. Water management can be more important than physical reinforcement for weathered and frequently saturated soils, and drainage ditches, or water-shedding ground cover, may offer better slope stabilization than trees. Information on the soils and hydrology of a landslide-prone area is therefore necessary for the development of appropriate management recommendations; simply reporting the probability of failure is not enough.

The objectives of this study were (1) to apply and evaluate a simplified slope-stability model to an area in Central Honduras that was severely affected by Hurricane Mitch, and (2) to develop landslide-susceptibility maps categorized according to local slope gradient (α) and relative wetness (W), the variables that most influence slope stability. Differentiation of susceptible zones into slope-wetness ($\alpha^* W$) classes is intended to assist land management at the farm and community level.

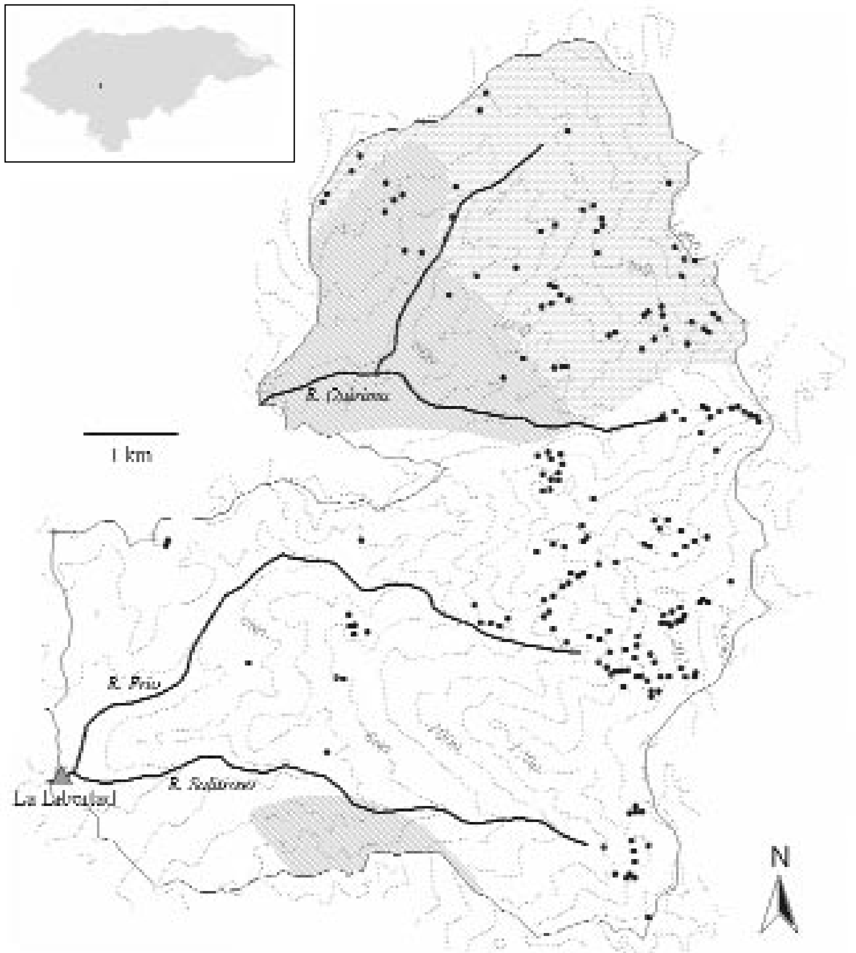

Figure 1

The study area comprises three contiguous watersheds: Upper Quirima (1), Rio Frio (2), and Rio Salitroso (3). Shading indicates the three geologic units: the Matagalpa Formation (dark), the Yojoa group (white) and the Valle de Angeles group (hatched). Points are locations of observed slope failure. The town of La Libertad, in the southwest corner of the study area, is located at 140 45' 24" N, 870 36' 42" W.

