STABILITY INDEX MAP OF MACON COUNTY, NORTH CAROLINA

FOR SHALLOW TRANSLATIONAL SLOPE MOVEMENT SUSCEPTIBILITY DURING A 5-INCH (125 MM) RECHARGE EVENT

By

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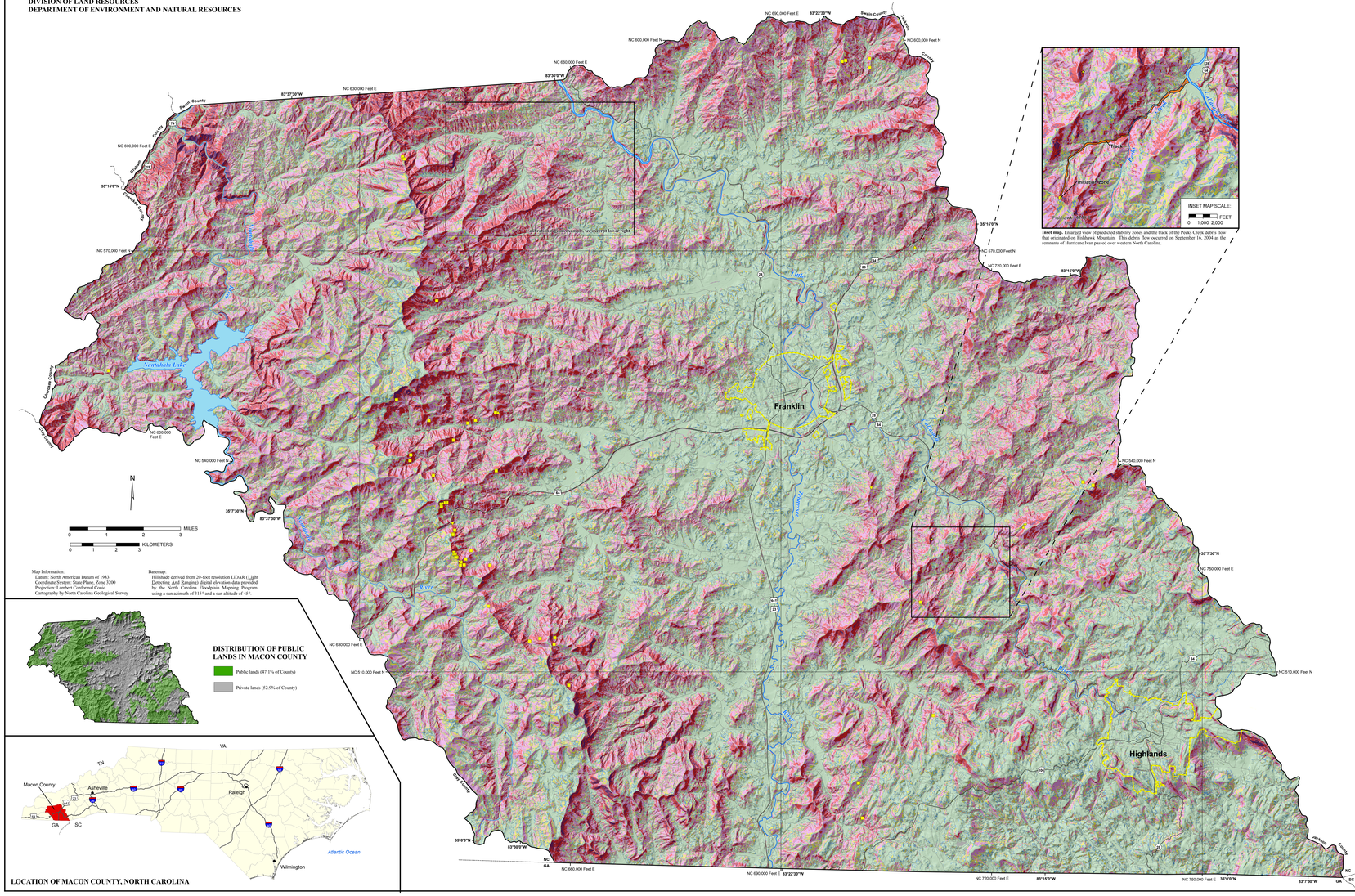
GEOLOGIC HAZARDS MAP SERIES 1
SLOPE MOVEMENT HAZARD MAPS OF MACON COUNTY, NORTH CAROLINA
SHEET 2 OF 3



