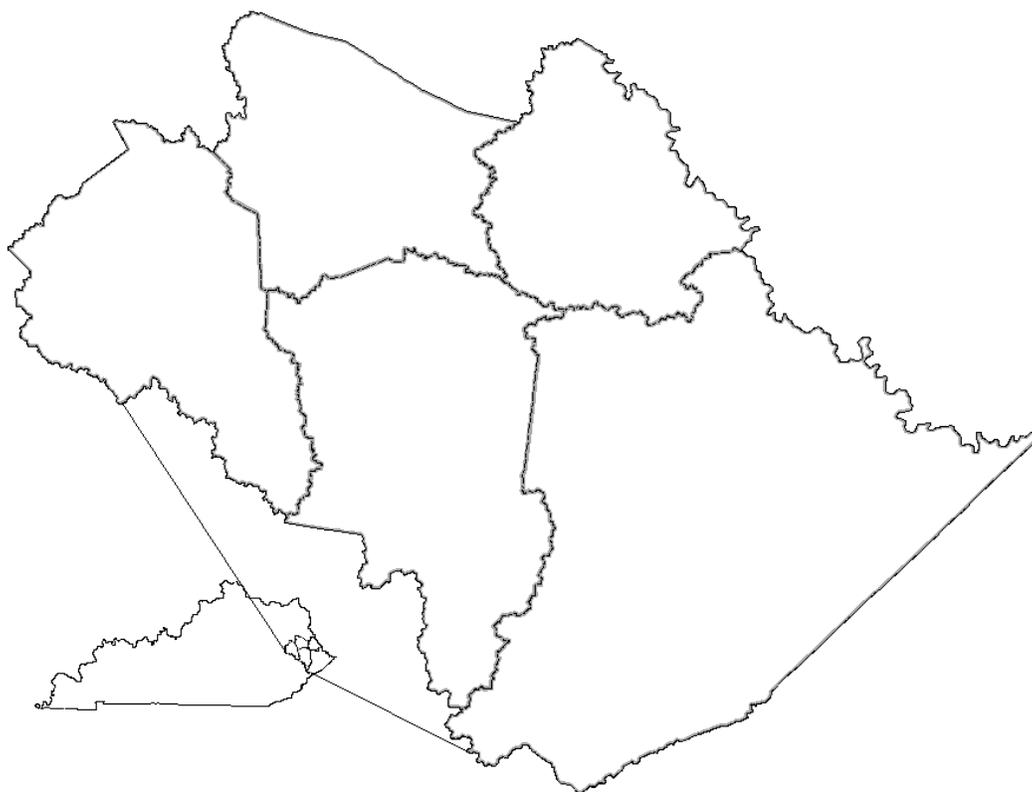


Multi-Jurisdictional Hazard Mitigation Plan for Landslides for the Big Sandy Area Development District, Kentucky



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INTRODUCTION

A landslide is a general term for the downslope movement of rock, soil, or both under the influence of gravity. Slope shape, rock, and soil type, and how fast the rock and soil move influence the style of movement and resulting landslide activity. Landslides occur when the strength of rocks or soil is exceeded by stress applied to those hillslope materials. Common stresses are gravity, increased pore-water pressure, earthquake shaking, and slope modification. Stresses 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 stresses imposed (driving forces) with the strength of the soil or rock (resisting forces). A slope will fail by (1) increases the stress, or (2) a change in resistance, both which cause a decrease in shear strength. The challenging part is that these stresses act over time and space at different scales, meaning landslide occurrences are influenced by contributions from both static causal conditions, as well as dynamic 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

Diverse terminology and definitions among geologists, engineers, and the public reflect 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. Landslides are classified into basic types (Fig. 1). The classifications presented here are from criteria by Varnes (1978) and Cruden and Varnes (1996) that are primarily based on the type of hillslope material and the type of movement. Material in a landslide mass

is either rock, soil, or a combination of both. The type of movement describes the mechanics of how the landslide mass is displaced, which is important for determining the level of hazard. Types of movement include fall, topple, slide, spread, and flow. “Type of movement” is often synonymous with “landslide type.”

Landslides have basic parts, including the surface of rupture, main scarp, landslide toe, tension cracks, and slide flanks. These parts play a role in the style of movement, velocity of the slide material, volume displaced, distance the slide might reach (extent), and any decisions regarding hazard mitigation and risk reduction.

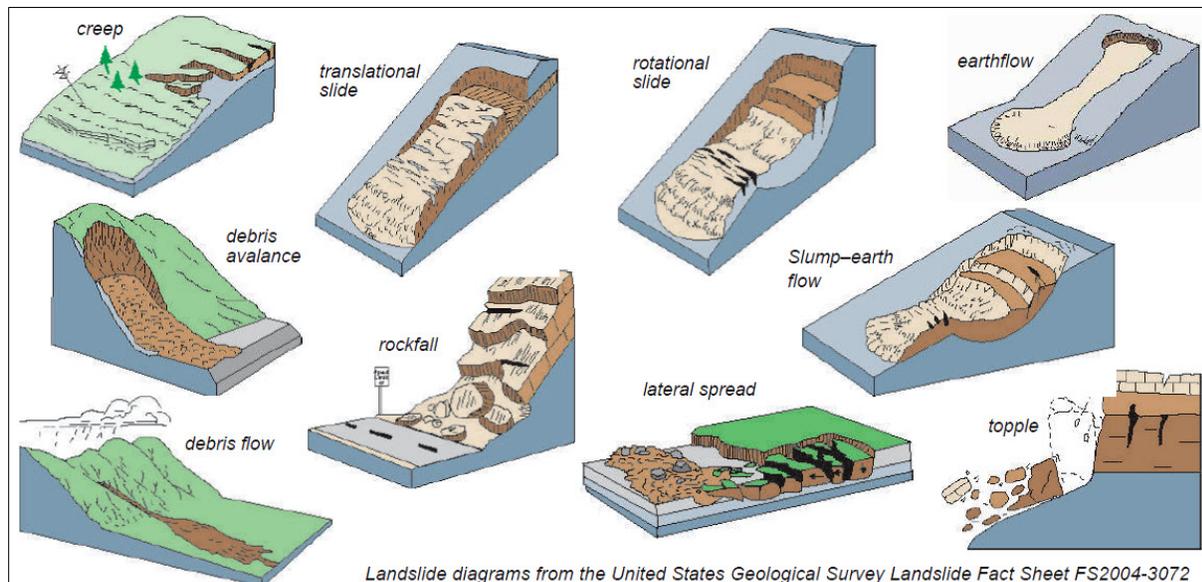


Figure 1. Landslide types.

Impact

Landslides occur statewide in Kentucky (Fig. 2). Landslides cost the state \$10 to \$20 million annually and cause damage to homes, commercial property, and transportation infrastructure (Fig. 3). These estimates are only for direct costs. Indirect costs such as road closures, decreased property values, and utility interruption are significant, but much more challenging to quantify. The sources of the annual direct cost estimates are from the Kentucky Transportation Cabinet, Kentucky Emergency Management, and the FEMA Landslide Loss Reduction (Wold and Jochim, 1989). Figure 3 shows roads that are classified based on Kentucky Transportation Cabinet (KYTC) maintenance cost for landslides (includes rockfalls) per route (Overfield and others, 2015). The cost data is compiled from KYTC maintenance records that span 2003 to 2009. An assessment of impacts, on roads for example, can support subsequent hazard and risk assessments.

The state and local government agencies that respond to landslides vary in their approaches to data collection, evaluation, and mitigation. Much of the economic loss and public cost is borne by federal, state, and local agencies responsible for disaster assistance and highway repair. Private costs involve mainly damage to land and homes, often resulting in financial ruin for homeowners. Damage from landslides is typically not covered under most homeowner’s insurance policies.

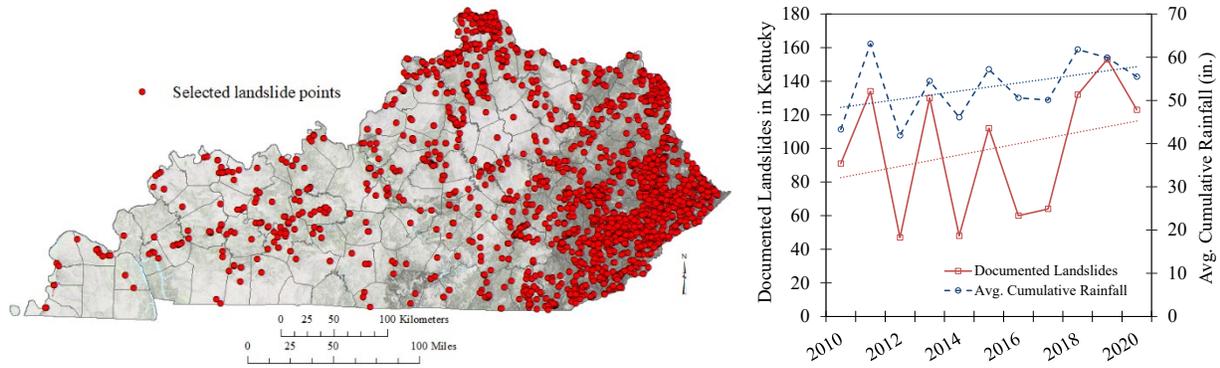


Figure 2. Documented landslide locations in Kentucky (left) and documented landslides versus statewide average cumulative rainfall (right). Dashed lines are linear trends.

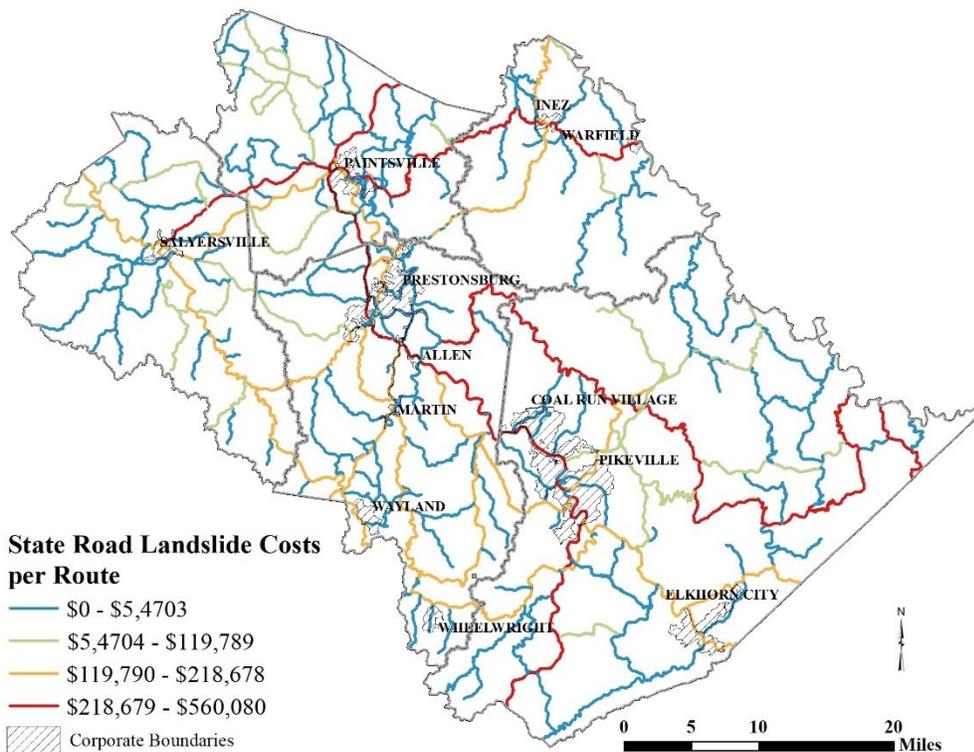


Figure 3. Landslide and rockfall costs per route in the Big Sandy Area Development District. These are only Kentucky Transportation Cabinet maintenance cost records that span 2003 to 2009. Large, expensive landslide mitigation projects are likely not included in these cost totals.

Landslides in the Big Sandy Area Development District (BSADD) that are documented in the Kentucky Geological Survey (KGS) landslide inventory database and contain information on failure date, landslide extent, failure location, damage, and cost is presented in a data table as **Appendix A**. Most documented landslides do not have associated impact data, thus most table cells are blank. However, this does not mean that the landslide did not have a negative impact, but that the information was not available. This table also does not include mapped landslides in Magoffin county that were used in creating the landslide susceptibility and risk maps for the entire 5-county area.

Purpose

The purpose of this plan is to implement measures designed to evaluate landslide hazards and reduce risk to individuals and property in the Big Sandy Area Development District (BSADD). The plan contains useful information for each community to incorporate mitigation strategies that will support building and infrastructure needs, land-use planning, event awareness, response, and recovery actions for communities in the region. The plan is an inclusive process that consists of three main tasks: (1) landslide susceptibility (2) landslide risk assessment and (3) mitigation strategy.

The landslide susceptibility and risk assessment helps to maintain and enhance the Big Sandy Area's local jurisdiction's Emergency Management Team's capacity to continuously make the region less vulnerable to hazards, improve coordination and communication with other relevant organizations, increase public understanding, support, demand for hazard mitigation, and reduce the high cost of recovery from hazards where economically feasible.

Areas of Governance

The BSADD is a multi-county, sub-state region authorized and organized pursuant to Statutes of the Commonwealth of Kentucky (KRS 147A). The Big Sandy Area Development District is charged with planning, promoting, and coordinating programs for regional economic and social development. Table 1 lists the designated member jurisdictions.

Table 1. Big Sandy Area Development District member jurisdictions.

County Code	Community Name/Jurisdiction	CID Number
210070 QBM0Z07TD	Allen, City of	210070
210069 QBM0Z07TC	Floyd County	210069
210071 QBM0Z07TE	Martin, City of	210071
210072 QBM0Z07TF	Prestonsburg, City of	210072
210073 QBM0Z07TG	Wayland, City of	210073
210074 QBM0Z07TH	Wheelwright, City of	210074
210339 QBM0Z0804	Johnson County	210339
210127 QBM0Z07UV	Paintsville, City of	210127
210158 QBM0Z07VP	Magoffin County	210158
210159 QBM0Z07VQ	Salyersville, City of	210159
210166 QBM0Z07VW	Martin County	210166
210362 QBM0Z080P	Inez, City of	210362
210364 QBM0Z080Q	Warfield, City of	210364
210298 QBM0Z07Z6	Pike County	210298
210263 QBM0Z07YE	Coal Run Village, City of	210263
210356 QBM0Z080K	Elkhorn City, City of	210356
210193 QBM0Z07WL	Pikeville, City of	210193

PLANNING PROCESS

This plan was prepared by the Kentucky Geological Survey (KGS) in close cooperation with stakeholders at the BSADD. While units of government, the BSADD Board of Directors and the Regional Mitigation Committee were closely involved with this planning process, this document is a result of and owned by the citizens of the area. Through local planning and the data collection, this plan is a document for the common vision of a safer more prepared region regarding emergencies associated with landslide hazards. Although this plan was compiled for submission, the pursuit of obtaining additional information and input

from local citizenry, major areas of interest, results from public meetings and broader community input has produced a detailed regional approach toward hazard mitigation. This plan goes beyond minimum requirements to document landslide hazards and conduct a broad risk assessment. A technical approach to model landslide susceptibility was conducted using updated high-resolution maps and sophisticated techniques to map landslide susceptibility.

Open public involvement and participation

The planning process involved BSADD specialists, BSADD stakeholders, planning agencies, and the public through in-person meetings and email correspondence. Participation included specifically reaching out to emergency management Directors, emergency management Area Managers, Mayors, County Judge Executives, Congressional Office Representatives, Flood Plain Coordinators, utilities officials, soil scientists, water management coordinators. The in-person meetings introduced and updated stakeholders about the FEMA-PDM project, discussed project goals, and outlined the benefits for the region. Presentations included of the scope of work, objective and technical aspects landslide susceptibility, risk assessment, and mitigation strategy. Critical stakeholder and public involvement included identification of high hazard areas, discussions of perceptions and tolerance of risk, and what in the plan will be useful. Example landslide susceptibility and risk map results were shared with stakeholders at the in-person meetings and with email correspondence. Several suggestions regarding shared common interests and what is useful to local officials were implemented into the map data and final plan.

In-person meetings occurred on March 28, 2019 and October 22, 2019. Email updates for stakeholder involvement occurred on April 2, 2020, August 14, 2020, December 10, 2020, and February 25, 2021. Quarterly reports from the sub-grantee (KGS and University of Kentucky Research Foundation) that documented details of the planning process, summary, and updates of project tasks for the relevant quarter, and anticipated activities were provided to Kentucky Emergency Management.

Review of technical data and existing plans

The plan is consistent with and supports the existing FEMA-approved Big Sandy ADD Multi-Jurisdictional Regional Hazard Mitigation Plan, as well as the Commonwealth of Kentucky Enhanced Multihazard Mitigation Plan. The plan data supports and enhances all parts of these plans including hazard mitigation goals of reducing risk, loss reduction, protecting the public, and reducing vulnerability to the built environment. Specifically, this plan addresses the BSADD plan Goal 4 “Protect public health, safety and welfare by increasing the public awareness of existing hazards and by fostering both individual and public responsibility in mitigating risks due to those hazards” and its subsequent Objective 4.1 “Educate the public about hazards prevalent in their jurisdiction.” This plan also addresses BSADD plan Goal 5 “increasing the technical capabilities of local jurisdictions to reduce potential losses” and its subsequent Objective 5.1 to “improve each jurisdiction's capability to identify and map vulnerable structures and critical facilities.” The landslide susceptibility and risk maps generated for this plan are intended to identify areas with the potential for slope movement and support goals of reducing losses in hazard areas, and emphasizing the general public needs to be aware of the potential risks and high potential risk areas.

HAZARD IDENTIFICATION AND RISK ASSESSMENT

Although hazard and risk are often used interchangeably, they are fundamentally different concepts. Hazard describes the natural phenomenon (a landslide), whereas risk ideally describes the probability of

loss or damage that could be caused by a landslide. The distinction between hazard and risk is of practical significance because measures and objectives designed for hazard mitigation may differ from objectives for risk reduction. Landslide processes fundamentally harbor significant uncertainty, including type of movement, rate of movement, earth materials, hydrologic triggers, slope stability calculations among other problems. Thus, the tools and approaches of reliable hazard and risk assessments vary widely and communication to stakeholders can be challenging. A successful and practical hazard and risk assessment provides a framework for quantitative risk analysis of slopes and landslides, requiring knowledge of the hazard, hazard analysis, identification of elements at risk, an analysis of the vulnerability, and a calculation of the risk using that knowledge base (IUGS Working Group on Landslides, 1997).

Geology

The BSADD is in the Eastern Kentucky Coal Field, part of the larger central Appalachian Basin. The 5-county area is 1,988 mi². Topographic relief can be as much as approximately 2,500 ft and the mean slope is 24.6°. The landscape is highly dissected, characterized by narrow ridges and sinuous alluvial valleys. Deeply incised stream drainages and variable hillslope morphologies range from long and narrow to bowl-shaped tributary valleys. Bedrock comprises flat-lying complex sequences of sandstones, siltstones, shales, coals, and underclay. For detailed information regarding mapped bedrock geology and specific rock descriptions, visit the Kentucky Geological Survey Geologic Map Service.

<https://kgs.uky.edu/kygeode/geomap/>

The hillslope morphology is often a good indicator of underlying bedrock geology, indicating the connection between bedrock and slope characteristics. For example, the more resistant lithologies, such as sandstones and siltstones, are often associated with steeper slopes and thinner soil cover. Shale beds, coals, and underclays weather easily and are known to be associated with high landslide occurrence (Crawford 2014; Chapella and others, 2019). Colluvial soil mantles slopes with varying thickness, and landslides are a dominant process that move soil and rock downslope. Colluvium transport downslope and its velocity range from imperceptible (creep) to rapid (catastrophic). Landslides that occur in colluvium are commonly thin (< 10 ft) translational slides or thicker rotational slumps, but both types have the capability of developing into damaging debris flows or debris slides, especially on steep slopes (Turner 1996; Crawford 2014).