Methods and Materials

Study Area. The study area comprises three contiguous watersheds in the central highlands of Honduras (Figure 1), those of the Rio Salitroso, the Rio Frio, and the headwaters of the Rio Quirima. All three rivers drain into Embalse Francisco Morazán—the reservoir of the largest hydroelectric dam in the nation, which provides Honduras with the majority of its electricity (Mangurian, 1997). Rapid siltation of the dam's reservoir is a serious concern to the government of Honduras and to international funding agencies (COHDEFOR, 1998; IADB, 1999). The study area lies within the municipality of La Libertad, Districto Comayagua (N 14˚ 47', W 87˚ 35') and covers an area of 46.1 km^2 (120 mi^2). Land use in the project area is predominantly agricultural, with coffee cultivation (*Coffea arabica*, L.) dominating upland areas and lowlands divided between cattle pasture and the production of maize and beans (*Zea mays*, L., *Phaseolus vulgaris*, L., *Phaseolus lunatus*, L.). Most farms are between 1 and 2 ha (2.5 and 5 ac) in size and are cultivated by the landowners (COHDEFOR, 1998).

The central Honduran highlands are semi-humid tropical. They receive an average of 1,900 mm (74.8 in) of precipitation annually, concentrated in a moderate rainy season from May through July and a heavy rainy season from September through November. Terrain is steeply dissected and soils are residual, of volcanic and sedimentary origin. Hurricane Mitch inflicted severe damage to the study area, triggering significant debris flows, mudslides, surface erosion, lowland flooding, and the consequent destruction of homes and farms (Cruz and Reyes, 2000).

Data collection. Elevation contours were hand-digitized in ArcView GIS (ESRI Inc., Redlands, CA) from 1:50,000 topographic basemaps (NIMA, Fairfax, VA). Contours were used to interpolate a raster Digital Elevation Model (DEM) at the 5 m scale (after Zhang and Montgomery, 1994). Slope and flow path were derived from the DEM.

A total of 63 soil samples were collected from the surface and 0.75 m (2.5 ft) depth (B-horizon). Sample sites were chosen to cover the range of observed soil and land-cover types; aspect, gradient, and landslide history were not considered in the selection of sample locations. Bulk density and saturated shear strength (τ_{sat}) (Torvane Shear Strength Device, ELE International, Lake Bluff, IL) were measured and recorded for each sample. The saturated strength represents the most conservative strength estimate for the sandy-clay soils that dominate the research area; soil strength properties can vary significantly with degree of saturation

(Fredlund, 2000), but the conservative estimate has proved successful in earlier landslide studies performed at the watershed scale (e.g. Iverson, 2000; Divakarla and Macari, 1998; Montgomery and Dietrich, 1994). Angle of soil friction for the samples (ϕ) was estimated from information on soil texture and porosity (Holtz and Kovacs, 1981), and saturated hydraulic conductivity (K_{sat}) was evaluated with the falling-head method (Reynolds, 1993) for 76 mm (3 in) inside diameter and 76 mm (3 in) height undisturbed soil cores, based on the average of three trials per sample. Soil thickness soil above bedrock (D) was measured at 50 points (road cuts and sample pits).

Three major soils were identified, and their distribution was mapped through correlation with surface lithology. Information on lithology was obtained from 1:500,000 U.S. Geologic Survey (USGS) maps for Honduras that were refined through field survey. This refinement was necessary because USGS geologic data were disaggregated to match the scale of our DEM. Disaggregation is known to introduce uncertainty to a spatial model (Heuvelink and Pebesma, 1999), but, when the process is justified with field survey, it allows the modeler to present more detailed, intuitive results for use in prediction and management (Miles et al., 2000; Montgomery and Dietrich, 1994). Lithologic types include limestone deposits (Valle de Angeles Group), pyroclastic rock (Matagalpa Formation) and calcareous shale (Yojoa Group). Measured soil properties were grouped by lithologic type to provide calibration parameters for the stability model.

