STABILITY INDEX MAP OF HENDERSON COUNTY, NORTH CAROLINA

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

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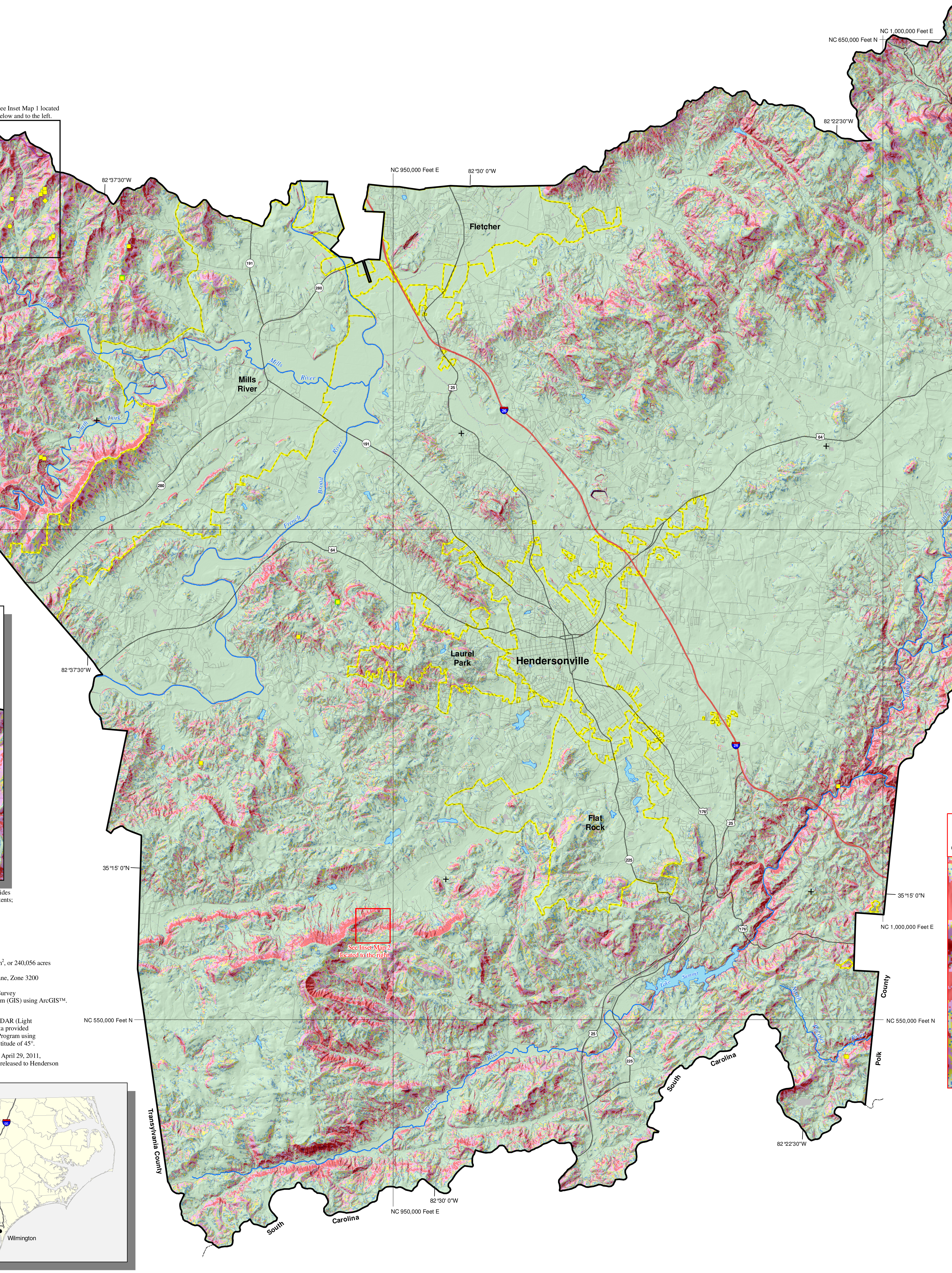