BSADD Landslide Problem Areas

Landslides are a common occurrence in the BSADD. Debris flows, translational landslides, slumps, and rockfalls all have the potential of initiating depending on the hillslope morphology, soils, bedrock geology, and hillslope hydrology, among other factors. The KGS landslide inventory database documents known, existing landslides from a variety of sources (Fig. 3). These locations provide a general view of landslide activity across the area. Locations come from KGS research, published maps, state and local government agencies, the public, and media reports. Landslide inventory maps can be used to identify preexisting landslides and serve as a basis for landslide hazard and risk assessments. The absence of landslides in an area does not infer that a landslide does not exist or that the ground is stable. A semi-quantitative confidence ranking is assigned to each landslide feature. Confidence rankings range from “1” (low confidence) through “8” (high confidence) and reflect the relative value of different data and amount of information available. For access to the full landslide inventory and associated map data see https://kgs.uky.edu/kgsmmap/helpfiles/landslide_help.shtm. The statewide inventory database can be downloaded here: https://uknowledge.uky.edu/kgs_data/4/

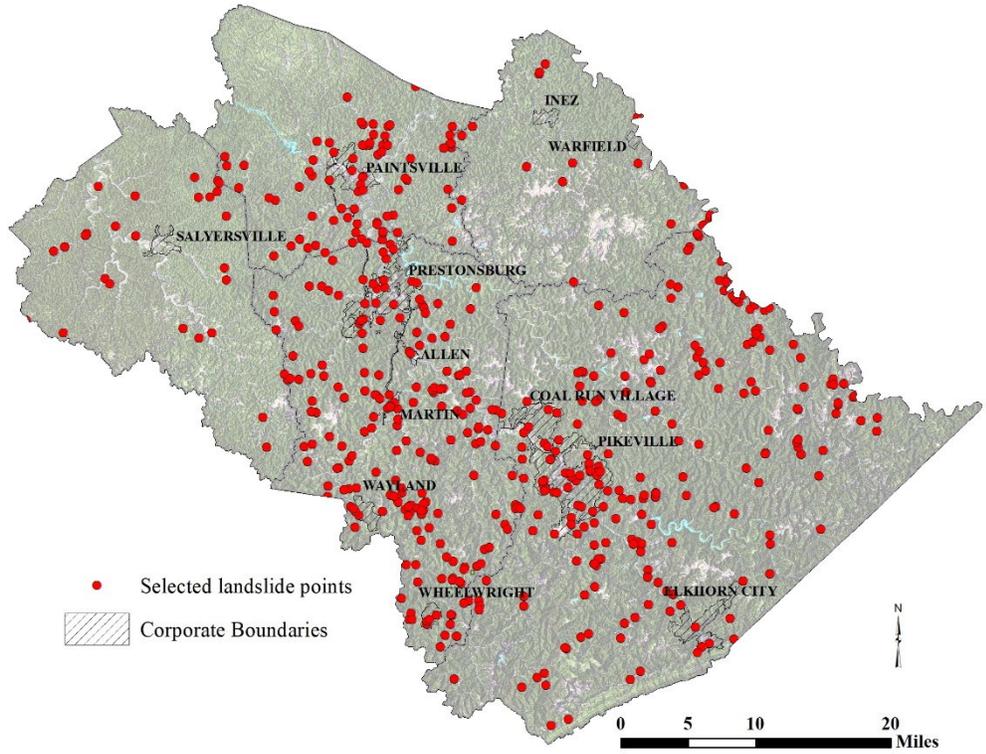


Figure 4. Selected landslide locations from the KGS landslide database. Not all documented landslides are shown on this map, for full access to the KGS landslide inventory see https://kgs.uky.edu/kgsmap/helpfiles/landslide_help.shtm

Examples of landslides in the BSADD (Figures 5–10)



Figure 5. Large landslide complex in Paintsville, Johnson County. This landslide damaged several homes and two streets in the area.



Figure 6. Distal toe of a damaging debris flow, Floyd County. The debris flow severely damaged a home and covered the road with debris.



Figure 7. Debris flow, Floyd County. This debris flow damaged a home and several adjacent structures on the property.



Figure 8. Landslide behind home, Pike County. This landslide initiated at an old contour mining area. The thick unconsolidated soil and rock severely damaged this home.



Figure 9. Landslide along stream bank that has damaged several buildings and property, Pike County.



Figure 10. Landslide that has displaced and damaged a road, Pike County.

Landslide Susceptibility

Landslide susceptibility is the relative tendency or potential for slope movement in an area (Highland and Bobrowsky 2008; Hearn and Hart 2019). A landslide-susceptibility map classifies or ranks slope stability in categories based on relationships of factors that contribute to instability, as opposed to a hazard map, which may indicate elements of time or estimated landslide extent (National Research Council 2004; Highland and Bobrowsky 2008). Landslide susceptibility maps in this report identify landslide-prone areas in the BSADD to provide the public, and local and state government agencies with descriptions and areas where landslides are likely to occur. The following sections describe the process and data used to model landslide susceptibility and risk, and ultimately producing maps and GIS datasets for the BSADD.

Landslide Inventory Data

To begin the process, we identified 1,054 landslides in Magoffin County (Fig. 11). Landslide extents were primarily mapped by visual inspection of a multidirectional hillshade derived from a 5-ft LiDAR digital elevation model (DEM). Secondary maps of slope, roughness, curvature, plan curvature, contour, and traditional hillshade, as well as aerial photography, were used to help identify landslide features and constrain confidence in mapping deposit extents. Extents of landslides that included features such as headscarps, flanks, toe slopes, and hummocky topography were digitized as GIS polygons. A range of sizes and shapes was observed, but landslide type, age, or potential activity was not determined. The mean landslide area is approximately 68,856 ft². Landslides under approximately 60 feet, for either width or length, generally stream-bank or roadway-embankment failures, were omitted from this study. While important, these smaller collapses typically have a different mode of failure and are controlled by different geomorphic parameters. This digitization did not characterize the landslides by type age or

determine future behaviors. The LiDAR DEM used for landslide identification in Magoffin County was generated in 2010. New landslides likely have occurred since this compilation. We used the Magoffin County landslide extents as the data catalyst for the landslide susceptibility and risk mapping. Landslide extents (polygons) were not mapped for the other BSADD counties.

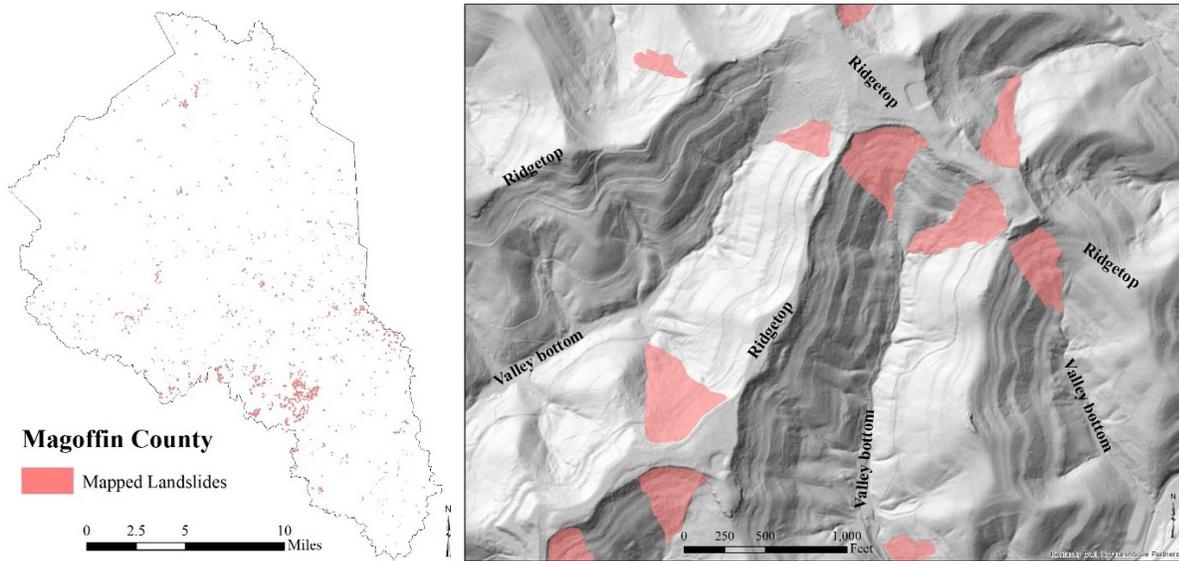


Figure 11. Landslide extents mapped in Magoffin County and zoomed-in example of hillshade map showing specific landslide deposit extents.

Geomorphic Data

Geomorphic maps of elevation, slope, terrain roughness, curvature, plan curvature, and aspect were generated from a resampled and smoothed digital elevation model (DEM) (Table 2). To obtain consistent geomorphic statistics, a circular buffer was generated around the centroid point of each mapped landslide from the Magoffin County inventory (Fig. 12). The landslide extent may, depending on the size and shape of the landslide, fall outside the buffer polygon. A buffer polygon that represents most of the landslide extent is superior to a single point in accounting for variability in landslide characteristics, however. The buffers for all 1,054 landslides were used to extract six statistical variables from each of the six geomorphic maps.

Table 2. Geomorphic variables calculated from the LiDAR.

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

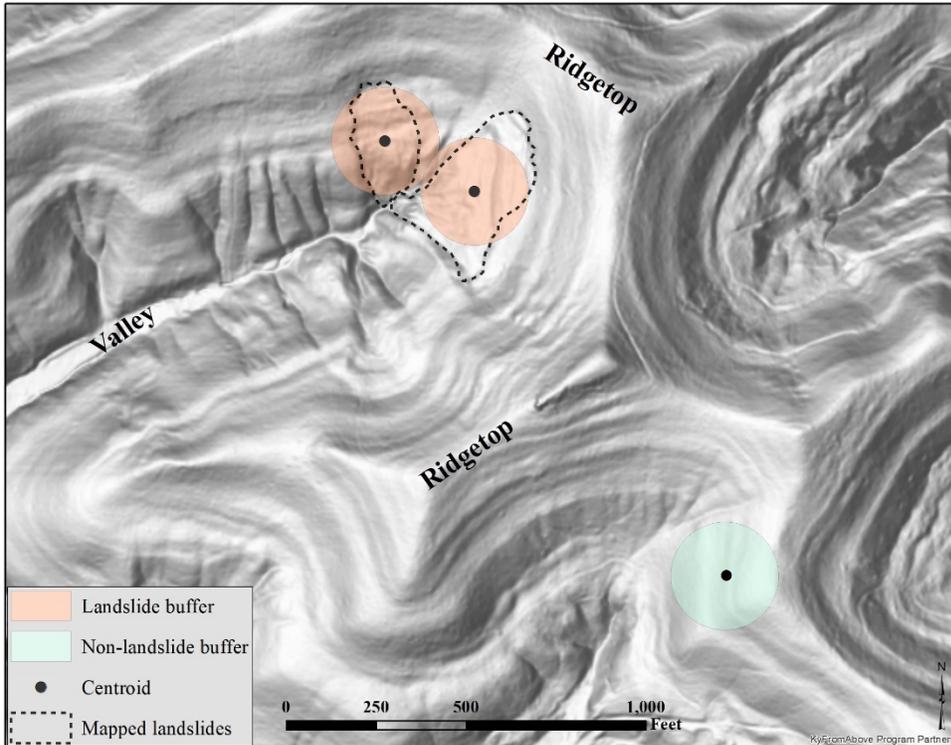


Figure 12. Landslide buffers around centroids of mapped landslides (pink) and a non-landslide (green), Magoffin County, Kentucky.

The GIS extraction process resulted in 36 individual statistical values for each landslide (maximum, minimum, range, mean, standard deviation, and sum of values within each buffer for each map—e.g., slope map). The buffer created for all mapped landslides had an area of 71,558 ft² (radius of 150 ft), which is the average area of the 1,054 inventoried landslides. We tested buffer radii of approximately 50, 100, 150, and 200 ft to determine which was the most effective. Although there is some co-dependence between variables, 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.

To prepare the susceptibility modeling, statistical data for non-landslide areas are required for the creation of a dependent variable called the indicator (1 or 0). Non-landslide areas must also have comparable buffer shapes so that contrasting feature statistics can be gathered. The same procedure (using a 150-ft radius buffer) was followed to generate geomorphic statistics for the non-landslide areas as for landslide areas (Fig. 12). The buffers were inspected for overlap between non-landslide areas and landslide areas and culled accordingly. Significant overlap dictated that 123 buffers be eliminated to maintain an equal number of random non-landslide and landslide statistics. Table 3 is an example subset of the entire 36-variable dataset, showing slope values for landslides and non-landslides. These statistics, plus the indicator variable, make up a binary dataset used in susceptibility model applied to all five counties.

Table 3. Example subset of the independent predictor variables related to slope and the indicator variable. The indicator variable is 1 for landslide buffers and 0 for non-landslide buffers. Each horizontal record is a landslide or non-landslide buffer.

Minimum slope	Maximum slope	Range of slope	Mean slope	Standard deviation slope	Sum of slope	Indicator
8.8	26.2	17.4	18.1	4.5	12,669.4	1
12.2	33.3	21.2	24.3	6.6	17,147.8	1
15.4	29.2	13.9	20.8	3.1	14,564.0	1
14.5	32.2	17.7	26.5	3.5	18,763.9	0
1.9	31.5	29.6	20.2	6.4	14,210.3	0
0.5	27.6	27.2	12.7	7.5	8,957.5	0

Model and Map Output

The modeling and resulting map production were a two-step process involving machine learning techniques. One, a bagged-trees technique elucidated the variables to gain a reliable first pass at variable importance. Bagged trees predict a weighted classification using the indicator variable to return an approximation of variable importance. Feature importance is a prediction of relative importance based on the combination of statistical variables. The technique is called “bagged trees” because it combines statistical results of many individual decision trees in order to improve model performance and reduce model overfitting ([Mathworks 2019b; https://www.mathworks.com/help/stats/treebagger-class.html](https://www.mathworks.com/help/stats/treebagger-class.html)). Two, a logistic regression technique models the **probability** of an event (a landslide) being a function of other variables, and quantifies probability based on statistical analysis of existing 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 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 variables. The two-step process avoids overcomplexity for the map results. The logistic regression indicates which modeled relationships are statistically significant to be used as inputs in map generation.

The bagged trees resulted in 12 variables being important and used in the logistic regression model. A threshold of feature importance of 0.8, just slightly above the average of 0.73, was a consistent mark of separation to choose the important variables (Table 4).

Table 4. Bagged trees result from highest importance to lowest (> 0.8 threshold).

Geomorphic Variable	Feature importance
Standard deviation plan curvature	1.08
Standard deviation elevation	1.06
Sum of plan curvature	1.03
Minimum slope	1.03
Mean plan curvature	1.01
Range elevation	0.95
Sum of roughness	0.95
Mean curvature	0.94
Sum of curvature	0.93
Mean roughness	0.92
Minimum curvature	0.89
Standard deviation curvature	0.83

We used JMP Pro statistical software package (SAS Institute Inc.) to conduct the logistic-regression analysis.

In logistic regression when the indicator variable is attributed (0, 1), the nominal response is:

$$\log\left(\frac{P(y=0)}{P(y=1)}\right) = \beta_0 + \beta_1V_1 + \beta_2V_2 + \dots + \beta_xV_x$$

where β_0 is the constant intercept, V is the geomorphic variables, and β is the coefficient estimates of responses 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, which increases or decreases with each value of the independent variable V —i.e., the rate of change in log-odds as V changes.

The above equation can also be written as:

$$z = \beta_0 + \beta_1V_1 + \beta_2V_2 + \dots + \beta_xV_x$$

where z is total contribution of all predictor variables, 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. We assumed the variables were not normally distributed or did not have linear relationships (Suzen and Doyuran 2004; Nandi and Shakoor 2009). Therefore, the logistic-regression analysis worked well because the primary unknown was the relationships among the variables.

The logistic regression analysis on the 12 variables found that eight geomorphic variables were statistically significant (p -value ≤ 0.05 ; Table 5). The p -value is defined as the largest probability, under the null hypothesis (default hypothesis that a quantity to be measured is zero about an unknown distribution). A very small p -value means that an extreme outcome in a set of results is unlikely under the null hypothesis, meaning that the statistical significance is large. Table 5 also shows the LogWorth ($-\log_{10}(p\text{-value})$), which is a transformation of the p -value and an easier way to visualize the relative weight of each variable. The higher the significance, the higher the LogWorth.

Table 5. Logistic regression results

Geomorphic Variable	p -value	LogWorth
Minimum slope	9.63829E-10	9.016
Minimum curvature	1.21899E-07	6.914
Standard deviation elevation	3.27341E-07	6.485
Range elevation	0.00004	4.446
Std. plan curvature	0.00004	4.359
Mean roughness	0.00133	2.875
Sum of roughness	0.00160	2.797
Std. curvature	0.02318	1.635

Five landslide-susceptibility classifications were determined manually by creating breaks of standard deviations from the mean. A compilation of the percent area, percent building, percent roads (state and local), and percent railroads that fall in each landslide susceptibility class are in the following tables (Tables 6–10). All buildings that exist on a less than 3-degree slope were excluded, which is approximately 62 percent of the buildings. A 50-ft buffer around the building footprints was used in the intersection with susceptibility to account for adjacent property or other structures. A 100-ft buffer was used for roads and railroads.

Table 6. Landslide susceptibility and intersection of assets for Magoffin County

Probability	Landslide Susceptibility	% Area	% Buildings (50-ft buffer)	% Roads (100-ft buffer)	% Railroads (100-ft buffer)
0–0.10	low	14.6	6.41	5.01	NA
0.11–0.27	low-moderate	43.1	77.47	59.63	
0.28–0.44	moderate	24.5	14.65	27.08	
0.45–0.61	moderate-high	12.9	1.32	6.87	
0.62–1.0	high	4.6	0.15	1.42	

Table 7. Landslide susceptibility and intersection of assets for Floyd County

Probability	Landslide Susceptibility	% Area	% Buildings (50-ft buffer)	% Roads (100-ft buffer)	% Railroads (100-ft buffer)
0–0.13	low	17.3	13.86	11.07	11.36
0.14–0.33	low-moderate	37.9	74.69	65.88	62.05
0.34–0.53	moderate	25.6	10.31	17.99	19.01
0.34–0.73	moderate-high	16.0	1.01	4.16	5.67
0.74–1.0	high	3.0	0.14	0.89	1.91

Table 8. Landslide susceptibility and intersection of assets for Johnson County

Probability	Landslide Susceptibility	% Area	% Buildings (50-ft buffer)	% Roads (100-ft buffer)	% Railroads (100-ft buffer)
0–0.10	low	14.3	6.32	4.72	6.04
0.11–0.28	low-moderate	44.1	75.67	61.82	42.55
0.29–0.45	moderate	24.1	16.24	25.34	29.81
0.46–0.63	moderate-high	12.6	1.53	6.28	10.86
0.64–1.0	high	4.7	0.24	1.84	10.75

Table 9. Landslide susceptibility and intersection of assets for Martin County

Probability	Landslide Susceptibility	% Area	% Buildings (50-ft buffer)	% Roads (100-ft buffer)	% Railroads (100-ft buffer)
0–0.12	low	15.5	8.13	7.28	11.10
0.13–0.32	low-moderate	41.7	74.48	61.96	58.22
0.33–0.52	moderate	23.6	15.31	23.69	21.30
0.53–0.72	moderate-high	15.1	1.89	5.60	6.96
0.73–1.0	high	3.8	0.19	1.47	2.42

Table 10. Landslide susceptibility and intersection of assets for Pike County

Probability	Landslide Susceptibility	% Area	% Buildings (50-ft buffer)	% Roads (100-ft buffer)	% Railroads (100-ft buffer)
0–0.12	low	17.1	10.44	9.01	7.84
0.13–0.34	low-moderate	38.8	76.77	66.13	61.18
0.35–0.56	moderate	24.8	11.55	19.38	22.09
0.57–0.77	moderate-high	15.9	1.09	4.76	7.45
0.78–1.0	high	3.2	0.15	0.76	1.42

The following figures show example area maps of landslide susceptibility in each BSADD county (Figures 13–17). The maps show susceptibility classifications derived from values of **probability** of an event (a landslide) being a function of other geomorphic variables. Data that occurs on less than 3-degree slope were excluded. The modeled probability and associated map classification is not a prediction of a scenario-based event (a rainfall event, for example) or a probability with a temporal component. The susceptibility is a static view based on observations and conditions of slopes.

