STABILITY INDEX MAP OF WATAUGA COUNTY, NORTH CAROLINA

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

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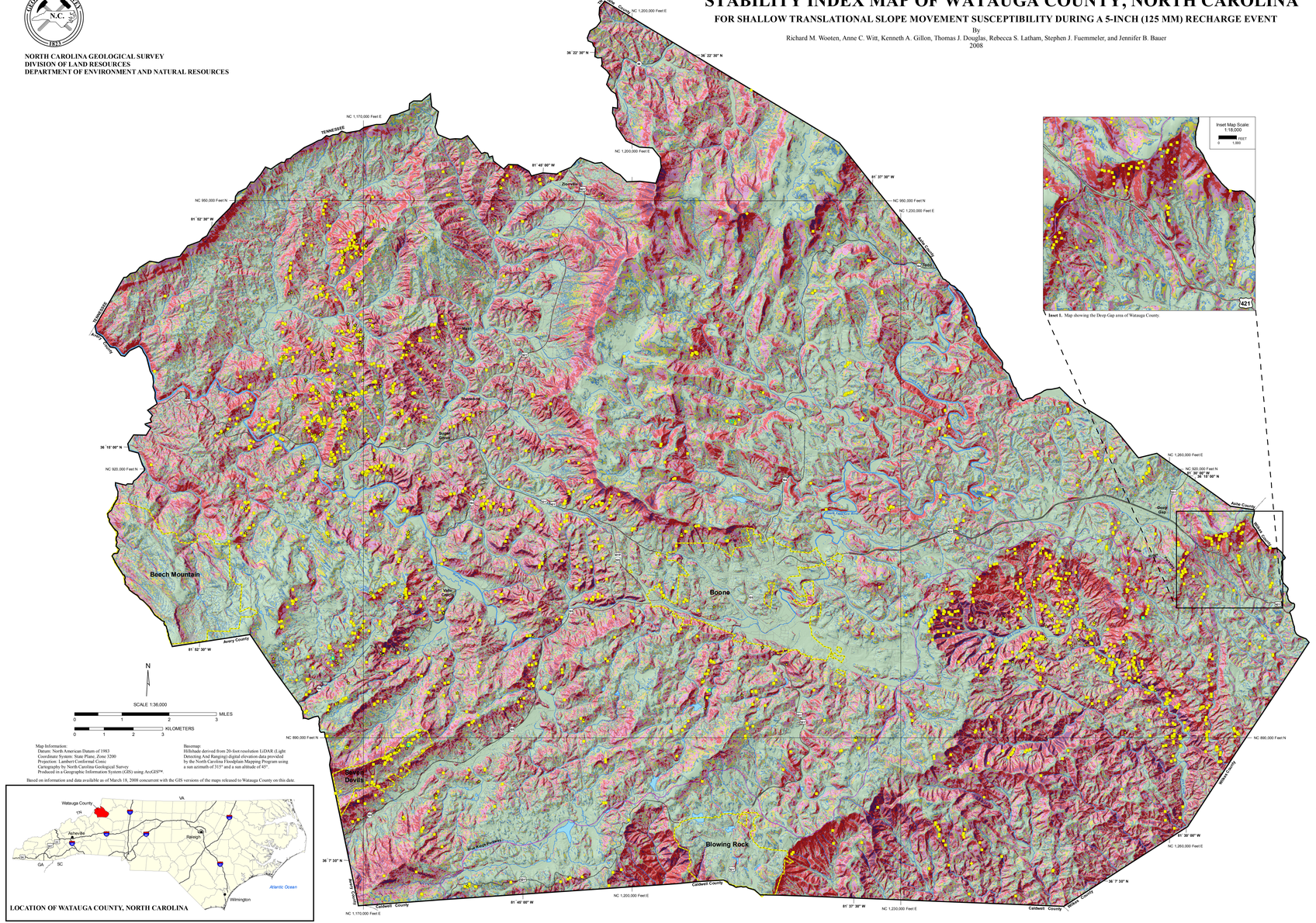
GEOLOGIC HAZARDS MAP SERIES 3
SLOPE MOVEMENT HAZARD MAPS OF WATAUGA COUNTY, NC
SHEET 2 OF 4, VERSION: MARCH 18, 2008



Map Information:
Datum: North American Datum of 1983
Coordinate System: State Plane, Zone 3200
Projection: Lambert Conformal Conic
Cartography by North Carolina Geological Survey
Produced in a Geographic Information System (GIS) using ArcGIS™

Based on information and data available as of March 18, 2008 concurrent with the GIS versions of the maps released to Watauga County on this date.