EXPLANATION

MAP FEATURES

Map Color Code	Predicted Stability Zone	Relative Debris/Earth Flow-Slide Hazard Ranking [1]	Stability Index Range[2]	Factor of Safety (FS)[3]	Probability of Instability [4]	Predicted Stability With Parameter Ranges Used in Analysis	Possible Influence of Stabilizing or Destabilizing Factors [5]
	Unstable	High	0	Maximum FS <1	100%	Range cannot model stability	Stabilizing factors required for stability
	Upper Threshold of Instability		0 - 0.5	>50% of FS ≤1	>50%	Optimistic half of range required for stability	Stabilizing factors may be responsible for stability
	Lower Threshold of Instability	Moderate	0.5 - 1	≥50% of FS >1	<50%	Pessimistic half of range required for stability	Destabilizing factors are not required for stability
	Nominally Stable		1 - 1.25	Minimum FS = 1	___	Cannot model instability with most conservative parameters specified	Minor destabilizing factors could lead to instability
	Moderately Stable	Low	1.25 - 1.5	Minimum FS = 1.25	___	Cannot model instability with most conservative parameters specified	Moderate destabilizing factors are required for instability
	Stable		>1.5	Minimum FS = 1.5	___	Cannot model instability with most conservative parameters specified	Significant destabilizing factors are required for instability

Table 1. Stability class definitions for stability index map delineated using SINMAP. Modified from Pack and others (1998, Table 1).

Roads
- Primary Roads
- Secondary Roads

Rivers
- Major Rivers
- Minor Rivers

Municipal boundaries

Slope Movements
- Debris or Earth Blowout
- Debris or Earth Flow
- Debris or Earth Slide
- Debris Slide and Flow

Note: Depicts only naturally occurring shallow translational slope movements used for model calibration.

Material definitions:

debris - Regolith that contains a significant proportion of coarse material in which 20% to 80% of the particles are greater than coarse sand (0.08 in. or 2 mm).

earth - Regolith in which about 80% or more of the particles are smaller than 0.08 in. (2 mm).

Mechanism definitions:

blowout - A type of slope failure in which water and material bursts forth from the ground and then proceeds downslope as overland flow. These are possibly caused by excessive pore water pressure.

flow - A type of slope movement in which the water content in the displaced mass is sufficient for the material to liquefy and resemble a viscous fluid.

slide - A slope movement initiated by slippage along a well -defined failure surface that is usually planar or curvi-planar.

Note: Definition of blowout from Hack and Goodlett (1960); All other definitions are in general accordance with Cruden and Varnes (1996).

Explanatory notes for Table 1:

[1] Relative Debris/Earth Flow/Slide Hazard Ranking. This column designates the relative hazard ranking for the initiation of shallow translational landslides on unmodified (i.e. natural) slopes.

[2] Stability Index Range. The stability index is a numerical representation of the relative hazard for shallow translational slope movement initiation based on the factors of safety computed at each point on a 20 ft. (6 m) digital elevation model grid derived from LiDAR elevation data. The stability index is a dimensionless number based of factors of safety generated by SINMAP that indicates the probability that a location is stable considering the most and least favorable parameters input into the model.

[3] Factor of Safety (FS). The factor of safety is a dimensionless number computed by SINMAP using the infinite slope equation that represents the ratio of the stabilizing forces that resist slope movement to destabilizing forces that drive slope movement. A FS >1 indicates a stable slope, a FS <1 indicates an unstable slope, and a FS =1 indicates the marginally stable situation where the resisting forces and driving forces are in balance.