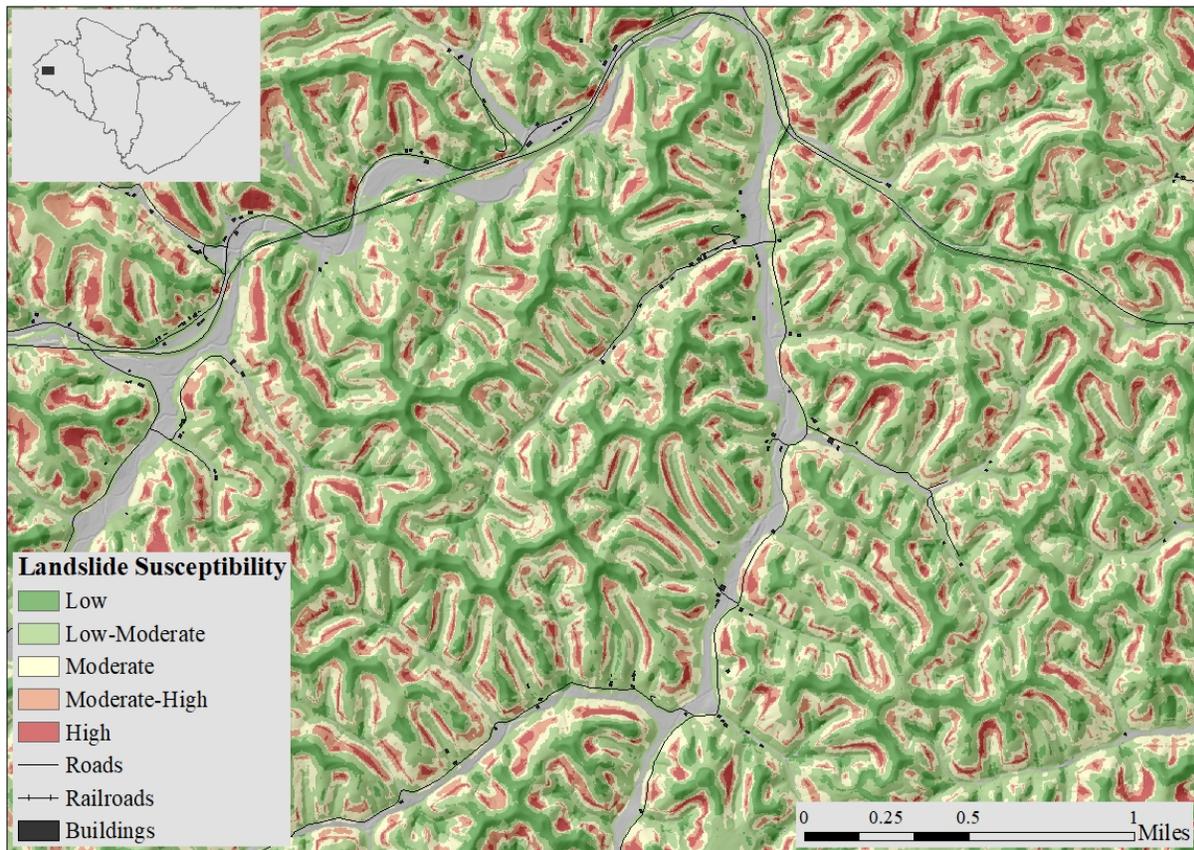


Figure 13. Landslide susceptibility in part of Magoffin County. See **Appendix B** for entire county map.

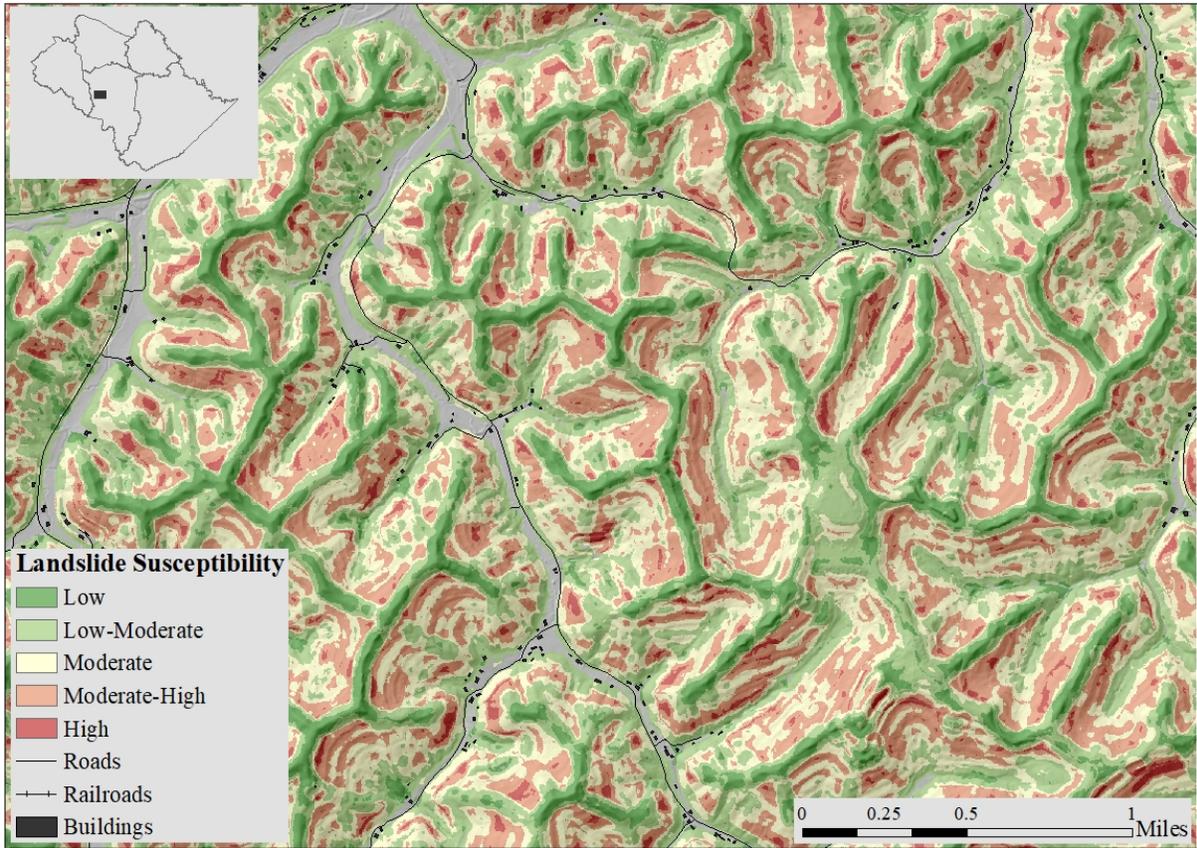


Figure 14. Landslide susceptibility in part of Floyd County. See **Appendix B** for entire county map.

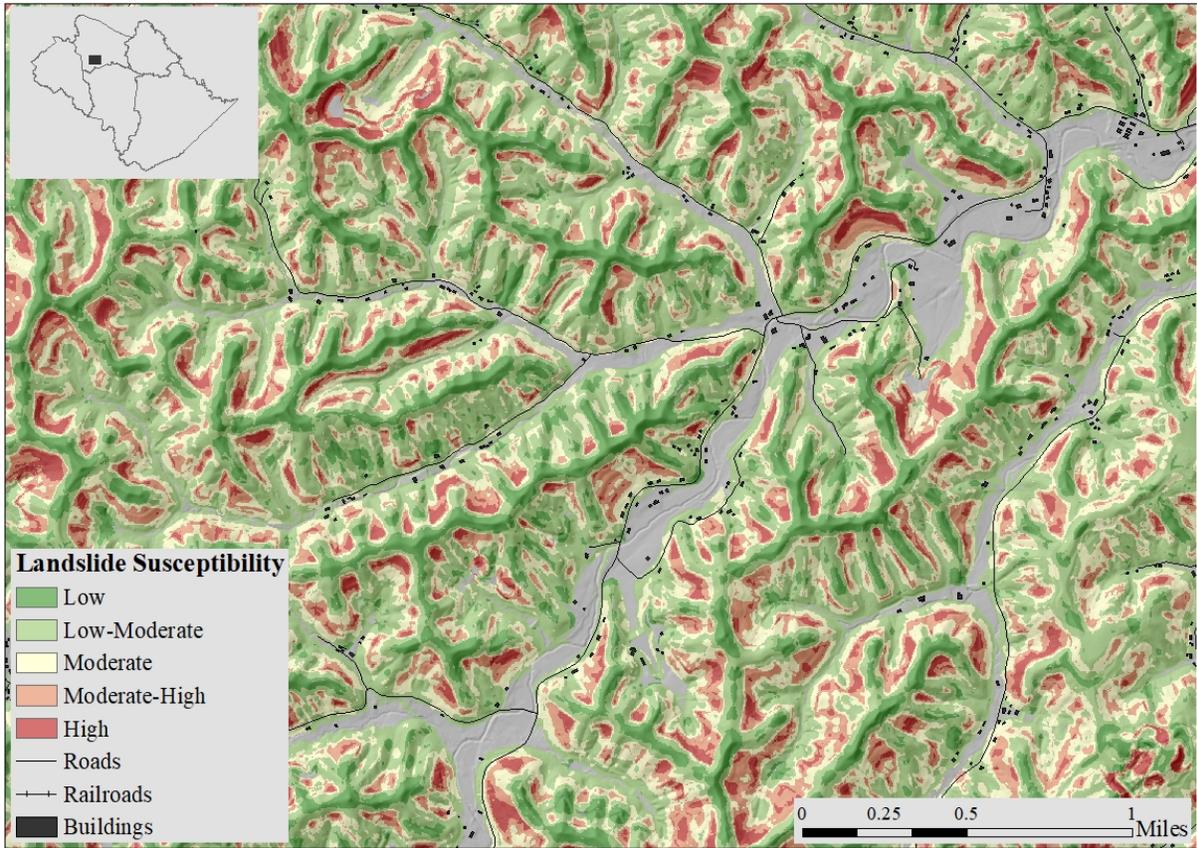


Figure 15. Landslide susceptibility in part of Johnson County. See **Appendix B** for entire county map.

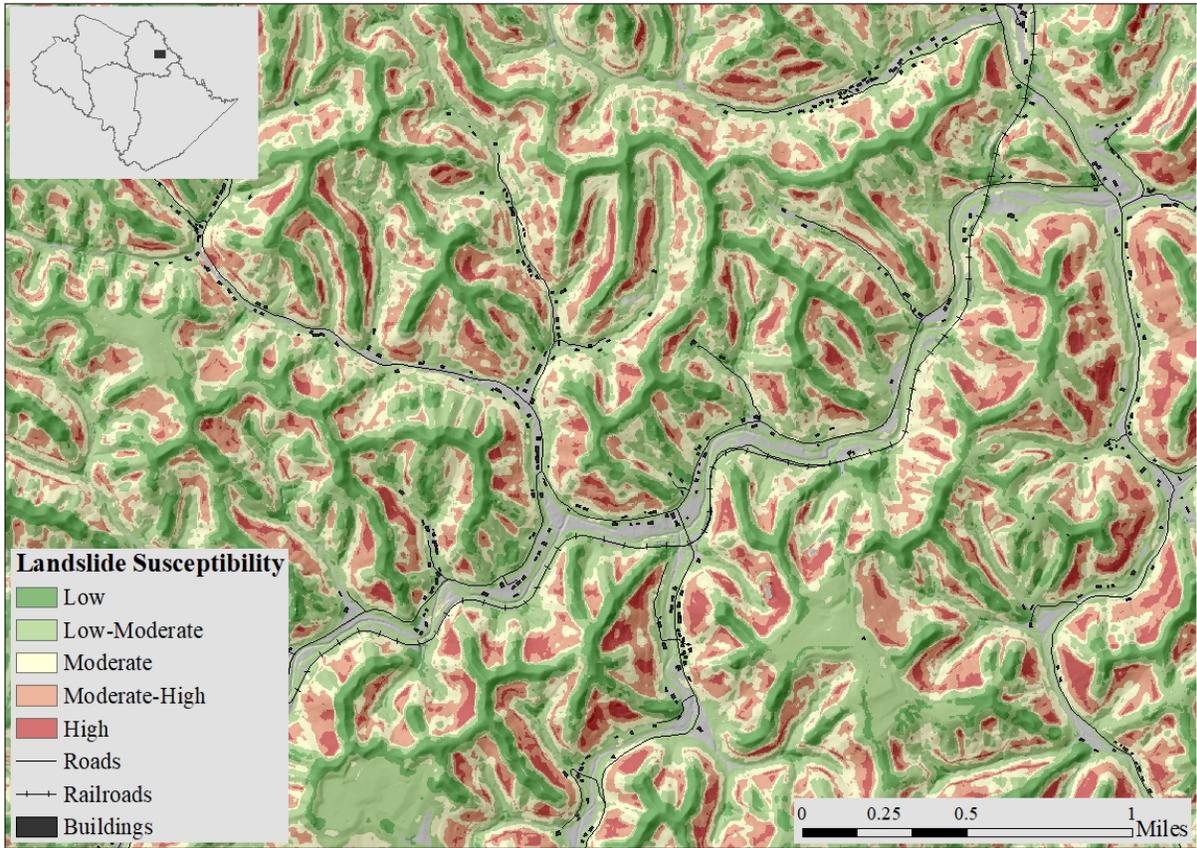


Figure 16. Landslide susceptibility in part of Martin County. See Appendix B for entire county map.

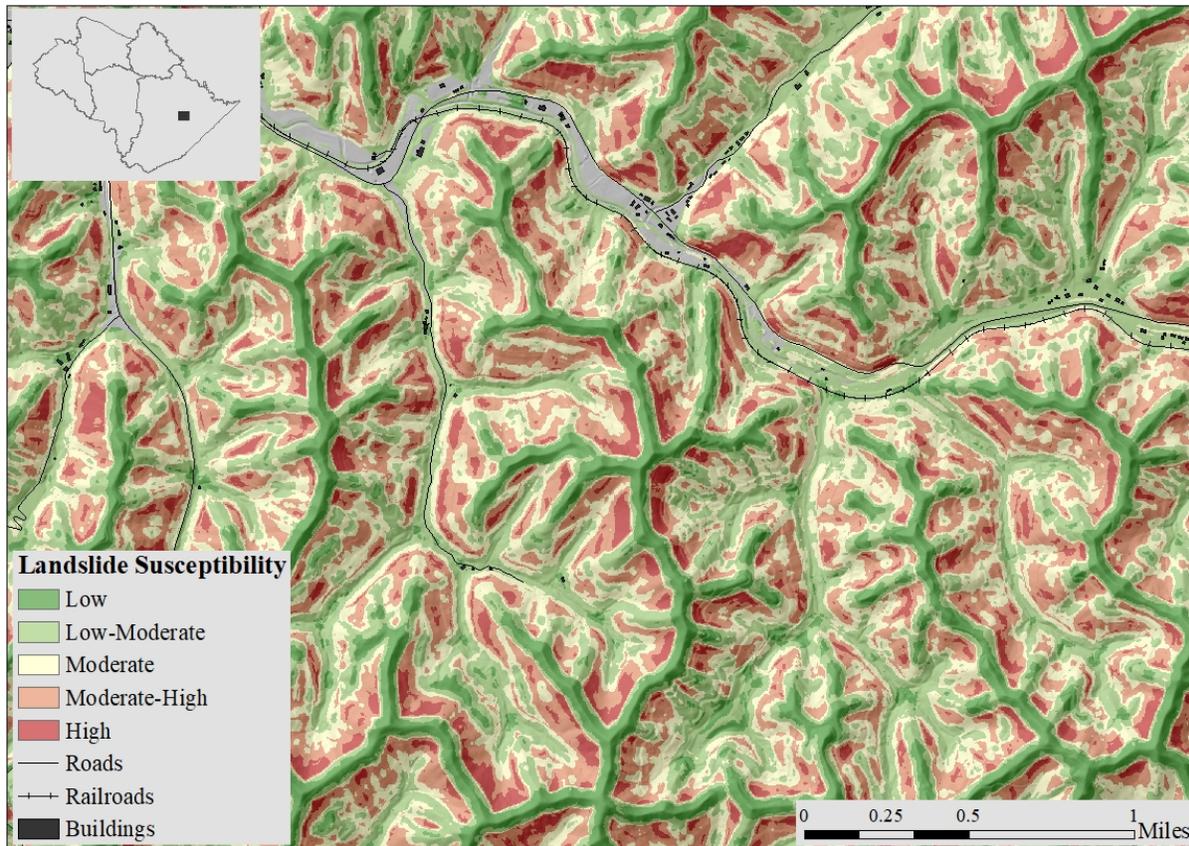


Figure 17. Landslide susceptibility in part of Pike County. See **Appendix B** for entire county map.

The maps represent geomorphic-based susceptibility modelling that focuses on physical slope characteristics, the quality of which is dependent on data accuracy and resolution of terrain models. The logistic-regression results show a connection between specific landslide morphologies, which indicates 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. Overall, the map emphasizes steep hillslopes and parts of ridgetops as having moderate, moderate-high, or high susceptibility. Steep slopes just below ridgetops and steep heads of catchments (often existing headscarps) are modeled as having moderate-high and high susceptibility. Steep planar slopes that are the sides of catchments or are above roads and streams are modeled as having moderate and moderate-high susceptibility. The map strikes a good balance between indicating existing deposits that have a moderate to high probability of subsequent movement, as well as assessing other parts of the slope that do not necessarily show obvious slope movement but may have features related to existing landslide activity. The majority of the flat alluvial valley bottoms were not considered in the analysis. The susceptibility map does not determine landslide type or potential runout or other temporal implications.

A landslide inventory of the neighboring Prestonsburg 7.5-minute quadrangle was used to validate the susceptibility model. The same methodology for landslide inventory described for Magoffin County used to identify the landslides in the Prestonsburg quadrangle. The same geomorphic variables (minimum slope, minimum curvature, standard deviation of elevation, range elevation, standard deviation of plan curvature, mean roughness, sum of roughness, and standard deviation of curvature) were used in the same logistic-regression model. For the Prestonsburg quadrangle landslides, 74.9 percent of the deposits were

in the moderate, moderate–high, or high landslide-susceptibility classifications. With the success of validating the susceptibility approach on a secondary inventory, the logistic regression results were applied to the entire BSADD. See **Appendix B** for full county maps.

Model limitations

A statistical, geomorphic-based landslide susceptibility model tends to simplify the variables that trigger landslides. Taking only those hillslope geomorphic factors that can be relatively easily mapped in an area, or derived from a DEM, generalizes landslide type and the causal factors such as hillslope hydrologic fluctuations (van Westen et al., 2003). Using a landslide inventory as the basis for this model assumes that landslides happen under the same combination of conditions throughout the study area and through time, whereas in reality, environmental factors change continuously.

Another more specific limitation occurred with heavily modified slopes (primarily roadcuts and surface mines). The landslide buffer of 150 ft used to extract the geomorphic statistics and generate the variables resulted in some artifacts in the susceptibility results. Because we used a circular buffer, roughly circular artifacts are present in some areas of the resulting map. This occurs most often with heavily modified parts of the landscape (surface mine operations, for example), where there are sharp unnatural breaks between steep slopes and flat, modified ground.

Landslide examples and model check

Several landslides occurred in the BSADD during the development of, or after the completion of the landslide susceptibility mapping. Locating the landslides and visually checking the performance of the maps in these areas proved successful (Figs. 18–21).