No reliable data on rainfall from Hurricane Mitch were available for the study area, and, because of the highly destructive nature of the storm, data from rainfall gauges throughout Honduras were of questionable quality (Hellin and Haigh 1999). Maximum 30-minute intensities of 71 mm hr^{-1} (2.8 in hr^{-1}) were reported from the south of the country (Hellin and Haigh, 1999), while a sustained intensity of nearly 107 mm hr^{-1} (4.2 in hr^{-1}) was recorded over one six-hour period in the north (McCown et al., 1998). Based on these reports, we used a steady-state recharge rate of 76 mm hr^{-1} (3 in hr^{-1}) for modeling purposes, considered conservative for maximum, multiple-hour, sustained rainfall intensity in central Honduras.

An inventory of recent landslides in the study area was established through a field survey in September 2000 and the interpretation of 1:40,000 black and white aerial photographs (USGS, Washington, D.C.) taken in March 2000. All landslides were mapped at the head scarp of the slope failure (after Pack et al. 1998). Point mapping was considered to be the most appropriate inventory method because (1) dense vegetation in the tropics introduces considerable uncertainty to slide-area maps and (2) volcanic soils may liquefy when disturbed, leading to mudslides that are only a secondary consequence of initial slope failure (Terlien et al., 1995).

Model implementation. Following Montgomery and Dietrich (1994), a physically based slope-stability model was used in this study. Physical models allow for relatively fine-scale hazard mapping (Pack et al., 1998) and tend to be less site-specific than multivariate statistical analyses (Montgomery and Dietrich, 1994). The model most commonly applied in the GIS environment is the infinite slope-stability model (e.g. Hammond et al., 1992; Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Terlien et al., 1995; Pack et al., 1998). This model evaluates slope stability based on an estimated potential for failure, expressed as (Hammond et al., 1992):

$$FS = \frac{c_r + c_s + \cos^2\theta\,[\rho_s g\,(D - Dw) + (\rho_s g - \rho_w g)\,Dw]\tan\phi}{D\,\rho_s g\,\sin\phi\cos\phi} \qquad (1)$$

where FS is the "factor of safety" for slope stability. (Values < 1 represent failure conditions.) Parameters c_r and c_s are the cohesion due to roots and soil, respectively ($ML^{-1}T^{-2}$), θ is the local slope gradient in degrees, ρs is the saturated bulk density of the soil (ML^{-3}), ρw is the unit density of water (ML^{-3}), D is the soil thickness above the failure plane (L), Dw is the saturated soil thickness above the failure plane (L), ϕ is the soil angle of friction in degrees, and g is the acceleration due to gravity (LT^{-2}).

Pack et al. (1998) adapted this equation in the Stability Index Mapping (SINMAP) model. SINMAP estimates shallow translational landslides by combining the infinite slope-stability equation with a steady-state hydrology model that calculates depth of saturation based on water recharge rate and soil transmissivity of water. In numerous applications, SINMAP has proven to be an effective tool for the rapid identification of potentially unstable zones in large land areas (Pack et al., 1998). Although shallow translational landslides were not the only type of slope failure identified in the study area, the infinite slope model was deemed appropriate because (1) the algorithm tends to be conservative for situations of deep-seated failure (Terlien et al., 1995), and (2) rotational failures and mudslides in the study area generally initiate as shallow debris flows.

Slope-wetness classification. Each grid cell was categorized according to relative wetness (W) and average slope (α). W was obtained from the SINMAP hydrology module and, for the deterministic case, represented the fraction of soil thickness predicted to be saturated under modeled conditions:

$$W = \left(\frac{R \cdot A}{T \sin\alpha}, 1 \right), \qquad (2)$$

where R and T are rainfall and transmissivity for each grid cell and A is the specific catchment area (upslope area per unit contour length; $L^2\ L^{-1}$). Values of W range from 0 to 1, and W=1 indicates complete saturation. Slope (α) was derived directly from the 5 m DEM and ranged from 0° to 53°. Four categories were used to characterize slope-wetness ($\alpha^* W$) variability in the study area: Class A, for grid cells in "rolling terrain" ($\alpha < 30°$) that are "moist" ($W < 0.5$) under simulation conditions; Class B, for cells in rolling terrain that are "wet" in model simulation ($\alpha < 30°$, $W \geq 0.5$); Class C, for moist cells in "steep terrain" ($\alpha \geq 30°$, $W < 0.5$); and Class D, for wet, steep terrain cells ($\alpha \geq 30°$, $W \geq 0.5$). The choice of 30° as a cutoff for steep terrain is consistent with the FAO definition of steeplands (Lal, 1999).