[4] Probability of Instability. This column shows the likelihood that the factor of safety computed within this map unit is less than one (FS <1, i.e., unstable) given the range of parameters used in the analysis (see table 3). For example, a <50% probability of instability means that a location is more likely to be stable than unstable given the range of parameters used in the analysis.

[5] Possible Influence of Stabilizing or Destabilizing Factors. Examples of stabilizing factors include increased soil strength, root strength and improved drainage; destabilizing factors include increased wetness due to road drainage or loading, or loss of root strength.

Slope Movements used in model calibration process	Predicted Stability Zone						Total
	Unstable	Upper Threshold	Lower Threshold	Nominally Stable	Moderately Stable	Stable	
Blowout	0	1	0	0	0	0	1
Debris/Earth Flow	9	29	4	2	1	4	49
Debris/Earth Slide	2	3	1	0	0	0	6
Debris/Earth Slide/Flow	0	1	1	0	1	0	3
Total	**11**	**34**	**6**	**2**	**2**	**4**	**59**
% of Total	19%	58%	10%	3%	3%	7%	100%

Table 2. Number of shallow translational slope movements that initiated on unmodified ground for each predicted stability zone.

ACKNOWLEDGEMENTS

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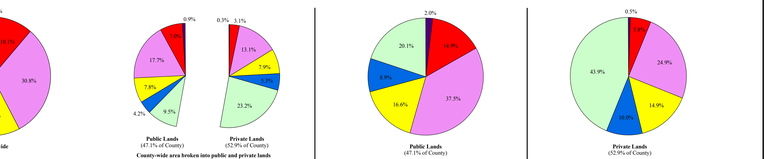
RELATIVE PERCENTAGES OF PUBLIC AND PRIVATE LANDS WITHIN EACH PREDICTED STABILITY ZONE



OVERVIEW OF THE STABILITY INDEX MAP

Introduction

In response to the number of slope movements (landslides) and the destruction caused by the remnants of Hurricanes Frances and Ivan in western North Carolina in September 2004, the North Carolina General Assembly authorized the North Carolina Geological Survey (NCGS) to produce landslide hazard maps for 19 western counties. Macon County was selected as the first county to be mapped because of the fatalities caused by a debris flow and the fast-growing population potentially at risk from other slope movements. The intent of the landslide hazard mapping program is to provide the public, local government, and local and state emergency agencies with a description and location of areas where slope movements have occurred, or are likely to occur, and the general areas at risk from these slope movements. The locations of previous slope movements are important because they often reoccur in the same general areas. This predictive mapping is not intended to substitute for a detailed, onsite analysis by a qualified geologist or engineer.

The slope movement hazard map series for Macon County consists of three maps, Geologic Hazards Map Series 1 (GHMS-1) Sheets 1, 2 and 3, designed to be used in conjunction with each other. This map is GHMS-1, Sheet 2. The accompanying maps are GHMS-1, Sheet 1, Slope Movements and Slope Movement Deposits Map of Macon County, North Carolina; and, GHMS-1, Sheet 3, Downslope Hazard Map of Macon County, North Carolina.

Stability Index Map (Geologic Hazards Map Series 1, Sheet 2)

This color-coded map delineates the predicted relative hazard rankings (high, moderate, and low) for the initiation of naturally occurring, shallow, translational slope movements (i.e., debris/earth flows, and debris/earth slides) in response to approximately 5-6 inches (125-154 mm) of rain within a 24-hour period. The three relative hazard rankings are generalized from the six predicted stability zones delineated on the map. Table 1 provides the definitions and additional information related to the hazard rankings, and the corresponding stability index categories and stability zones. The Stability Index Map does not predict that shallow translational slope movements will occur, but predicts that if they do, where they are more likely to initiate given the assumptions and input parameters used in the analysis. Debris/earth flows and debris/earth slides typically originate where thin (usually less than 6 ft or 2 m thick) soil overlies relatively low permeability layers such as bedrock or weathered bedrock on steep slopes, typically those greater than 30 degrees. This map is intended to indicate the distribution of high and moderate hazard areas where further slope stability analysis and assessment, including field verification, is recommended prior to undertaking ground disturbing activities.