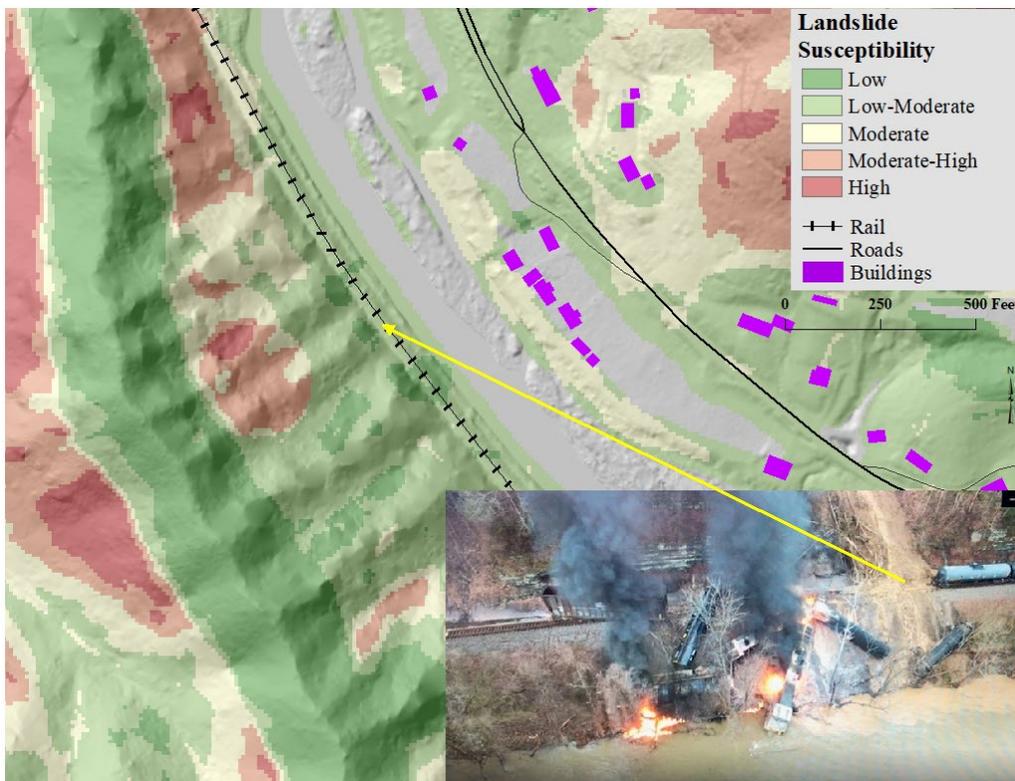


Figure 18. A landslide caused a train derailment in Pike County on February 13, 2020. The landslide likely initiated from the pink and red area upslope, above the railroad.

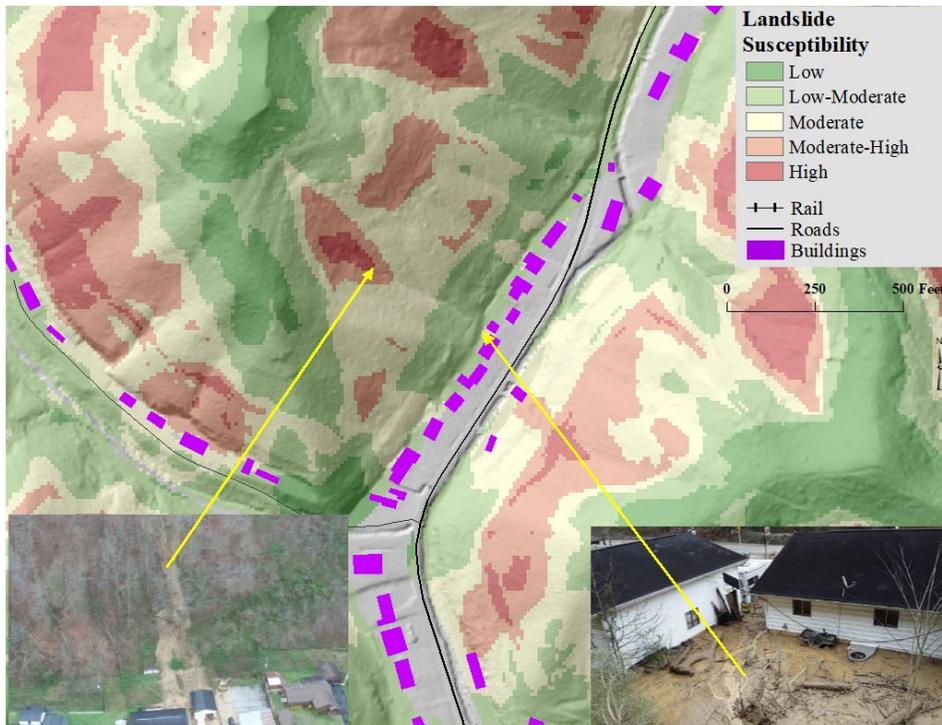


Figure 19. A narrow landslide occurred on April 12, 2020, on a slope above Chloe Road in Pike County. The landslide damaged two buildings.

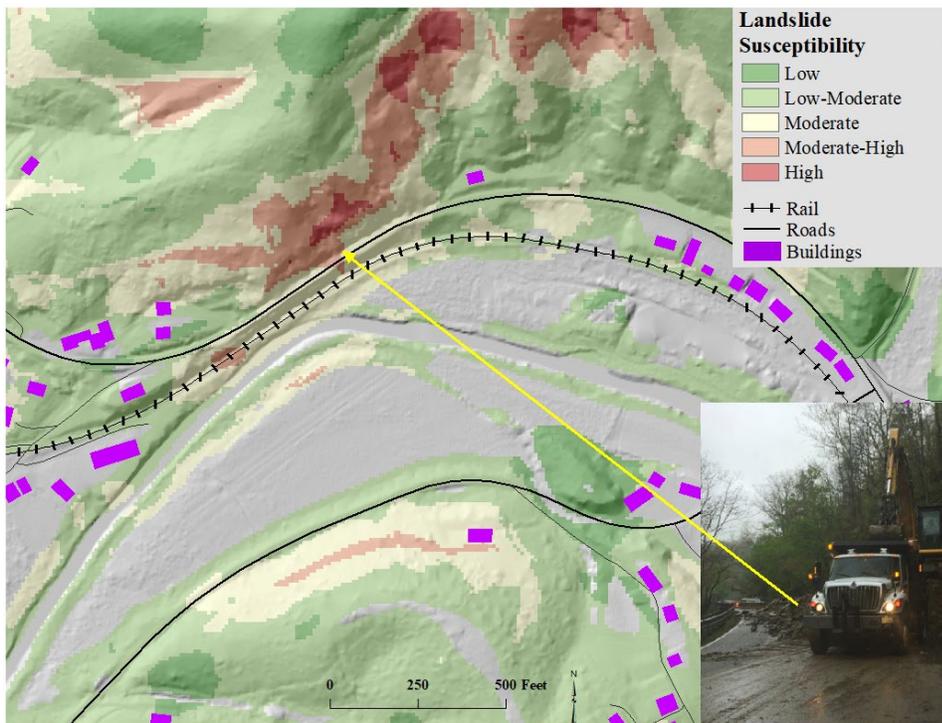


Figure 20. A landslide occurred on April 24, 2020 along KY 550 in Floyd County. The landslide occurred on the slope above KY 550 and above a railroad. Note the moderate-high and high classification to a broad swath of the slope above the road.

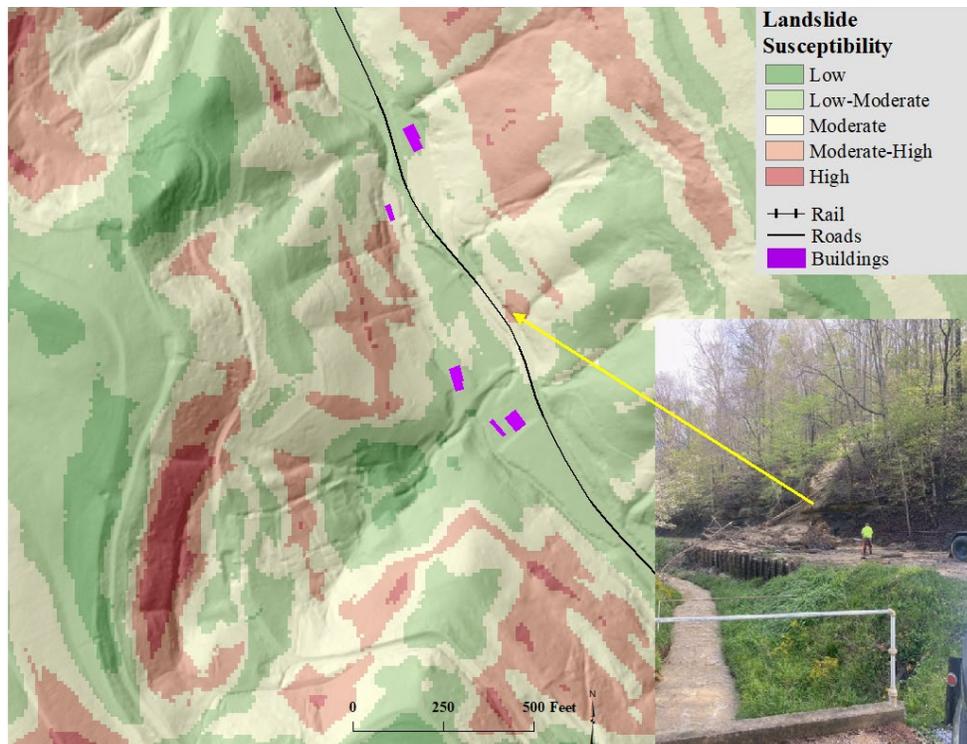


Figure 21. A landslide occurred on April 27, 2020 along KY 881 in Pike County. The landslide initiated on the slope above the road.

Risk Assessment

Generally, risk is the measure of the probability of the severity of an adverse effect to health, property, or the environment (Cruden and Fell, 1997). There are many working definitions of landslide risk, and assessments are often based on mixtures of information that range from well-established knowledge to broad assumptions due to lack of data (Lee, 2015). Landslide risk assessments attempt to estimate the product of hazard and consequences, finding the most useful combination of landslide susceptibility and risk components. Modelling reliable risk results are challenging due to the complexity of the many aspects of landslide hazards and the vulnerability of the built environment to landslides. Hindering factors include quantitative heterogeneity of vulnerability of different elements at risk (*EaR*) for qualitatively similar landslide mechanisms, and variability in temporal vulnerability (Uzielli, et al., 2008; van Westen et al., 2006).

The risk assessment presented here should be considered a static socio-economic risk, not scenario-specific or time-dependent as spatial and temporal components were not considered. However, the spatial distribution of elements at risk (assets) used in the risk calculation and the resulting map can be used as a decision-making tool and general guide to public safety.

Risk Inputs

At its core, **Risk** = **Hazard** x **Vulnerability** x **Consequence**

H is the probability a landslide exists, or conditions are likely for its existence. The logistic regression landslide susceptibility results in this report are used as the **H** input.

A lack of a clear definition of vulnerability and lack of common language related to vulnerability and landslides poses many challenges. Here, **V** is defined as the susceptibility of *EaR* having an adverse result to landslide activity, intensity, and magnitude. While there are many distinctions in the capacity to deal with landslides (including social, economic, physical, cultural, and environmental vulnerability) **V** is considered as a degree of loss expressed as a scale of 0 (no loss) to 1 (total loss).

C is an estimate of the value of *EaR* (exposure or infrastructure). The consequences in this risk assessment can be categorized as societal (consideration of population and infrastructure assets) and economic (consideration of the value of assets). Here, we are using **V** = 1 and **C** is the product of *EaR* and their economic value.

This risk assessment uses intersection between landslide hazard, consequences, and vulnerability. The purpose of the risk assessment is to identify areas vulnerable to the threat of landslides and provide the information to public and local and state government agencies. The resulting map represents quantitative landslide risk showing a broad socio-economic risk.

Methodology

EaR in this assessment include population, roads, railroads, building footprints, and general land type. Kernel density maps were generated for population, roads, and railroads. The kernel density technique constructs a spatial view that accurately reflects a known quantity from a point or a line. Population was generated from census block group population numbers (2018) divided per building. Not all building footprints are homes but calculating a population density this way provides a more realistic distribution of people than a population density map based on census block group data.

EaR were divided up into five asset categories, major roads, local roads, railroads, developed land, and open land. General monetary values were obtained from various government and industry sources (Table 11). KYTC = Kentucky Transportation Cabinet, UK Agriculture = University of Kentucky Agriculture Department, FHFA = Federal Housing Finance Agency ACW = Aberdeen Carolina & Western Railway.

Table 11. Elements at risk and their estimated monetary value.

Infrastructure	Value	Source
Major Road	\$24,000,000 per Mile	KYTC
Local Road	\$14,000,000 per Mile	KYTC
Developed Land	\$95,000 per Acre	FHFA
Open Land	\$1,800 per Acre	UK Agriculture
Railway	\$1,000,000 per Mile	ACW Railway

Infrastructure dataset rasters were created spatially with 10-ft cells for consistency with the landslide susceptibility maps. The population densities and infrastructure monetary values are subdivided to be an equivalent value per 10 ft x 10 ft cell. Population densities and the infrastructure monetary values are normalized logarithmically, with the population having a max equal to the densest population in the county and the monetary values have a max that contains the infrastructure with the highest estimated value. Realistic spatial footprints of all roads and railroads were created by buffering the line data: railroads received a buffer approximately 10 feet across, local roads received a buffer of 20 feet or 10 feet for county and private respectively, state roads received a 30 foot buffer, and the US Highways in the area and the extent of the Bert T. Combs Mountain Parkway were buffered 100 feet. Building footprints were buffered 50 feet to include adjacent property value in the asset.

The economic values were normalized as to not skew the risk towards the most expensive asset. The normalization increases in exponential bins, (\$1-\$10, 10-100, 100-1,000, 1,000-10,000...) with the highest value being \$100,000 to account for the estimated highest asset value of roadways in the area.

Risk Calculation and Map Classification

To produce a landslide risk map, the hazard and elements at risk components were compiled and used in a quantitative risk calculation. The hazard input is the logistic regression, landslide susceptibility results. The vulnerability is the probability of damage to an element from the threat, a scale of loss – zero for no damage expected to one which assumes complete destruction. Due to the lack of comprehensive vulnerability data such as landslide behavior and building resistance, the vulnerability received a value of one, assuming total loss. Consequences are the elements at risk categorized into societal (population at risk) and economic (monetary value at risk).

$$Risk = (H) * (V) * [(C1) + (C2) + (C3)]$$

Where, H = Hazard (landslide susceptibility), V = vulnerability (1), C = Consequence, which is the product of economic and societal elements at risk.

The resulting risk factor is classified into 3 risk classifications: low, moderate, and high. Areas not designated in a risk class (no color), mostly ridgetops or valley bottoms, are designated as such because of the low hazard likelihood combined with undeveloped land. These areas that exclude a classification rank could be moved into a risk classification if infrastructure development occurred.

To create risk datasets and maps for each county, risk was classified using the standard deviation of the natural log of the risk results.

$$\log_e (Risk)$$

The risk factor value and associated classification is in the following tables (Tables 12–16). The county natural log approach necessarily leads to county boundary Risk Factor classification threshold differences. However, a regional approach is precluded due to a lack of an assessment for other counties in eastern Kentucky, or in other states in the Appalachian Plateau.

Table 12. Magoffin County

Risk Factor	Percent Area (%)	Landslide Risk Classification
0 – 0.0023	15.8	Excluded
0.0024 – 0.0102	70.3	Low
0.0103 – 0.0213	12.0	Moderate
0.0214 – 1	1.9	High

Table 13. Floyd County

Risk Factor	Percent Area (%)	Landslide Risk Classification
0 – 0.0036	14.9	Excluded
0.0037 – 0.0182	74.1	Low
0.0183 – 0.0403	9.6	Moderate
0.0404 – 1	1.4	High

Table 14. Johnson County

Risk Factor	Percent Area (%)	Landslide Risk Classification
0 – 0.0032	15.5	Excluded
0.0033 – 0.015	70.9	Low
0.016 – 0.0324	11.6	Moderate
0.0325 – 1	2.0	High

Table 15. Martin County

Risk Factor	Percent Area (%)	Landslide Risk Classification
0 – 0.0034	14.8	Excluded
0.0035 – 0.016	71.5	Low
0.017 – 0.0344	12.2	Moderate
0.0345 – 1	1.5	High

Table 16. Pike County

Risk Factor	Percent Area (%)	Landslide Risk Classification
0 – 0.0035	15.4	Excluded
0.0036 – 0.0186	72.7	Low
0.0187 – 0.043	10.7	Moderate
0.0431 – 1	1.2	High

The resulting maps indicate low, moderate, and high landslide risk areas. In general, high concentrations of buildings, roads, and railroads that intersect or are in the vicinity of high landslide susceptibility areas are classified as moderate or high risk. Broad, large hillslopes with little to no infrastructure are classified as low risk (blue areas on maps). High concentrations of buildings and roads along steep streambanks and below steep slopes are classified as high risk. Data that occurs on less than 3-degree slope were excluded.

The risk maps do not consider scenario-based elements and should be considered a static socio-economic risk map. Final risk results generated with the risk equation were resampled with a radial smoothing window of approximately 50 feet for noise reduction (Figs. 22–26). See **Appendix C** for the full county risk maps.

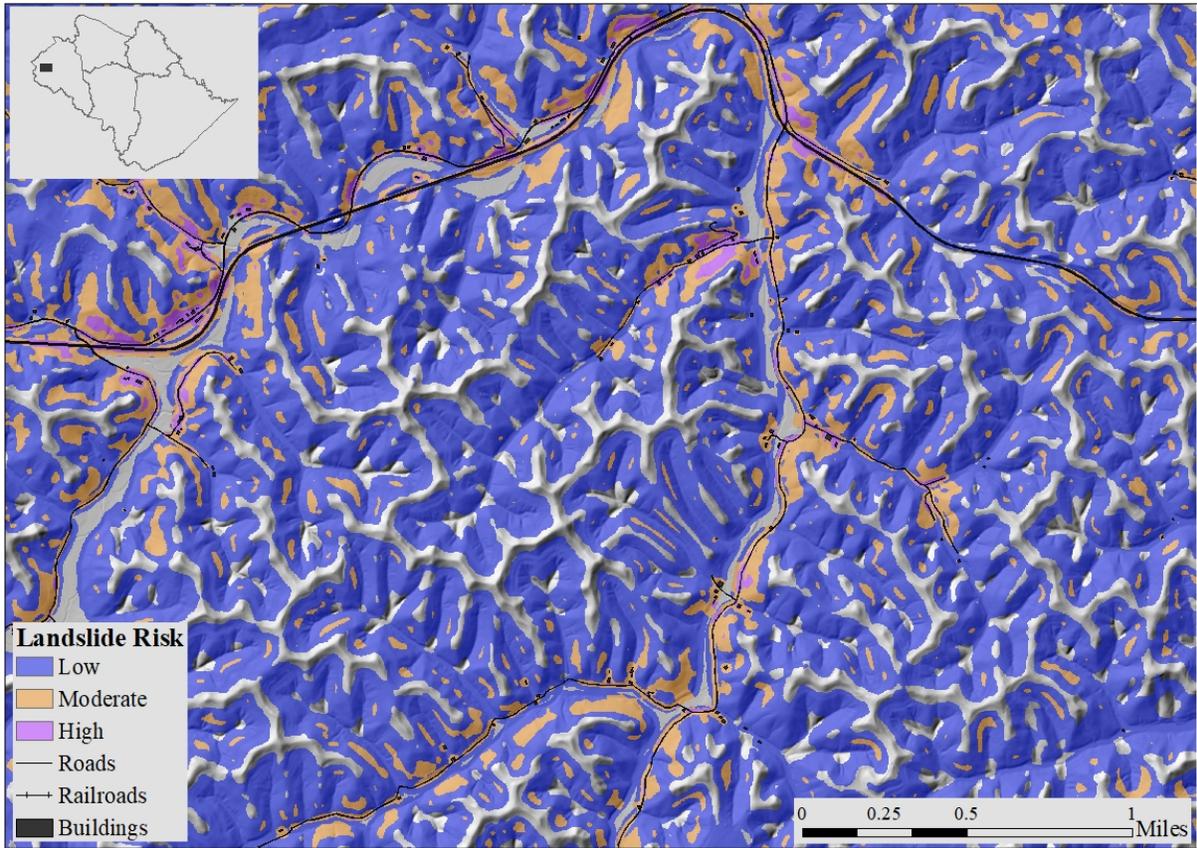


Figure 22. Landslide risk in part of Magoffin County. See **Appendix C** for the full county risk maps.

