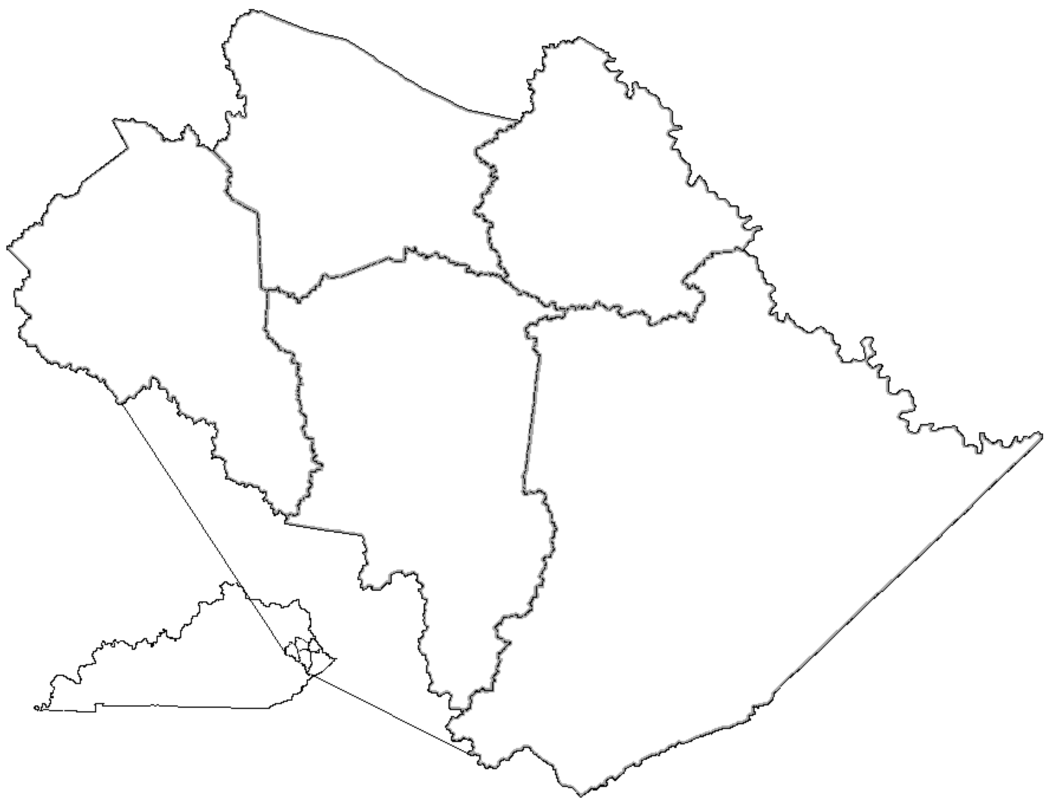
# Multi-Jurisdictional Hazard Mitigation Plan for Landslides for the Big Sandy Area Development District, Kentucky



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

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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.

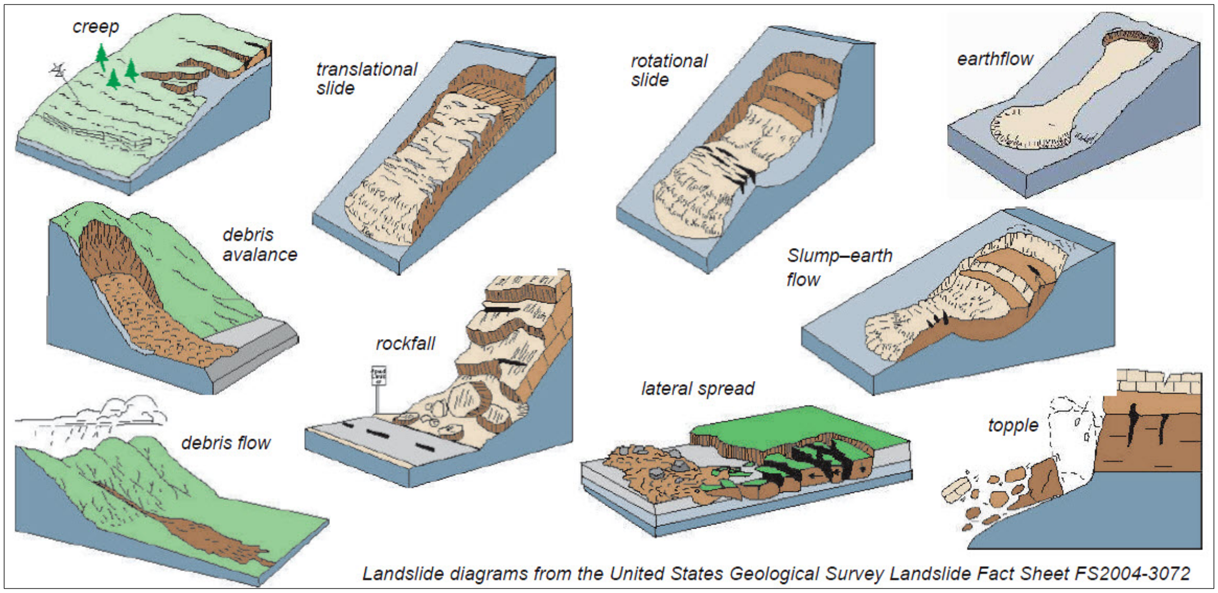


Figure 1. Landslide types.

## 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.

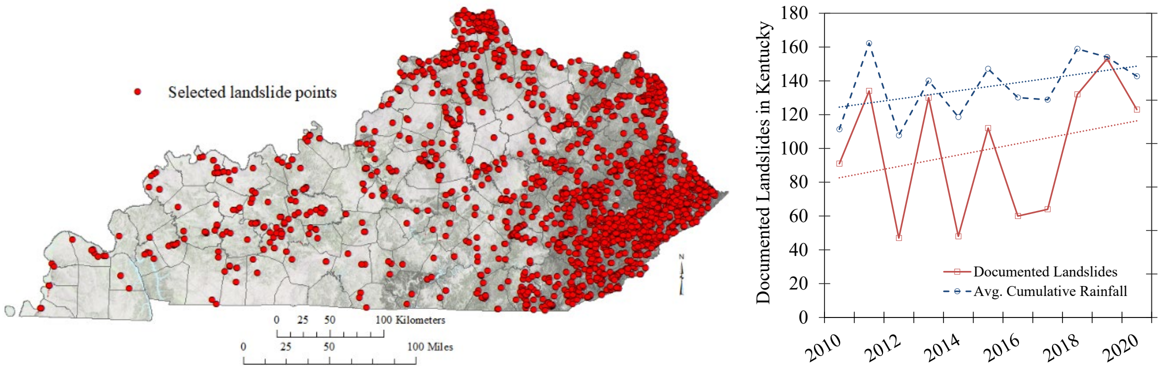


Figure 2. Documented landslide locations in Kentucky (left) and documented landslides versus statewide average cumulative rainfall (right). Dashed lines are linear trends.

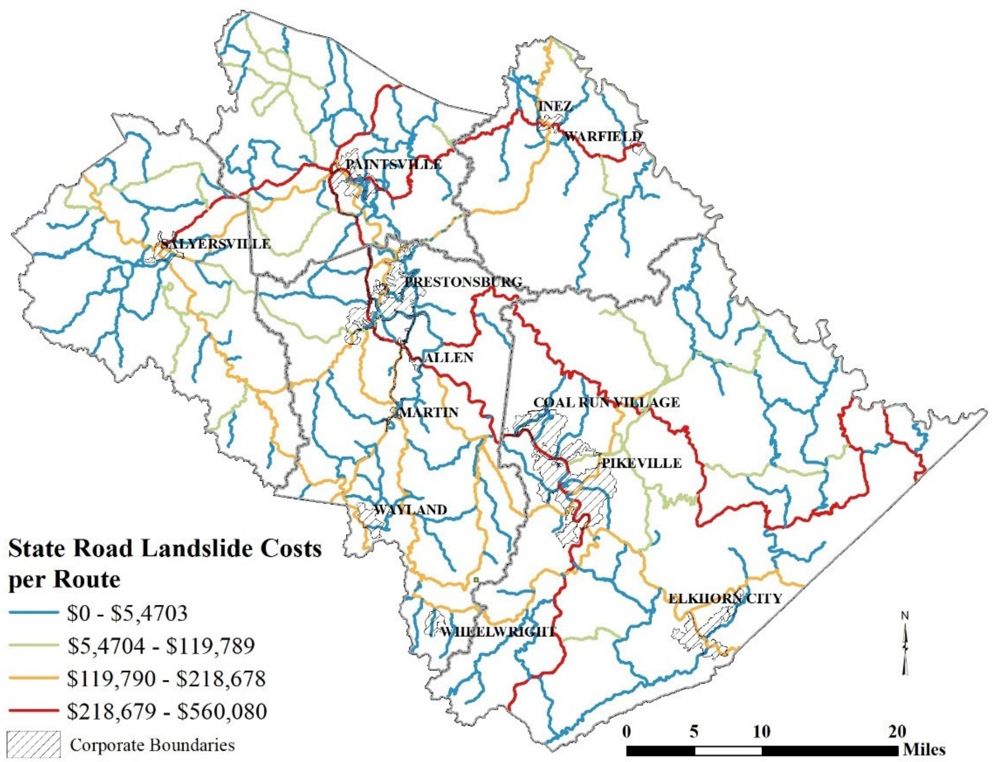


Figure 3. Landslide and rockfall costs per route in the Big Sandy Area Development District. These are only Kentucky Transportation Cabinet maintenance cost records that span 2003 to 2009. Large, expensive landslide mitigation projects are likely not included in these cost totals.

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 $mi^2$. 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/kgsmap/helpfiles/landslide_help.shtm. The statewide inventory database can be downloaded here: https://uknowledge.uky.edu/kgs_data/4/

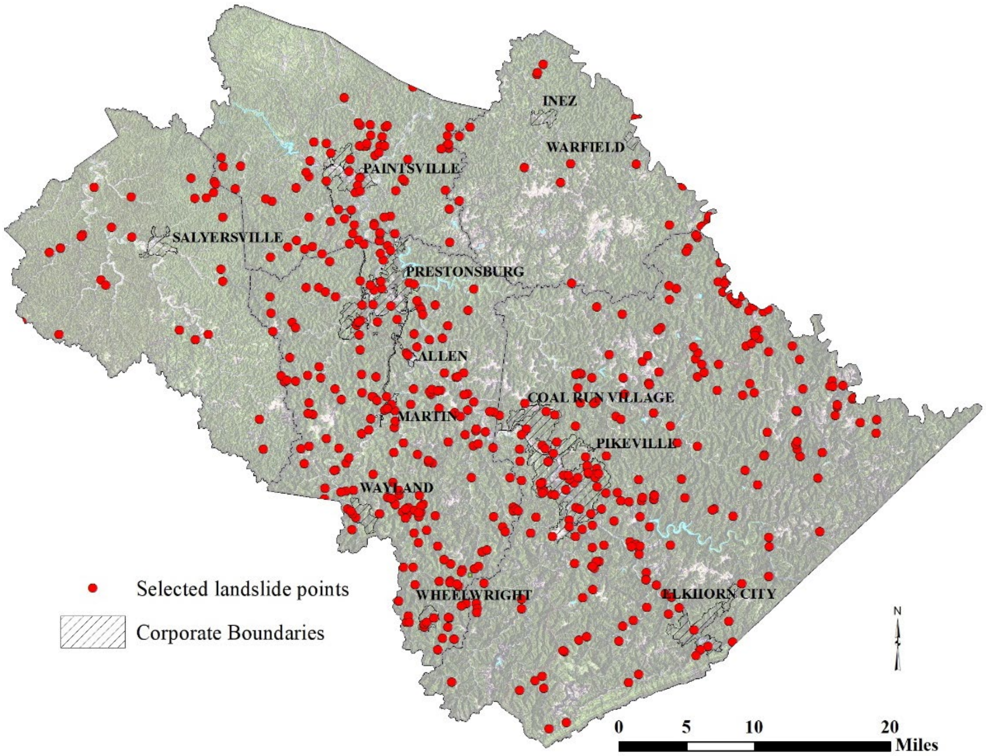


Figure 4. Selected landslide locations from the KGS landslide database. Not all documented landslides are shown on this map, for full access to the KGS landslide inventory see https://kgs.uky.edu/kgsmap/helpfiles/landslide_help.shtm

*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 $ft^2$. 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.

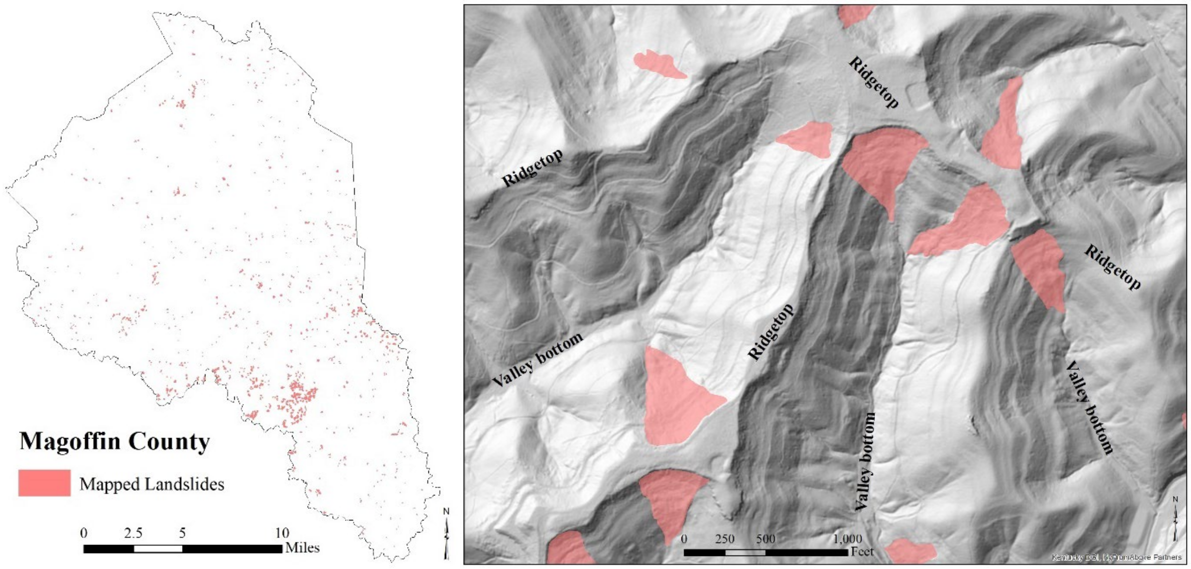


Figure 11. Landslide extents mapped in Magoffin County and zoomed-in example of hillshade map showing specific landslide deposit extents.