Map Production

The map was produced using SINMAP (Stability INdex MAPping) software, an ArcView™ 3.x extension developed by Pack and others (1998) for use in a geographic information system (GIS). SINMAP computes a factor of safety using the infinite slope model (Pack and others, 1998, and Hammond and others, 1991) based on input hydrologic, soil and topographic data for each pixel on a 20 ft (6 m) LiDAR (Light Detecting And Ranging)-derived digital elevation model grid. The factor of safety is a dimensionless number computed by comparing the ratio of stabilizing forces to destabilizing forces at a location. A FS>1 indicates stable conditions, whereas a FS<1 indicates stable conditions given the assumptions and parameters input into the model. SINMAP then assigns a stability index based on the computed factors of safety. The six stability zones are assigned relative hazard rankings (high, moderate, and low) based on the calculated stability index ranges, and known slope movement occurrences.

Input parameters include values for recharge, soil transmissivity (soil permeability or hydraulic conductivity multiplied by soil thickness), and upper and lower bounded values for the soil properties (i.e., unit weight, thickness, effective friction angle, effective cohesion). SINMAP randomly samples the bounded input parameter values from uniform probability distributions as a means to account for the variability and uncertainty inherent in natural systems. Soil properties were obtained from the U.S. Department of Agriculture digital soil survey of Macon County (U.S. Dept. of Agriculture, 1996), augmented by field data collected by NCGS staff, data from the North Carolina Department of Transportation soil-testing database, and literature values given in Hammond and others (1991). The stabilizing affect of vegetation is accounted for in the dimensionless cohesion parameter with input values for root cohesion compiled from literature references. Refer to Table 3 on this map for parameter values correlated with the soil survey map units and calibration regions used in this model. Slope and topographic convergence derived from the LiDAR elevation data are used to model saturation in convergent hollow areas.

The 5-inch (125 mm) steady state recharge value used in the SINMAP analysis approximates an equivalent amount of rainfall within a 24-hour period. This recharge value is used because historical evidence (Eschner and Patric, 1982; Neary and Swift, 1987; and Witt, 2005) and recent examples in North Carolina indicate that 5 inches (125 mm) of rainfall in a 24-hour period is a critical threshold amount for triggering debris/earth flows and slides. Rainfall analysis at the U.S.D.A. Forest Service's Coweeta Hydrologic Laboratory in Macon County, however, show that 3-10% of rainfall from storms is direct runoff (storm flow) rather than recharge (Hewlett and others, 1984). If this is the case, then as much as 6 inches (154 mm) of rainfall could be required to produce the 5 inches (125 mm) of recharge used in the SINMAP analysis.

Model Calibration

The model calibration (i.e., the parameter adjustment process) was conducted as recommended by the developers of SINMAP (Pack and others, 1998). Initial model runs used ranges of parameter values selected and constrained from the sources described above. Parameter values (primarily dimensionless cohesion) were then adjusted within reasonable ranges so that the majority of the locations of slope movements used for calibration were captured in the high hazard (upper threshold and unstable) zones. Table 2 on this map shows the types and distributions by SINMAP class of 59 naturally occurring, shallow, translational slope movements used to calibrate and verify the model results.