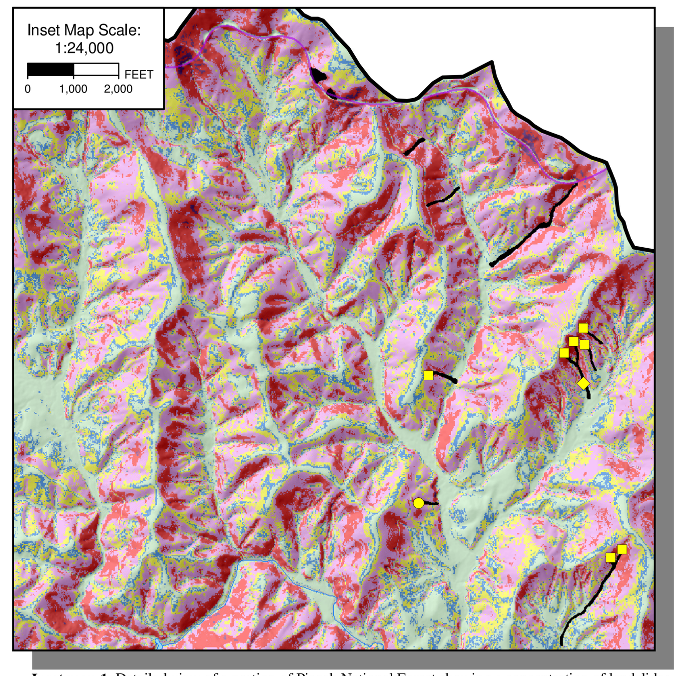
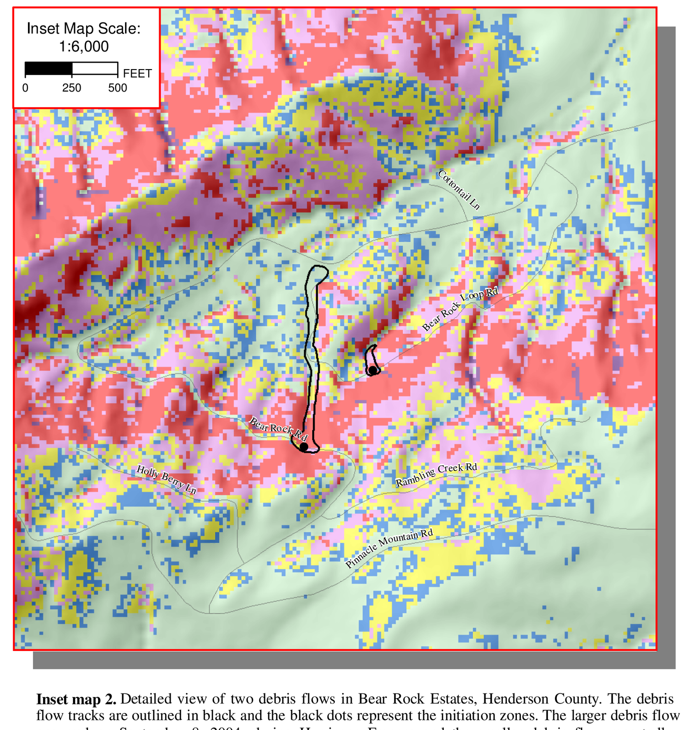
GEOLOGIC HAZARDS MAP SERIES 5
SLOPE MOVEMENT HAZARD MAPS OF HENDERSON COUNTY, NORTH CAROLINA
SHEET 2 of 3, VERSION: APRIL 29, 2011