*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 |

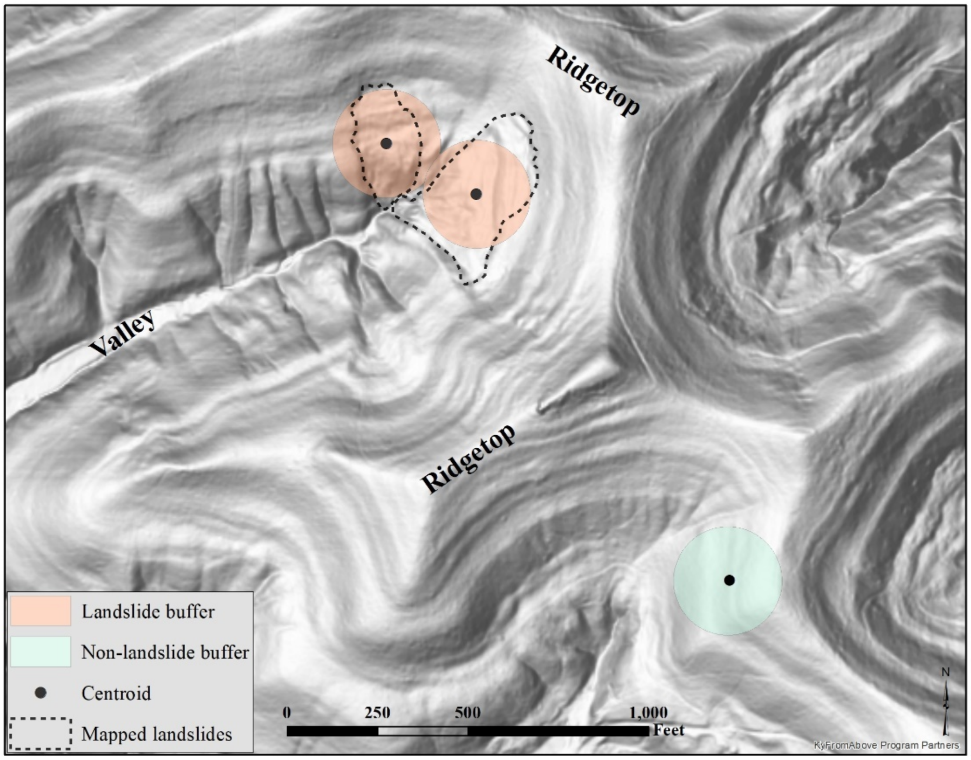

Figure 12. Landslide buffers around centroids of mapped landslides (pink) and a non-landslide (green), Magoffin County, Kentucky.

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 ft$^2$ (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). 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:

$$log\left(\frac{P(y=0)}{P(y=1)}\right) = \beta_0 + \beta_1 V_1 + \beta_2 V_2 + \cdots + \beta_x V_x$$

where $\beta_0$ is the constant intercept, $V$ is the geomorphic variables, and $\beta$ 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:

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

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 $\leq 0.05$; 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 ($-log_{10}$ ($p$-$value$)), 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.

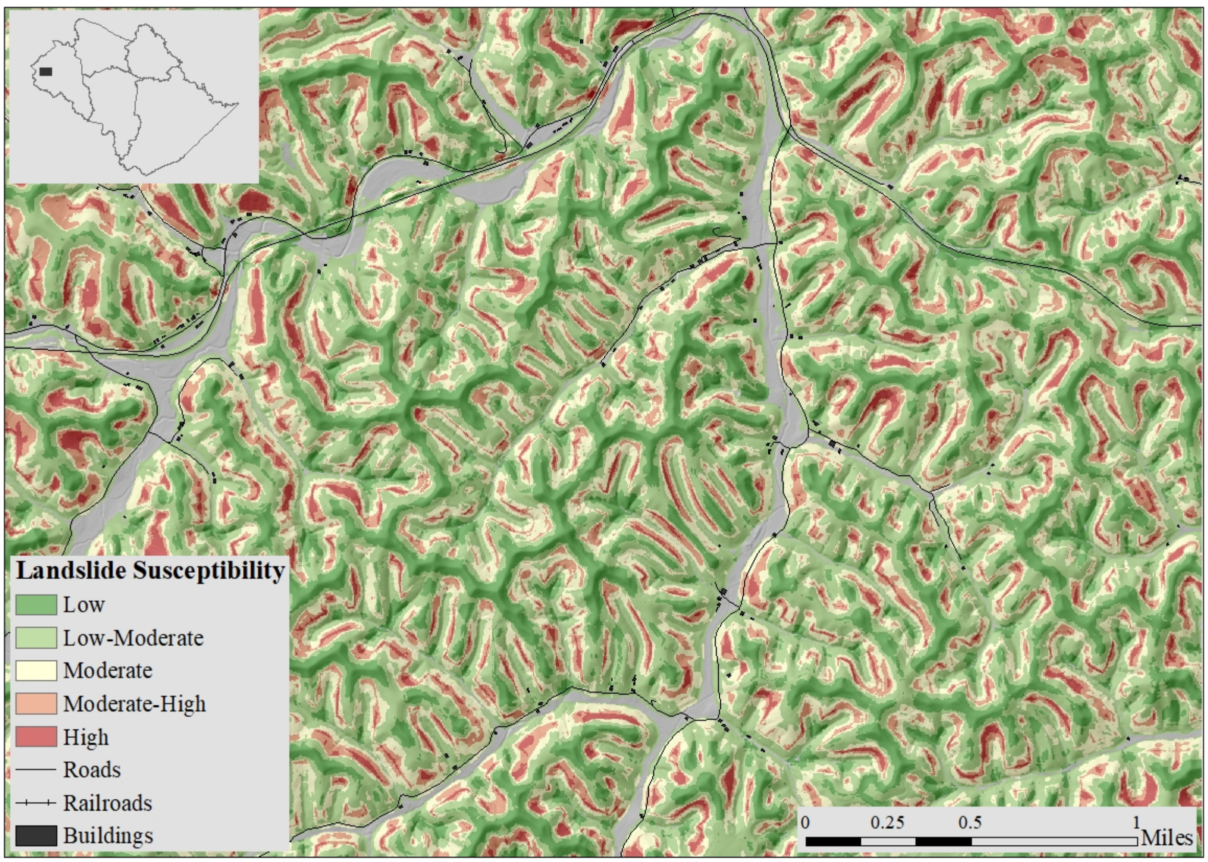


Figure 13. Landslide susceptibility in part of Magoffin County. See **Appendix B** for entire county map.

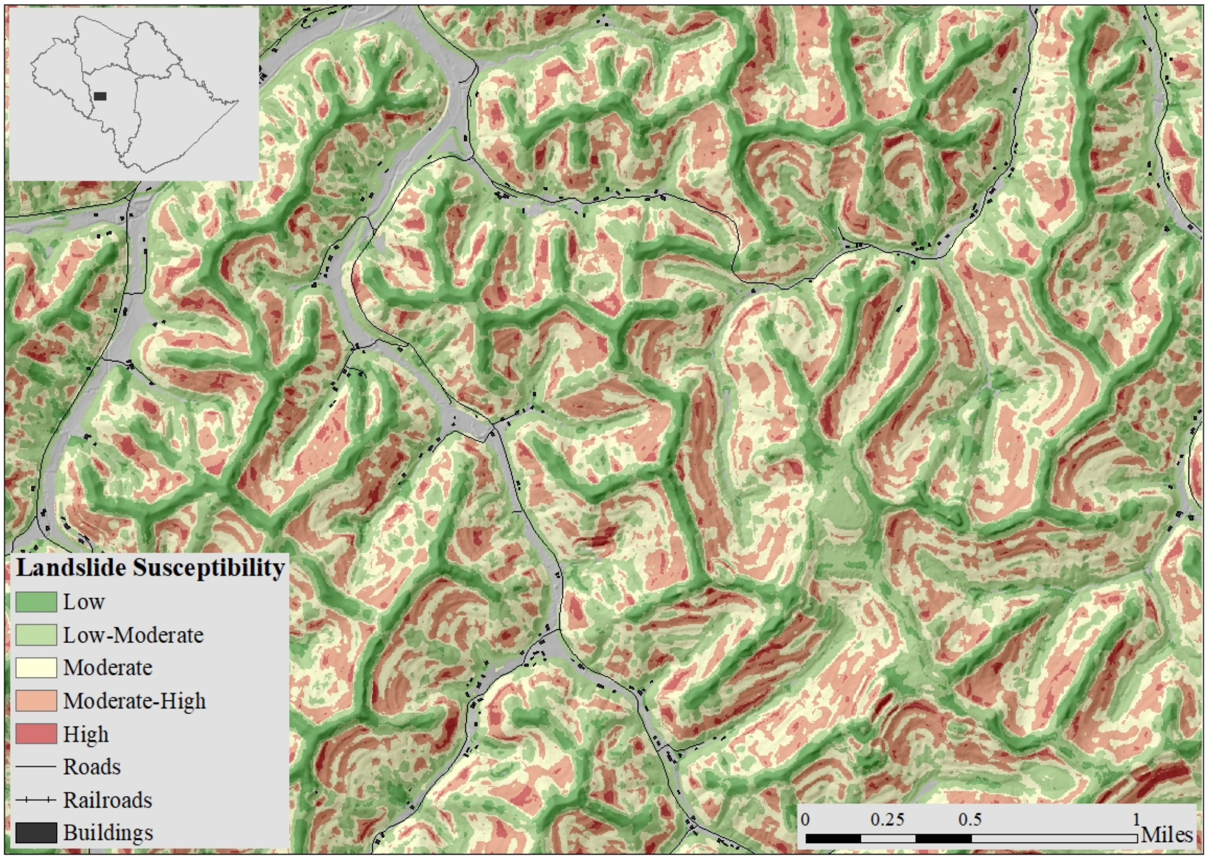

Figure 14. Landslide susceptibility in part of Floyd County. See **Appendix B** for entire county map.

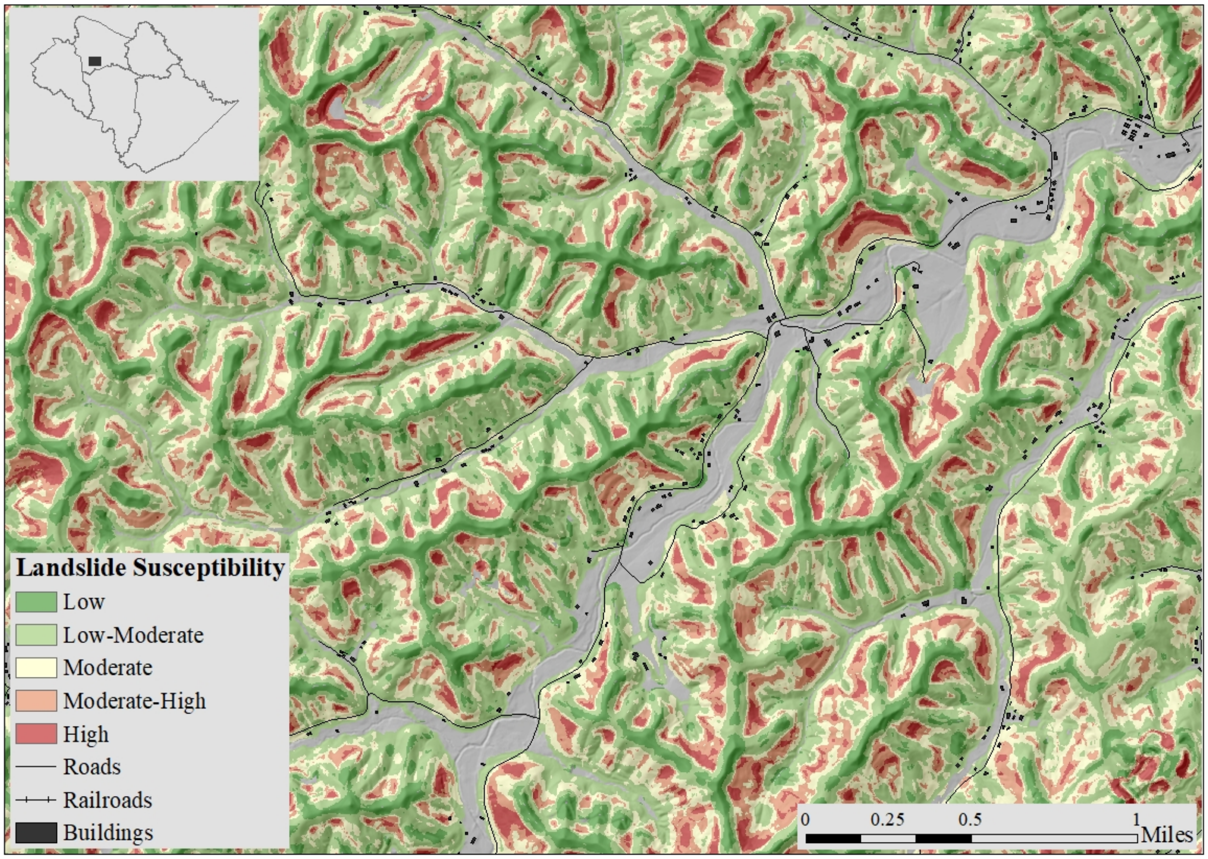

Figure 15. Landslide susceptibility in part of Johnson County. See **Appendix B** for entire county map.