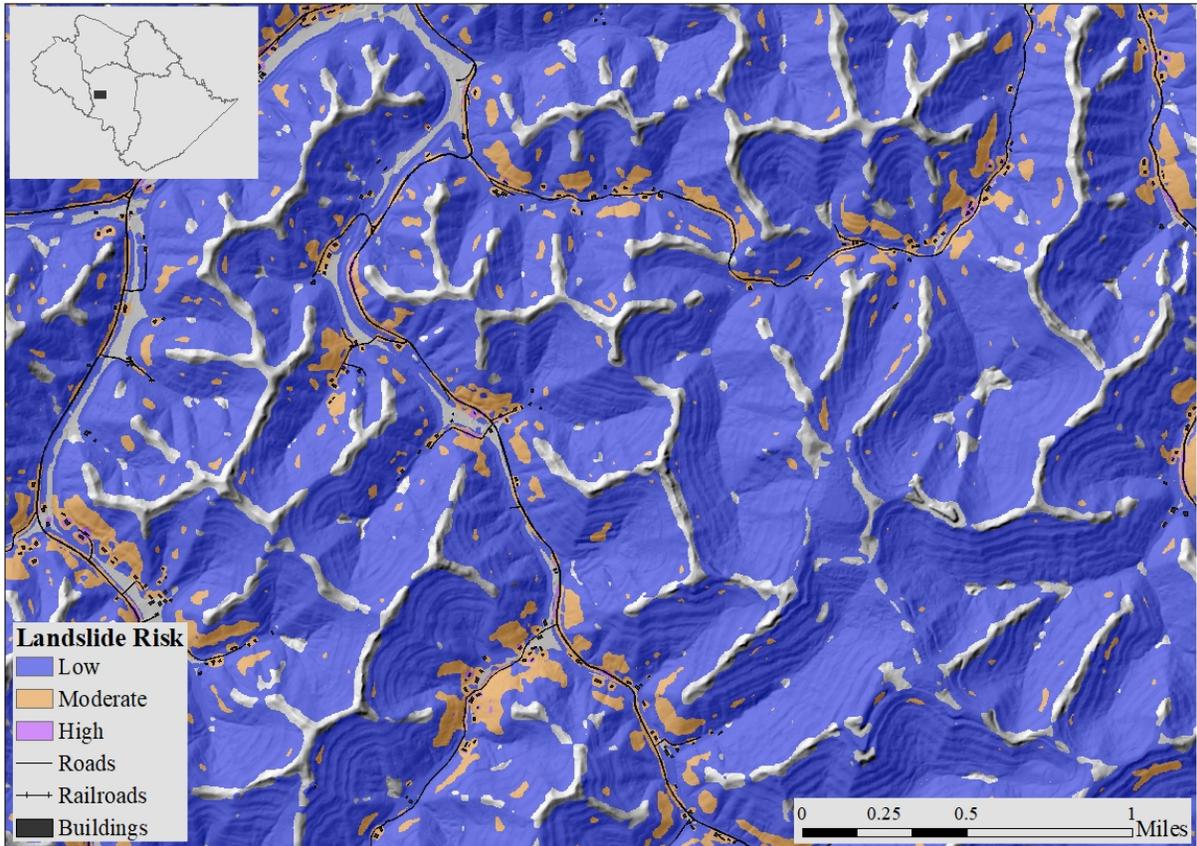


Figure 23. Landslide risk in part of Floyd County. See **Appendix C** for the full county risk maps.

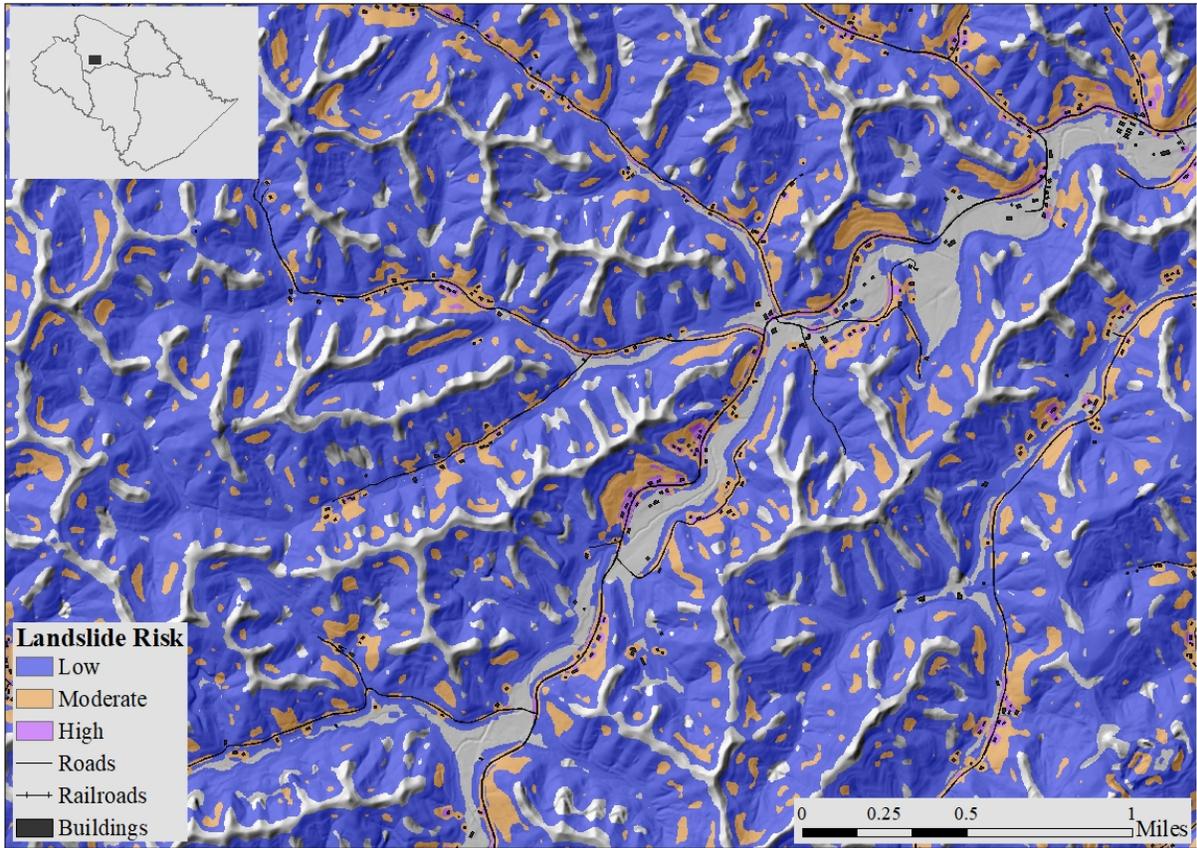


Figure 24. Landslide risk in part of Johnson County. See **Appendix C** for the full county risk maps.

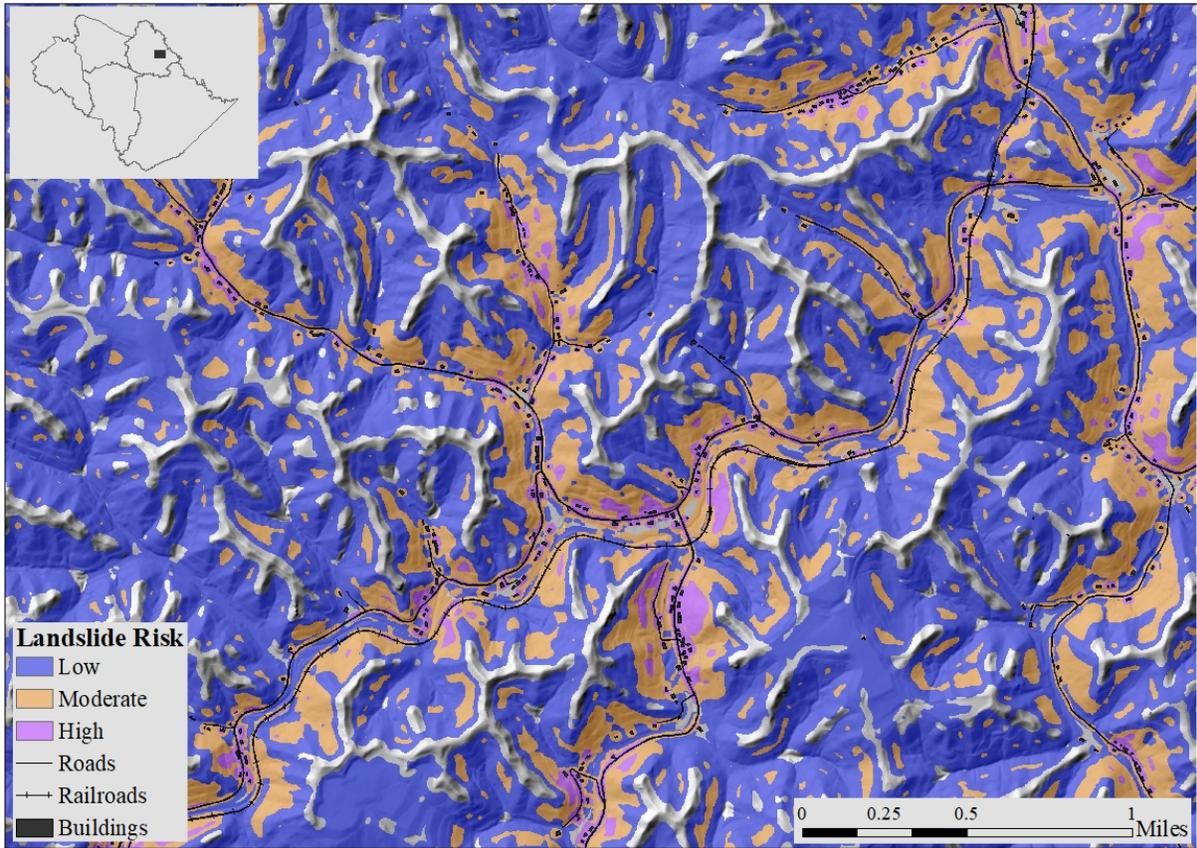


Figure 25. Landslide risk in part of Martin County. See **Appendix C** for the full county risk maps.

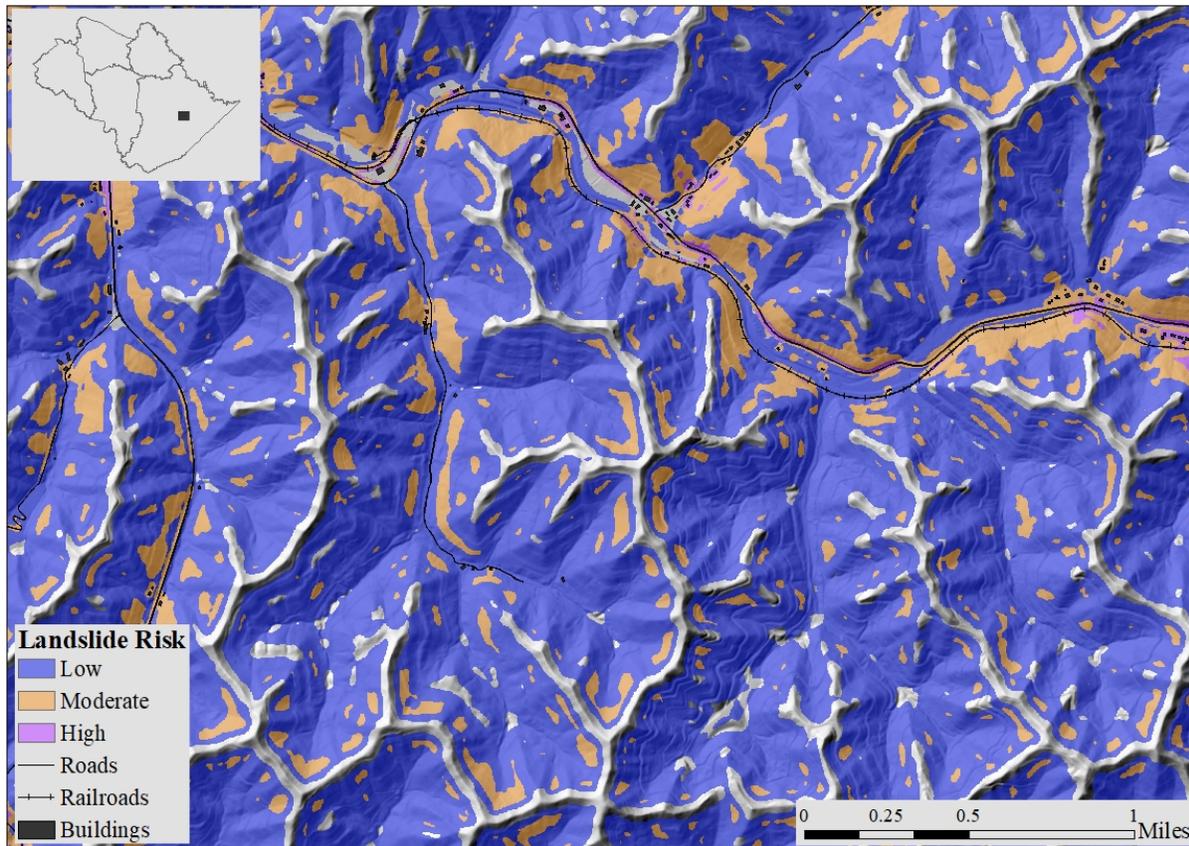


Figure 26. Landslide risk in part of Pike County. See **Appendix C** for the full county risk maps.

Model Limitations

Statistical models of landslide susceptibility (like the one presented in this plan) generally ignore the temporal and behavioral aspects of landslides and are not able to predict the impact of changes in the controlling conditions of slope stability (water table fluctuations, land use changes, climatic change, for example). Statistical models that use parameters related to existing landslides, for which we know little about, cannot therefore provide full temporal probability information, landslide magnitude, and frequency, and thus are difficult to use in quantitative risk assessments. Rainfall or variations of soil pore-water pressure with time were not considered in this plan, and the risk results are not expected loss over time. No landslide runout modeling was performed.

Economic values were obtained from various sources and all generalized as total value for the element in question. These could not be validated to historic repair costs, though there is record of historic road repair costs. Building and developed land values were determined from a small sample of property values. This analysis lacks data on other highly vulnerable elements, such as powerlines, water lines and sewerage lines, therefore these elements are not included in the risk assessment. Population considerations did not include where populations would be at any given moment. Vulnerability was assumed at the maximum value (1), which is not likely the case uniformly across the study area. The maximum rating for vulnerability is also attributed to there being no structural integrity data for infrastructure. Because this plan discusses a static, socio-economic approach to risk, a recognition of how

changing conditions and opportunities could impact community resilience in the long term need to be considered in future assessments.

MITIGATION STRATEGIES

Hazard mitigation is any sustained action taken to reduce or eliminate the long-term risk to human life and property from hazards (FEMA, 2011). The intent of mitigation planning, therefore, is to maintain a process that leads to hazard mitigation actions. Mitigation plans identify the natural hazards that impact communities, identify actions to reduce losses from those hazards, and establish a coordinated process to implement the plan. Integration of landslide hazard data and risk information into a multi-jurisdictional plan should revolve around goals of establishing resilience as a value of the community and provide the opportunity to manage development that does not lead to increased hazard vulnerability, as well as strengthening the safety of citizens. The hazard identification, landslide susceptibility, and landslide risk are the basis for a strategy that considers the following values within plan goals, projects, and plan maintenance (www.fema.gov/multi-hazard-mitigation-planning):

- 1) Land Use and Future Development
- 2) Transportation
- 3) Housing, Public Facilities, and Other Infrastructure
- 4) Economic Development
- 5) Natural Resource Protection
- 6) Historic Properties and Cultural Resources

Implementation of Mitigation Measures

Goals

The primary goal of the maps and data presented in this plan is to protect the public, reduce potential losses identified in the landslide susceptibility and risk assessment, and reduce overall vulnerability to the built environment from landslides. A key component of achieving these goals is communicating and disseminating a consistent message that reflects the landslide data, susceptibility and risk methods, and results. The plan content can serve as a blueprint for hazard mitigation actions, decision-making, and guide a work flow from the risk assessment (problem identification) to goals setting to mitigation action development, as well as plan maintenance and updates (Fig. 27).

Specific Ideas/Projects

Spatial assessment of landslide hazard and vulnerability

- Improve map and GIS data, access Kentucky Geological Survey landslide inventory database
- Evaluation of areas where landslides may occur, be informed about potential hazardous areas
- Completing an inventory of locations where critical facilities, other buildings, and infrastructure are vulnerable to landslides
- Evaluating and establishing tolerable risk criteria
- Develop and maintain a database to track community vulnerability to landslides
- Establish effective communication avenues to discuss the landslide hazard and risk assessment process and limitations

- Establish frequent workshops or symposiums that convene to discuss mitigation strategies, hazard and risk assessment data and maps, other resources for stakeholders, and future work

Manage Development

- Create a plan to implement reinforcement measures in high-susceptibility and high-risk areas
- Define steep slope/high-risk areas in land use and comprehensive plans and create guidelines or restricting new development in those areas
- Creating or increasing setback limits on parcels near high-susceptibility and high-risk areas
- Locate utilities outside of landslide areas to decrease the risk of service disruption
- Incorporate economic development activity restrictions high-susceptibility and in high-risk areas

Prevent Impact to Roads

- Evaluate state and local roads that intersect high susceptibility areas (Fig. 27).
- Implementing monitoring mechanisms/procedures (i.e., visual inspection or electronic monitoring systems)
- Applying soil stabilization measures, such as planting soil stabilizing vegetation on steep, publicly owned slopes
- Using debris-flow mitigation measures that may reduce damage in sloping areas, such as stabilization, energy dissipation, and flow control measures
- Establish setback requirements and using large setbacks when building roads near slopes of marginal stability
- Install catch-fall nets for rocks at steep slopes and roadcuts near roadways

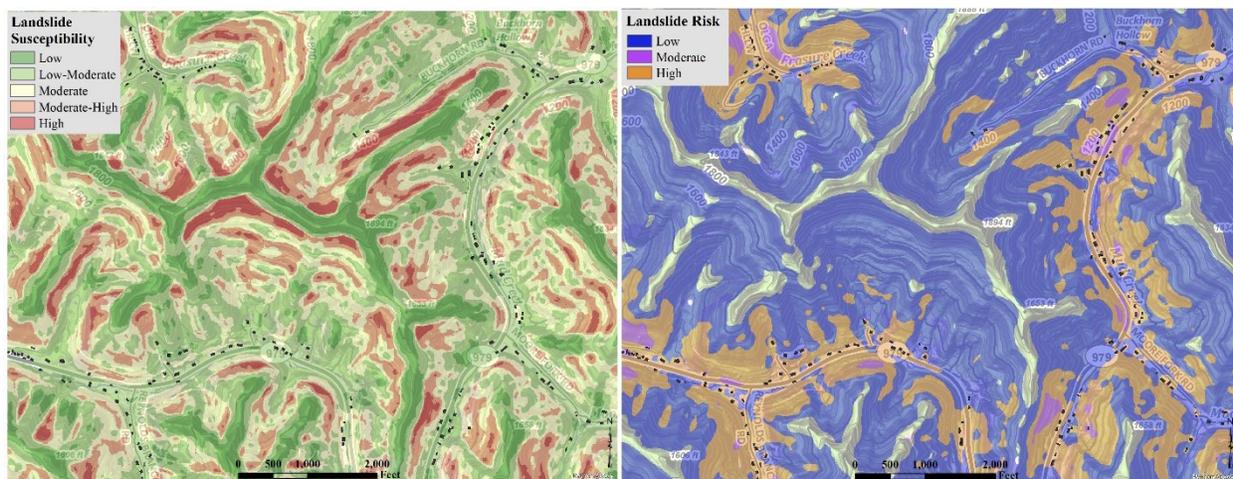


Figure 27. Landslide susceptibility (left) and landslide risk (right) for part of Floyd County. Note the differences in where the moderate to high hazards occur on slopes versus the moderate to high risk areas.

Figure 28 is an example map that shows landslide susceptibility overlaid with state roads and buildings. The roads are classified based on Kentucky Transportation Cabinet (KYTC) maintenance cost for landslides (includes rockfalls) per one-mile road segment (Overfield and others, 2015). The thicker the line, the higher the cost. The data is generated from KYTC records that span 2003 to 2009. Spatial

overlays such as this are a good foundation for mitigation strategy goals, as well as implementing specific projects.