Inset map 1. Detailed view of a portion of Pisgah National Forest showing a concentration of landslides triggered by the storm of November 3-6, 1977. Black polygons show debris flow tracks and slide extents; those without associated yellow initiation zone symbols initiated on modified ground.



Inset map 2. Detailed view of two debris flows in Bear Rock Estates, Henderson County. The debris flow tracks are outlined in black and the black dots represent the initiation zones. The larger debris flow occurred on September 8, 2004, during Hurricane Frances and the smaller debris flow reportedly occurred in the mid-1990s. This inset shows the maximum recommended scale (1:6,000) for using the landslide hazard map data. *Note: These debris flows initiated on slopes modified by human activities and were not used to calibrate the SINMAP model.*

Map Information:
Area of Henderson County: 375mi², 971.5km², or 240,056 acres
Datum: North American Datum of 1983
Coordinate System: North Carolina State Plane, Zone 3200
Projection: Lambert Conformal Conic
Cartography by North Carolina Geological Survey
Produced in a Geographic Information System (GIS) using ArcGIS™.

Basemap:
Hillshade derived from 20-foot resolution LiDAR (Light Detecting And Ranging) digital elevation data provided by the North Carolina Floodplain Mapping Program using an artificial sun azimuth of 315° and a sun altitude of 45°.

Based on information and data available as of April 29, 2011, concurrent with the GIS versions of the maps released to Henderson County on this date.

GRID NORTH

1:48,000
0 1 2 3 MILES
0 1 2 3 KILOMETERS

LOCATION OF HENDERSON COUNTY, NORTH CAROLINA

EXPLANATION

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 instability	Destabilizing factors are not required for instability
	Nominally Stable	Low	1 - 1.25	Minimum FS = 1	___	Cannot model instability with most conservative parameters specified	Minor destabilizing factors could lead to instability
	Moderately Stable		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).

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 or undisturbed) 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 foot (6 meter) digital elevation model grid derived from LiDAR elevation data. The stability index is a dimensionless number based on factors of safety generated by SINMAP that indicates the probability that a location is stable considering the most and least favorable parameters for stability input into the model. The breaks in the ranges of values for the stability index categories are the default values recommended by the program developers.

[3] **Factor of Safety (FS).** The factor of safety is a dimensionless number computed by SINMAP using a modified version of the infinite slope equation, as used in Pack and others (1998), that represents the ratio of the stabilizing forces that resist slope movement to destabilizing forces that drive slope movement (Figure 1). 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 (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.** Stabilizing factors include increased soil strength, root strength, or improved drainage. Destabilizing factors include increased wetness or loading, or loss of root strength.

MAP FEATURES

Roads
- Interstates
- Primary roads
- Secondary roads
- Blue Ridge Parkway

Rivers
- Rivers
- Lakes

Political Boundaries
- Municipal boundaries
- Henderson County boundary

Slope Movement Initiation Zones
- Debris or earth flow
- Debris or earth slide and flow
- Debris or earth slide
- Green halo indicates a detailed study location

Note: Locations of slope movement initiation zones shown on this map sheet depict only shallow translational movements on unmodified slopes. These locations were used to calibrate the SINMAP model (Sheet 2). For a comprehensive listing and locations of the types of slope movements and deposits identified and/or field verified in Henderson County, see Sheet 1 (Slope Movements and Slope Movement Deposits Map).

SLOPE MOVEMENT DEFINITIONS

Materials

debris – A soil that contains a significant proportion of coarse material; 20 to 80 percent of the particles are greater than coarse sand (0.08 inches or 2 millimeters), with the remainder finer than 0.08 inches or 2 millimeters.

earth – A soil in which approximately 80 percent or more of the particles are smaller than 0.08 inches (2 millimeters).

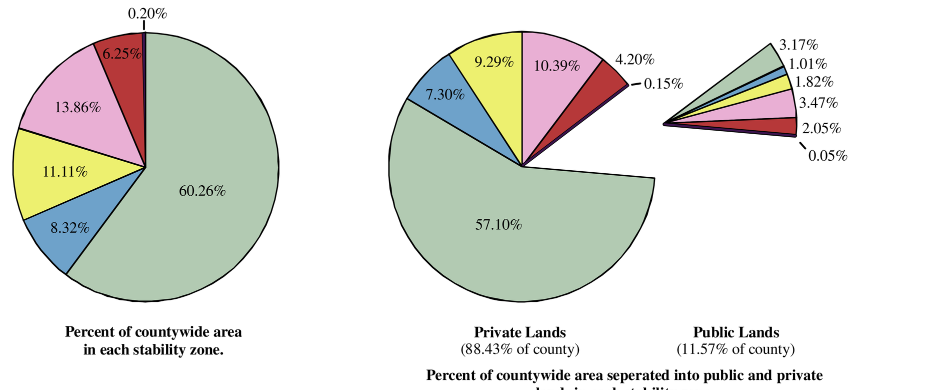
Mechanisms

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

slide – Slides are slope movements initiated by outward or downward rupture of displaced material along a well-defined, typically planar or curvi-planar failure surface. Where the geometry of the failure surface is not known, the term slide is applied. Where known, the slide is classified as rotational or translational (see slide-rotational and slide-translational).

Note: The above definitions are in general accordance with Cruden and Varnes (1996) and Jackson (1997) and represent slope movement types that can be modeled using SINMAP.

AREA AND LANDSLIDE STATISTICS FOR EACH STABILITY ZONE



Percent of countywide area in each stability zone.