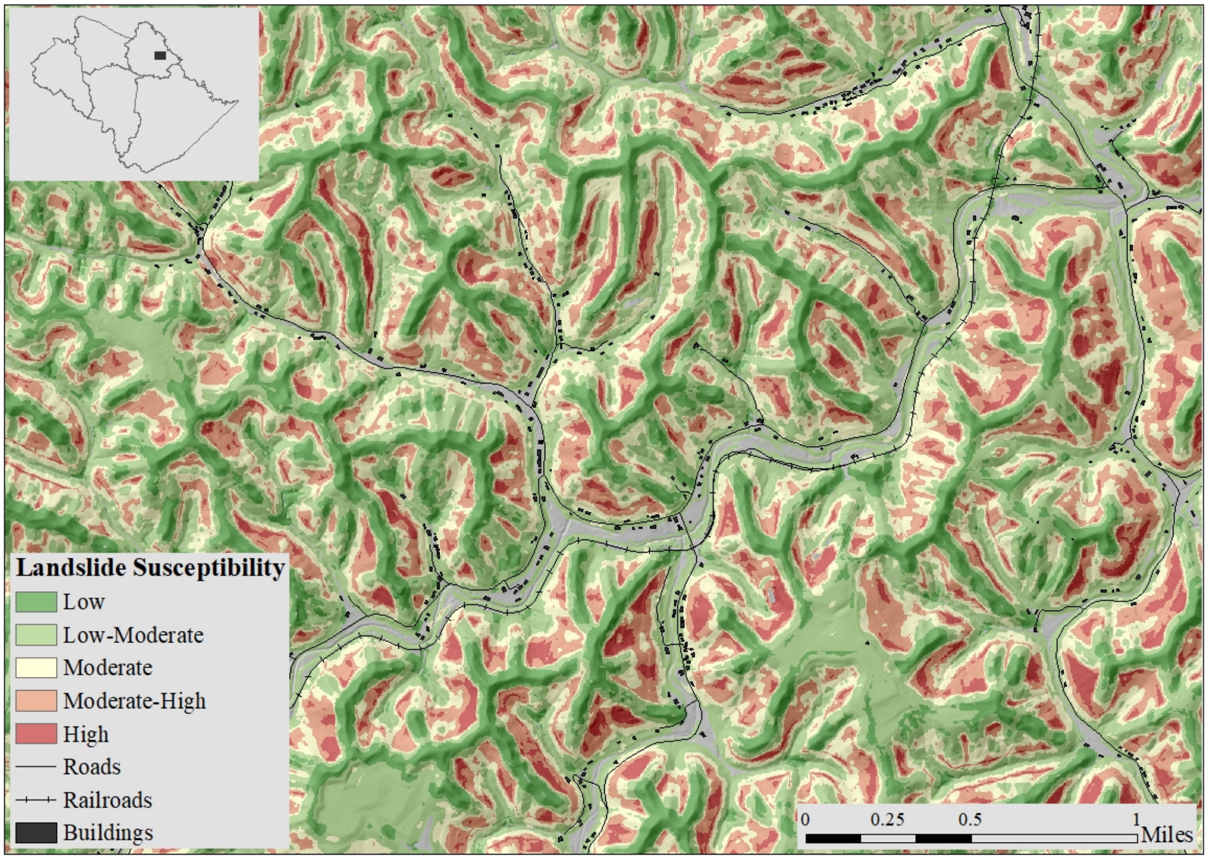

Figure 16. Landslide susceptibility in part of Martin County. **See Appendix B** for entire county map.

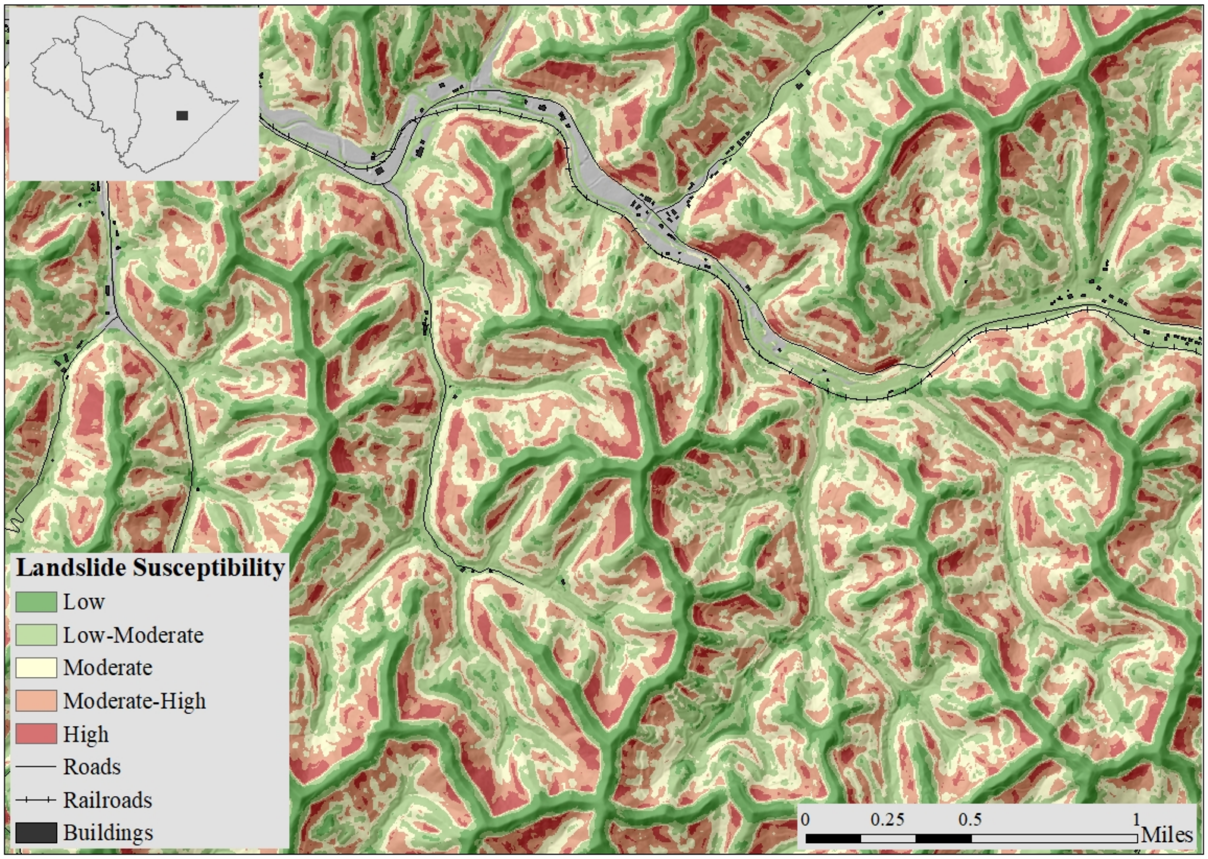

Figure 17. Landslide susceptibility in part of Pike County. See **Appendix B** for entire county map.

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).

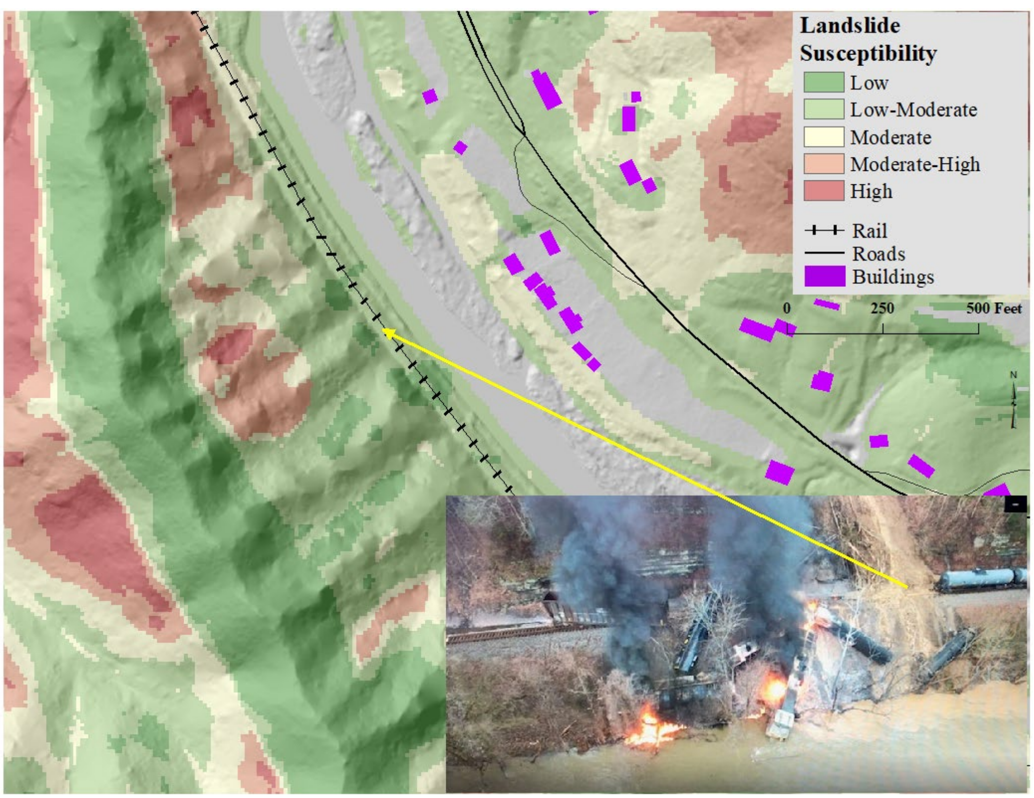


Figure 18. A landslide caused a train derailment in Pike County on February 13, 2020.
The landslide likely initiated from the pink and red area upslope, above the railroad.

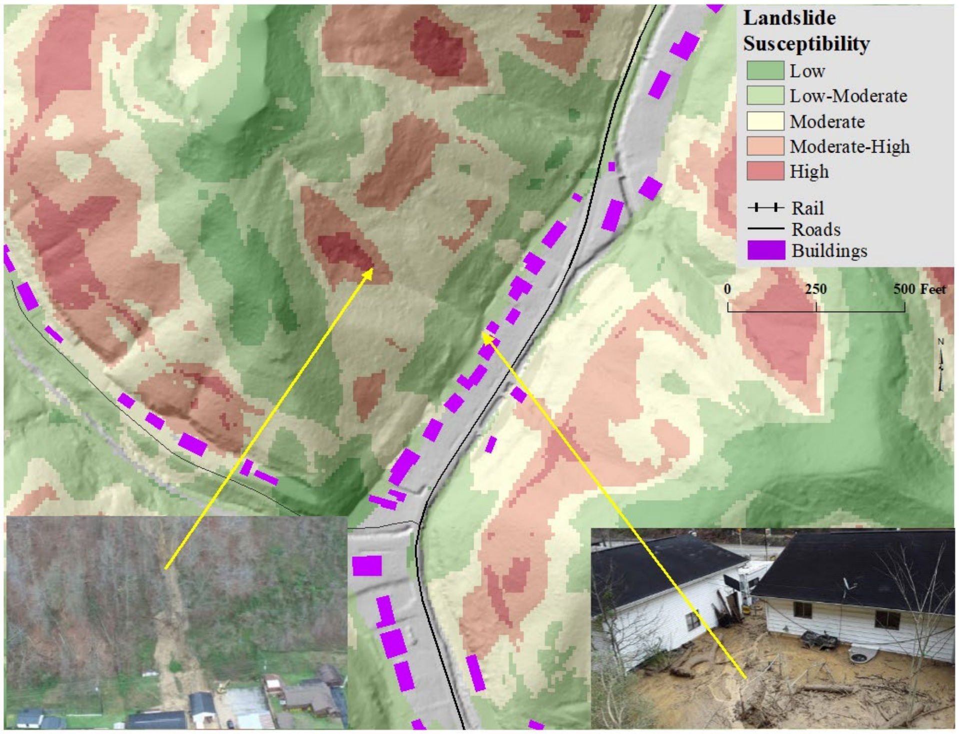

Figure 19. A narrow landslide occurred on April 12, 2020, on a slope above Chloe Road in Pike County. The landslide damaged two buildings.

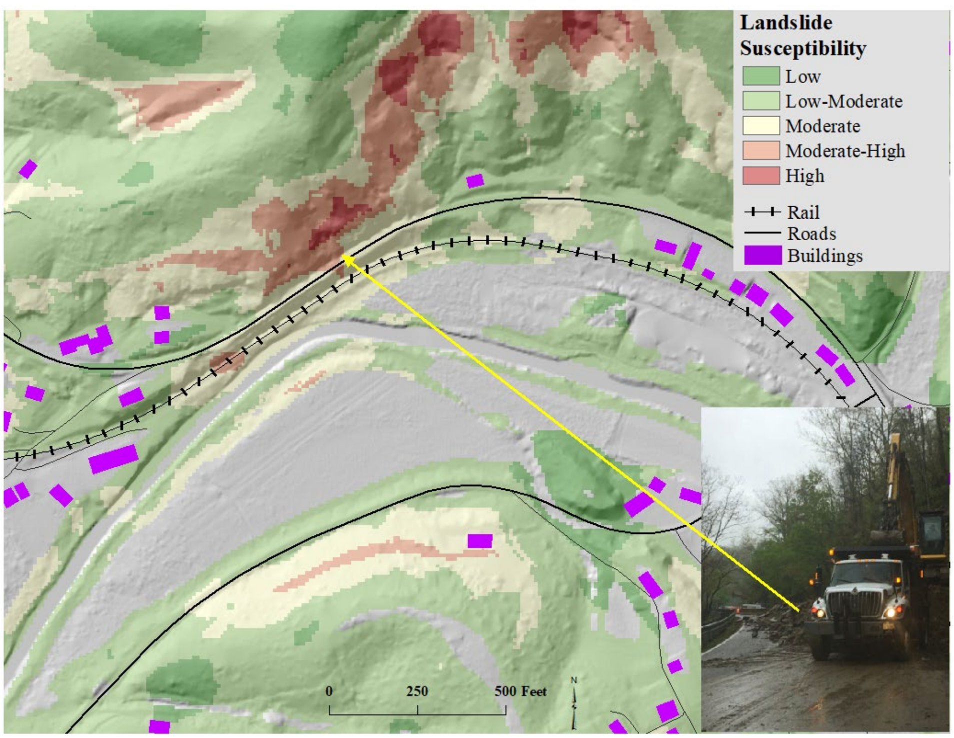

Figure 20. A landslide occurred on April 24, 2020 along KY 550 in Floyd County. The landslide occurred on the slope above KY 550 and above a railroad. Note the moderate-high and high classification to a broad swath of the slope above the road.

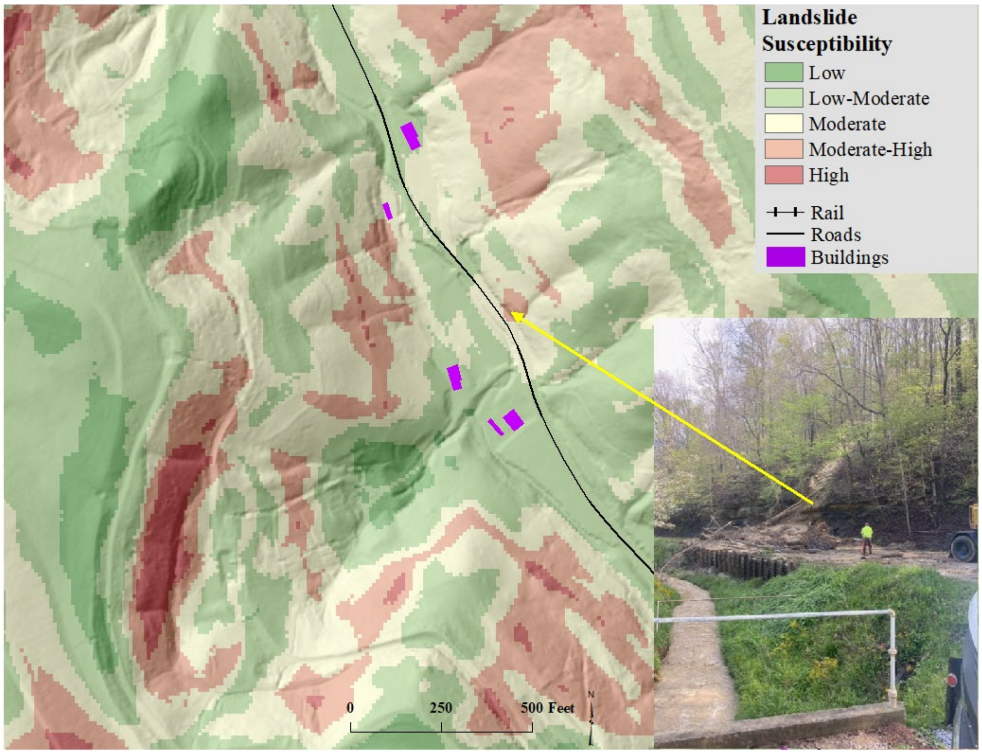


Figure 21. A landslide occurred on April 27, 2020 along KY 881 in Pike County. The landslide initiated on the slope above the road.