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

LOCATION OF WATAUGA COUNTY, NORTH CAROLINA

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 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).

Roads
- Primary Roads
- Secondary Roads
- Blue Ridge Parkway

Rivers
- Major Rivers
- Minor Rivers
- Municipal boundaries
- Watauga County boundary

Slope Movement Initiation Zones
- Debris/Earth Blowout
- Debris/Earth Flow
- Debris/Earth Slide
- Debris/Earth Composite
- Green Halo Indicates a Detailed Study location

Note: Depicts only shallow translational slope movements that occurred on unmodified slopes used for model calibration.

Material definitions:

debris – Soil that contains a significant proportion of coarse material in which 20% to 80% of the particles are greater than sand sized in the range of 0.08 inches (2 mm).

earth – Soil in which about 80% or more of the particles are smaller than 0.08 inches (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 displacing 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) and Jackson (1997).

Percentage of County in each Predicted Stability Zone

Percentage of Landslides in each Predicted Stability Zone

Explanatory notes for Table 1:

[1] Relative Potential for Shallow Translational Slope Movements to Initiate. This column designates the relative hazard ranking of the potential for debris flows to initiate 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 on 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 a modified version used in Pack et al. (1998) of 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 or improved drainage; destabilizing factors include increased wetness or loading, or loss of root strength.

	Stable	Mod Stable	Quasi-Stable	Lower Threshold	Upper Threshold	Unstable	Total
Area (km2)	237	77	127	191	132	24	787
% of Region	30%	10%	16%	24%	17%	3%	100%
# Landslides	25	29	111	575	1019	343	2102
% of Slides	1%	1%	5%	27%	48%	16%	100%
Frequency/Unit Area	0.1	0.4	0.9	3.0	7.7	14.4	2.7

Table 2. Statistical summary for each stability class in Watauga County.

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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 Carolin a Geological Survey (NCGS) to map landslide hazard areas in the state. The mountainous Watauga County was selected as the second county after Macon County to be mapped because of the large number of landslides and the 14 landslide deaths associated with the August 13 - 14, 1940 storm, and the fast -growing population potentially at risk from 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 a nd location of areas where slope movements have occurred, or are likely to occur, and the general extent and impact 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 intended to substitute for a detailed, onsite analysis by a qualified geologist or engineer.

The slope movement hazard map series for Watauga County consists of four maps, Geologic Hazards Map Series 3 (GIHMS -3) Sheets 1, 2, 3, a nd 4 designed to be used in conjunction with each other. This map is Sheet 2: The accompanying maps are Sheet 1, Slope Movements and Slope Movement Deposits Map of Watauga County, North Carolina, and Sheet 3, Map Showing Zone of Potential Rock Fall Pathways in Watauga County, North Carolina, and Sheet 4, Map Showing Zone of Potential Rock Slope Instability, with Generalized Bedrock Geologic Compilation.

Stability Index Map (Geologic Hazards Map Series 3, Sheet 2)

This color -coded map delineates the predicte d 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 parameters used to create the predicted stability zones shown on the map. Table 1 does not predict that shallow translational slope movements will occur, but it predicts that if they do, where they are more likely to initiate given the assumptions and input parameters used i n 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 20 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 slo pe model (Pack and others, 1998, and Hammond and others, 1992) 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 (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. The model output is normalized to a dimensionless stability index range (0 - 1.25) and stability zones are assigned relative hazard rankings (high, moderate, and low) based on the calculated stability index ranges, and known slope movement occurrences.

Model input parameters include upper and lower bounded values for recharge, soil transmissivity (soil permeability or hydraulic conductivity multiplied by soil thickness), and other soil properties (i.e., unit weight, thickness, effective friction angle, effect ive cohesion, and soil/root cohesion). Because of the lack of detailed information, a uniform probability distribution to account for the variability and uncertainty inherent in natural systems. Visual -manual soil classifications and descriptions by NCGS ste ff and laboratory soil test results were used to correlate basic soil properties with mapped bedrock units and landslide deposits across the county. In addition, detailed geologic studies and soil testing was conducted at six debris flow initiation zones identified on the map. These soil classifications, descriptions and test results, along with literature values for soil properties given in Hammond and others (1992) and U.S. Dept of Agriculture (1996) were used to constrain reasonable ranges of soil inpu t parameters for the stability model runs. This correlation between soil properties and the parent geologic material was developed because a modern digital soil survey for Watauga County was not available.