Private Lands (88.43% of county) **Public Lands** (11.57% of county)

Percent of countywide area seperated into public and private lands in each stability zone.

	Stable	Moderately Stable	Nominally-Stable	Lower Threshold	Upper Threshold	Unstable	Total
Area (km^2)	581.7	80.3	107.2	133.8	60.4	1.9	965.2
% of Region	60.3%	8.3%	11.1%	13.9%	6.3%	0.2%	100%
Number of Landslides	0.0	0.0	1.0	3.0	17.0	2.0	23.0
% of Slides	0.0%	0.0%	4.3%	13.0%	73.9%	8.7%	100%
Landslides/km^2	0.00	0.00	0.01	0.02	0.28	1.06	0.0

Table 2. Statistical summary for each stability zone in Henderson County.

OVERVIEW OF THE STABILITY INDEX MAP

Background and Purpose

The North Carolina General Assembly authorized the North Carolina Geological Survey (NCGS) to produce landslide hazard maps for 19 western counties in response to the number of slope movements (landslides) and destruction caused by the remnants of Hurricanes Frances and Ivan in western North Carolina (N.C) in September 2004. 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 and their deposits are important because slope movements often reoccur in the same general areas, and they typically deposit material in areas where there are pre-existing slope movement deposits.

The slope movement hazard map series for Henderson County, N.C. consists of three maps (Geologic Hazards Map Series 5 (GHMS-5, Sheets 1, 2, and 3)) that are designed to be used in conjunction with each other. Brief descriptions of this map (Sheet 2) and accompanying maps follow.

1. Sheet 1 Slope Movement and Slope Movement Deposits Map, shows the extent and distribution of known historical slope movements (all types) and pre-existing slope movement deposits.
2. Sheet 2 (this map), Stability Index Map, shows where naturally occurring, shallow, translational slope movements (e.g., debris flows) may begin on slopes without prior ground disturbing activity in response to a major rainfall event.
3. Sheet 3, Map of Known and Potential Debris Flow Pathways, shows where debris flows may travel if they occur.

These printed maps are smaller scale representations of the digital spatial data that have been created for use in a Geographic Information System (GIS) (Wooten et al. 2011). The NCGS's landslide hazard map products are not intended to be a substitute for a detailed, site-specific analysis by a qualified geologist or engineer.

Stability Index Map (Geologic Hazards Map Series 5 Sheet 2)

This color-coded map shows the predicted relative hazard rankings (high, moderate, and low) for the initiation of shallow, translational slope movements (i.e., debris/earth flows, and debris/earth slides) in response to approximately 5-6in (125-154mm) or more of recharge within a 24-hour period. A 5in recharge event is approximately equal to an addition of 5in of groundwater. This analytical mapping method applies to slopes that have not been modified by ground disturbing human activities such as excavations and/or embankments. The map does indicate, however, those areas where destabilizing modifications to the ground can lead to instability (Table 1). Debris flows and similar types of landslides make up nearly 83% of the landslides recorded in Henderson County. Throughout western N.C., debris flows have resulted in the greatest number of landslide fatalities and damage of all reported landslide types. Six people died from two separate debris flows that were among the 44 landslides reported in Henderson County triggered by the July 15-16, 1916 storm.

The three relative hazard rankings are generalized from the six predicted stability zones shown on the map. Table 1 provides the definitions and additional information related to the predicted stability zones, relative hazard rankings, and the corresponding stability index ranges. Table 2 provides the statistical summary of slope movements for each stability zone. The Stability Index Map does not predict that shallow translational slope movements will occur, but it forecasts 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 on steep slopes (those greater than 20 degrees or 40 percent) where thin (usually less than 6ft- or 2m-thick) soil overlies relatively low permeability layers such as bedrock. This map is intended to indicate the distribution of high and moderate hazard areas where further slope stability analysis and assessment, including field verification, are 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 GIS. SINMAP computes a factor of safety (FS) based on the input hydrologic, soil and topographic data for each pixel on a 20ft (6m) LiDAR (Light Detecting And Ranging)-derived digital elevation model grid. The factor of safety (FS) is a dimensionless number that represents the ratio of the stabilizing forces to destabilizing forces at a location. A FS<1 indicates unstable 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. Figures 1 and 2 give basic information on parameters used in the SINMAP model to compute factors of safety and the infinite slope equation.

