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Landslide Susceptibility Map of Magoffin County, Kentucky

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Landslide Susceptibility of Magoffin County, Kentucky

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Purpose

The purpose of this map is to identify landslide-prone areas in Magoffin County in order to provide the public, as well as local and state government agencies, information about where landslides are likely to occur. This map represents geomorphic-based susceptibility modeling that focuses on physical slope characteristics and morphology, the quality of which is dependent on data accuracy and resolution of terrain models. The availability of high-resolution (5-ft digital elevation model) lidar derived datasets allows for the generation of terrain elevation derivatives such as hillshades, slope, aspect, curvature, and roughness, as well as identification of existing landslide deposits. These high-resolution lidar derived datasets, coupled with landslide inventory mapping, enable us to produce detailed, high-resolution landslide susceptibility maps. To access a web visualization of this map online visit the KGS Landslide Information Map service.

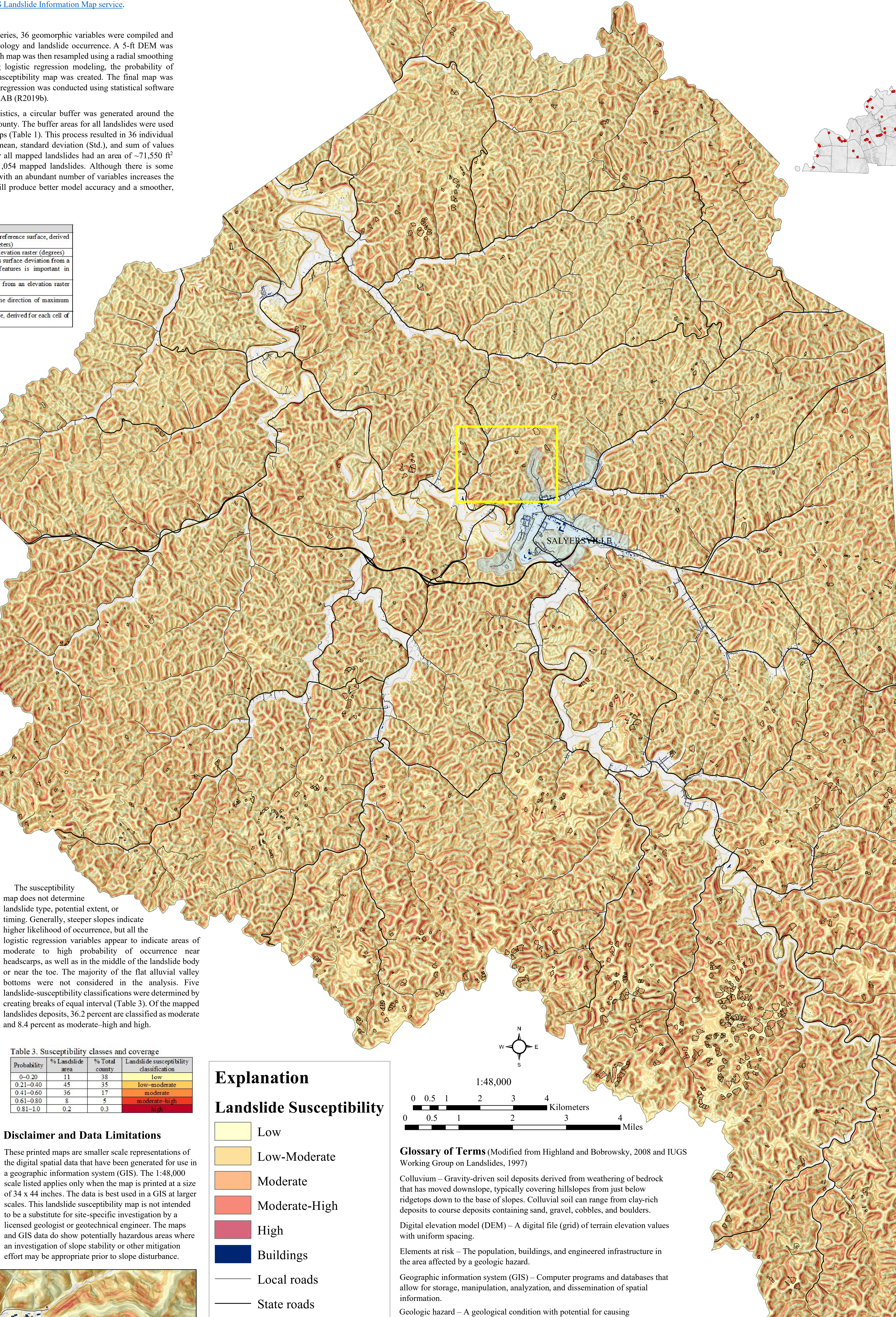
Map Production

To produce each landslide-susceptibility map in this series, 36 geomorphic variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. A 5-ft DEM was resampled to 10-ft cells to generate geomorphic maps. Each map was then resampled using a radial smoothing window of approximately 50-ft to reduce noise. Using logistic regression modeling, the probability of landslide occurrence was determined, and a landslide susceptibility map was created. The final map was produced using ArcGIS (ArcMap) v. 10.7.1. The logistic regression was conducted using statistical software JMP Pro (v. 14), as well as data analytics software MATLAB (R2019b).

To obtain consistent and systematic geomorphic statistics, a circular buffer was generated around the centroid point of 1,054 mapped landslides in Magoffin County. The buffer areas for all landslides were used to calculate six statistical values from six geomorphic maps (Table 1). This process resulted in 36 individual values for each landslide (maximum, minimum, range, mean, standard deviation (Std.), and sum of values within each buffer for each map). The buffer created for all mapped landslides had an area of ~71,550 ft^2 (radius of ~150 ft), which is the average area of the 1,054 mapped landslides. Although there is some codependence between variables, we argue that starting with an abundant number of variables increases the probability of capturing the strongest correlations and will produce better model accuracy and a smoother, more realistic map.

Table 1. Geomorphic variables

Geomorphic variable	Definition
Elevation	Vertical distance of a point above or below a reference surface, derived as a representation of the earth's surface (meters)
Slope	Gradient or steepness from each cell of an elevation raster (degrees)