Total and unstable land areas were tabulated by $\alpha^* W$ class and lithologic group. Observed slide systems were also categorized by lithology and $\alpha^* W$ of the surrounding grid cell, and significance of the lithology by $\alpha^* W$ class interaction was tested with the χ^2 statistic. Finally, a map was generated that indicates stability prediction and $\alpha^* W$ class for each grid cell in the study area.

Results and Discussion

Soil strength and hydrology were variable within and between lithologic groups (Table 1). Soils overlying Yojoa Group rock were deep and well-drained (D = 3.0 m [10 ft], K_{sat}

Table 1. Mechanical and hydrologic parameters used in the slope stability model.

Parameter	Rock group	n	Mean	Range	Standard deviation
ρ_{sat} (Mg m^{-3})	Yojoa group	8	1.83	1.80 - 1.86	0.027
	Valle de Angeles group	8	1.69	1.63 - 1.72	0.044
	Matagalpa formation	14	1.74	1.67 - 1.85	0.066
ϕ(°)	Yojoa group	8	31.8	35.1 - 28.6	3.20
	Valle de Angeles group	8	29.3	30.4 - 29.1	0.97
	Matagalpa formation	14	28.7	25.6 - 31.7	2.94
τ_{sat} $^{(kPa)}$	Yojoa group	8	9.9	6.0 - 13.2	3.5
	Valle de Angeles group	8	8.9	4.0 - 13.1	4.4
	Matagalpa formation	14	6.2	3.2 - 10.0	2.4
log K_{sat} (m s^{-1})	Yojoa group	8	-3.97	-4.44 - 3.74	0.34
	Valle de Angeles group	8	-4.52	-4.76 - 4.20	0.27
	Matagalpa formation	14	-4.73	-5.22 - 4.17	0.39
D (m)	Yojoa group	8	3	1.50 - 4.50	n/a
	Valle de Angeles group	8	1	0.50 - 1.50	n/a
	Matagalpa formation	14	3.25	1.50 - 5.00	n/a

	Area (km^{-2})	No. landslide systems	Slide density (km^{-2})
Yojoa group	29.03	43	1.48
Valle de Angeles group	8.06	8	0.99
Matagalpa formation	9.00	30	3.33

$= 1.06^{*}10^{-1}$ mm•s^{-1} [$4.17^{*}10^{-3}$ in s^{-1}]). These soils were also the coarsest found in the study area and had the greatest mean ϕ (31.8°). Soils of the Valle de Angeles group had greater clay content, were relatively shallow (ϕ = 29.3°, D = 1.0 m [3.3ft]), and were moderately well-drained with a lower average K_{sat} ($3.02^{*}10^{-2}$ mm•s^{-1} [$1.19^{*}10^{-3}$ in s^{-1}]). Soils of the Matagalpa Formation were deep (D = 3.3 m [11 ft]), highly weathered, and clay-rich. These deposits had the lowest K_{sat} ($1.86^{*}10^{-2}$ mm•s^{-1} [$7.32^{*}10^{-4}$ in s^{-1}]) and ϕ (28.6°), but exhibited cohesion under nonsaturated conditions. Landslide density was greatest for the Matagalpa Group, at 3.33 landslide systems per square kilometer (8.66 per square mile).

The SINMAP approach to instability modeling was quite successful in describing slope failure in the study area, identifying 75% of the 81 observed slide systems as sites of expected failure during Mitch. While the SINMAP-defined threshold of instability is sensitive to a number of soil parameters (notably K_{sat} and ϕ; Zaitchik et al., in press), relative stability predictions are governed primarily by α and W (Pack et al., 1998). Local gradient α was derived from the DEM, while relative wetness W takes into account α, contributing area, water recharge rate, and hydrology. It is useful to examine the relative and absolute values of α and W for each soil type and zone of predicted instability.