**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** = **H**azard **x** **V**ulnerability **x** **C**onsequence

**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.

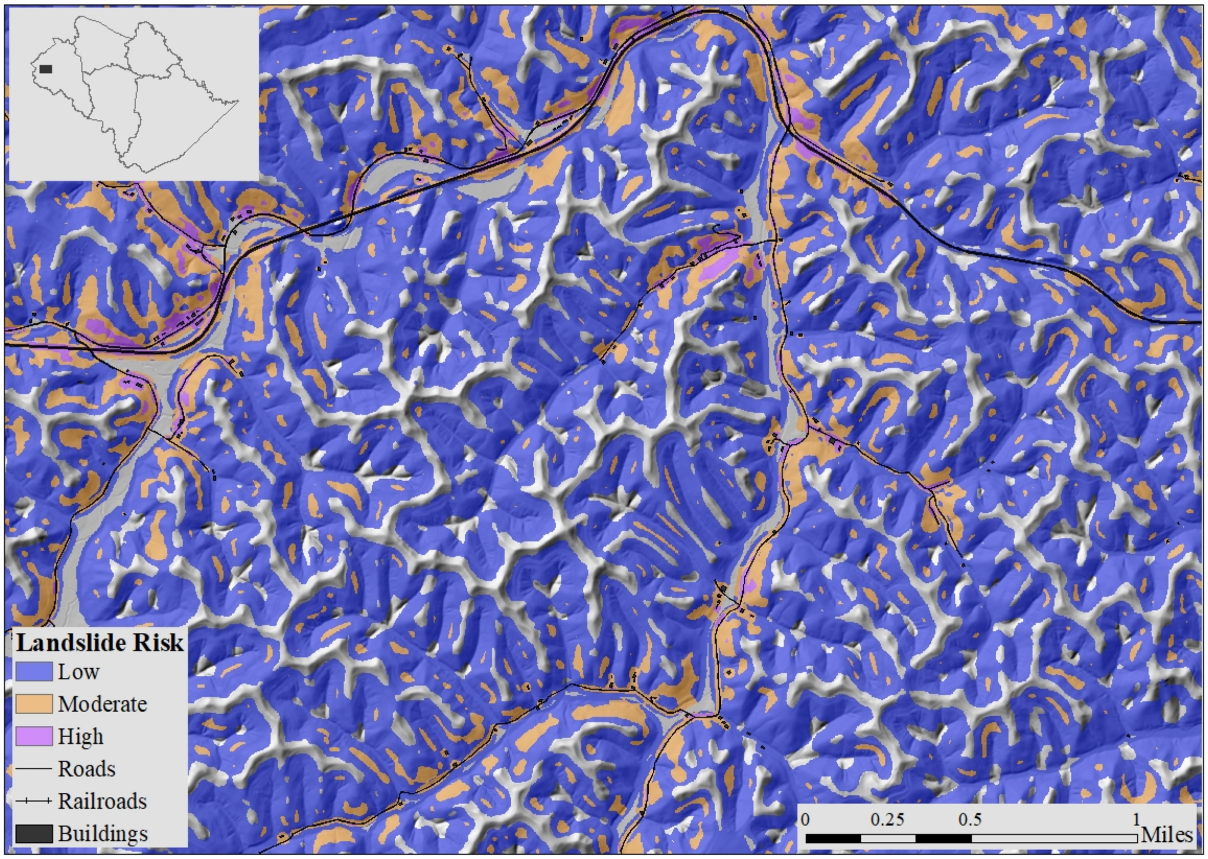

Figure 22. Landslide risk in part of Magoffin County. See **Appendix C** for the full county risk maps.

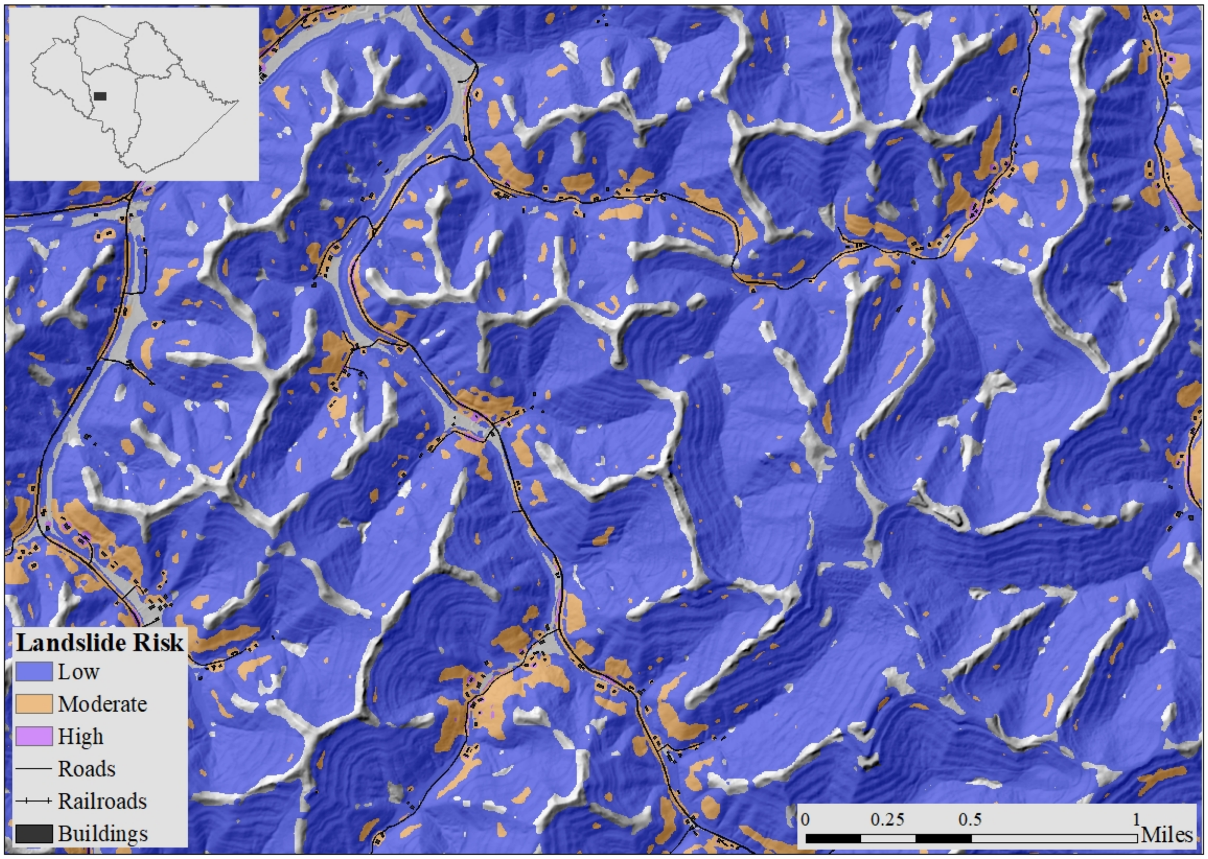

Figure 23. Landslide risk in part of Floyd County. See **Appendix C** for the full county risk maps.

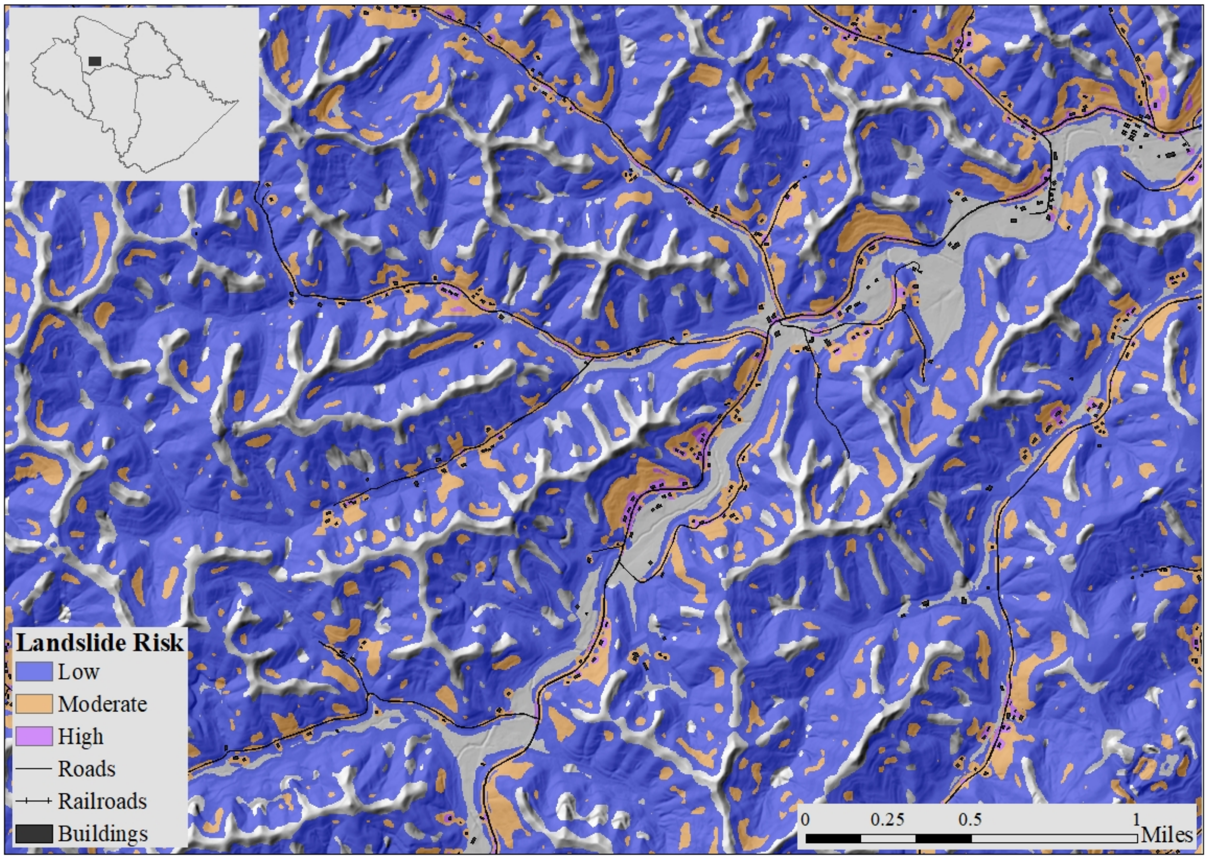

Figure 24. Landslide risk in part of Johnson County. See **Appendix C** for the full county risk maps.

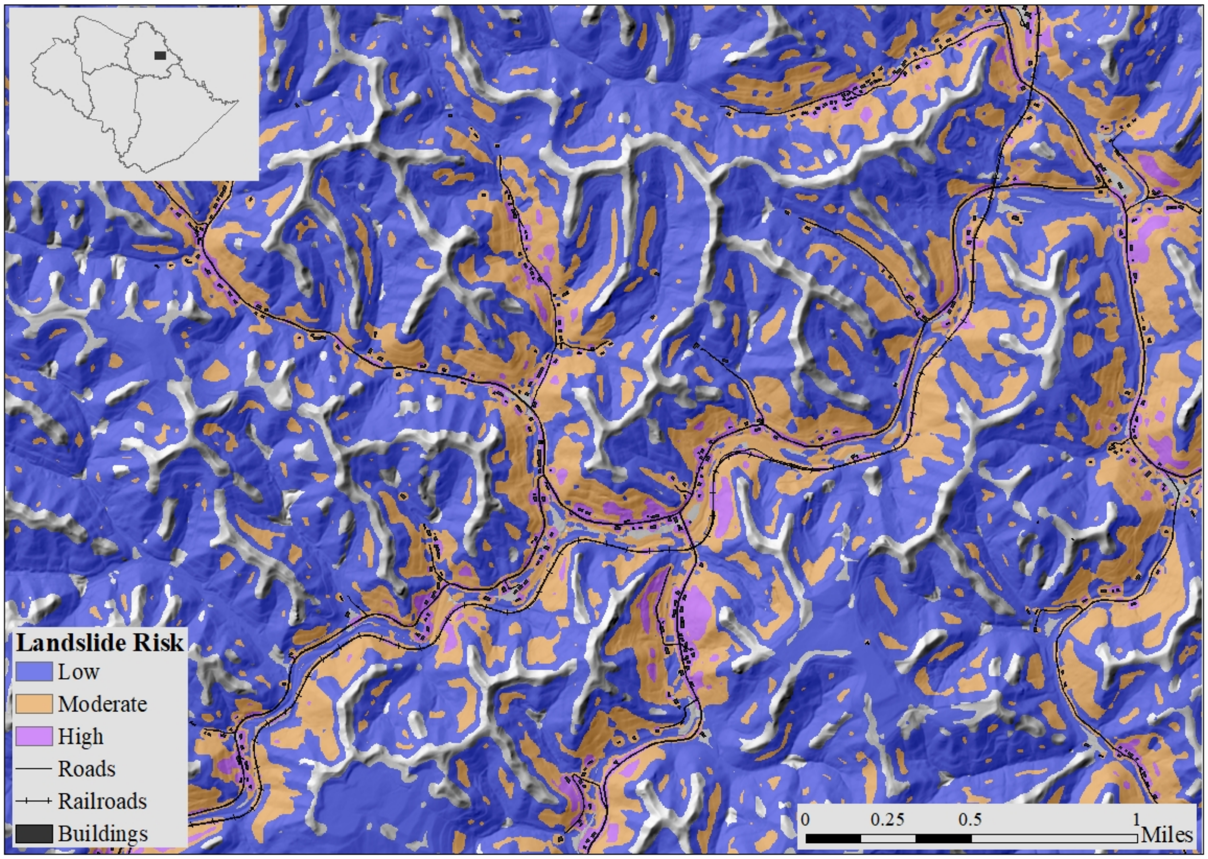

Figure 25. Landslide risk in part of Martin County. See **Appendix C** for the full county risk maps.