Terrain roughness	A degree of terrain irregularity calculated as surface deviation from a smoothing window; scale of landscape features is important in choosing a smoothing-window size
Curvature	The second derivative value from each cell from an elevation raster (1/100 of a z-unit)
Plan curvature	Curvature of the surface perpendicular to the direction of maximum slope (1/100 of a z-unit)
Aspect	Compass direction of a downhill-facing slope, derived for each cell of an elevation raster



Landslide Susceptibility Model

Logistic regression models the probability of an event (a landslide) being a function of other variables, and quantifies probability based on statistical analysis of past landslides. Existing landslides are often susceptible to reactivation, which makes modeling the probability of occurrence and developing a susceptibility map with logistic regression particularly important.

The model uses a logistic function to model a binary dependent variable, called the indicator. The indicator was created with buffers covering landslides or non-landslide areas. A buffer was created partially covering the mapped landslide polygons ($N = 1{,}054$) in Magoffin County. A buffer was also created around the centroid of a non-landslide area ($N = 1{,}054$). The buffer has a radius of approximately 150 ft. The buffers are attributed with a 1 (landslide) or 0 (non-landslide). Since the geomorphic dataset contains the statistical information on presence or absence of a landslide, the results are log-odds for the value labeled "1" (landslides), which is a combination of one or more of the independent geomorphic variables. The value predicted is a probability of an event ranging from 0 to 1—i.e., an estimate of the maximum likelihood that a landslide will be influenced by the statistics of observed independent geomorphic variables.

Logistic regression results derive a coefficient of responses (β values) and determine which variables are significant (p-values). Low p-values indicate the data are unlikely to support a lack of difference; i.e., low p-values ($<$ 0.05) are relevant additions to the model because they are related to changes in the indicator variable. The coefficients express the effects of the predictor independent variables on the relative risk of being a landslide or not a landslide.

$$z = \beta_0 + \beta_1 V_1 + \beta_2 V_2 + \cdots + \beta_x V_x$$

where z is total contribution of all predictor variables (V), a model of relative risk of features in the landscape being a landslide or not a landslide. The cumulative distribution logistic function is:

$$P = \frac{1}{1 + e^{-z}}$$

where P is the cumulative estimated output probability of an event occurring (landslide occurrence or nonoccurrence). The output is confined between 0 and 1. The logistic regression analysis works well because the primary unknown is the relationships among the variables. We found that eight geomorphic variables were significant (p-value of ≤ 0.05). Table 2 shows the LogWorth ($-\log_{10}(p\text{-value})$), which is a transformation of the p-value and a way to visualize the relative weight of each variable. The higher the significance, the higher the LogWorth.