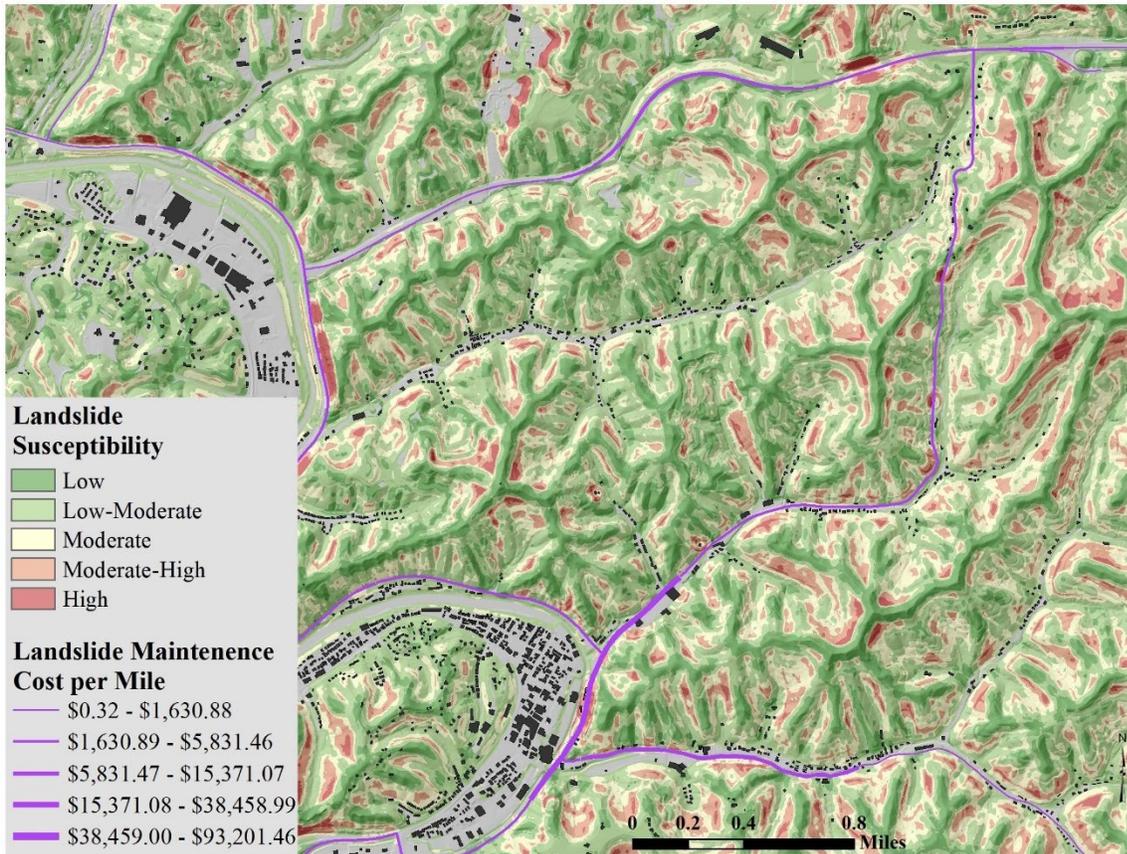


Figure 28. Landslide susceptibility overlaid by state road segments classified by cost per mile in part of the Pikeville area. These are only Kentucky Transportation Cabinet maintenance cost records that span 2003 to 2009. Large, expensive landslide mitigation projects are likely not included in these cost totals. Building footprints are shown as black polygons.

DISCLAIMER AND DATA LIMITATIONS

The figures and printed maps are smaller scale representations of the digital spatial data that have been generated for use in a Geographic Information System (GIS). The data is best used in a GIS at larger scales. This landslide susceptibility and risk maps are not intended to be a substitute for site-specific investigation by a licensed geologist or geotechnical engineer. The maps and GIS data do show an intersection between potentially hazardous areas and infrastructure where an investigation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

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Appendix A – Selected landslides in the BSADD from part of the KGS landslide inventory database. Not all documented landslides have impact information (failure dates, dimensions, failure location, damage, and cost) shown here.

County	Failure Date	Failure Year	Track Length (ft)	Width (ft)	Failure Location	Damage	Cost
Floyd		2019				break in pavement	
Floyd					above and below road	break in pavement, road closure	
Floyd		2015			above road, stream at bottom	damage to property	
Floyd	3/14/2015	2015	1500			damage to road and homes below	
Floyd	4/3/2015	2015	1000			damage to two homes and property	
Floyd	2/22/2015	2015	1400			damaged home, road, fence	
Floyd	3/6/2015	2015	100			damaged property	
Floyd	4/2/2015	2015			above road	damaged road and guardrail, slide hit a driver	
Floyd	2/16/2018	2018				home damaged	
Floyd			525			home threatened	
Floyd						home threatened	
Floyd		2018				home threatened	
Floyd	4/7/2018	2018				home threatened	
Floyd		2019				home threatened	
Floyd					above road	house threatened	
Floyd	5/20/2017	2017			below road, stream at bottom	large brake in pavement	
Floyd		2016				large break in pavement	
Floyd		2019				large cracks in road	
Floyd		2016			below road	pavement buckled, break in pavement	
Floyd	2/16/2016	2016			road cut	road blocked	
Floyd	3/25/2018	2018			above road	road blocked	
Floyd	6/12/2018	2018			above road	road blocked	
Floyd		2018			above road	road blocked	
Floyd	4/24/2020	2020				road blocked	
Floyd	1/3/2017	2017				road closure	
Floyd	4/23/2017	2017			above road	road closure	
Floyd		2017				road failure	
Floyd	5/11/2016	2016			above road	two lands blocked; NB road closed for weeks	
Floyd	2/6/2010	2010				yes	
Floyd						yes	
Floyd	5/8/2009	2009				yes	
Floyd	5/8/2009	2009				yes	
Floyd					above road, stream at bottom	yes	
Floyd	1/30/2013	2013			above road, stream at bottom	yes	
Floyd	5/2/2005	2005				yes	
Floyd	4/9/2013	2013			road cut	yes	
Floyd		2014			above road	yes	
Floyd	2/22/2014	2014			above road	yes	
Floyd	4/30/2014	2014			above home	yes	
Floyd		2014				yes	
Floyd							

County	Failure Date	Failure Year	Track Length (ft)	Width (ft)	Failure Location	Damage	Cost
Magoffin		2017			below road		
Magoffin		2019					
Magoffin		2019					
Magoffin		2019					
Magoffin		2019					
Magoffin							
Magoffin							
Magoffin		2019					
Martin		2018				multiple breaks in pavement	
Martin						road damage	146,150
Martin	7/1/2010	2010			below road	yes	
Martin							
Martin							
Martin							
Martin							
Martin							
Martin							
Martin							
Martin							
Martin							
Martin							
Martin					above road		
Martin		2019					
Martin		2019					
Martin		2019					
Martin		2019					
Pike	3/2/2018	2018			above road	all lanes blocked	
Pike	1/24/2019	2019				both lanes blocked	
Pike		2019				boulders on road	
Pike		2019		2500		break in pavement	
Pike		2019				cut off 12 homes	
Pike	4/3/2015	2015				damage to home	
Pike	12/22/2018	2018				damage to home	
Pike		2019				damaged business	
Pike						damaged home	
Pike	1/19/2016	2016				damaged home	
Pike	3/12/2020	2020				damaged power lines, road blocked	
Pike		2016				damaged road, road closure	
Pike		2019				damaged Town and Country shipping center	
Pike	4/3/2015	2015				destroyed church, damaged several homes	
Pike	7/2/2017	2017				driveway blocked for several days	
Pike		2017				embankment failure	
Pike		2018?				embankment failure	
Pike		2017				embankment failure	
Pike					above road	fence damaged and vehicle accident	
Pike	2/14/2018	2018				home threatened	
Pike	2/14/2018	2018			above road	home threatened	
Pike	3/1/2018	2018				home threatened	
Pike	2/11/2018	2018				home threatened	

County	Failure Date	Failure Year	Track Length (ft)	Width (ft)	Failure Location	Damage	Cost
Pike	2/10/2018	2018				home threatened	
Pike		2015			natural slope	homes damaged	
Pike	3/5/2015	2015			above home	knocked home off foundation	
Pike	2/10/2018	2018			above and below road	large section of road failure	
Pike	2/13/2020	2020				railroad blocked, train derailment, injured persons	
Pike	4/3/2015	2015				reported gas line damage, home threatened	
Pike		2018			above road	road and stream threatened	
Pike	3/25/2018	2018			above road	road blocked	
Pike	12/21/2018	2018			road cut	road blocked	
Pike		2019				road blocked	
Pike		2019				road blocked	
Pike	12/17/2019	2019				road blocked	
Pike	2/10/2020	2020				road blocked	
Pike	4/27/2020	2020				road blocked	
Pike	3/4/2015	2015				road closure	
Pike	5/29/2017	2017				road closure	
Pike		2015			below road	road closure for a month	
Pike	3/10/2015	2015			road cut	road damage, closed	
Pike	5/12/2017	2017		100	below road, stream at bottom	road failure	145,000
Pike						road failure	
Pike						road failure	
Pike			500			several homes threatened	
Pike	2/10/2018	2018				slide blocking both lanes	
Pike		2019				structures threatened	
Pike	2/11/2020	2020				tree and power line damage	
Pike		2019				tree slid into garage, slide behind home	
Pike	5/19/2017	2017			above road	two condos damaged; residents evacuated	
Pike	4/12/2020	2020				two damaged homes, mud, and soil in homes	
Pike	5/11/2009	2009			below road, stream at bottom	yes	
Pike	4/15/2007	2007			below road	yes	
Pike	7/17/2010	2010				yes	
Pike			280	371		yes	
Pike					above and below road	yes	
Pike					above road	yes	
Pike					above and below road	yes	
Pike	1/1/2008	2008	75	103	above road	yes	130,000
Pike	3/14/2011	2011				yes	
Pike	6/15/2006	2006			above road	yes	
Pike	1/21/2012	2012				yes	
Pike	3/15/2011	2011				yes	
Pike	5/10/2009	2009				yes	
Pike	6/5/2013	2013				yes	
Pike		2011				yes	
Pike	1/14/2014	2014			above road	yes	

Appendix B – Landslide Susceptibility Maps



Landslide Susceptibility of Magoffin County, Kentucky Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch, Ashton A. Killen

Purpose

The purpose of this map is to identify landslide-prone areas in Magoffin County in order to provide the public and local and state governmental agencies with maps, plans, and more vehicle accidents as likely to occur. This map represents geomorphic-based susceptibility modeling that focuses on physical slope characteristics and morphology, the results of which is dependent on data accuracy and resolution of terrain models. The availability of high-resolution (1.5-m digital elevation model) bathymetric and imagery (Landsat) derived datasets allows for the generation of terrain elevation derivatives such as hillshade, slope, aspect, curvature, and roughness, as well as identification of existing landslide deposits. These high-resolution, data-derived datasets, coupled with landslide inventory mapping, enable more productive landslide and landslide susceptibility maps.

Map Production

To produce a landslide-susceptibility map, 36 geomorphic variables were compiled and used to approximate the connection between slope morphology and landslide occurrence. A 1.5-m DEM was resampled to 1-m cells in order to generate geomorphic maps. Each map was then resampled using a spatial smoothing window of approximately 15 m to reduce noise. The used logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map. The final map was produced using ArcView (ArcInfo v. 10.7.1). The logistic regression was conducted using statistical software JMP Pro v. 10, as well as data analysis software MATLAB R2010b.

To obtain conditional 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 the statistical values from all surrounding cells. This process resulted in 36 individual values for each landslide (maximum, minimum, range, mean, standard deviation, SD), and sum of values within each buffer for each map. The buffer created for all mapped landslides had a radius of ~1,200 ft (radius of 1.25 ft), which is the average area of the 1,054 mapped landslides. Although there is some correspondence between variables, to assure that mapping with an abundant number of variables increases the probability of capturing the strongest conditions and will produce better model accuracy and a smoother, more realistic map.

Geomorphic variable	Description
Elevation	Vertical distance of space above or below a reference surface, derived from a digital elevation model (DEM).
Slope	Gradient or measure, from cell to cell, of elevation (rate of change).
Terrain roughness	Measure of terrain roughness derived from the standard deviation of the resampled elevation values of each cell. Terrain roughness is important in determining susceptibility to landslides.
Curvature	The second derivative value from each cell and from an elevation value (1/1000 ft).
Line curvature	Curvature of the surface perpendicular to the direction of maximum slope (1/1000 ft).
Aspect	Compass direction of a terrain's slope, derived from the cell of the elevation.

Landslide Susceptibility Model

To produce a landslide-susceptibility map, 36 variables were compiled and used to approximate the connection between slope morphology and landslide occurrence.

These geomorphic variables were evaluated using logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map.

Logistic regression models the probability of an event (i.e., landslide) using a function of the variables, and quantifies the relationship between each variable and the probability of landslide occurrence.

During landslides are often susceptible to conditions, which include modeling the probability of occurrence and developing a susceptibility map with logistic regression parameters important.

If one is logistic function to model a binary dependent variable, called the indicator, the indicator was created with buffer centers, landslides or non-landslide areas. A buffer was created around each mapped landslide polygon (1-1054) 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 120 feet. The buffers are defined with 1 (landslide) or 0 (non-landslide) since the non-landslide dataset contains the indicator function as presence or absence of a landslide, the

Logistic regression results derive a coefficient of response (P values) and statistics which variables are significant (p-values). P-values indicate the data are unlikely to accept a lack of difference, i.e., the probability (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:

$$P = e^{(a + b_1X_1 + b_2X_2 + \dots + b_nX_n)}$$

where a is the constant term, b_1, b_2, \dots, b_n are the model coefficients of all predictor variables (X_1, X_2, \dots, X_n), and P is the relative risk of being a landslide or not a landslide. The cumulative distribution function is:

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

The map strikes a good balance between indicating existing deposits that have a moderate to high probability of subsequent non-event, as well as assessing other parts of the slope that do not necessarily show obvious slope movement but may have features related to existing landslide activity.

The susceptibility map does not determine landslide types, present extent or extent, or temporal implications. 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 and landslides, as well as the stability of the landslide body or area due to the capacity of the digital values between cells, not considered in the analysis. Five landslide-susceptibility classifications were determined manually by creating bins of standard deviations from the mean. Of the mapped landslide deposits, 81 percent are classified as moderate to high percent in moderate-high and high.

Geomorphic variable	p-value	Wald	df	sig.	Exp. B	95% CI for Exp. B
Maximum slope	1.08E-079	9.709	1	.002	1.014	1.008, 1.020
Minimum elevation	1.12E-077	1.233	1	.001	0.999	0.992, 1.006
SD elevation	1.22E-074	1.039	1	.002	1.014	1.008, 1.020
Range of slope	0.0001	24.739	1	<.001	1.014	1.008, 1.020
Line curvature	0.0001	24.739	1	<.001	1.014	1.008, 1.020
Maximum roughness	0.0001	116.422	1	<.001	1.014	1.008, 1.020
Sum of curvature	0.0001	2.417	1	.002	1.014	1.008, 1.020
SD elevation	0.0001	2.417	1	.002	1.014	1.008, 1.020

*Other factors with an odds ratio were not included in the analysis.



Best map (yellow box) on laptop map showing part of Magoffin County.

Glossary of Terms

Digital elevation model (DEM): A digital file of terrain elevation and ground position data, collected from the laser and optical satellite systems, typically at the foot of slopes in surface between heights from 0 to 9999.

Geographic information system (GIS): Computer programs and databases that allow for storage, manipulation, analysis and dissemination of geographic information.

Geologic hazard: A geological condition that is potential threat to life or infrastructure includes both natural and man-made features.

Geomorphology: Science of the present configuration of the Earth's surface. Study of classification, description, nature and origin of landforms and the history of geologic changes as recorded by these surface features.

Landslide susceptibility map: This type of map depicts areas that have potential of landsliding, created by considering factors to cause landslides, such as steep slopes or geological units, with past distribution of landforms considered.

Landslide inventory map: This type of map depicts areas where landslides have occurred. Inventory maps can be both point locations and specific contours of landslides.

Landslide risk map: This type of map quantifies the landslide hazard and its potential of occurrence in the context of the present, landform relationship and socioeconomic effects on the community.

Mitigation: Activities that reduce or eliminate the probability of a hazard occurrence, and/or lessen the effects of the hazard when they do occur.

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 data is best used in a GIS at larger scales. This landslide susceptibility map is not intended to be a substitute for site-specific analysis by a licensed geologist or geotechnical engineer. The map and GIS data do show potential landslide areas where an investigation of slope stability or other geotechnical analysis may be appropriate prior to site disturbance.



Location of Magoffin County, Kentucky



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

Landslide Basics

A landslide is a second term for the continuous movement of rock, soil, or both under the influence of gravity. The type 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 the diagram below: (a) creep (b) rotational landslide or slump-spread (c) debris flow. The translated landslide is labeled with specific parts, which were used for the landslide inventory mapping and analysis in the susceptibility modeling.

Landslide 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, landslide, 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 processes that explain their occurrence.



Landslides are caused by stresses on steep slopes that exceed the strength of the hillside soil. Stresses can include increased porewater pressure (from rainfall), gravity, or some type of slope modification (excavation or excavation). A single slope is not that balance the stresses imposed (in big forces with the strength of the material (existing forces). A slope will fail if these conditions are disturbed by (1) increase the stress, or (2) a change in resistance both which cause a decrease in shear strength. The challenging part is that these stresses occur over time and space at different scales, meaning landslides are operated by causal conditions and triggers.

Examples of driving forces:

- Increase of weight at the top of the slope by adding artificial fill
- Loose or protruded material
- Removal of the toe of a slope by ungrouted cuts or natural stream erosion

Examples of change resisting forces:

- Rooted soil, increase in water pore-pressure from rainfall or in stream banks, from rapid fall of water level in the stream
- Vegetative material
- Expansion and contraction of swelling clay soils with wetting-drying cycles
- Wetting of weak rocks

Explanation

Landslide Susceptibility

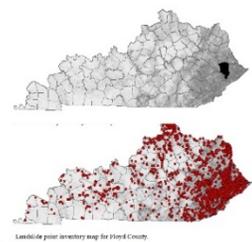
- Low
- Low-Moderate
- Moderate
- Moderate-High
- High
- Building footprints
- Local roads
- State roads
- Railroads
- Corporate boundaries
- Mapped landslides



The Kentucky Geological Survey would like to thank Kentucky Emergency Management and the Federal Emergency Management Agency (FEMA) for funding support and sponsorship of this planning project. FEMA Pre-Disaster Mitigation grant project number and title are FDMC-P1-01-0217-0001, Multi-hazard-resistant Flood Mitigation Plan for the Bluegrass in the Big Sandy Area Development District.

Landslide Susceptibility of Floyd County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch



Purpose

The purpose of this map is to identify landslides in terms of their causes in order to provide the public and local and state government agencies with descriptions and areas where landslides are likely to occur. This map represents geospatial-based susceptibility modeling that uses geospatial data, descriptive statistics, and geostatistics to model the relationship between terrain attributes and landslide occurrence. The availability of high-resolution (1.5 m) digital elevation models (DEMs) and vector data (roads, railroads, and corporate boundaries) allows for the production of more accurate and detailed maps. The availability of high-resolution (1.5 m) DEMs and vector data (roads, railroads, and corporate boundaries) allows for the production of more accurate and detailed maps.

Map Production

To produce a landslide-susceptibility map, 29 geospatial variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. A 1.5-m DEM was reprojected to 3-m cells in order to generate geospatial maps. Each map was then reprojected to a final geographic coordinate system of approximately 15 m to reduce noise. We used logistic regression modeling to determine the probability of landslide occurrence and, in turn, created a landslide susceptibility map. The final map was produced using ArcGIS (ArcMap) v. 10.1. The logistic regression was conducted using statistical software SPSS (v. 17) as well as data management software SAS (v. 9.2).

To obtain consistent and systematic geospatial statistics, a circular buffer was generated around the centroid point of 1,054 mapped landslides in neighboring Maguffin County. The buffer area for all landslide areas used to calculate the statistical values from six geospatial maps. This process resulted in 30 individual values for each geospatial variable, elevation, aspect, slope, curvature, and distance. Each value was then standardized to a mean of 0 and a standard deviation of 1. The buffer area for all mapped landslides was 71,350 ft (radius of 150 ft), which is the average size of a 1,054 mapped landslides. Although there is some correspondence between variables, we note that creating with an arbitrary number of variables increases the probability of correlation. The statistical correlations and will produce better model accuracy and a statistical, more variable map.