Model input parameters include upper and lower bounded values for recharge to the shallow groundwater system, soil transmissivity (soil permeability or hydraulic conductivity multiplied by soil thickness), and other soil properties (i.e., unit weight, thickness, effective internal friction angle, and effective cohesion). SINMAP randomly samples the bounded input parameter values using a uniform probability distribution to account for the variability and uncertainty inherent within the natural system. Soil properties were obtained from the U.S. Department of Agriculture digital soil survey of Henderson County (U.S. Department of Agriculture, 2008). Mapped soil units were then combined into eight "calibration regions" having similar ranges of soil texture, hydraulic conductivity and soil depth. These data were augmented by field data collected by NCGS geologists and constrained by values from hydraulic conductivity and triaxial testing of soil at five detailed study sites (two debris flow initiation zones in Henderson County, two potential debris flow initiation zones in DuPont State Forest adjacent Henderson County), soil gradation and Atterberg limit tests of 82 soil samples, and data from the North Carolina Department of Transportation triaxial testing database. These soil classifications, descriptions, and test results, along with literature values for soil properties given in Hammond et al. (1992) were used to constrain reasonable ranges of soil input parameters for the stability index modeling.

The stabilizing affect of vegetation is accounted for as root cohesion in the dimensionless cohesion parameter. Input values for root cohesion were constrained using the results of recent research at the U.S. Forest Service Coweeta Hydrologic Laboratory in Macon County, N.C. (Hales et al. 2009). SINMAP uses slope and topographic convergence derived from the LiDAR elevation data to model increased soil moisture in areas of concave topography.

The 5in (125mm) steady state recharge value used in the SINMAP model 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 N. C. indicate that 5in (125mm) of rainfall within a 24-hour period is an approximate threshold for triggering debris/earth flows and slides on slopes not modified by human activities. Watershed studies at the Coweeta Hydrologic Laboratory, however, show that 3-19% 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 6in (~150mm) of rainfall could be required to produce the 5in (~125mm) of recharge used in the SINMAP model analysis.

Model Calibration

The model calibration (i.e., the parameter adjustment process) was performed as recommended by the developers of SINMAP (Pack and others, 1998) using the known 23 shallow, translational slope movements shown in Table 2 (e.g., debris flows and debris slides) that occurred on unmodified slopes (i.e., those without obvious ground-disturbing activity). Initial model runs used ranges of parameter values selected and constrained from the sources described above. Parameter values (primarily dimensionless cohesion, soil thickness, internal friction angle, and hydraulic conductivity) were then adjusted within reasonable ranges to maximize the number of slope movement locations per unit area captured in the high hazard (upper threshold and unstable) SINMAP zones.

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FS = factor of safety:
a = topographic catchment area
C = dimensionless cohesion = (**Cr** + **Cs**)/(**h**$\mathbf{p_s}$**g**)
Cr = root cohesion; **Cs** = soil cohesion;
h = soil thickness; $\mathbf{p_s}$ = soil density; **g** = gravity constant
$\mathbf{h_w}$ = height of water;
R = recharge
r = water density ($\mathbf{p_w}$) to soil density ($\mathbf{p_s}$) ratio
T = soil transmissivity = soil hydraulic conductivity x **h**
Ø = soil internal angle of friction
θ = slope

$$h_w/h = \text{Relative wetness} = \min\left(\frac{R\,a}{T\sin\theta}, 1\right)$$

$$FS = \frac{C + \cos\theta\left[1 - \min\left(\frac{R\,a}{T\sin\theta}, 1\right) r\right]\tan\phi}{\sin\theta}$$

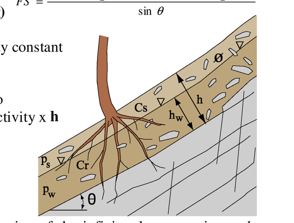

Figure 1. Schematic showing the modified version of the infinite slope equation and slope conditions used in SINMAP (adapted from Pack and others, 1998).