Table 2. Logistic regression result values

Geomorphic variable	p-value	β-coefficient	LogWorth
Minimum slope	9.63829E-10	0.093	9.016
Minimum curvature	1.21899E-07	–1.310	6.914
Std. elevation	3.27341E-07	0.163	6.485
Range elevation	0.00004	–0.039	4.446
Std. plan curvature	0.00004	–4.292	4.359
Mean roughness	0.00133	119.402	2.875
Sum of roughness	0.00160	–0.167	2.797
Std. curvature	0.02318	–2.271	1.635

Regression results show a connection between specific landslide morphologies that indicate a certain probability of landslide occurrence. The logistic regression model produced a landslide susceptibility map indicating where landslides are likely to occur based on the geomorphic conditions. The map indicates both existing deposits that have a moderate to high probability of subsequent movement, and locations that do not necessarily show obvious slope movement but may have features related to existing landslide activity.

The susceptibility map does not determine landslide type, potential extent, or timing. Generally, steeper slopes indicate higher likelihood of occurrence, but all the logistic regression variables appear to indicate areas of moderate to high probability of occurrence near headscarps, as well as in the middle of the landslide body or near the toe. The majority of the flat alluvial valley bottoms were not considered in the analysis. Five landslide-susceptibility classifications were determined by creating breaks of equal interval (Table 3). Of the mapped landslides deposits, 36.2 percent are classified as moderate and 8.4 percent as moderate–high and high.

Table 3. Susceptibility classes and coverage

Probability	% Landslide area	% Total county	Landslide susceptibility classification
0–0.20	11	38	low
0.21–0.40	45	35	low–moderate
0.41–0.60	36	17	moderate
0.61–0.80	8	5	moderate–high
0.81–1.0	0.2	0.3	high

Disclaimer and Data Limitations

These printed maps are smaller scale representations of the digital spatial data that have been generated for use in a geographic information system (GIS). The 1:48,000 scale listed applies only when the map is printed at a size of 34 x 44 inches. The data is best used in a GIS at larger scales. This landslide susceptibility map is not intended to be a substitute for site-specific investigation by a licensed geologist or geotechnical engineer. The maps and GIS data do show potentially hazardous areas where an investigation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