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 (Hales and others, 2007). The slope angle input parameter was generated from the LiDAR elevation data to model saturation in convergent hollows.

The 5 -inch (125 mm) steady state recharge value used in the SINMAP analysis approximates an equiva lent 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 sufficient amount to initiate most shallow translational debris/earth flows and slides. Watershed studies at the U.S.D.A. Forest Service Coweeta Hydrologic Laboratory in Macon County, however, show that 3 -10% of rainfall from storms is direct runo ff (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 ca libration (i.e., the parameter adjustment process) was performed as recommended by the developers of SINMAP (Pack and others, 1998). Initial model input and output parameter values were selected from literature, or from field measurements. Model runs were primarily dimensionless cohesion, soil cohesion, soil thickness, slope angle of friction, and hydraulic conductivity) were then adjusted within reasonable ranges so that the majority of the slope movement locations 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 the known 2,102 shallow, translational slope movements (e.g., debris flows, debris slides and blowouts) that occurred on unmodified slope s (i.e., those without obvious ground -disturbing activity) appropriate for use in calibrating and verifying the model results.

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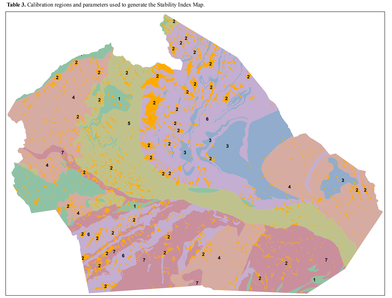
CALIBRATION REGIONS AND PARAMETER VALUES USED TO GENERATE THE STABILITY INDEX MAP

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	Cul, Cus, Pygp, PzZmgb, Zca, Zcbc, Zcbgr, Zcco, Zcn, ZYgg	0.80	46.15	0.25	0.34	24	42
2	slope movement deposits	3.72	172.44	0.10	0.19	21	35
3	Dsp, Zatss, Zattn, Zas, Zatss	0.64	449.51	0.17	0.19	21	42
4	Ybsg, Ywsg, Zabg	0.94	208.67	0.21	0.26	21	42
5	Ysp, Ynsg	0.35	38.45	0.23	0.28	21	42
6	SThnd, Ypp, Zaba, Zata, Zatmgb, Zcbg, Zgma, Zgmg	0.65	64.01	0.22	0.25	21	42
7	Pzmy, Pzthrv, Zgmag, Zgmf, Zgms, Zgmu, Zgrrv, Zgmwgf	0.50	52.21	0.21	0.25	21	42

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



Explanatory notes for Table 2:

[1] Region - A numbered area used in the SINMAP modeling process with similar soil, geologic and hydrologic properties derived from the Geologic Compilation Map of the county (GIHMS-3, sheet 4) and mapped slope movement deposits shown on the Slope Movement and Slope Movement Deposits Map (GIHMS-3, sheet 1). Each region is made up of geologic map units, which were grouped according to similar geologic and 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 - The specific bedrock and slope movement deposit geologic units that comprise each Region.

[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 field tests at six sites in the county, and checked against values for similar soil types reported in the literature. Soil thickness was derived primarily from field data. The recharge rate was modeled as 5 inches (125 mm) 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 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 soil and root cohesion relative to the soil density and thickness, as shown in Pack and others (1998). Upper and lower bounding values used for soil cohesion were constrained by values from triaxial shear strength testing of soil at six sites, and soil gradation and Atterberg limits testing of soil at 98 sites in the county. Root cohesion values were based on measured values at the U.S. Forest Service Coweeta Hydrologic Laboratory in Macon County, North Carolina (Hales and others, 2007).

[5] Friction Angle (degrees) Low/High - The upper and lower bounding values for the internal soil friction angle. Internal friction is the friction between individual grains within a mass of material. Upper and lower bounding values used for soil friction angle were constrained by values from triaxial shear strength testing of soil at six sites, and soil gradation and Atterberg limits testing of soil at 98 sites in the county.