Only 10.2% of the total study area (4.7 km^2 [12.2 mi^2]) was classified as steep terrain (Classes C and D). This small area accounted for 45.2% of all areas predicted to be unstable and 61.7% of all slides observed from Hurricane Mitch (Table 2). It is important to note that the majority of steep-slope failures occurred in Class C areas, where W was < 0.5. These landslides probably occurred under partially saturated conditions and can be referred to as "slope-driven" failures that generally occur in soils that are moderately drained to well-drained.

Wet, rolling terrain (Class B) accounted for 28.2% of the study area (11.9 km^2) but 42.4% of areas predicted to be unstable. Class B slopes were not extremely steep (α < 30°) but became saturated or submerged under Hurricane Mitch conditions. Class B soils are found in low-lying terrain, along the borders of streams and rivers, and in zones of topographic convergence in low K_{sat} soils. Only 22.2% of all slide systems were found in Class B areas, but several of these triggered deep, extensive mudflows typical of saturated clay soils (Terlien, 1995). In one case, a set of failures on Class B terrain gave rise to a 6 km long mudflow that damaged or put at risk 50 farms (Cruz and Reyes,2000); this was by far the largest soil-failure event in the study area. So, while Class C failures accounted for the majority of landslides during Hurricane Mitch, the "saturation-driven" failures observed in Class B areas are cause for concern. Additionally, slope stabilization techniques that are generally effective against slope-driven landslides, including tree planting and contour cropping, can actually reduce the stability of slopes prone to deep, saturation-driven failure (Collison et al., 1995; Simon et al., 1990; Royster, 1979). Slope-stability management must involve an array of diverse, site-targeted methodologies.

There was a marked relationship between surface lithology and failure process in the study area. For the coarse-textured Yojoa Group, the majority of predicted and observed failures occurred on steeper slopes (Classes C and D), with few Class B failures observed (Table 2). Some small-debris slides were also found on Class A slopes, but no large failure systems were initiated on rolling terrain. For the Valle de Angeles Group, however, the majority of the area was identified as Class B. Failure under these conditions was

Table 2. Surface lithology and $\alpha^* W$ classification.

Rock group	Group area (A_G)	Area predicted unstable (U_G)[†]	$\alpha^* W$ class[††]	Percent of A_G	Percent of U_G	Number of observed slides [¶]	Number of observed predicted unstable
	km^2	km^2		%	%		
Yojoa	29.0	2.7	A	76.2	29.8	11	3
			B	12.2	16.2	4	3
			C	11.5	53.5	20	16
			D	0.1	0.5	8	8
Valle de Angeles	8.1	2.0	A	15.9	6.5	0	0
			B	79.4	74.7	5	4
			C	2.5	10.0	2	2
			D	2.2	8.7	1	1
Matagalpa	9.0	3.2	A	45.2	24.8	2	0
			B	45.0	47.4	9	8
			C	9.2	26.1	10	8
			D	0.6	1.7	9	8
Area totals	46.1	7.9	A	61.6	12.4	13	3
			B	28.2	42.4	18	15
			C	9.7	42.3	32	26
			D	0.5	2.9	18	17

[†] **Predicted probability of failure > 0.5**

[††] **Class A: $\alpha < 30°$, W < 0.5: Class B: a < 30°, W < 0.5; Class C: a < 30°, W < 0.5: Class D: a < 30°, W > 0.5.**

[¶] **To account for spatial uncertainty in the landslide inventory, slope-wetness classifications are based on the greatest slope and wetness values found within 35 m of the mapped failure. All slides were mapped after Hurricane Mitch.**

driven by rapid surface saturation that compromised the soil matrix even on relatively gentle slopes. The Matagalpa Formation was associated with both slope- and saturation-driven failure. These volcanic deposits are formed on steep slopes in the headwaters of the study area and are kept stable, in part, by soil cohesion, which is lost when positive pore pressures build. Large masses of soil become plastic, or even liquid, resulting in shallow debris flows in steep areas and deep failures and flows in zones of topographic convergence (Terlien et al., 1995). The lithologic group by α^*W class interaction was significant for observed slope failures (χ^2 = 17.9, p = 0.0065), suggesting that there is potential for a soil-specific approach to landslide management.