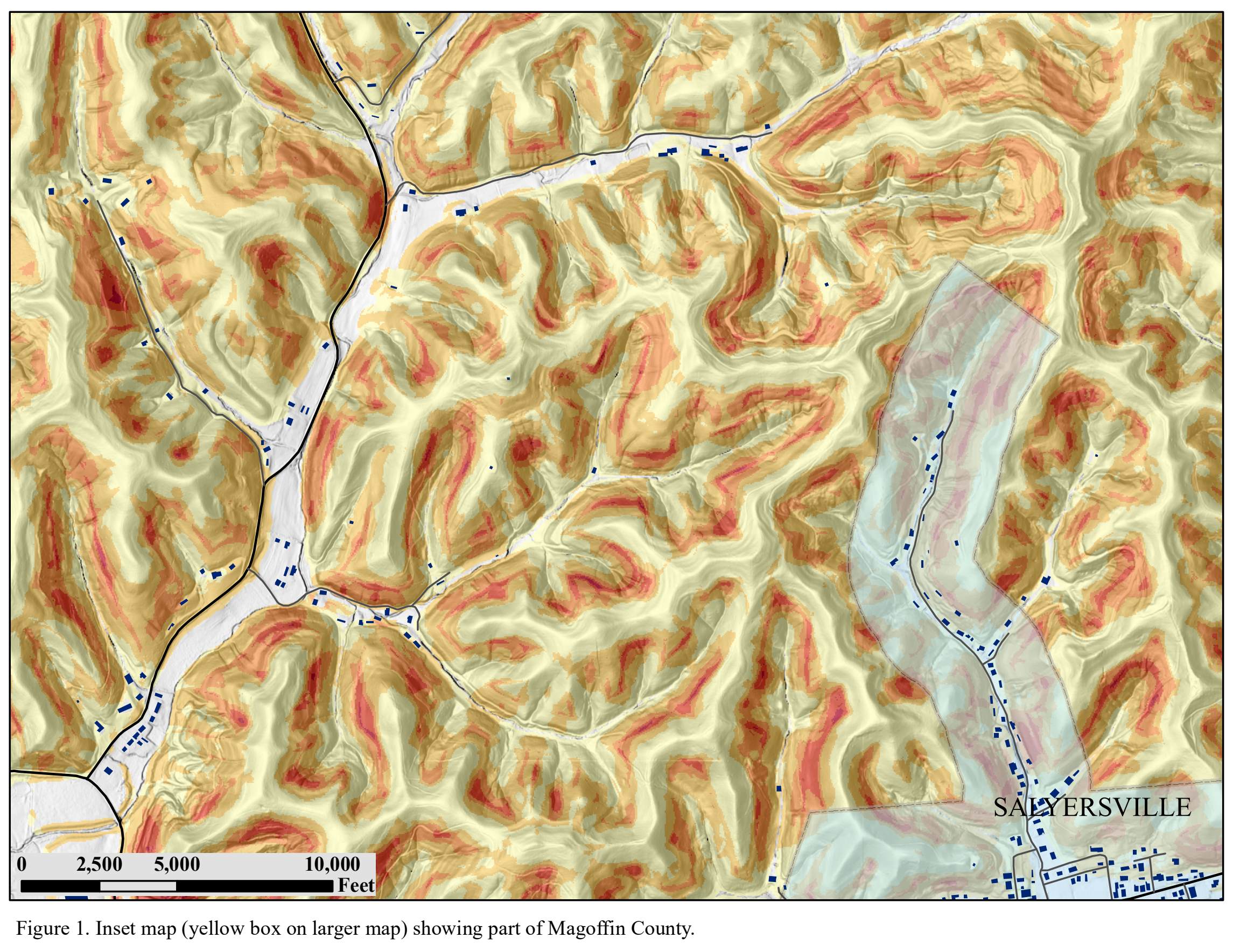


Figure 1. Inset map (yellow box on larger map) showing part of Magoffin County.

Explanation

Landslide Susceptibility

🟨 Low
🟨 Low-Moderate
🟧 Moderate
🟥 Moderate-High
🟥 High
🟦 Buildings
— Local roads
━ State roads
┼ Railroads
🟦 Corporate boundaries
⬚ Mapped landslides

References

Highland, L.M. and Bobrowsky, P., 2008, The landslide handbook—A guide to understanding landslides. U.S Geological Survey Circular 1325.

IUGS Working Group on Landslides – Committee on Risk Assessment, 1997, Quantitative assessment for slopes and landslides – The state of the art, In: D.M. Cruden and R. Fell (eds), Landslide Risk Assessment – Proceedings of the Workshop on Landslide Risk Assessment, Honolulu, Hawaii, USA, 19–21 February 1997 (Rotterdam: A.A. Balkema), 3-12

Glossary of Terms (Modified from Highland and Bobrowsky, 2008 and IUGS Working Group on Landslides, 1997)

Colluvium – Gravity-driven soil deposits derived from weathering of bedrock that has moved downslope, typically covering hillslopes from just below ridgetops down to the base of slopes. Colluvial soil can range from clay-rich deposits to course deposits containing sand, gravel, cobbles, and boulders.

Digital elevation model (DEM) – A digital file (grid) of terrain elevation values with uniform spacing.

Elements at risk – The population, buildings, and engineered infrastructure in the area affected by a geologic hazard.

Geographic information system (GIS) – Computer programs and databases that allow for storage, manipulation, analyzation, and dissemination of spatial information.

Geologic hazard – A geological condition with potential for causing undesired consequences, including threats to life or infrastructure. Examples of geologic hazards include landslides, earthquakes, volcanism, tsunamis, sinkholes, sinkhole flooding, and radon exposure.

Geomorphology – Scientific study of the landforms on the Earth's surface and of the processes that have shaped them.

Head scarp – The upslope part of a landslide where initial movement occurs and intersects the undisturbed ground surface.

Landslide inventory map – A map displaying areas where landslides have occurred. Map detail can range from reconnaissance-level point locations to larger extents of landslides that document more of the landslide features and processes.

Landslide susceptibility map – A map classifying areas that have the potential (as opposed to only a history) of slope movement. Areas determined by correlating factors that contribute to landslides, such as steep slopes or weak bedrock, with past distributions of landslides considered.