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

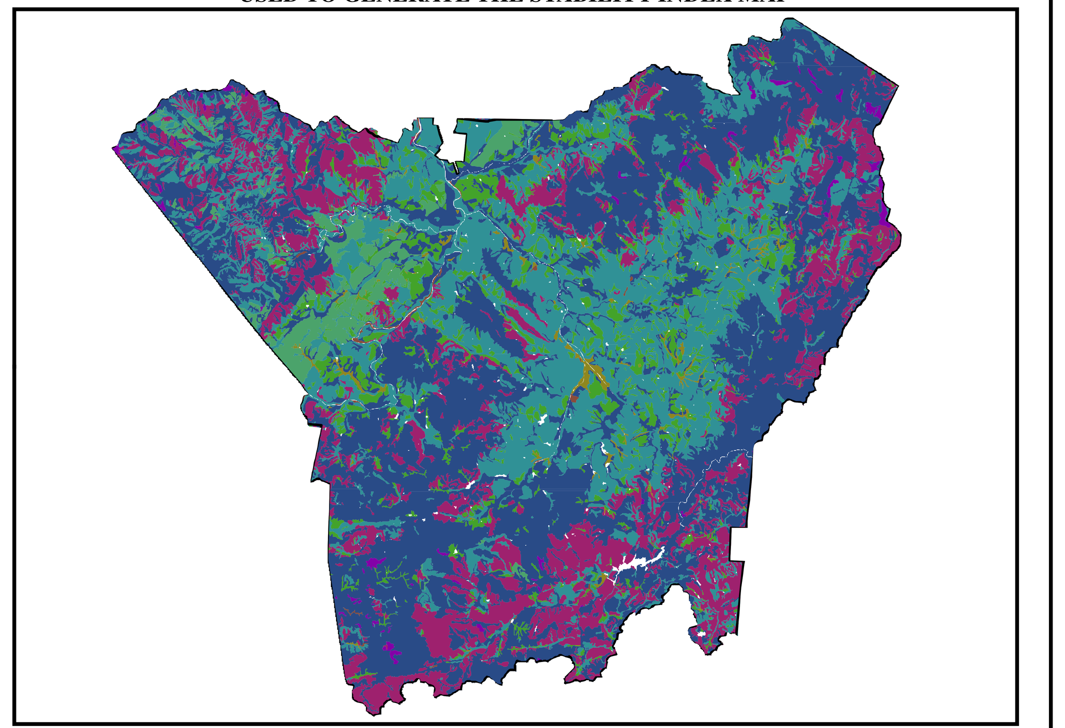

Figure 2. SINMAP calibration regions for Henderson County derived from the Soil Survey Geographic database for Henderson County (United States Department of Agriculture, 2008). Uncolored areas on the map represent water.

Region [1]	Calibration 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	Ae, Su	0.05	267	0.08	0.12	23	42
2	ArG	1.54	32	0.04	0.22	33	45
3	BaB, BaC, Ko, TeB, TeC	0.03	86	0.57	0.59	23	42
4	Co, EnB, HyB, HyC, HyE, PoE, PoF, PoG, Ro, SpF, TsC, TsE	0.11	646	0.16	0.23	23	42
5	BrC, BrE, BrF, EvC, EwE, EwF, EwG	0.09	472	0.18	0.25	22	42
6	AhE, AhF, AhG, CaG, CfE, CfF, Cu, DeA, DeB, EdC, EdE, EdF, To, TuC, TuE, TuF	0.12	414	0.20	0.22	24	45
7	Ha	0.15	46	0.11	0.76	23	42
8	FaC, FaE, FaF, TaF	0.09	133	0.18	0.23	23	42

Explanatory notes for Table 3:

[1] **Region.** A numbered area used in the SINMAP modeling process with similar soil, geologic, and hydrologic properties derived from the Soil Survey Geographic database for Henderson County (United States Department of Agriculture, 2008). Each region is made up of map units grouped according to similar soil properties. 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] **Calibration Unit.** Abbreviations for soil map units from the Soil Survey Geographic database for Henderson County (United States Department of Agriculture, 2008) grouped into calibration regions.

[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 by the thickness of the soil. Values for soil hydraulic conductivity were derived primarily from the Soil Survey Geographic database for Henderson County (United States Department of Agriculture, 2008) and checked against values at three detailed study sites, data from elsewhere in the county, and those reported in the literature. Values for soil thickness were derived primarily from field data collected by the N.C. Geological Survey. The recharge rate was modeled as 5in (125mm) per day, the minimum threshold rate for debris flows to initiate in the Southern Appalachians (Eschner and Patric, 1982). The value for T/R represents length of hillslope, in meters, required to develop soil saturation during the 24-hour 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 the effective internal soil friction angle. Internal friction is the friction between individual grains within a mass of material.

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