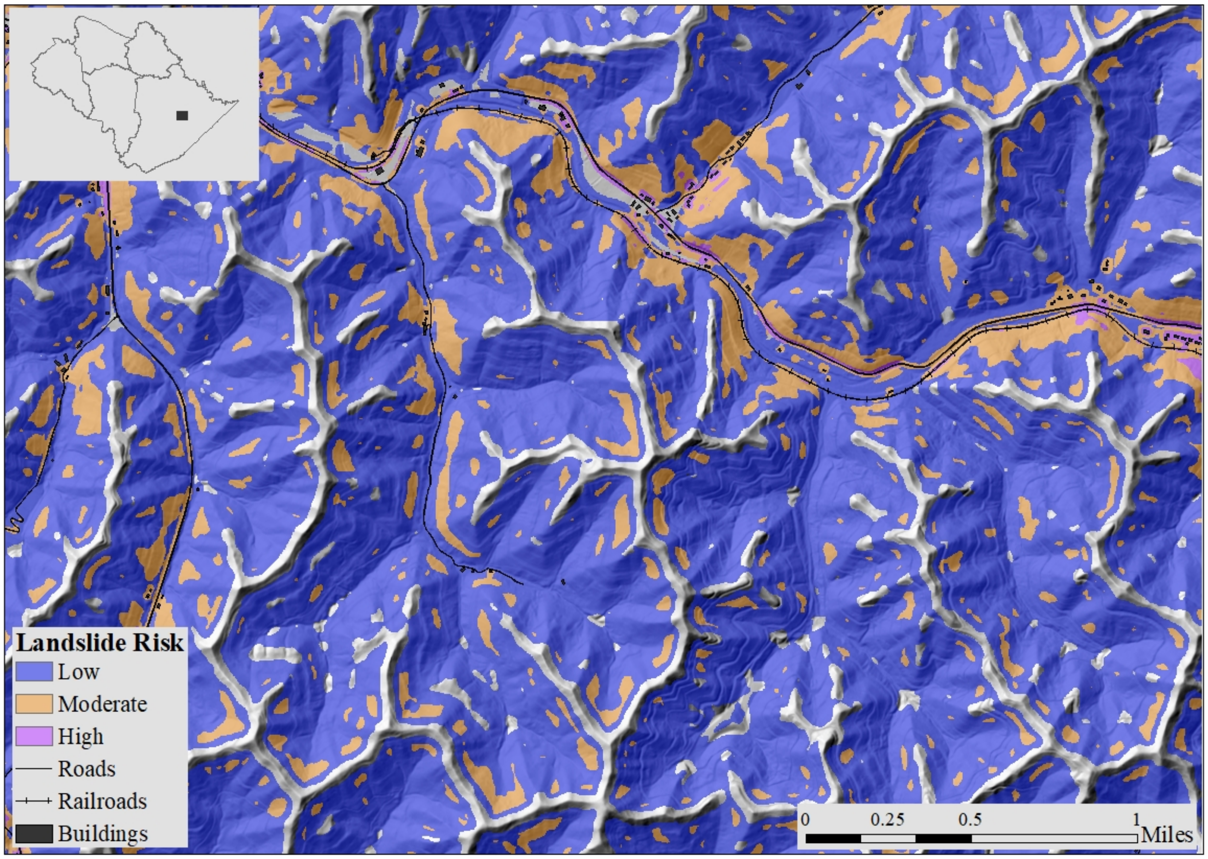

Figure 26. Landslide risk in part of Pike County. See **Appendix C** for the full county risk maps.

*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*

<u>Spatial assessment of landslide hazard and vulnerability</u>

- 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

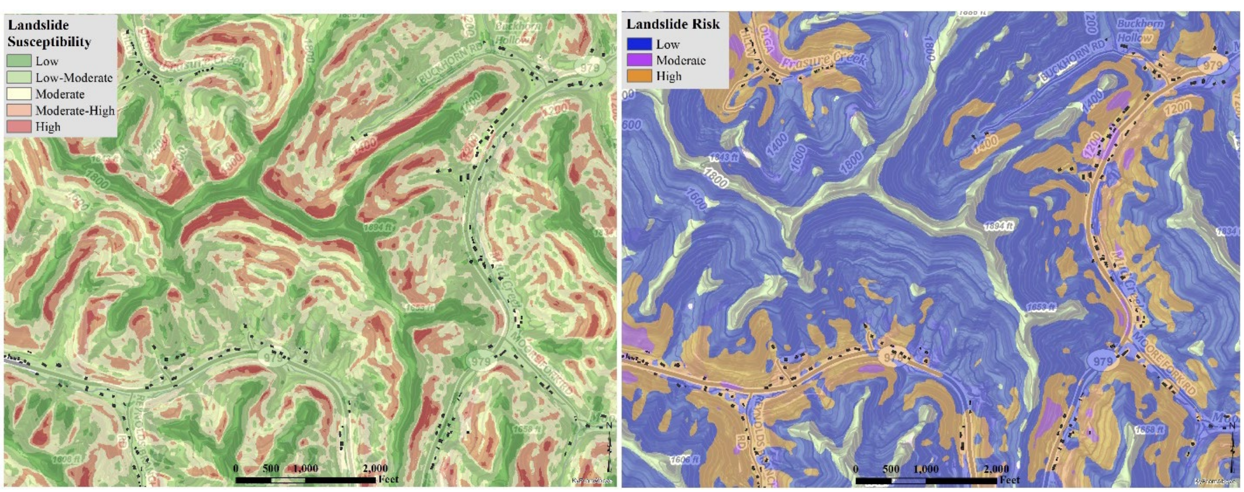

Figure 27. Landslide susceptibility (left) and landslide risk (right) for part of Floyd County. Note the differences in where the moderate to high hazards occur on slopes versus the moderate to high risk areas.

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.

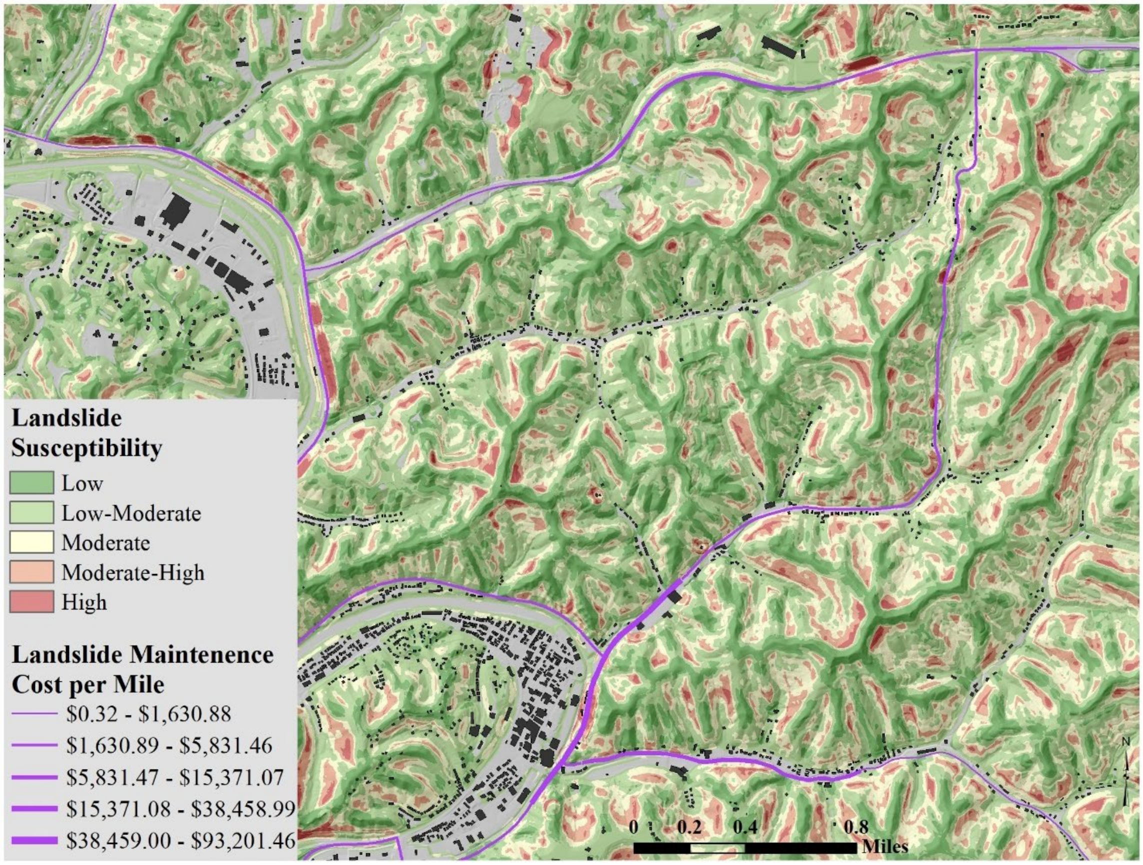

Figure 28. Landslide susceptibility overlaid by state road segments classified by cost per mile in part of the Pikeville area. These are only Kentucky Transportation Cabinet maintenance cost records that span 2003 to 2009. Large, expensive landslide mitigation projects are likely not included in these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

## ACKNOWLEDGEMENTS


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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 | |
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| County | Failure Date | Failure Year | Track Length (ft) | Width (ft) | Failure Location | Damage | Cost |
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| Floyd | 2/10/2011 | 2011 | | | | | |
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| Floyd | 7/19/2012 | 2012 | | | | | |
| Floyd | 5/2/2005 | 2005 | | | | | |
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| Floyd | 6/28/2014 | 2014 | | | above road | | |
| Floyd | | | | | above road | | |
| Floyd | | | | | above road | | |
| Floyd | 11/19/2014 | 2014 | | | above road, stream at bottom | | |
| Floyd | 11/19/2014 | 2014 | | | road cut | | |
| Floyd | | 2005 | | | | | |
| Floyd | 4/20/2015 | 2015 | | | road cut | | |
| Floyd | 3/13/2016 | 2016 | | | | | |
| Floyd | | 2016 | | | | | |
| Floyd | | 2015 | | | | | |
| Floyd | 2/10/2018 | 2018 | | | | | |
| Floyd | 3/25/2018 | 2018 | | | | | |
| Floyd | | 2018 | | | | | |
| Floyd | 9/25/2018 | 2018 | | | above road | | |
| Floyd | | 2018 | | | | | |
| Floyd | 12/31/2018 | 2018 | | | | | |
| Floyd | | 2019 | | | | | |
| Floyd | | | | | | | |
| Floyd | | 2019 | | | road cut | | |

| County | Failure Date | Failure Year | Track Length (ft) | Width (ft) | Failure Location | Damage | Cost |
|---|---|---|---|---|---|---|---|
| Floyd | | 2019 | | | | | |
| Floyd | | | | | | | |
| Floyd | | 2019 | | | | | |
| Floyd | 10/29/2020 | 2020 | | | | | |
| Johnson | 3/12/2015 | 2015 | | | | break in pavement | |
| Johnson | | 2019 | | | | break in road, 2-week lane closure | |
| Johnson | 2/17/2018 | 2018 | | | | large arcuate break in road | |
| Johnson | | 2013 | | | below road | large arcuate crack in road | |
| Johnson | | 2018 | | | | large break in pavement | |
| Johnson | 12/12/2016 | 2016 | | | above road | road blocked | |
| Johnson | 1/24/2017 | 2017 | | | above road | road blocked | |
| Johnson | | 2016 | | | above road | road closure | |
| Johnson | | 2017 | | | | road failure | |
| Johnson | 2/16/2016 | 2016 | | | below road | road surface collapse | |
| Johnson | | 2015 | 380 | 450 | above and below road | several damaged homes and damaged road | |
| Johnson | | | | | below road | yes | |
| Johnson | 3/4/2011 | 2011 | | | above road | yes | |
| Johnson | 4/15/2011 | 2011 | | | | yes | |
| Johnson | | | | | above and below road | yes | |
| Johnson | 3/2/2012 | 2012 | | | below road, stream at bottom | yes | |
| Johnson | 3/2/2012 | 2012 | | | below road, stream at bottom | yes | |
| Johnson | | 2010 | | | | yes | |
| Johnson | | 2010 | | | | yes | |
| Johnson | | 2013 | | 225 | | yes | |
| Johnson | 10/7/2008 | 2008 | | | | | |
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| Johnson | 2/24/2016 | 2016 | | | | | |
| Johnson | | 2015 | | | road cut | | |
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| Johnson | | 2019 | | | | | |
| Johnson | | 2019 | | | | | |
| Johnson | | 2019 | | | | | |
| Magoffin | 2/20/2018 | 2018 | | | | break in pavement | |
| Magoffin | | 2018 | | | above and below road | break in pavement | |
| Magoffin | | 2020 | | | | break in pavement | |
| Magoffin | | 2020 | | | | break in pavement, both lanes affected | |
| Magoffin | 1/28/2015 | 2015 | | | above road | road blocked | |
| Magoffin | 3/3/2017 | 2017 | | | above road | road blocked | |
| Magoffin | 12/28/2016 | 2016 | | | road cut | road closure, vehicles damaged, lives threatened | |
| Magoffin | | | | | below road, stream at bottom | yes | |
| Magoffin | | | | | | | |
| Magoffin | 1/30/2013 | 2013 | | | | | |
| Magoffin | | | | | | | |
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| Magoffin | | | | | | | |
| Magoffin | | 2014 | | | below road, stream at bottom | | |
| Magoffin | | | | | above road | | |
| Magoffin | | | | | | | 600,000 |
| Magoffin | 4/3/2015 | 2015 | | | above road | | |
| Magoffin | | 2017 | | | below road, stream at bottom | | |

| 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 | | | | | |
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| Magoffin | | 2019 | | | | | |
| Martin | | 2018 | | | | multiple breaks in pavement | |
| Martin | | | | | | road damage | 146,150 |
| Martin | 7/1/2010 | 2010 | | | below road | yes | |
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| 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 | |

| County | Failure Date | Failure Year | Track Length (ft) | Width (ft) | Failure Location | Damage | Cost |
|---|---|---|---|---|---|---|---|
| Pike | 8/15/2013 | 2013 | 150 | 175 | above home | yes | |
| Pike | 3/3/2014 | 2014 | | | above road | yes | |
| Pike | | | | | above road | yes | |
| Pike | | | | | above road | yes | |
| Pike | | 2019 | | | | yes | |
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| Pike | | | | | above road | | |
| Pike | | | | | bridge embankment | | |
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| Pike | 12/9/2012 | 2012 | | | above road | | |
| Pike | | 2009 | | | | | |
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| Pike | | 2003 | | | | | |
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| County | Failure Date | Failure Year | Track Length (ft) | Width (ft) | Failure Location | Damage | Cost |
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| County | Failure Date | Failure Year | Track Length (ft) | Width (ft) | Failure Location | Damage | Cost |
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| Pike | 4/2/2015 | 2015 | | | stream at bottom | | |
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| Pike | | 2017 | | | | | |
| Pike | | 2017 | | | | | |
| Pike | | 2018 | | | | | |
| Pike | 9/28/2018 | 2018 | | | | | |
| Pike | 12/24/2018 | 2018 | | | | | |
| Pike | | 2018 | | | | | |
| Pike | | 2019 | | | | | |
| Pike | | 2019 | | | above road | | |