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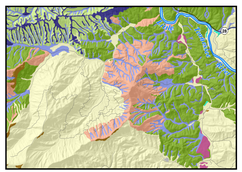
CALIBRATION REGIONS AND PARAMETER VALUES USED TO GENERATE THE STABILITY INDEX MAP

Region[1]	Soil Unit[2]	T/R (m) Low[3]	T/R (m) High[3]	Dimensionless Cohesion Low[4]	Dimensionless Cohesion High[4]	Friction Angle (degrees) Low[5]	Friction Angle (degrees) High[5]
1	RbF, RkF, Ub, UfB, W	0	0	0.20	0.35	24	45
2	ScE	1.5	9.9	0.20	0.35	24	40
3	CaE, CaL, CaF, CcF	2.5	49.5	0.20	0.35	30	40
4	CgD, CgE, CgF	2.5	14.9	0.20	0.35	24	40
5	ArA, BkB2, BkC2, BrC, BrD, HaB2, HaC2, HaD2, HmA, StB, ToA	4.5	14.9	0.20	0.35	20	37
6	CaE, CaL, CaF, DrB, StC, StD, StE,	4.5	44.6	0.20	0.35	24	40
7	BuD, BuF, CsC, CsD, CsE, SeD, SeE, SoF	5	29.7	0.20	0.35	24	40
8	BuC, BuD, BuE, BuF, ChE, ChF	9.9	44.6	0.20	0.35	20	40
9	BeA, CdB, CdE, CdD, CsE, CsD, CsE, CsF, DgB, DsB, DsC, EdB, EaC, EdE, EdF, EoC, EoD, EoE, EoF, ExC, ExD, ExE, ExF, FaD, FaE, FaF, MeA, OwE, PwC, PwD, PwE, PwF, ReA, ReA, SbC, SbD, SbE, ScB, ScC, ScA, TrE, TrF, TuC, TwB, TwC, WoC, WeD, WeE, WeF	14.9	44.6	0.20	0.35	24	40

Table 3. Calibration regions and parameters used to generate the Stability Index Map.



Excerpt of county-wide calibration regions map. SCALE 1:48,000

Explanatory notes for Table 3:

[1] Region - A numbered area used in the SINMAP modeling process that has similar soil and hydrologic properties. These regions were derived from the detailed soil units for Macon County (U.S. Dept. of Agriculture, 1996). Individual upper and lower bounded value estimates for T/R, (ratio of soil transmissivity to recharge) dimensionless cohesion, and soil friction angle were derived for each region.

[2] Soil Units - Soil map unit abbreviations from the Soil Survey of Macon County (U.S. Dept. of Agriculture, 1996).

[3] T/R (m) Low/High - The upper and lower bounding values for the ratio of soil transmissivity (T) to the rate of recharge (R). Transmissivity was calculated by multiplying the hydraulic conductivity (permeability) of the soil unit by the thickness of the soil unit. Both soil depth and permeability were derived from the soil survey (U. S. Dept. of Agriculture, 1996). The recharge rate used was 5 inches (125 mm) per day. This is the 24-hour rainfall threshold threshold rate for debris flows to initiate in the Blue Ridge. The value for T/R represents length of hillslope, in meters, required to develop soil saturation during the recharge period considered.

[4] Dimensionless Cohesion Low/High - The upper and lower bounding values for dimensionless cohesion. These calculated estimates were derived using the ratio of the combined values for effective soil and root cohesion relative to the soil density and thickness, as shown in Pack and others (1998).

[5] Friction Angle (degrees) Low/High - The upper and lower bounding values for effective internal soil friction angle. Internal friction is the friction between individual grains within a mass of material. Failure occurs when internal friction is overcome along a shearing plane at a given angle.

DISCLAIMER OF LIABILITY

The Hurricane Recovery Act of 2005 (Section 6) directs the Department of Environment and Natural Resources (DENR) to ensure that maps indicating areas vulnerable to landslides be made available for the 19 counties included in the Major Disaster Declarations for Hurricanes Frances and Ivan.

The North Carolina Geological Survey was tasked to prepare these maps and is committed to providing users with accurate, useful and current information. All electronic and/or hardcopy products (maps, data, text, etc.) produced by this landslide hazard mapping program are considered public information and may be redistributed and/or copied. These products, however, are intended to serve for general planning purposes only, and are provided on an "as is" basis. These maps and products do not substitute for an on-the-ground site assessment by a qualified geologist or engineer.

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