Considering the diverse nature of slope failure within this study area, it is not surprising that the post-Mitch farm survey (World Neighbors, 2000) failed to identify a link between agroecology and landslide prevention at the regional scale. The surveyors' definition of agroecology included practices as biophysically disparate as, for example, agroforestry and live mulch. Agroforestry may stabilize a shallow soil, where tree roots reach to bedrock, or a well-drained cohesionless soil (Montgomery et al., 2000), such as those found in Class C areas of the Yojoa Group. The increase in depth and rate of infiltration associated with new trees can, however, have a negative impact on stability when a potential failure plane exists below the rooting zone (Collison et al., 1995). Conventional recommendations that involve terracing and tree planting for slope stabilization could lead to destabilization on deep, clay-rich soils of the Matagalpa Formation. Live mulch, on the other hand, could be an excellent tool for landslide prevention on a moderately sloped, poorly drained site (i.e. Class B). The shallow roots of the mulch will not reinforce soil along potential planes of failure, but certain mulches can shed water effectively and, when oriented parallel to the slope gradient, may act as thatched roofs (e.g. Triomphe, 1996). Presumably, this will reduce soil saturation and a buildup of positive pore pressures while providing protection from surface erosion.

The $\alpha^* W$ classification approach may be applied to land management at the farm and hillside scale. Two examples are shown in Figure 2. Where a conventional slope stability map identifies both Site 1 and Site 2 as areas of potential instability, the $\alpha^* W$ map indicates that the instability in Site 1, located on a steep Yojoa Group slope, is fairly well drained in the backslope. In this area, integration of deep-rooted woody species into the agricultural system could enhance effective soil strength. The bottom slope, however (located in the South Central area of the map), is both steep and prone to saturation. The site is near a stream channel, so physical drainage is a viable option. Filter strips were also recommended for the banks of the stream channel (Cruz and Reyes, 2000). Site 2, on the other hand, represents a zone of topographic convergence in deep Matagalpa Formation material. Gently graded drainage trenches have been dug in existing landslide scars, a nearby road-cut is recommended to be graded back, and vegetation with local grasses is the favored biophysical stabilization method. Water management in this case should be prioritized over soil reinforcement.

Preferred management practices for the four $\alpha^* W$ classes are listed in Table 3. These are proposed based in part on the work of other researchers (Keller and Sherar, 2000; Pla, 1997; Collison et al., 1995; Howell et al., 1991), and are presented as "rules of thumb" to be refined and modified with future field experience.

Summary and Conclusion

Spatially distributed slope-stability models have provided a tool for rapid characterization of landslide susceptibility in large land areas. For land managers concerned with small-scale forest clearing or siting of infrastructure, information on relative susceptibility is generally sufficient—the management decision is one of use or non-use, and low-risk sites are preferable to high-risk sites. For tropical smallholders, however, the biophysical conditions that drive slope instability are as important as relative landslide risk. Few farmers are in a position to relocate their homes or fields, so management decisions involve modification, not elimination, of current land-use practices.

In the absence of human disturbance or geologic faults, relative stability of a slope is controlled primarily by local slope gradient and degree of saturation. The steady-state hydrology module of a model such as SINMAP can, when properly calibrated, provide estimates of the absolute and relative saturation level of soils in the landscape. This information, combined with slope gradient data from a DEM, allows us to define $\alpha^{*}W$ classes of landslide risk and to identify soils and topographic formations associated with each class. This process requires no more data than the slope-stability model itself, yet it provides stakeholders with new and meaningful information for site-specific landslide management.

A further advantage is that slopes can be classified according to gradient and wetness through field survey (Table 3) when model data is not available; this means that management principles based on $\alpha^{*}W$ classification can be applied in an approximate manner for slope-stabilization efforts at similar sites around the region. It is expected that the introduction of a slope-wetness component to management discussions will make the exchange of ideas between farmers, agencies, and land planners more fruitful and ultimately help to reduce human vulnerability to catastrophic slope failure.