| County | Failure Date | Failure Year | Track Length (ft) | Width (ft) | Failure Location | Damage | Cost |
|---|---|---|---|---|---|---|---|
| Pike | | 2019 | | | | | |
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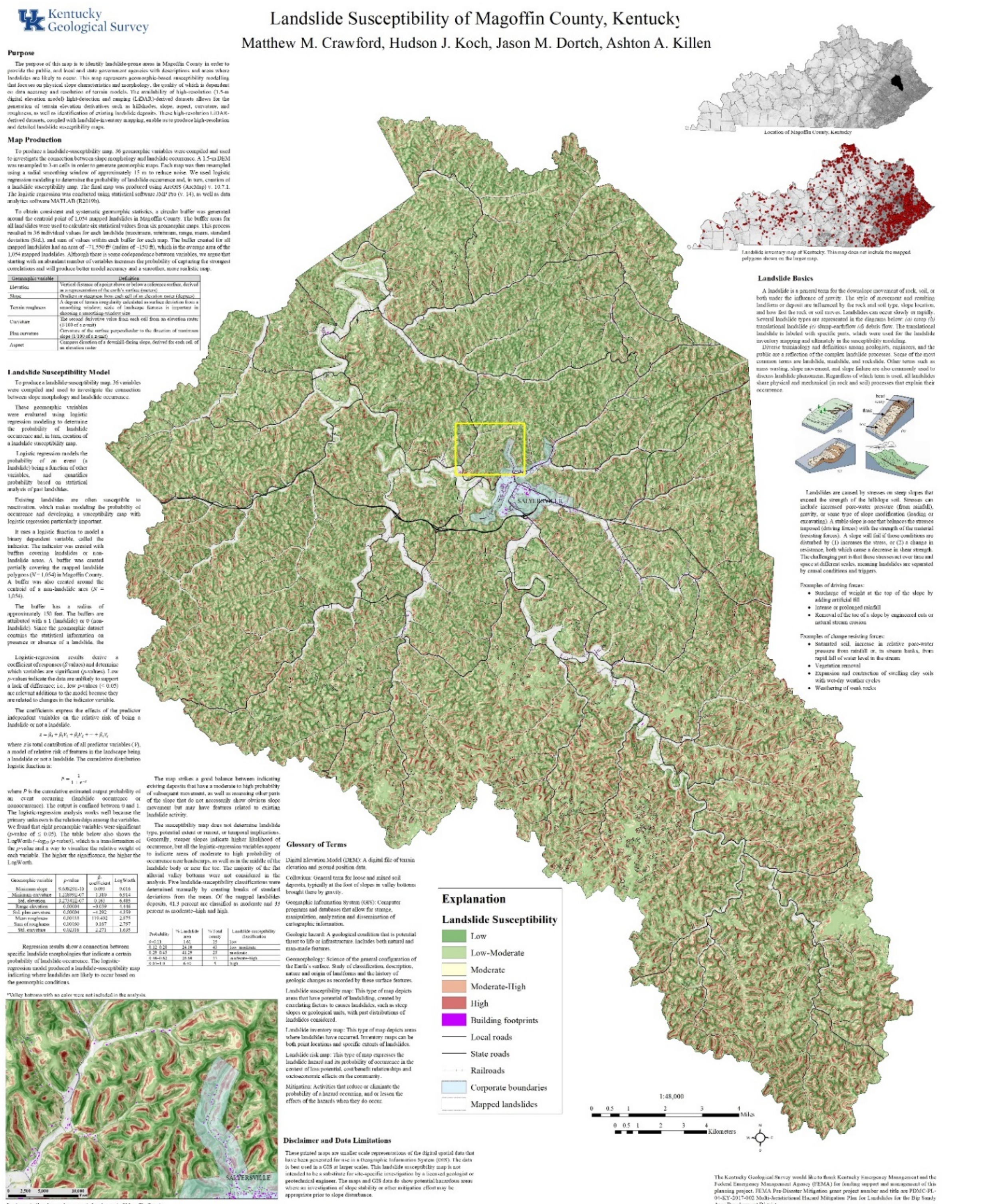
| Pike | | 2019 | | | | | |

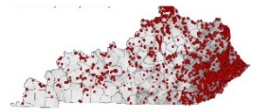
# Appendix B – Landslide Susceptibility Maps



Kentucky Geological Survey

# Landslide Susceptibility of Floyd County, Kentucky

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



Landslide point inventory map for Floyd County.

## Purpose

The purpose of this map is to identify landslide-prone areas in Floyd 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 modelling that focuses on physical slope characteristics and morphology, the quality of which is dependent on data accuracy and resolution of terrain models. The availability of high-resolution (1.5-m digital elevation model) light-detection 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 existing landslide deposits. These 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, 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 resampled using a radial smoothing window of approximately 15 m 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 (ArcMap) v. 10.7.1. The logistic regression was conducted using statistical software JMP Pro (v. 14), as well as data analytics software MATLAB (R2019b).

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

| 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<br>Terrain roughness | Gradient or steepness from each cell of an elevation raster (degrees)<br>A degree of terrain irregularity calculated as surface deviation from a smoothing window; scale of landscape features is important in choosing a smoothing-window size |
| Curvature | The second derivative value from each cell from an elevation raster (1/100 of a z-unit) |
| Plan curvature | Curvature of the surface perpendicular to the direction of maximum slope (1/100 of a z-unit) |
| Aspect | Compass direction of a downhill-facing slope, derived for each cell of an elevation raster |

## Landslide Susceptibility Model

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

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

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

$$z = \beta_0 + \beta_1 V_1 + \beta_2 V_2 + \cdots + \beta_n V_n$$

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

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

where $P$ is the cumulative estimated output probability of an event occurring (landslide occurrence or nonoccurrence). The output is confined between 0 and 1. The logistic-regression analysis works well because the primary unknown is the relationships among the variables. We found that eight geomorphic variables were significant ($p$-value of ≤ 0.05). The table below also shows the LogWorth ($-log_{10}$ ($p$-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.

| Geomorphic variable | $p$-value | $\beta$-coefficient | LogWorth |
|---|---|---|---|
| Minimum slope | 0.00000 | 0.093 | 9.016 |
| Minimum curvature | 0.00000 | 1.310 | 5.914 |
| Std. elevation | 0.00000 | 0.163 | 6.885 |
| Range elevation | 0.00004 | −0.089 | 4.416 |
| Std. plan curvature | 0.00004 | −4.292 | 4.350 |
| Mean roughness | 0.00133 | 119.402 | 2.875 |
| Sum of roughness | 0.00160 | 0.107 | 2.797 |
| Std. curvature | 0.02318 | 2.271 | 1.635 |

Regression results show a connection between specific landslide morphologies that indicate a certain probability of landslide occurrence. The logistic-regression model produced a landslide-susceptibility map indicating where landslides are likely to occur based on the geomorphic conditions. The map 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 susceptibility map does not determine landslide type, potential extent or runout, 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 near headscarps, as well as in the middle of the landslide body or near the toe. The majority of the flat alluvial valley bottoms were not considered in the analysis. Five landslide-susceptibility classifications were determined manually by creating breaks of standard deviations from the mean.

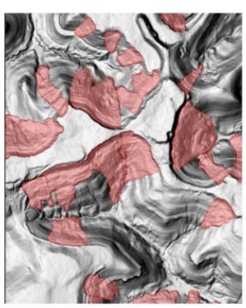
| Probability | % Total county | Landslide susceptibility classification |
|---|---|---|
| 0–0.14 | 17 | low |
| 0.15–0.33 | 38 | low–moderate |
| 0.34–0.53 | 26 | moderate |
| 0.54–0.73 | 16 | moderate–high |
| 0.74–1.0 | 3 | high |



## Explanation

### Landslide Susceptibility

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



Landslide inventory example in Magoffin County.

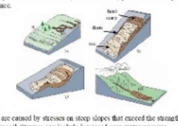
Inset map (yellow box on larger map) showing part of Floyd County.


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

## Landslide Basics

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

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



Landslides are caused by stresses on steep slopes that exceed the strength of the hillslope soil. 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 material (resisting forces). A slope will fail if these conditions are disturbed 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 landslides are separated by causal conditions and triggers.

Examples of driving forces:

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

Examples of change resisting forces:

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

## Glossary of Terms

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

Colluvium: General term for loose and mixed soil deposits, typically at the foot of slopes in valley bottoms brought there by gravity.

Geographic Information System (GIS): Computer programs and databases that allow for storage, manipulation, analyzation 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, 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 correlating factors to causes landslides, such as steep slopes or geological units, with past distributions of landslides considered.

Landslide inventory map: This type of map depicts areas where landslides have occurred. Inventory maps can be both point locations and specific extents 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, 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 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 object that generates internal force.

## 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 investigation by a licensed geologist or geotechnical engineer. The maps and GIS data do show potential hazardous areas where an investigation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

The Kentucky Geological Survey would like to thank 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 PDMC-PL-04-KY-2017-002 Multi-Juristictional Hazard Mitigation Plan for Landslides for the Big Sandy Area Development District.

Kentucky Geological Survey

# 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 modelling that focuses on physical slope characteristics and morphology, the quality of which is dependent on data accuracy and resolution of terrain models.

The availability of high-resolution (1.5-m digital elevation model) light-detection 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 existing landslide deposits. These high-resolution LiDAR-derived datasets, coupled with landslide-inventory mapping, enable us to produce high-resolution and detailed landslide susceptibility maps.

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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 resampled using a radial smoothing window of approximately 15 m 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 (ArcMap) v. 10.7.1. The logistic regression was conducted using statistical software JMP Pro (v. 14), as well as data analytics software MATLAB (R2019b).

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This process resulted in 36 individual values for each landslide (maximum, minimum, range, mean, standard deviation (Std.), and sum of values within each buffer for each map. The buffer created for all mapped landslides had an area of ~71,550 ft² (radius of ~150 ft), which is the average area of the 1,054 mapped landslides. Although there is some codependence between variables, we argue that starting with an abundant number of variables increases the probability of capturing the strongest correlations and will produce better model accuracy and a smoother, more realistic map.

| Geomorphic variable | Definition |
|---|---|
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| 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 z-unit) |
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## Landslide Susceptibility Model

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

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

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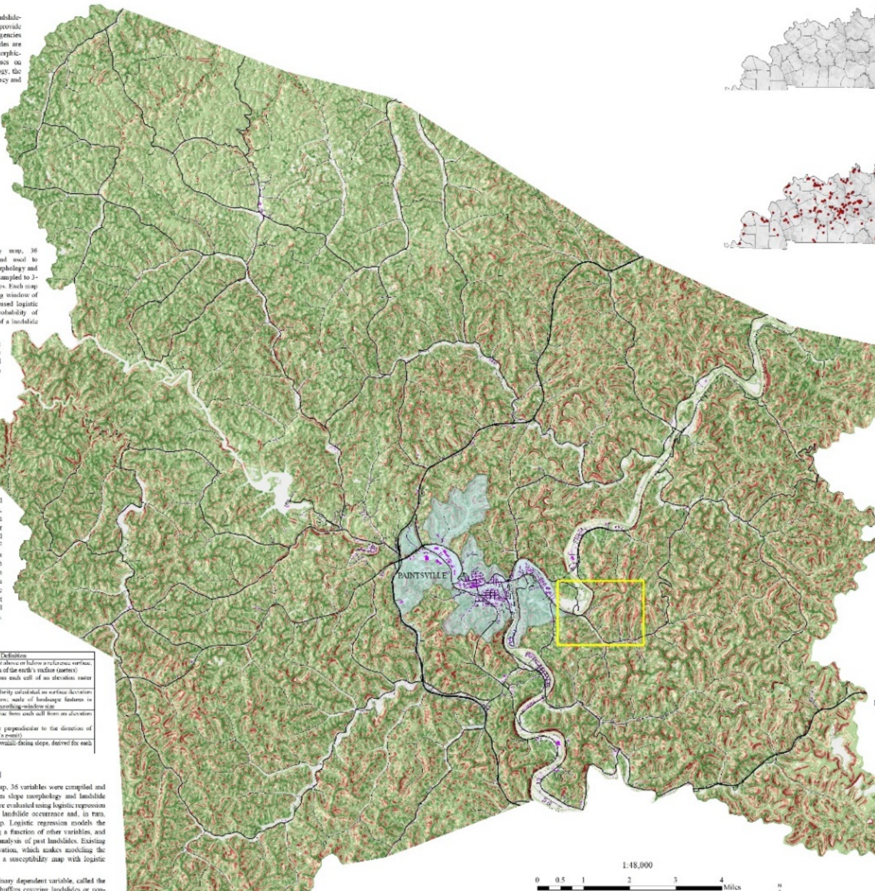


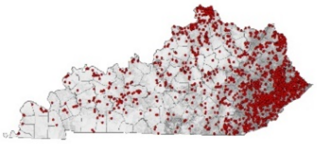

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| Geomorphic variable | p-value | β-coefficient | LogWorth |
|---|---|---|---|
| Minimum slope | 9.63529E-10 | 0.093 | 9.016 |
| Minimum curvature | 1.21899E-07 | −1.310 | 6.914 |
| Std. elevation | 3.27841E-07 | 0.168 | 6.485 |
| Range elevation | 0.00004 | −0.090 | 4.446 |
| Std. plan curvature | 0.00004 | −1.292 | 4.359 |
| Mean roughness | 0.00133 | 119.402 | 2.875 |
| Sum of roughness | 0.00160 | −0.167 | 2.797 |
| Std. curvature | 0.02318 | 2.271 | 1.635 |

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

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| Probability | % Total county | Landslide susceptibility classification |
|---|---|---|
| 0–0.11 | 14 | low |
| 0.12–0.28 | 44 | low–moderate |
| 0.29–0.47 | 24 | moderate |
| 0.48–0.63 | 13 | moderate–high |
| 0.64–1.0 | 5 | high |

## Explanation

### Landslide Susceptibility

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

## Landslide Basics

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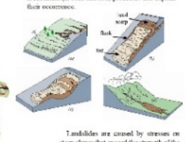


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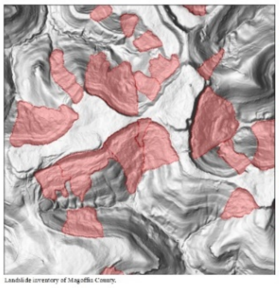
Risk: Probability of occurrence or expected loss as a result of exposure to a hazard.

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



Landslide inventory of Magoffin County.

Inset map (yellow box on larger map) showing part of Johnson County.