Geospatial variable	Description
Elevation	Vertical distance of a point above or below a reference surface, derived as a representation of the earth's surface elevation.
Slope	Oblique or response from soil out of an object or mass (diagonal).
Aspect	A degree of bearing or orientation in relation to another direction from a starting point, angle of landscape features is important in characterizing geospatial data.
Curvature	Curvature of a surface, which is the rate of change of slope.
Distance	Distance from a point to a line or another point.
Aspect	Orientation of a horizontal line, derived for each cell of an elevation map.

Landslide Susceptibility Model

To produce a landslide-susceptibility map, 30 variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. These geospatial variables were analyzed using logistic regression modeling to determine the probability of landslide occurrence and, in turn, create a landslide susceptibility map. Logistic regression models the probability of an event (a landslide) being a function of other variables, and statistical probability based on statistical analysis of past landslides. Training landslides are often susceptible to regression, which makes modeling the probability of occurrence and developing a susceptibility map with logistic regression particularly accurate.

If used a logistic function to model a binary dependent variable, called the outcome. The outcome was created with binary dependent variables or non-binary variables. A buffer was created partially covering the mapped landslide polygons (N = 1,054) in neighboring Maguffin 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 feet. The buffer area overlapped with a landslide or non-landslide. Since the geospatial dataset contains the statistical information, we present or absent of a landslide, the result are landslide or non-landslide (1 = landslide, 0 = non-landslide), which is a combination of one or more of the independent geospatial variables. The value predicted is a probability of an event ranging from 0 to 1, an estimate of the maximum likelihood that a landslide will be influenced by the statistics of observed independent geospatial variables.

Logistic regression results derive a coefficient of response (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 dependent variable. The coefficients express the effects of the predictor independent variables on the relative risk of being a landslide or non-landslide.

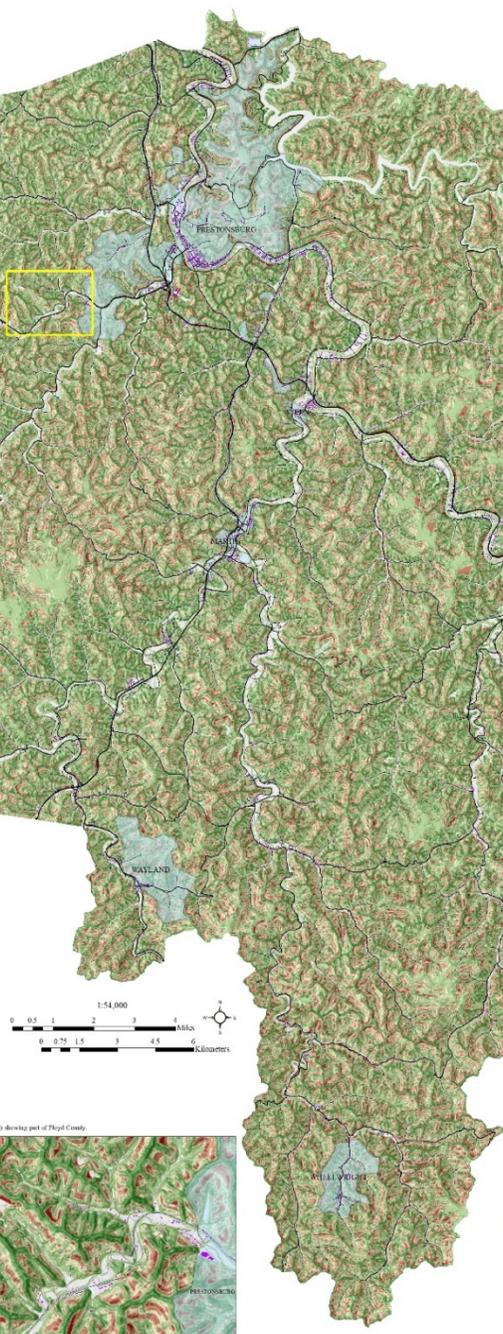
$$P = \frac{e^{(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n)}}{1 + e^{(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n)}}$$

where P is the cumulative estimated event probability of an event occurring (landslide occurrence or non-occurrence). The model is defined between 0 and 1. The logistic regression model will become the primary outcome in the relationship across the variables. We found that eight geospatial variables were significant (p-value < 0.05). The table below shows the LogWorth (Log-p-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.

Geospatial variable	p-value	LogWorth	LogWorth
Minimum elevation	0.0002	1.037	0.014
Maximum elevation	0.0002	1.037	0.014
Aspect	0.0004	1.037	0.014
Range curvature	0.0004	1.037	0.014
Min. slope curvature	0.0004	1.037	0.014
Max. slope curvature	0.0004	1.037	0.014
Max. slope curvature	0.0004	1.037	0.014
Max. slope curvature	0.0004	1.037	0.014

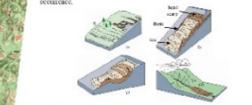
Regression results show a connection between specific landslide morphology that indicate a certain probability of landslide occurrence. The logistic regression model produced a landslide-susceptibility map indicating where landslides are likely to occur based on the geospatial conditions. The map utilizes a good balance between including existing data that have a correlation to high probability of subsequent occurrence, as well as including other parts of the slope that do not necessarily show obvious slope movement but are more strongly related to causing landslide activity.

The susceptibility map does not determine landslide type, potential event or nature, or temporal implications. Generally, steeper slopes indicate higher likelihood of occurrence, but all the geospatial variables appear to indicate areas of moderate to high probability of occurrence and landslides, as well as in the middle of the landslide body or near the toe. The majority of the final values between 0 and 1 are considered to be the middle five landslide-susceptibility classifications were determined similarly by certain terms of statistical deviation from the mean.



Landslide Basics

A landslide is a general term for the downslope movement of rock, soil, or both under the influence of gravity. The rate of movement and resulting failure 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 the diagram below. (a) creep (10 traditional landslides) (b) deep-seated failure (10) (c) debris flow. The traditional landslide is labeled with specific parts which were used for the landslide inventory mapping and delineation in the susceptibility modeling.



Landslides are caused by stresses on steep slopes that exceed the strength of the hillside soil. Stresses can include increased pore-water pressure (from rainfall), gravity, or some type of slope modification (loading or excavation). A single slope can fail because the stresses imposed (driving forces) with the strength of the material (resisting forces). A slope will fail if these conditions are described by (1) increases in the stress, or (2) a change in resistance, both which cause a decrease in slope strength. The challenging part is that these stresses are not static and change at different rates, causing landslides to be separated by causal conditions and triggers.

- Examples of driving forces:
- Redundancy of weight at the top of the slope by additional fill
 - Excavation or produced material
 - Expansion or contraction of swelling clay soils with wet-dry weather cycles

- Examples of causal conditions:
- Increased soil moisture in shallow pore-water pressure from rainfall
 - In-situ stress loads from rapid fall of water level in the stream
 - Expansion and contraction of swelling clay soils with wet-dry weather cycles
 - Weakening of weak rocks

Glossary of Terms

Digital Elevation Model (DEM): A digital file of terrain elevation and ground position data.

Catastrophic: General term for those landslides that are large and rapid and deposits, typically in the form of debris in valley bottoms brought there by gravity.

Geospatial Information System (GIS): Computer programs and databases that allow for storage, manipulation, and retrieval and dissemination of geospatial information.

Geologic Inland: A geological condition that is potential threat to life and infrastructure. Landslides both occur and contribute to them.

Geomorphology: Science of the general configuration of the Earth's surface. Study of landform, description, origin and origin of landforms and the history of geologic changes as recorded by these surface features.

Landslide susceptibility map: This type of map depicts areas that have a potential of landslide, created by considering factors to assess landslide, such as steep slopes or geologic units, with past distribution of landslide occurrence.

Landslide inventory map: This type of map depicts areas where landslides have occurred. Inventory maps can be both local or regional and specific to individual landslides.

Landslide risk map: This type of map expresses the landslide hazard and its probability of occurrence in the context of the potential cost-benefit relationships and socioeconomic effects on the community.

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

Explanation

Landslide Susceptibility

- Low
- Low-Moderate
- Moderate
- Moderate-High
- High
- Building footprints
- Local roads
- State roads
- Railroads
- Corporate boundaries

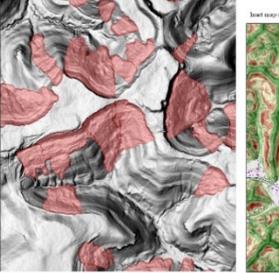
Probability: The likelihood of an event occurring, typically measured as a ratio of favorable cases to possible cases.

Relief: Difference in elevation between high and low points of the land surface.

Risk: Probability of occurrence or expected loss as a result of exposure to a hazard.

Stress: Force per area, acting on the surface internally and also external pressure acting on the object that generates internal stress.

Disclaimer and Data Limitations: These printed maps are neither scale representations of the digital spatial data that have been generated nor are a Geographic Information System (GIS). The data is best used for GIS or digital maps. This landslide susceptibility map is not intended to be a substitute for site-specific investigations by a licensed geologist or professional engineer. The maps use GIS data to show potential landslide areas where the uncertainties of slope stability or other variables may be appropriate prior to slope disturbance.



Landslide inventory compiled in Maguffin County.

Public features with no data were not included in the analysis.

The Kentucky Geological Survey, made in part, Kentucky Emergency Management and the Federal Emergency Management Agency (FEMA) for funding support and management of this planning project. FEMA Pre-Disaster Mitigation grant project number and title are FDMC-PE-16-KY-0117-002, Multi-hazard Mitigation Hazard Mitigation for the 100-year Flood Risk, KY-16-0001.

Landslide Susceptibility of Johnson County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch

Purpose

The purpose of this map is to identify landslide-prone areas in Johnson County in order to provide the public, and local and state government agencies with descriptions and areas where landslides are likely to occur. This map represents geomorphic-based susceptibility modeling that focuses on general slope characteristics and morphology, the quality of which is dependent on data accuracy and resolution of terrain models.

The availability of high-resolution (1.5-m digital elevation model) topographic and ranging (LIDAR-derived) datasets allows for the generation of terrain elevation derivatives such as hillshades, slope, aspect curvature, and roughness, as well as identification of terrain landslide deposits. These high-resolution, LIDAR-derived datasets, coupled with landslide-inventory systems, enable us to produce high-resolution and detailed landslide susceptibility maps.

Map Production

To produce a landslide-susceptibility map, 36 geomorphic variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. A 1.5-m DEM was resampled to 3-m cells in order to generate geomorphic maps. Each map was then processed using a multivariate regression model to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map.

The final map was produced using ArcGIS (ArcView) v. 10.7.1. The logistic regression was implemented using ArcGIS software (SPSS v. 18), as well as data analysis software (MATLAB (R2010b)).

To obtain consistent and systematic geomorphic statistics, a circular buffer was generated around the centroid point of LIDAR mapped landslides in Johnson County. The buffer areas for all landslides were used to calculate the statistical values from its geomorphic maps.

This process resulted in 36 individual values for each landslide occurrence, elevation, aspect, slope, roughness, curvature, and area of values within each buffer for each map. The buffer centroid for all mapped landslides had an area of 71,550 ft² (about 1.30 ha), which is the average area of the LIDAR mapped landslides. Although there is some correspondence between variables, we argue that deriving 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.

Geomorphic variable	Description
Elevation	Vertical distance of a specific location relative to sea level as a representation of the earth's surface (meters)
Slope	Inclination or exposure from rock wall of an elevation area (degrees)
Roughness	A degree of terrain irregularity calculated as surface deviation
Curvature	A measure of the curvature of the surface, based on its curvature in three dimensions
Aspect	Direction of maximum slope, perpendicular to the direction of contour lines (1-360 degrees)
Aspect	Curvature of the surface along a slope, derived by wall, cell or elevation meter

Landslide Susceptibility Model

To produce a landslide-susceptibility map, 36 variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. These geomorphic variables were evaluated using logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map. Logistic regression models the probability of an event in landslide being a function of other variables, and quantitative 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.

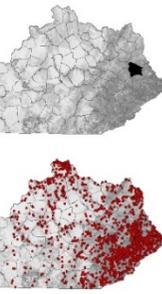
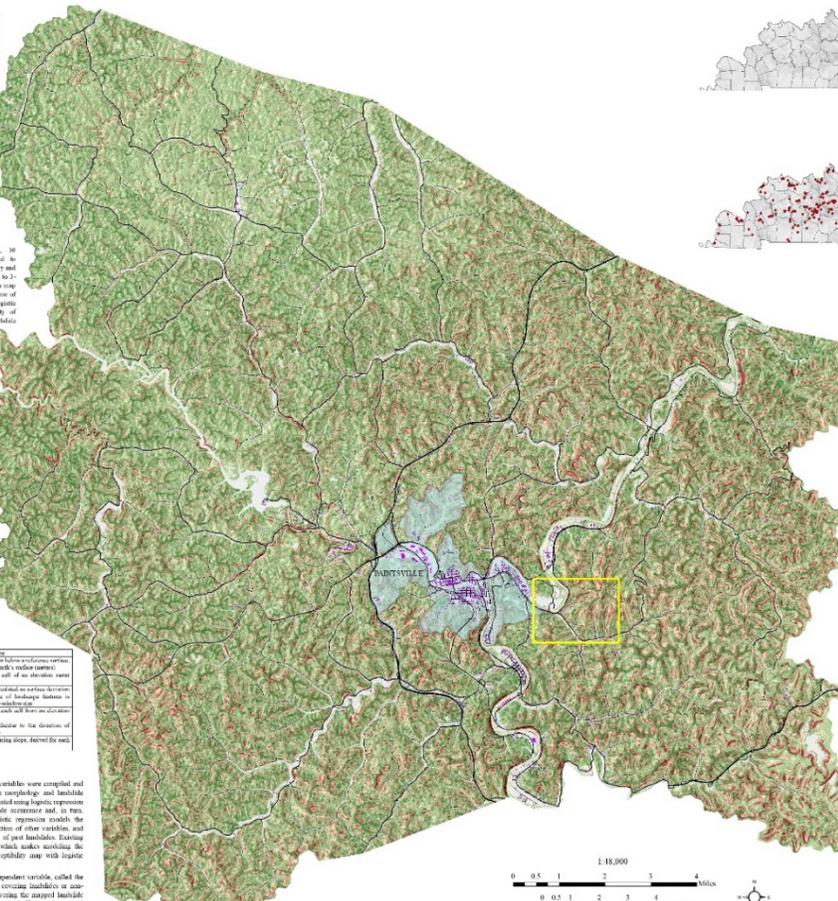
To use a logistic function to model a binary dependent variable, called the outcome, the outcome was created with buffer covering landslides or non-landslide areas. A buffer was created around the mapped landslide polygons (0.1-1.0 m in Johnson County). A buffer was also created around the centroid of a non-landslide event (0.1-1.0 m). The buffer has a radius of approximately 150 feet. The buffers are combined with a (landslide or 0 non-landslide) from the geographic dataset to create the statistical independent variables. The result was a binary variable for the dependent variable (1 = landslide, 0 = non-landslide), 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, as a measure of the chance that a landslide will be induced by the statistics of observed independent geomorphic variables.

Logistic regression results derive a coefficient of response (β) values and intercept which variables are significant (p-values). Low p-values indicate the data are unlikely to support a lack of difference. In low p-values (0.05) are returned, additional to the model because they are related to changes in the independent variables. The coefficient response the effects of the independent variables on the relative risk of a landslide or not a landslide.

where \ln is the natural logarithm of all positive variables (β), a model of relative risk of failure as the likelihood of a landslide or not a landslide; the covariate distribution logistic function is:

$$P = \frac{e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n}}{1 + e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n}}$$

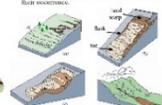
where P is the multivariate estimated upper probability of an event occurring (landslide occurrence or non-occurrence). The output is confined between 0 and 1. The logistic regression model on works well because the primary unknown is the independent energy variables.



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 is largely 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 the diagram below: creep (A), rotational landslide (B), translational landslide (C), debris flow (D), and traditional landslide (E) which includes debris flow, which were used for the landslide inventory mapping and ultimately to 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, landslide, and landslide. Other terms such as slope failure, slope movement, and slope failure are also commonly used to describe landslide phenomena. Regardless of which term is used, all landslides are physical and mechanical in nature and soil processes that explain their occurrence.



Landslides are caused by stresses on steep slopes that exceed the strength of the landslide soil. Stresses on a slope include increased pore-water pressure (from rainfall, irrigation, or snow melt), slope modification (excavation or excavation). A stable slope is one that balances the stresses imposed (driving forces) with the strength of the material (resisting forces). A slope will fail if these conditions are exceeded by (1) increasing the stresses, or (2) changing in resistance, both which cause a decrease in slope strength. The challenging part is that these stresses act over time and space at different scales, causing landslides to be sequential by varied conditions and triggers.

Examples of driving forces:

- Increase of weight at the top of the slope by artificial fill (e.g.)
- Intense or prolonged rainfall
- Removal of the toe of a slope by engineered cuts or natural stream erosion

Examples of change resisting forces:

- Increased soil moisture in active pore-water pressure from rainfall, or in snow banks from rapid fall of water level in the stream
- Vegetation removal
- Expansion and contraction of swelling clay soils with varying weather cycles
- Weakening of weak rocks

Explanation

Landslide Susceptibility

- Low
- Low-Moderate
- Moderate
- Moderate-High
- High
- Building footprints
- Local roads
- Slate roads
- Railroads
- Corporate boundaries

Glossary of Terms

Digital Terrain Model (DTM): A digital file of terrain elevation and ground position data.

Coefficient: General term for those and related soil deposits, typically at the base of slopes in valleys between floodplains or terraces.

Geographic Information System (GIS): Computer program and database that allow for storage, manipulation, analysis and dissemination of geographic information.

Catastrophic hazard: A geological condition that is potential threat to life or infrastructure. Includes both natural and man-made hazards.

Geomorphology: Science of the general configuration of the earth's surface; study of classification, description, nature and origin of landforms and the history of geologic changes as recorded by these surface features.

Landslide susceptibility map: This type of data depicts areas that have potential of landslides, created by correlating factors to cause landslides, such as steep slopes or potential faults, with past distributions of landslides occurrence.

Landslide inventory map: This type of data depicts areas where landslides have occurred. Inventory maps can be both point locations and specific events of landslides.

Landslide risk map: This type of map expresses the landslide hazard and its probability of occurrence in the context of local potential, cost/benefit relationships and socioeconomic effects on the community.

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

Probability: The likelihood of an event occurring, typically measured as a ratio of favorable cases to possible cases.

Relief: Difference in elevation between high and low points of the land surface.

Risk: Probability of occurrence or repeated loss as a result of exposure to a hazard.

Stress: Force per area, acting on any surface internally and also external pressure acting on the object that produces internal force.

We found that only geomorphic variables were significant (p-value of < 0.05). The table below also shows the LogP ratio (log(p-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 LogP ratio.

Geomorphic variable	p-value	LogP ratio
Minimum slope	0.000000	2.010
Maximum slope	0.000000	2.010
Soil depth	0.000000	2.010

Regression results show a connection between specific landslide morphologies that indicate a certain probability of landslide occurrence. The logistic regression model produced a likelihood-susceptibility map indicating where landslides are likely to occur based on the geomorphic conditions.

Probability	% Total Area	Landslide Susceptibility
0.000000	0.000000	Very Low
0.000000	0.000000	Low
0.000000	0.000000	Low-Moderate
0.000000	0.000000	Moderate
0.000000	0.000000	Moderate-High
0.000000	0.000000	High

Inset map below (not on larger map) showing part of Johnson County



Disclaimer and Data Limitations

This project was an aerial photo interpretation of the digital spatial data that has been presented in a Geographic Information System (GIS). The data is not used in a way that implies that the landslide susceptibility map is not intended to be a substitute for site-specific investigation by a licensed geologist or professional engineer. The user and GIS data do not show potential locations that are an interpretation of slope and dry or other data that are not available for the appropriate prior to slope disturbance.

Landslide Susceptibility of Martin County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch

Purpose

The purpose of this map is to identify landslide-prone areas in Martin County in order to provide the public and local state government agencies with information on areas where landslides are likely to occur. This map represents geospatially-based susceptibility modeling that involves an analysis of slope characteristics and morphology, the results of which is dependent on data accuracy and resolution of source models. The probability of high resolution (2-m digital elevation model) data-obtained and using (LIDAR)-derived datasets allows for the generation of terrain elevation characteristics 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 occurrence mapping, enable us to produce high-resolution and detailed landslide susceptibility maps.