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Figure 2

Two locations identified for site-specific slope stabilization. Site 1 is located on a steep slope in an area of Yojoa Group lithology. Site 2 is a zone of topographic concentration with lithology of the Matagalpa Formation. Arrows indicate existing landslide scars, and the black line outlines zones of expected failure.

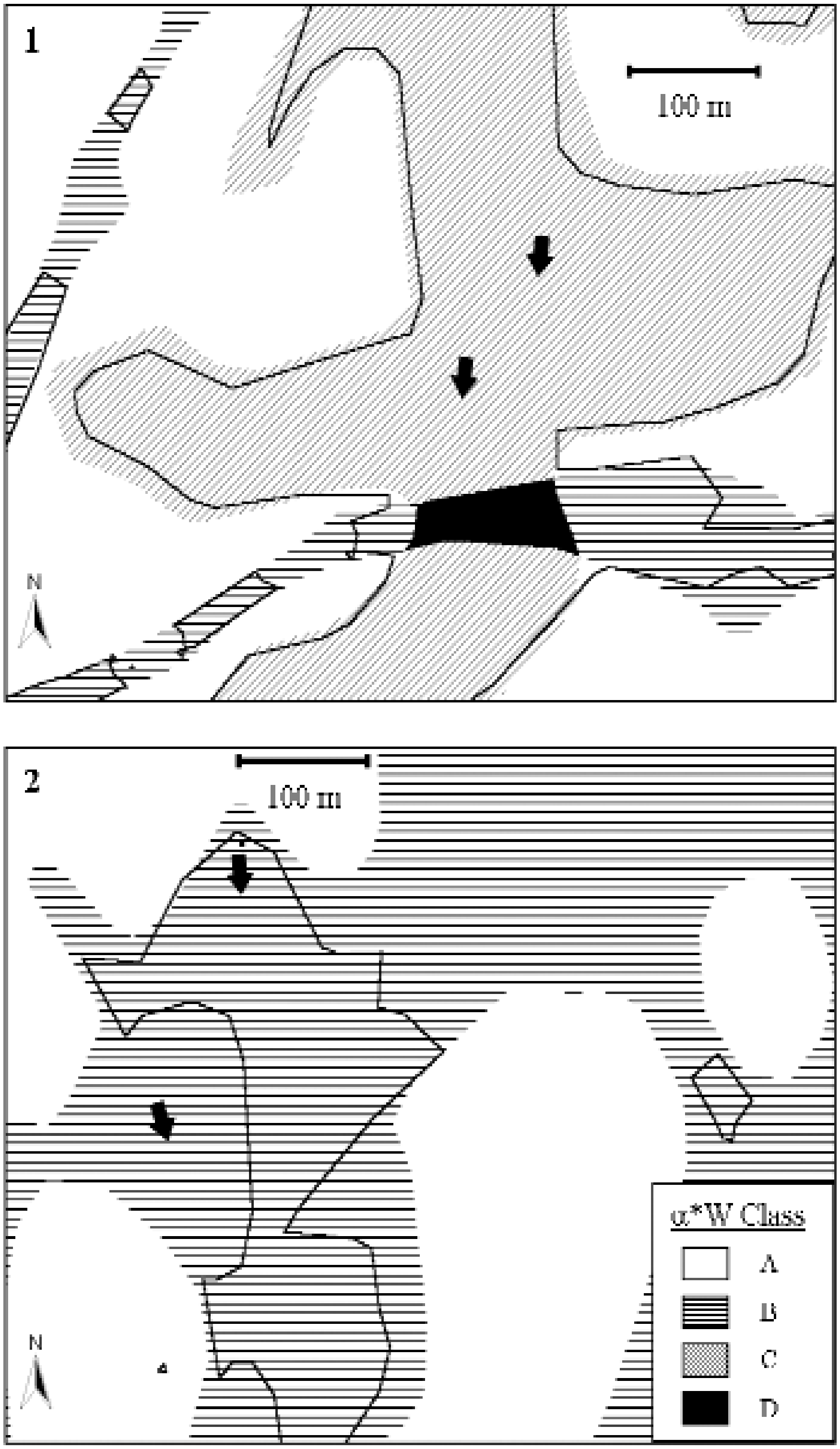

Table 3. Preferred management techniques for α^*W classes.