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

## Disclaimer and Data Limitations

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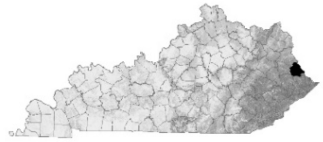
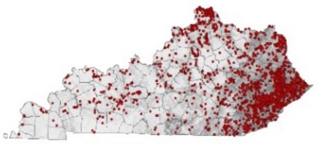
The Kentucky Geological Survey would like to thank Kentucky Emergency Management and the Federal Emergency Management Agency (FEMA) for funding support and management of this planning project. FEMA Pre-Disaster Mitigation grant project number and title are PDMC-PL-04-KY-2017-002 Multi-Jurisdictional Hazard Mitigation Plan for Landslides for the Big Sandy Area Development District.

# Landslide Susceptibility of Martin County, Kentucky

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

Kentucky Geological Survey





Landslide point inventory map for the state of Kentucky.

## Purpose

The purpose of this map is to identify landslide-prone areas in Martin 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 modelling that focuses on physical slope characteristics and morphology, the quality of which is dependent on data accuracy and resolution of terrain models. The availability of high-resolution (1.5-m digital elevation model) light-detection 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 existing landslide deposits. These 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, 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 resampled using a radial smoothing window of approximately 15 m 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 (ArcMap) v. 10.7.1. The logistic regression was conducted using statistical software JMP Pro (v. 14), as well as data analytics software MATLAB (R2019b).

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

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

## Landslide Susceptibility Model

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

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

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

$$z = \beta_0 + \beta_1 V_1 + \beta_2 V_2 + \cdots + \beta_n V_n$$

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

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

where $P$ is the cumulative estimated output probability of an event occurring (landslide occurrence or nonoccurrence). The output is confined between 0 and 1. The logistic-regression analysis works well because the primary unknown is the relationships among the variables. We found that eight geomorphic variables were significant ($p$-value of $< 0.05$). The table below also shows the LogWorth ($-\log_{10}$ ($p$-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.

| Geomorphic variable | $p$-value | $\beta$ coefficient | LogWorth |
|---|---|---|---|
| Minimum slope | 0.00000 | 0.093 | 9.016 |
| Minimum curvature | 0.00000 | 1.319 | 6.914 |
| Std. elevation | 0.00000 | 0.163 | 6.485 |
| Range elevation | 0.00004 | −0.039 | 4.446 |
| Std. plan curvature | 0.00004 | 4.292 | 4.359 |
| Mean roughness | 0.00133 | 119.402 | 2.875 |
| Sum of roughness | 0.00160 | −0.167 | 2.797 |
| Std. curvature | 0.02318 | −2.271 | 1.635 |

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

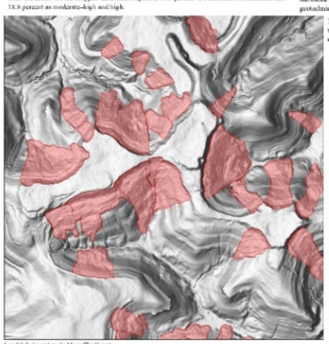
The susceptibility map does not determine landslide type, potential extent or runout, or temporal implications. Generally, steeper slopes indicate higher likelihood of occurrence, but all the logistic-regression variables appear to indicate areas of moderate to high probability of occurrence near headscarps, as well as in the middle of the landslide body or near the toe. The majority of the flat alluvial valley bottoms were not considered in the analysis. Five landslide-susceptibility classifications were determined manually by creating breaks of standard deviations from the mean. Of the mapped landslides deposits, 45.3 percent are classified as moderate and 18.8 percent as moderate–high and high.

| Probability | % Total county | Landslide susceptibility classification |
|---|---|---|
| 0–0.13 | 15 | low |
| 0.14–0.32 | 42 | low–moderate |
| 0.33–0.52 | 24 | moderate |
| 0.53–0.72 | 15 | moderate–high |
| 0.73–1.0 | 4 | high |


## Explanation

### Landslide Susceptibility

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



Landslide inventory in Magoffin County.

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The maps and GIS data do show potential hazardous areas where an investigation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

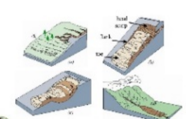
Inset map (yellow box on larger map) showing part of Martin County.

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

## Landslide Basics

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

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




Landslides are caused by stresses on steep slopes that exceed the strength of the hillslope soil. 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 material (resisting forces). A slope will fail if those conditions are disturbed 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 landslides are separated by causal conditions and triggers.

Examples of driving forces:

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

Examples of change resisting forces:

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

## Glossary of Terms

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

Colluvium: General term for loose and mixed soil deposits, typically at the foot of slopes in valley bottoms brought there by gravity.

Geographic Information System (GIS): Computer programs and databases that allow for storage, manipulation, analyzation 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, 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 correlating factors to causes landslides, such as steep slopes or geological units, with past distributions of landslides considered.

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

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Kentucky Geological Survey

# Landslide Susceptibility of Pike County, Kentucky

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

## Purpose

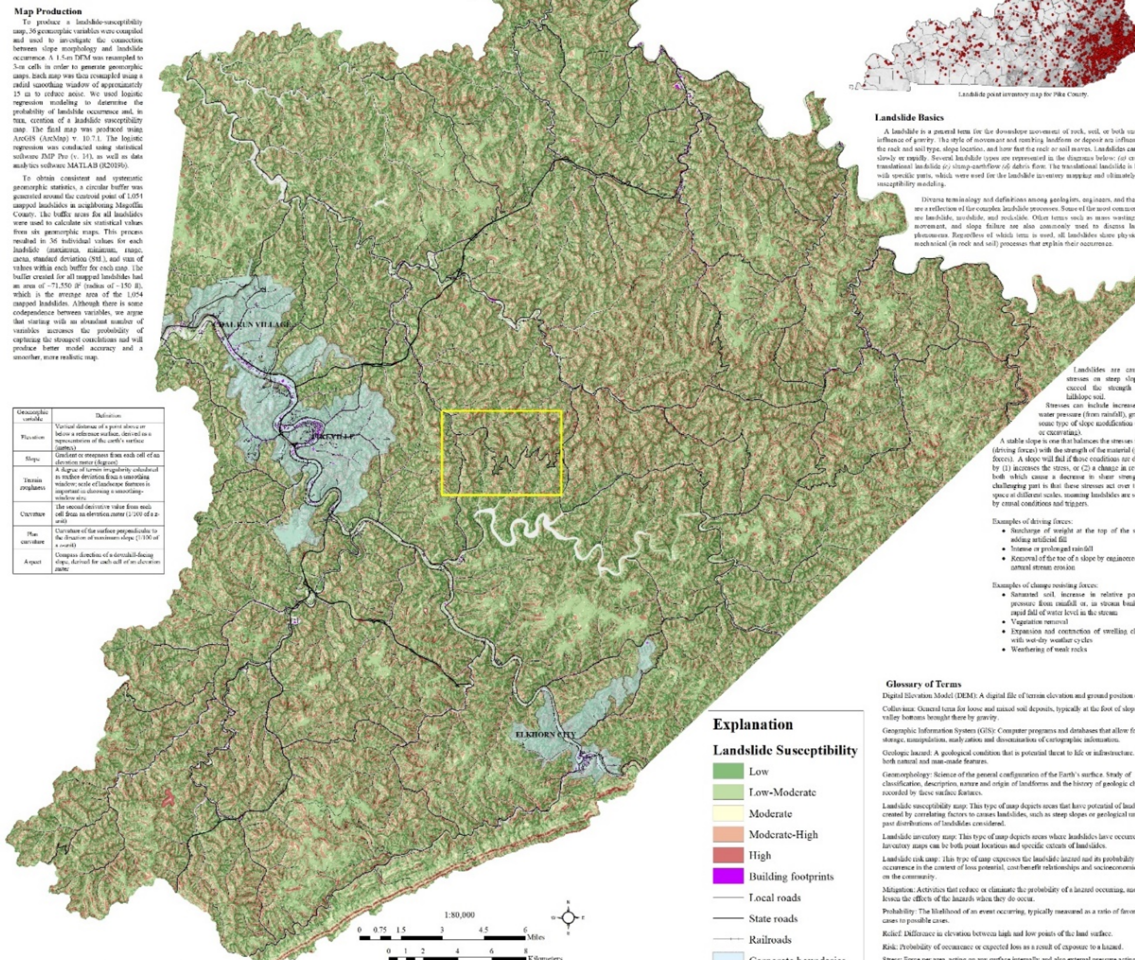
The purpose of this map is to identify landslide-prone areas in Pike County in order to provide the public, and local and state government agencies with descriptions and areas where landslides are likely to occur. This map represents geomorphic-based susceptibility modelling that focuses on physical slope characteristics and morphology, the quality of which is dependent on data accuracy and resolution of terrain models. The availability of high-resolution (1.5-m digital elevation model) light-detection 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 existing landslide deposits. These high-resolution LiDAR-derived datasets, coupled with landslide-inventory mapping, enable us to produce high-resolution and detailed landslide susceptibility maps.

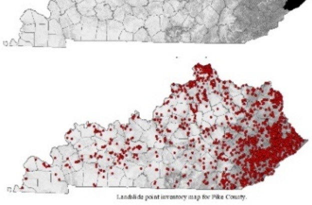
## Map Production

To produce a landslide-susceptibility map, 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 resampled using a radial smoothing window of approximately 15 m 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 (ArcMap) v. 10.7.1. The logistic regression was conducted using statistical software JMP Pro (v. 14), as well as data analytics software MATLAB (R2019b).

To obtain consistent and systematic geomorphic statistics, a circular buffer was generated around the centroid point of 1,054 mapped landslides in neighboring Magoffin County. The buffer areas for all landslides were used to calculate six statistical values from six geomorphic maps. This process resulted in 36 individual values for each landslide (maximum, minimum, range, mean, standard deviation (Std.), and sum of values within each buffer for each map. The buffer created for all mapped landslides had an area of ~71,550 ft² (radius of ~150 ft), which is the average area of the 1,054 mapped landslides. Although there is some codependence between variables, we argue that starting with an abundant number of variables increases the probability of capturing the strongest conditions and will produce better model accuracy and a smoother, more realistic map.

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



Landslide point inventory map for Pike County.

## Landslide Basics

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

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

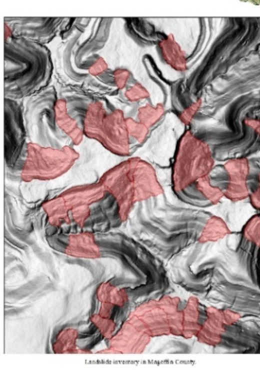
Risk: Probability of occurrence or expected loss as a result of exposure to a hazard.

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

## Explanation

### Landslide Susceptibility

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



Landslide inventory in Magoffin County.

## Landslide Susceptibility Model

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

$$z = \beta_0 + \beta_1 V_1 + \beta_2 V_2 + \cdots + \beta_i V_i$$

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

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

where $P$ is the cumulative estimated output probability of an event occurring (landslide occurrence or nonoccurrence). The output is confined between 0 and 1. The logistic-regression analysis works well because the primary unknown is the relationships among the variables. We found that eight geomorphic variables were significant ($p$-value of $\leq 0.05$). The table below also shows the LogWorth ($-\log_{10}$ ($p$-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.

| Geomorphic variable | p-value | β-coefficient | LogWorth |
|---|---|---|---|
| Minimum slope | 0.00000 | 0.093 | 9.018 |
| Minimum curvature | 0.00000 | −1.310 | 5.914 |
| Std. elevation | 0.00000 | 0.163 | 6.485 |
| Range elevation | 0.00004 | -0.039 | 4.446 |
| Std. plan curvature | 0.00004 | 4.292 | 4.359 |
| Mean roughness | 0.00133 | 119.402 | 2.875 |
| Sum of roughness | 0.00160 | −0.167 | 2.797 |
| Std. curvature | 0.02318 | −2.271 | 1.635 |

Regression results show a connection between specific landslide morphologies that indicate a certain probability of landslide occurrence. The logistic-regression model produced a landslide-susceptibility map indicating where landslides are likely to occur based on the geomorphic conditions. The map 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 susceptibility map does not determine landslide type, potential extent or runout, 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 near headscarps, as well as in the middle of the landslide body or near the toe. The majority of the flat alluvial valley bottoms were not considered in the analysis. Five landslide-susceptibility classifications were determined manually by creating breaks of standard deviations from the mean. Of the mapped landslides deposits, 45.3 percent are classified as moderate and 18.8 percent as moderate–high and high.

| Probability | % Total county | Landslide susceptibility classification |
|---|---|---|
| 0–0.12 | 17 | low |
| 0.13–0.32 | 39 | low-moderate |
| 0.33–0.52 | 25 | moderate |
| 0.53–0.73 | 16 | moderate-high |
| 0.74–1.0 | 3 | high |

Inset map (yellow box on larger map) showing part of Pike County.


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

## Disclaimer and Data Limitations

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This landslide susceptibility map is not intended to be a substitute for site-specific investigation by a licensed geologist or geotechnical engineer. The maps and GIS data do show potential hazardous areas where an investigation of slope stability or other mitigation effort may be appropriate prior to slope disturbance.