Landslide hazard map – A map that may visualize landslide susceptibility but also focuses on factors such as landslide scale, time, and extent.

Landslide risk map – A map that depicts the landslide hazard and its probability of occurrence in the context of loss potential, cost/benefit relationships, and socio-economic effects on the community.

Lidar – A form of remote sensing used to produce detailed laser scans of Earth's surface.

Mitigation – Activities that reduce or eliminate the probability of a hazard occurring, and or lessen the effects of the hazards when they do occur.

Pore-water pressure – The pressure exerted by water held in pore spaces in rock and soil on its surroundings; a key element in slope stability.

Probability – The likelihood of an event occurring, typically measured as a ratio of specific outcomes to the total number of possible outcomes. Expressed as a number from 0 to 1.

Relief – The difference in elevation between highest and lowest points of the surface in an area.

Risk – A measure of probability of occurrence or expected loss as a result of exposure to a hazard.

Risk assessment – The process of risk analysis and evaluation.

Stress – A measure of internal force per area acting on any surface as a function of its area.

Vulnerability – The degree of loss to a given element or set of elements at risk with the area affected by the geologic hazard. Expressed as a scale of 0 (no loss) to 1 (total loss).

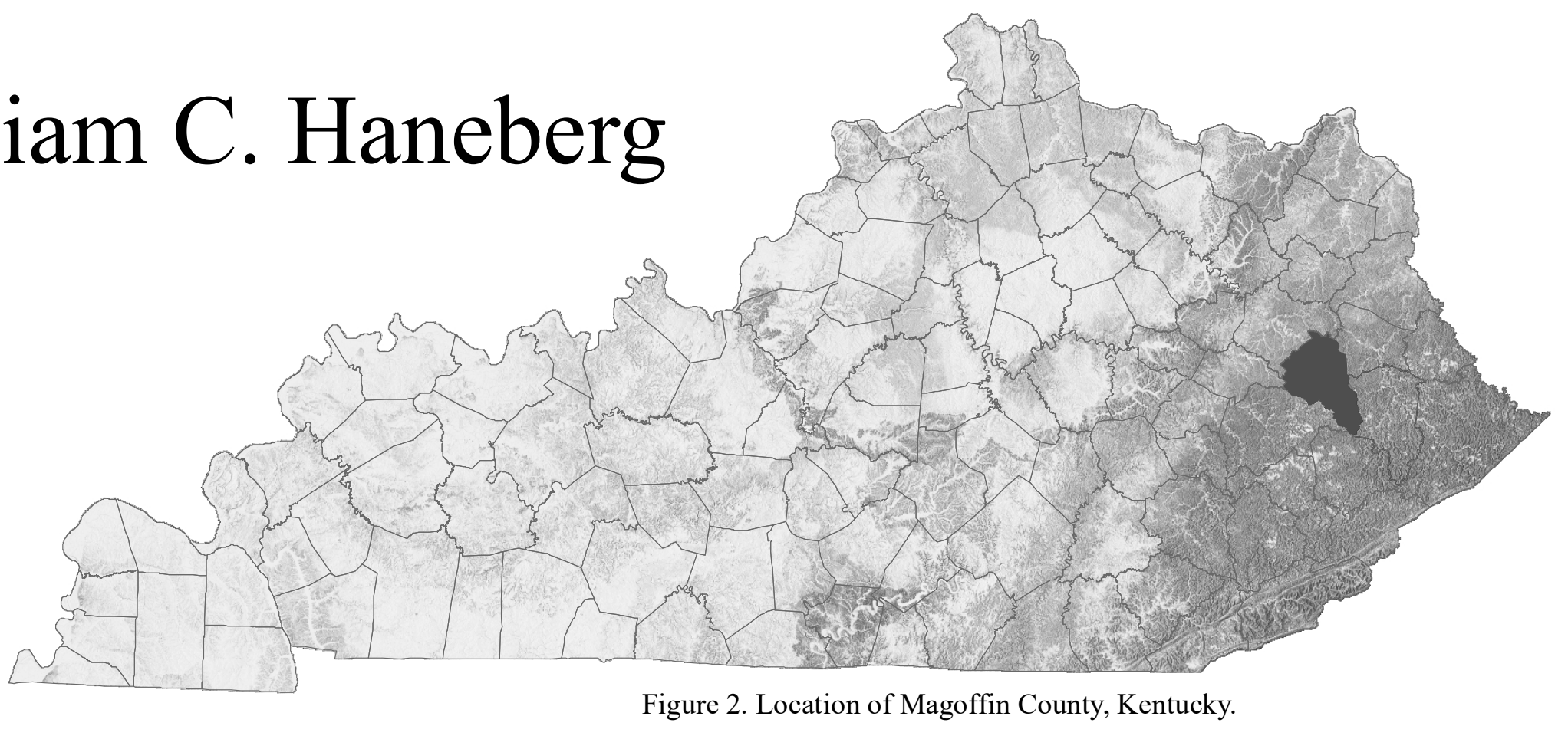


Figure 2. Location of Magoffin County, Kentucky.

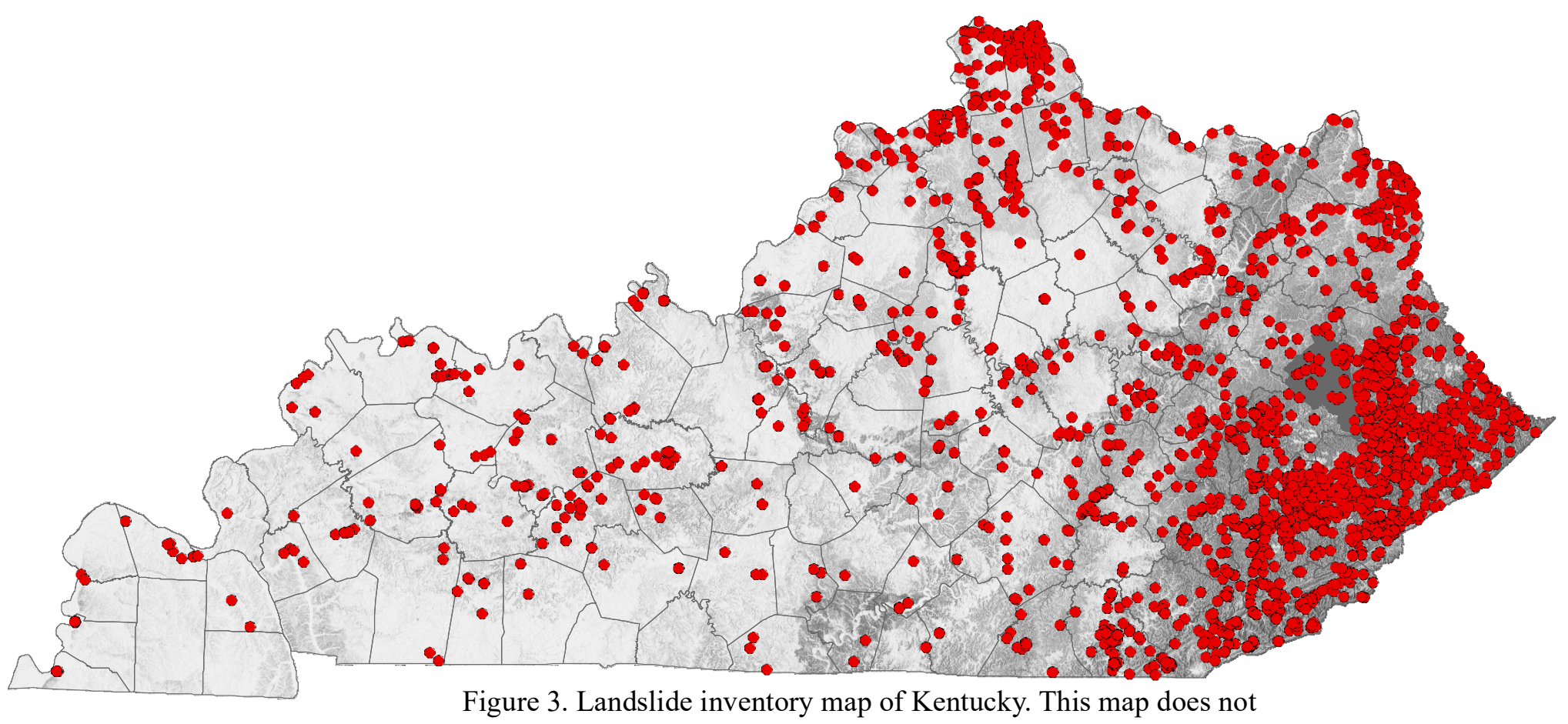


Figure 3. Landslide inventory map of Kentucky. This map does not include the mapped polygons shown on the larger map.