Class	Slope	Wetness	Identifiers	Potential for slope failure	Suggested remediation measures
A	< 30˚	dry to moist	Coarse or well-drained soil; rolling terrain; dries out quickly after rain events	low, unless degraded or disturbed	Generally none necessary. Good locations for infrastructure or intensive agriculture. Surface erosion is the primary soil management concern.
B		wet or saturated	Clay-rich, cohesive soil: frequently wet; saturation and ponding during and after rainstorms; wetland vegetation; concave slopes with large contributing areas.	moderate; higher for steeper slopes within the class and when the toe slope is excavated or naturally scoured	Gently sloped grass or stone lined drainage ditches, thick ground cover with tall grass or mulch. Trees only valuable if roots reach to bedrock, and not recommended in the absence of additional ground cover. Ensure that roads are well-drained through outsloping, rolling dips or ditch / culvert system. Avoid steep or tall road cuts.
C	> 30˚	dry to moist	Coarse or well-drained soil; steep slopes; dries out quickly after rain events; slopes convex, flat, or mildly concave.	moderate; high on cleared or extremely steep (> 50˚) slopes.	Incorporation of trees and shrubs into the agricultural system. Buffer strips of grasses and woody plants at the bottom slope and along roads or rivers. Erosion control netting (if available) for use in establishing woody plantings. Re-route roads where possible, or reinforce the road cut with vegetation, gabion, or other engineered measures. Careful disposal or removal of spoils from road construction.
D		wet or saturated	Clay-rich, cohesive soil; obstructed drainage; steep, concave slopes; overland flow during rainstorms and ponding in local depressions.	high under all conditions	Candidate areas for protection. Avoid slope cutting for roads or terraces, and avoid as sites for infrastructure, either on or below. Stone-lined drainage ditches and thick ground cover are recommended; trees only beneficial if roots reach to bedrock. Grass rows should be oriented diagonally or down slope to maximize shedding effect; avoid contour planting, especially on active slide zones.

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Examining the targeting of conservation tillage practices to steep vs. flat landscapes in the Minnesota River Basin

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ABSTRACT: Conservation tillage practices are being prescribed as a remedy to reduce soil erosion and phosphorus losses and to increase water-holding capacity of agricultural soils. This study evaluates the targeting of conservation tillage practices to steep vs. flat landscapes in the Minnesota River Basin. Tillage practices were identified using remote sensing techniques in nine subwatersheds of the Lower Minnesota River watershed and analyzed in relation to topography. A Landsat Thematic Mapper (TM) image acquired during the 1997 planting season was used to identify conventional and conservation tillage practices at a 30 m (33 yd) resolution. Conservation tillage has been adopted on 32% to 54% of the cropland in the subwatersheds studied, while average cropland slope steepness ranges from 1.5% to 2.8%. A linear regression of percent adoption of conservation tillage vs. average slope steepness had a slope of 3.45 and an r^2 of 0.07. This shows that there was no significant targeting of conservation tillage to steeper topography across subwatersheds. Within a subwatershed, however, there was a slight tendency toward greater adoption of conservation tillage on steeper landscapes, up to slope steepnesses of 5%, then a significant decline in the adoption of conservation tillage. Overall, farmers in the Lower Minnesota River watershed seem to be adopting conservation tillage for reasons unrelated to soil conservation.

Keywords: Adoption, highly erodible land, topography

In recent years, adoption of conservation tillage has increased. Conservation tillage systems retain at least 30% of the soil surface covered with crop residue after a crop is planted. Conservation tillage systems including no-till (NT), ridge-till, strip-till, mulch-till, and reduced-till have been promoted to control soil erosion in corn and soybean growing areas of the Midwest United States. Studies show the adoption of conservation tillage methods can substantially reduce soil

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