Map Production

To produce a landslide susceptibility map, 36 geospatial variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. A 1.5-m DEM was resampled to 3-m cells in order to generate geospatial maps. Each map was then resampled using a digital smoothing method of approximately 1.5 to reduce noise. We used logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map. The final map was produced using ArcGIS (ArcInfo) v. 10.1.1. The logistic regression was conducted using statistical software (SPSS v. 17), as well as data analysis software (MATLAB v. R2010b).

To obtain consistent and accurate geospatial statistics, a circular buffer was generated around the centroid point of 1,251 mapped landslides in neighboring Magoffin County. The buffer areas for all landslides were used to calculate the statistical values from six geospatial maps. This process resulted in 30 individual values for each landslide (maximum, minimum, range, mean, standard deviation (SD), and sum of value within each buffer for each map). The buffer created for all mapped landslides had an area of ~7,530 ft² (radius of ~150 ft), which is the average area of 1,251 mapped landslides. Although there is some correspondence between variables, we agree that variation with an absolute amount of variables increases the probability of error, the strongest correlation will produce better model accuracy and a smoother, more realistic map.

Geospatial variable	Definition
Position	Vertical distance of a point from the horizontal reference surface, derived as a representation of the earth's surface elevation
Slope	Vertical distance of a point from the horizontal reference surface (degrees)
Distance variables	A range of corresponding statistical values (maximum, minimum, range, mean, standard deviation, sum) of value within each buffer for each map
Curvature	The curvature of a surface, derived from the second-order derivative of the surface elevation
Aspect	Direction of the steepest slope, derived from the first-order derivative of the surface elevation

Landslide Susceptibility Model

To produce a landslide susceptibility map, 36 variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. These geospatial variables were combined using logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map. Logistic regression models the probability of an event (in this case, a landslide) based on other variables, and provides probability based on statistical analysis of past landslides. Statistical models are often susceptible to overfitting, which involves modeling the probability of occurrence and developing a susceptibility map with logistic regression particularly difficult.

We used 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 around the centroid of each landslide polygon (N = 1,251) in neighboring Magoffin County. A buffer was also created around the centroid of a non-landslide area (N = 1,056). The buffer has a radius of approximately 150 feet. The buffer is attributed with a likelihood of 0 (non-landslide), since the geospatial distance contains the statistical information on presence or absence of a landslide, the result is a likelihood for the value. Likelihood (L) is calculated, which is a combination of one or more of the independent geospatial variables. The value predicted is a probability of an event ranging from 0 to 1 (i.e., an estimate of the occurrence). likelihood, that a landslide will be influenced by the statistics of observed independent geospatial variables.

Logistic regression results derive a coefficient of response (β values) and determine which variable are significant (p-values). Low p-values indicate we are not unlikely to reject a null hypothesis, i.e., low p-values (<0.05) indicate we are not unlikely to reject a null hypothesis, i.e., low p-values indicate we are not unlikely to reject a null hypothesis, i.e., low p-values indicate we are not unlikely to reject a null hypothesis.

$$z = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n$$

where z is the total contribution of all predictor variables (X), a model of relationship of presence in the landscape based on a landslide or non-landslide. The cumulative distribution function is:

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

where P is the cumulative estimated output probability of an event occurring (landslide occurrence or non-occurrence). The output is a likelihood of occurrence, but all the logistic regression variables were used to determine the probability of occurrence. We found that eight geospatial variables were significant (p-values of <0.05). The table below shows the log-likelihood (log-likelihood value), which is a transformation of the p-value and a way to visualize the relative weight of each variable. The higher the log-likelihood, the higher the log-likelihood.

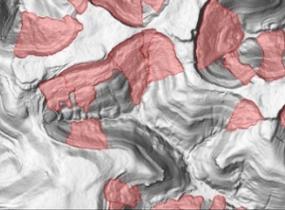
Geospatial variable	presence	absent	Log Likelihood
Maximum elevation	10000	7000	3.016
Range elevation	10000	1000	0.014
Sum elevation	10000	4000	1.146
Mean elevation	10000	4000	0.099
Standard deviation	10000	10000	0.009
Sum curvature	10000	-2000	1.000

Regression results show a connection between specific landscape 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 geospatial conditions. The map shows a good balance between indicating critical aspects that have a moderate to high probability of subsequent movement, as well as showing other parts of the slope that are not necessarily where erosion slope movement may have occurred related to existing landslide activity.

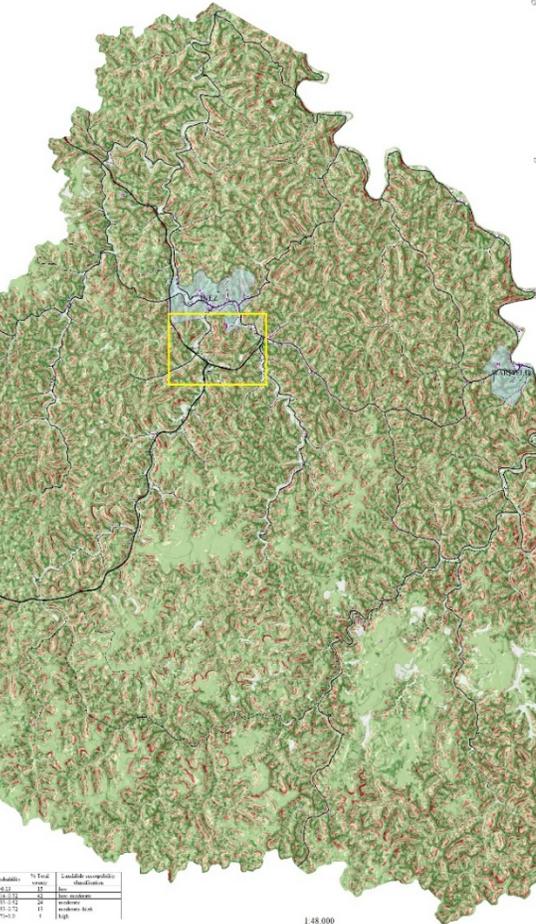
The susceptibility map does not determine landslide type potential areas or extent, or temporal relationships. Consequently, slopes vary in terms of landslide frequency, but all the logistic regression variables appear to indicate areas of moderate to high probability of occurrence over landslides, as well as in the middle of the landslide body or near the top. The majority of the final output buffer areas were not considered in the analysis. Five landslide susceptibility classifications were determined manually by creating breaks of coded deviations from the output of the logistic regression analysis. A 5 percent threshold was used, and 1.5 is placed as moderate-high and high.

For maps and GIS data do slope potential hazard areas where an interpretation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

Best maps (left) have the largest steep downslope part of Martin County.



Landslide inventory in Magoffin County.



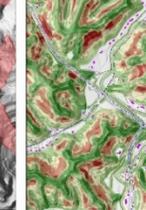
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Disclaimer and Data Limitations

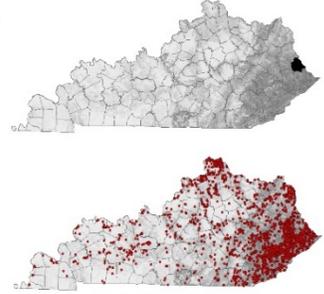
These related maps are neither a substitute for a professional engineering or architectural design, nor a substitute for site-specific investigation by a licensed geologist or geotechnical engineer.

For maps and GIS data do slope potential hazard areas where an interpretation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

Best maps (left) have the largest steep downslope part of Martin County.



*Valley bottom with no order was not included in the analysis.



Landslide point inventory map for the state of Kentucky.

Landslide Basics

A landslide is a general term for the downslope movement of rock, soil, or both under the influence of gravity. The rate of movement and resulting location of 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 the diagram below: (a) open slope; (b) translational landslide; (c) slump-slides; (d) debris flow; (e) rotational landslide; (f) debris flow; (g) debris flow; (h) debris flow; (i) debris flow; (j) debris flow; (k) debris flow; (l) debris flow; (m) debris flow; (n) debris flow; (o) debris flow; (p) debris flow; (q) debris flow; (r) debris flow; (s) debris flow; (t) debris flow; (u) debris flow; (v) debris flow; (w) debris flow; (x) debris flow; (y) debris flow; (z) debris flow; (aa) debris flow; (ab) debris flow; (ac) debris flow; (ad) debris flow; (ae) debris flow; (af) debris flow; (ag) debris flow; (ah) debris flow; (ai) debris flow; (aj) debris flow; (ak) debris flow; (al) debris flow; (am) debris flow; (an) debris flow; (ao) debris flow; (ap) debris flow; (aq) debris flow; (ar) debris flow; (as) debris flow; (at) debris flow; (au) debris flow; (av) debris flow; (aw) debris flow; (ax) debris flow; (ay) debris flow; (az) debris flow; (ba) debris flow; 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Landslide Susceptibility of Pike County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch

Purpose

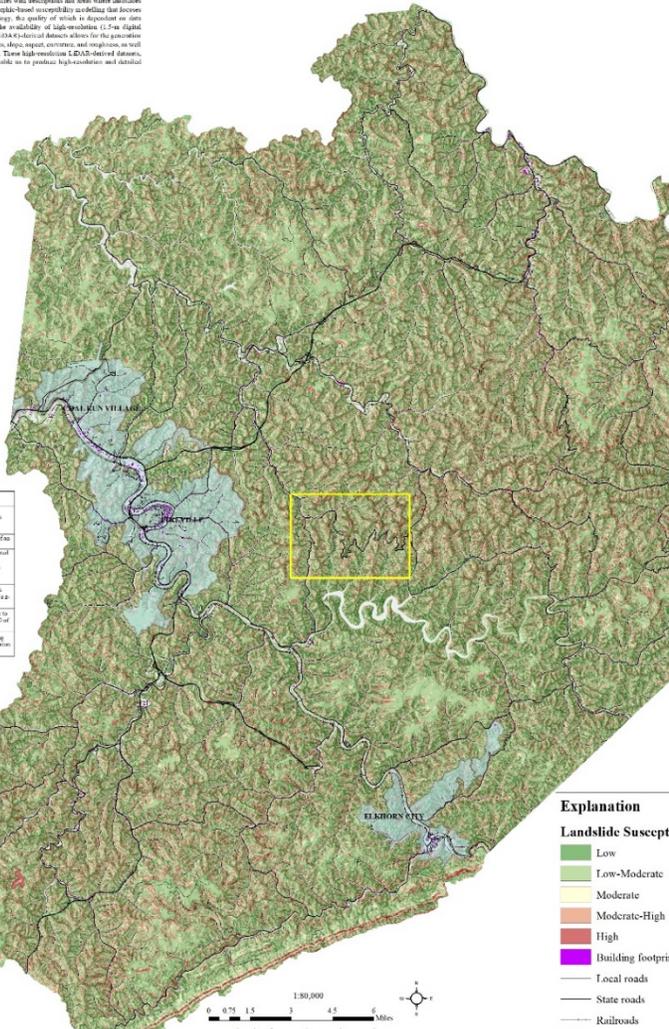
The purpose of this report was to identify landslide-prone areas in Pike County in order to provide the public and local area government agencies with descriptions and areas where landslides are likely to occur. This map represents potential landslide susceptibility modeling that focuses on physical slope characteristics and morphology; the quality of rocks is dependent on data accuracy and resolution of terrain models. The availability of high-resolution (1.5-m digital elevation model) high-resolution and mapping (1:25,000) data is critical for the generation of terrain elevation derivatives such as hill-slopes, slope, aspect, curvature, and roughness, as well as identification of existing landslide deposits. Three high-resolution LIDAR-derived datasets, coupled with landslide inventory mapping, enable us to produce high-resolution and detailed landslide susceptibility maps.

Map Production

To produce a landslide-susceptibility map, geospatial variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. A 1.5-m DEM was resampled to 3-m cells in order to generate geospatial maps. Each map was then compiled using a radial variational window of approximately 15 m to derive maps. The best logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map. The final map was produced using ArcGIS (ArcSWH) v. 10.1. The logistic regression was conducted using statistical software SPSS (v. 19), as well as data analysis software MATLAB (R2010b).

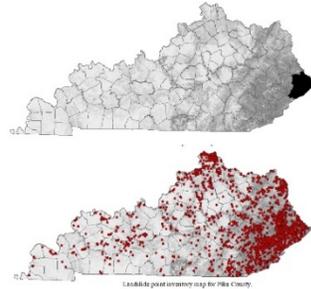
To obtain consistent and systematic geospatial statistics, a circular buffer was generated around the centroid point of 1,051 mapped landslide in neighboring Maguffin County. The buffer sizes for all landslides were used to calculate six statistical values from the geospatial maps. The values resulted in 36 individual values for each landslide (curvature, elevation, aspect, aspect, maximum deviation (MSD), and sum of values within each buffer for each map). The buffer sizes for all mapped landslides had an area of 71,250 ft² (about 1.58 ha), which is the average area of the 1,054 mapped landslides. Although there is some correspondence between variables, we argue that varying with an abundant number of variables increases the probability of capturing the strongest conditions and will produce better model accuracy and a smoother, more realistic map.

Abbreviation	Definition
Planation	Vertical distance of a point along an slope before a reference surface, defined as a representation of the earth's surface.
Slope	Direction or measure from each cell of the DEM.
Aspect	A degree of terrain irregularity calculated in which determining a variable value, such as elevation, based on a reference surface.
Curvature	The second derivative value from each cell of the DEM.
Plan curvature	Curvature of the surface perpendicular to the direction of maximum slope (170° or 190°).
Aspect	Direction of maximum slope, defined for each cell of an elevation map.



Explanation

- Landslide Susceptibility**
- Low
 - Low-Moderate
 - Moderate
 - Moderate-High
 - High
 - Building footprints
 - Local roads
 - State roads
 - Railroads
 - Corporate boundaries



Landslide Basics

A landslide is a general term for the downslope movement of rock, soil, or both under the influence of gravity. This type of movement and resulting failure is dependent on the influence of 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 the diagram below. For some of the traditional landslides (1) steep-sloped failure, the washment boundary is labeled with landslide type, which were used for the landslide inventory map and ultimately for 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 landslides, slides, and rockfalls. Other terms such as mass wasting, slope movement, and slope failure are also commonly used to discuss landslide phenomena. Features of which type is used, all landslides have physical and mechanical (in rock and soil) processes that explain their occurrence.

Landslides are caused by stresses on steep slopes that exceed the strength of the landslide soil. Stressors can include increased pore-water pressure (from rainfall, gravity, or some type of slope modification (landfill construction)).

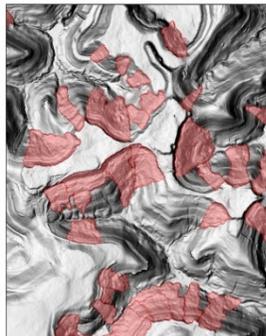
A stable slope will fail if the stresses imposed (driving forces) with the strength of the material (resisting forces). A slope will fail if these conditions are disturbed by (1) increased stress, or (2) a change in resistance, both which cause a decrease in their strength. The challenging part is that these stresses act over time and types of different scales, causing landslides are sequenced by event conditions and triggers.

- Examples of driving forces:**
- Change of weight at the top of the slope by adding additional fill
 - Loose or prolonged rainfall
 - Removal of the toe of the slope by engineered cut or natural stream erosion

- Examples of slope resisting forces:**
- Increased soil moisture in relative pore-water pressure from rainfall or, in winter, from rapid fall of water level in the stream
 - Vegetative removal
 - Expansion and contraction of swelling clay soils with wet-dry weather cycles
 - Weathering of weak rocks

Glossary of Terms

- Digital Elevation Model (DEM):** A digital file of terrain elevation and ground point data. Colored lines for the lines and signal soil deposits, typically at the base of slopes in valley bottom through them by gravity.
- Geographic Information System (GIS):** Computer programs and databases that allow for storage, manipulation, analysis, and dissemination of cartographic information.
- Geologic hazard:** A geological condition that is potential threat to life or infrastructure. Includes both natural and man-made features.
- Geomorphology:** Science of the general configuration of the Earth's surface. Study of classification, description, origin and evolution of landforms and the history of pedologic changes as recorded by these landforms.
- Landslide inventory map:** This type of map depicts areas where landslides have occurred, inventory maps can be both point locations and specific areas of landslides.
- Landslide risk map:** This type of map expresses the landslide hazard and its probability of occurrence in the context of loss potential, cost/benefit relationships and socioeconomic effects on the community.
- Mitigation:** Activities that reduce or eliminate the probability of a hazard occurring, or lower the effects of the hazard when they do occur.
- Probability:** The likelihood of an event occurring, typically measured as a ratio of favorable cases to possible cases.
- Relief:** Difference in elevation between high and low points of the land surface.
- Risk:** Probability of occurrence or expected loss as a result of exposure to a hazard.
- Stress:** Force per area, acting on any surface internally and also external pressure acting on the shape that generates internal force.



Landslide Susceptibility Model

To produce a landslide-susceptibility map, 36 variables were compiled and used to investigate the connection between slope morphology and landslide occurrence. These geospatial variables were used to create logistic regression modeling to determine the probability of landslide occurrence and, in turn, creation of a landslide susceptibility map. Logistic regression models the probability of an event (a landslide) being a function of other variables, and statistical probability based on statistical analysis of past landslides. Existing landslides are often susceptible to reactivation, which makes evaluating the probability of occurrence and developing a susceptibility map with logistic regression particularly important.

It 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 around each mapped landslide polygon (0.75 to 1.50 m). The buffer has a radius of approximately 150 feet. The buffers are overlaid with a 1:5000 map. Since the geospatial dataset contain the metadata information on presence or absence of a landslide, the result are log-odds for the value labels (1 = landslide), which is a combination of one or more of the independent geospatial variables. The value predicted is probability of occurrence (relative likelihood) that a landslide will be observed by the statistics of observed independent geospatial variables.

Logistic regression models derive a coefficient of regression (b) values and determine which variables are significant (p-values). Low p-values indicate the data are unlikely to suggest a lack of dependence. Low p-values (p < 0.05) are not random additions to the model because they are related to changes in the indicator variable. The coefficient measures the effects of the predictor independent variables on the relative risk of being a landslide or not a landslide.

where P is the cumulative estimated output probability of an event occurring (landslide occurrence or non-occurrence). The output is modified between 0 and 1. The logistic regression analysis will measure the primary relationship in the relationship among the variables. We found that eight geospatial variables were significant (p-values of < 0.05). The table below also shows the Log(Odds) (log_e of odds), which is a transformation of the coefficient and a way to visualize the relative weight of each variable. The higher the significance, the higher the Log(Odds).

Geospatial Variable	Coef.	Exp. Coef.	Log(Odds)
Planation	0.0002	1.0002	0.0002
Slope	0.0002	1.0002	0.0002
Aspect	0.0004	1.0004	0.0004
Curvature	0.0004	1.0004	0.0004
Plan curvature	0.0004	1.0004	0.0004
Aspect	0.0004	1.0004	0.0004
MSD	0.0004	1.0004	0.0004
Sum of values	0.0004	1.0004	0.0004

Regression models show a connection between specific landslide geomorphologies 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 geospatial conditions. The map utilizes a good balance between indicator coding, showing that have a moderate to high probability of subsequent movement or not in respect other parts of the slope that do not necessarily show obvious slope movement but may have features related to causing landslide activity.

The susceptibility map shows not delineate landslide types, potential extent or amount or temporal implications. 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 and landslides, as well as in the middle of the landslide body or near the toe. The accuracy of the final digital relief features were not considered in the analysis. Five landslide-susceptibility classifications were determined manually by creating breaks of standard deviation from the mean. Of the mapped landslide deposits, 45 percent are classified as moderate and 18.8 percent as moderate-high and high.

Probability	Total	Landslide Susceptibility
0.0002	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10
0.0004	10	10

Disclaimer and Data Limitations

This product map is an aerial scale. The landslide susceptibility map is not intended to be a substitute for representations of the digital spatial data and the atmospheric interpretation by a licensed geologist or geotechnical engineer. The maps and GIS data show potential hazardous areas, which are investigation of slope stability or other mitigation, client and user is best to use in GIS at larger scales.

Best map resolution for larger map showing part of Pike County



*Valley bottom with no color were not included in the analysis.

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