Landslide Basics

A landslide is a general term for the downslope movement of rock, soil, or both under the influence of gravity. The style of movement and resulting landform or deposit are influenced by the rock and soil type, slope location, and how fast the rock or soil moves. Landslides can occur slowly or rapidly. Several landslide types are represented in Figure 4: *(a)* creep *(b)* translational landslide *(c)* slump-earthflow *(d)* debris flow. The translational landslide is labeled with specific parts, which were used for the landslide inventory mapping and ultimately in the susceptibility modeling.

Diverse terminology and definitions among geologists, engineers, and the public are a reflection of the complex landslide processes. Some of the most common terms are landslide, mudslide, and rockslide. Other terms such as mass wasting, slope movement, and slope failure are also commonly used to discuss landslide phenomena. Regardless of which term is used, all landslides share physical and mechanical (in rock and soil) processes that explain their occurrence.

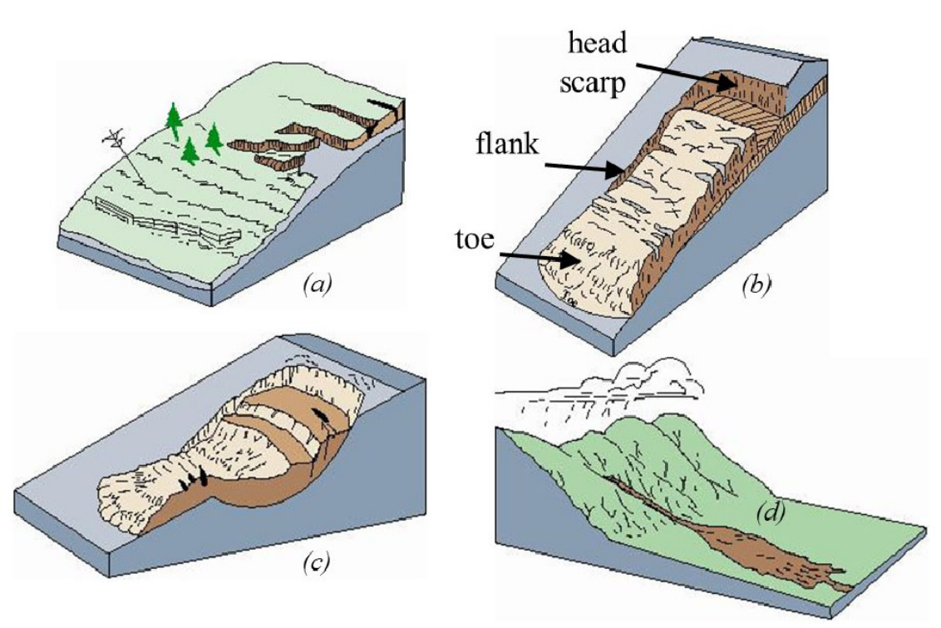


Figure 4. Landslide types, (a) creep (b) translational landslide (c) slump-earthflow (d) debris flow. Modified from Highland and Bobrowsky, 2008.

Landslides are caused by forces on steep slopes that exceed the strength of the hillslope soil. Forces can include increased pore-water pressure (from rainfall), gravity, or some type of slope modification (loading or excavating). A stable slope is one that balances the forces imposed (driving forces) with the strength of the material (resisting forces). A slope will fail if those conditions are disturbed by (1) increases the force, or (2) a change in resistance, both which cause a decrease in shear strength. The challenging part is that these forces act over time and space at different scales, meaning landslides are separated by causal conditions and triggers.

Examples of driving forces:

- Surcharge of weight at the top of the slope by adding artificial fill
- Intense or prolonged rainfall
- Removal of the toe of a slope by engineered cuts or natural stream erosion

Examples of change resisting forces:

- Saturated soil, increase in relative pore-water pressure from rainfall or, in stream banks, from rapid fall of water level in the stream
- Vegetation removal
- Expansion and contraction of swelling clay soils with wet-dry weather cycles
- Weathering of weak rocks

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