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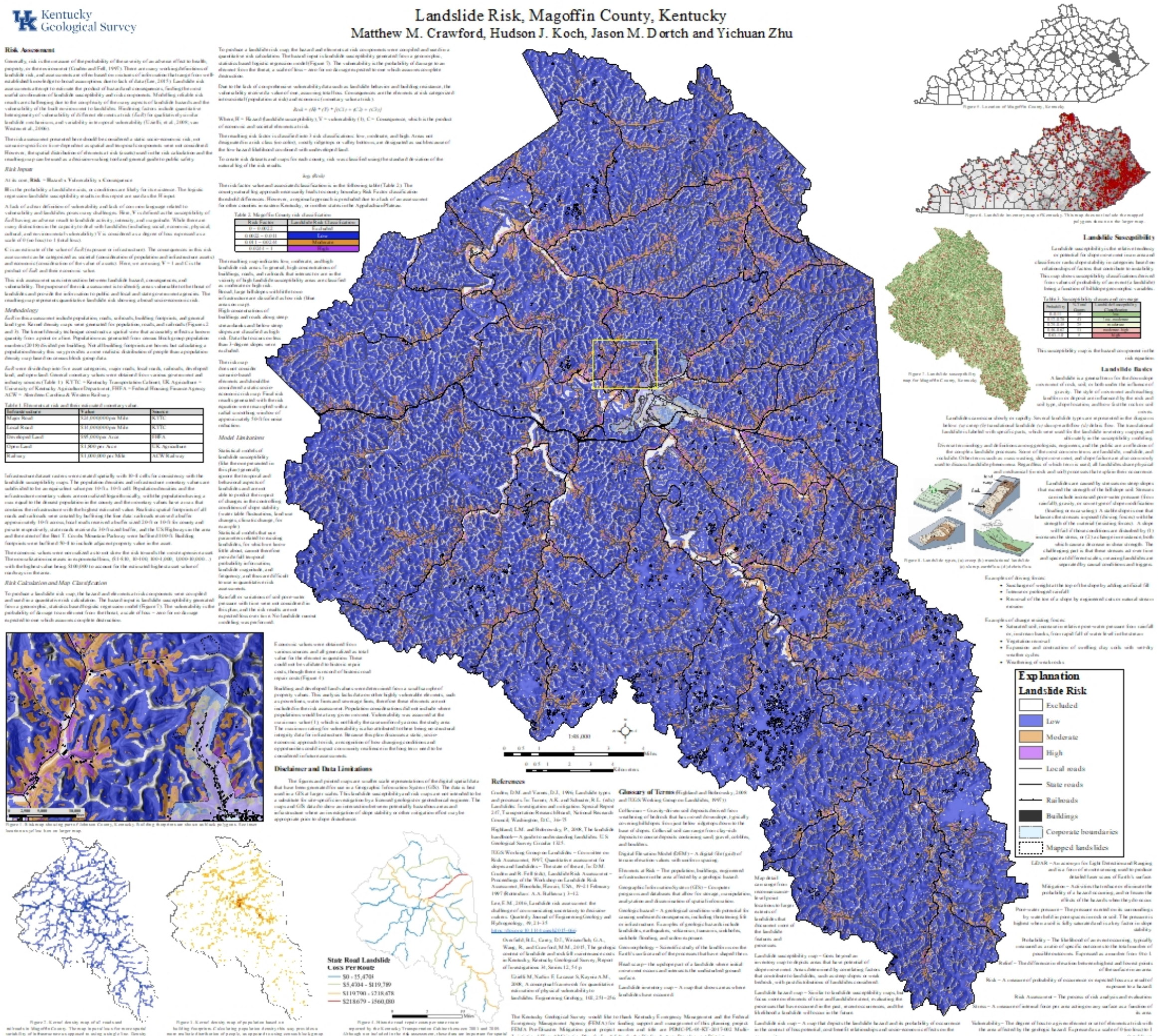
# Appendix C – Landslide Risk Maps



# Landslide Risk, Floyd County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch and Yichuan Zhu

Kentucky Geological Survey

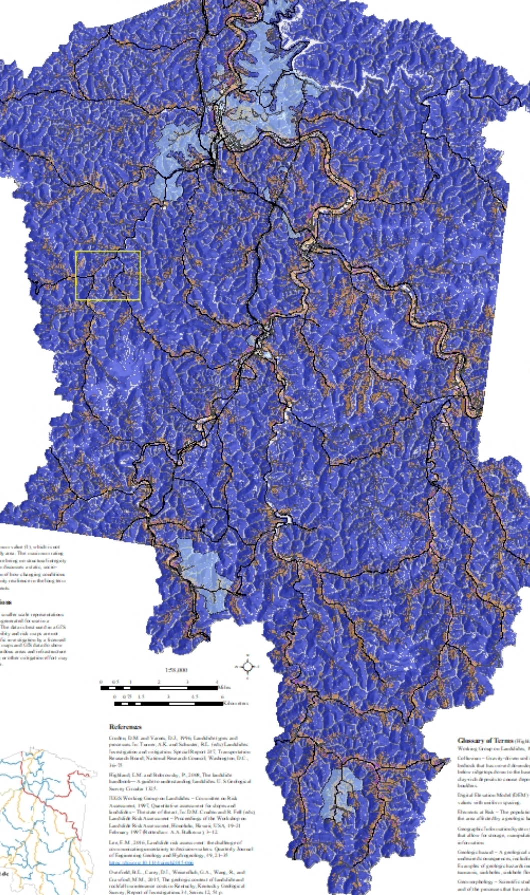
## Risk Assessment

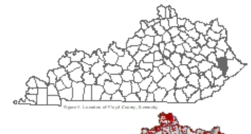
### Risk Inputs

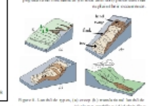
### Methodology

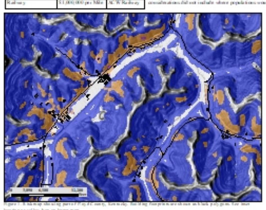
### Risk Calculation and Map Classification

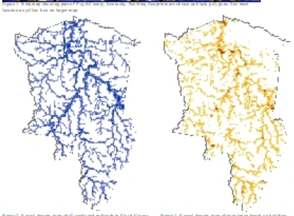
### Model Limitations

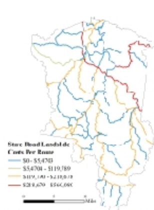










## Disclaimer and Data Limitations

## Landslide Susceptibility

## Landslide Basics

## References

## Glossary of Terms

Kentucky Geological Survey

# Landslide Risk, Johnson County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch and Yichuan Zhu

## Risk Assessment

Table 1. Elements at risk and their replacement costs

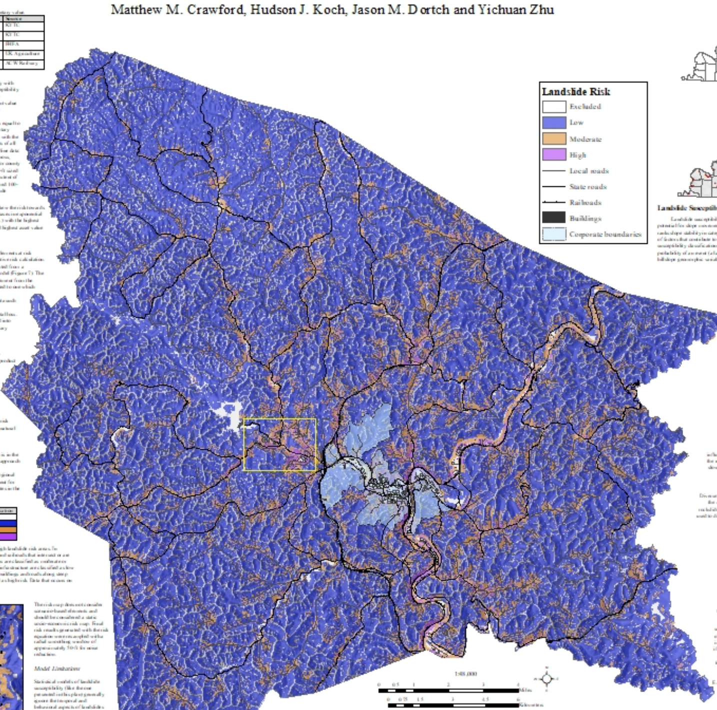
| Infrastructure | Value | Source |
|---|---|---|
| Major Road | [illegible] | KYTC |
| Local Road | [illegible] | KYTC |
| Developed Land | [illegible] | BREA |
| Open Land | [illegible] | UK Agriculture |
| Railway | [illegible] | [illegible] |

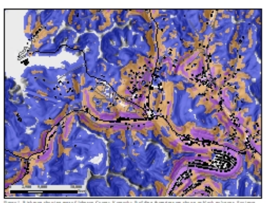
### Risk Calculation and Map Classification

$$log(Risk)$$

Table 2. Johnson County risk classification

| Risk Factor | Landslide Risk Classification |
|---|---|
| 0 – 0.0025 | Excluded |
| 0.0025 – 0.0125 | Low |
| 0.0125 – 0.0278 | Moderate |
| 0.0278 – 1 | High |



### Model Limitations

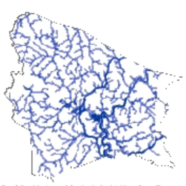
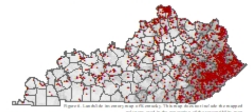


Figure 1. Location of Johnson County, Kentucky.



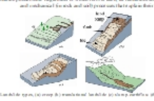
## Landslide Susceptibility

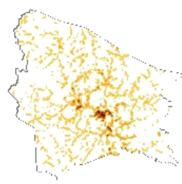
Table 3. Susceptibility classes and coverage

| Probability | % Total county | Landslide susceptibility classification |
|---|---|---|
| [illegible] | [illegible] | low |
| [illegible] | [illegible] | low–moderate |
| [illegible] | [illegible] | moderate |
| [illegible] | [illegible] | moderate–high |
| [illegible] | [illegible] | high |

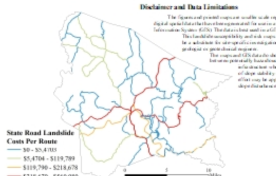
This susceptibility map is the hazard component in the risk equation.

Figure 7. Landslide susceptibility map for Johnson County, Kentucky.





## Disclaimer and Data Limitations





## References


## Glossary of Terms

Kentucky Geological Survey

# Landslide Risk, Martin County, Kentucky

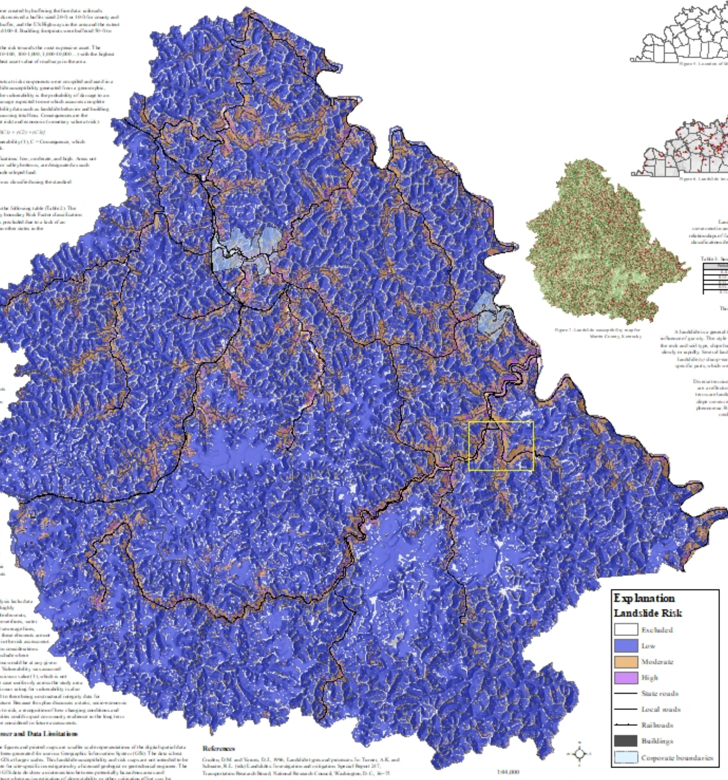
Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch and Yichuan Zhu

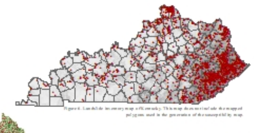
## Risk Assessment

[illegible]

## Disclaimer and Data Limitations

[illegible]



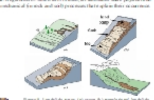



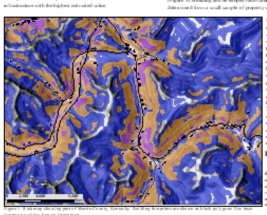
## Landslide Susceptibility

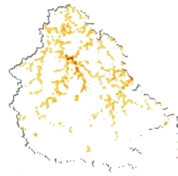
[illegible]

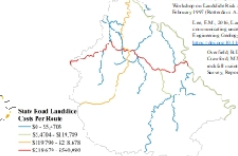
## Landslide Basics

[illegible]










## References

[illegible]


## Glossary of Terms

[illegible]

Kentucky Geological Survey

# Landslide Risk, Pike County, Kentucky

Matthew M. Crawford, Hudson J. Koch, Jason M. Dortch and Yichuan Zhu

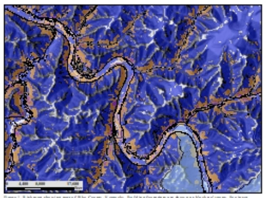


Figure 1. Risk map showing part of Pike County, Kentucky. Building footprints are shown as black polygons. See inset location on large map.

## Risk Assessment

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

$$\log_e(Risk)$$

Table 2. Pike County risk classification

| Risk Factor | Landslide Risk Classification |
|---|---|
| 0 – 0.0016 | Excluded |
| 0.0016 – 0.0087 | Low |
| 0.0087 – 0.0458 | Moderate |
| 0.0458 – 1 | High |

### Model Limitations

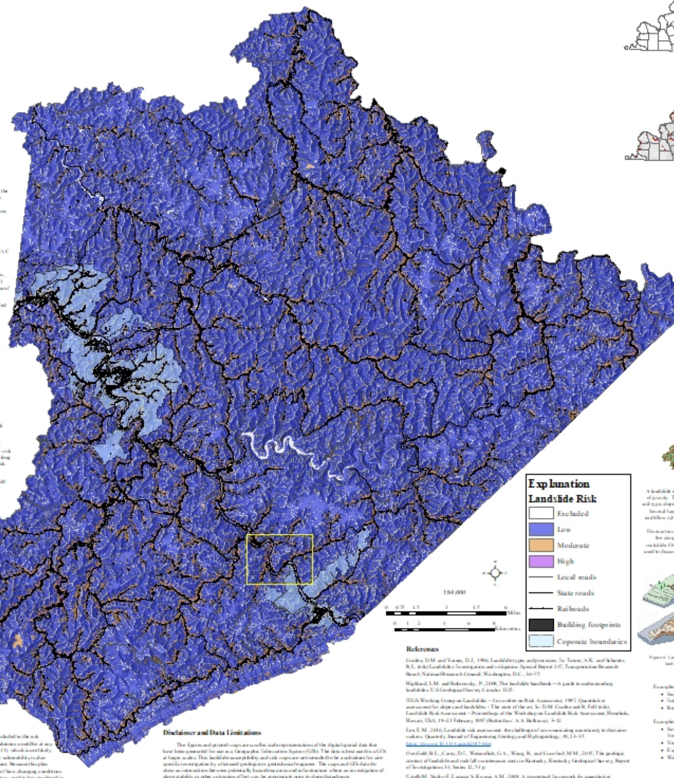



Figure 2. Location of Pike County, Kentucky.

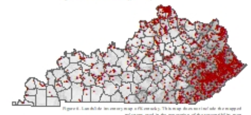


Figure 4. Landslide inventory map of Kentucky. This map does not include the mapped polygons used in the generation of the susceptibility map.

## Landslide Susceptibility

Table 3. Susceptibility classes and coverage

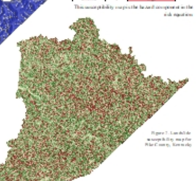
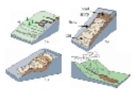


Figure 3. Landslide susceptibility map for Pike County, Kentucky.

## Landslide Basics



## Disclaimer and Data Limitations

## References

## Glossary of Terms