Kentucky Geological Survey
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Kentucky Geological Survey Landslide Inventory: From Design to Application

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Abstract

The Kentucky Geological Survey is compiling a landslide inventory database to better document the distribution and geologic context of Kentucky's landslides. The database provides users with easy access to landslide information, raises awareness of landslide causes, and will help prevent property damage or injury. The database was used to create an online landslide information map, which provides online access to landslide data and gives users the ability to customize the map using other data layers pertinent to landslides. The database design is based on common attributes collected by other states with active inventories and landslide hazard programs, as well as attributes necessary to document landslides in Kentucky and help with future research goals. A comprehensive landslide inventory database serves as a foundation for understanding landslide distribution, assisting land-use planning decisions, creating hazard maps, and modeling landslide susceptibility.

Introduction

In Kentucky, as in other places in the world, a combination of steep slopes, excessive water amounts, geology, and slope modification are the main causes of landslides. From 1973 to present, the Kentucky Transportation Cabinet has compiled 870 geotechnical reports documenting landslides that have affected roadways and have proposed landslide corrections (Fig. 1). Although the exact costs for mitigating these slides are not known, they are significant. For fiscal years 2002 to 2009, the Transportation Cabinet's maintenance database documented landslide and rockfall repairs totaling $31.8 million. From 2003 to 2013, the Kentucky Hazard Mitigation Grant Program funded or will fund projects that acquire landslide-damaged homes or stabilizes the area for a total of $5.3 million. Along the Mississippi River in Hickman, one of the largest landslides in the state affected numerous buildings and the town's water supply (Fig. 2), costing the U.S. Army Corps of Engineers more than $17 million to stabilize the slope. Indirect costs associated with landslides, such as commerce hindered by road closures, devalued property, and environmental effects, often exceed direct costs. Hazard mitigation efforts continue across Kentucky to help citizens facing landslide problems; however, obtaining funding and implementing these projects can take years.

The State and local government agencies that respond to or document landslides vary, and the data collection, assessment, and documentation of landslide activity among these agencies vary widely. Several state geological surveys participate in landslide inventory projects, collecting data for displaying and analyzing landslide information (landslides.usgs.gov/research/inventory).

Purpose

The landslide inventory database stores and updates landslide data and distributes the data to the public. Compiling landslide locations into a database allows landslides and rockfalls to be analyzed in a geologic and geomorphic context along with other data. Landslide activity is more likely in areas of existing slides; that is, landslides tend to recur in the same place, although the style and rate of movement may be different. Knowing landslide locations and their relationship to geologic properties (bedding, mineral composition, porosity, slope, thickness, strength, etc.) can mitigate potential problems associated with construction of roads, foundations, and bridges, and contribute to overall practical hillslope development. In addition to detailed landslide locations and associated geology, information in a landslide database can communicate frequency, slide type (mechanics), material, damage, and mitigation costs.

Figure 1. Landslide damage along the now abandoned Ky. 10, Lewis County.

Figure 2. Repaired landslide in Hickman, Fulton County.

A standardized landslide inventory database provides a single overview of landslide distribution, and allows relationships, patterns, and attributes to be displayed in a geologic context (Sarikhan and Stanton, 2009; Foster and others, 2012; Mazengarb and others, 2010). A landslide inventory database can also help State and local agencies prevent damage and loss of life, and assist in an effective response to a landslide. As population grows and development continues in both urban and rural parts of Kentucky susceptible to landslides, a foundation for assessing landslide hazards is imperative. In addition, tools must be developed to ensure that these hazards are noticed and citizens are educated about landslide risks. It is a challenge to streamline landslide information collected by different organizations, which limits the data based on that organization's goals. Compiling a landslide inventory database that can be accessible, disseminated easily, and assist users will be of benefit to all of Kentucky, however.

Landslide Basics

"Landslide" is a broad term referring to the downslope movement of rock, soil, or both under the influence of gravity. The type of material involved in a landslide and its style of movement influence decisions for hazard mitigation and risk reduction. For example, shales present slope-stability problems because of their clay content and capability of holding large amounts of water, making proper drainage important for construction of buildings, roads, tunnels, retaining walls, and other infrastructure. Clayey to silty soils that develop on steep slopes underlain by shale-dominated bedrock are also susceptible to sliding.

The majority of landslides in Kentucky occur in colluvial soils or along the soil-bedrock contact (Gray and Gardner, 1977; Outerbridge, 1987; Fleming and Johnson, 1994; Crawford, 2012). Colluvium is formed by weathering and erosion of rock and soil, allowing movement and deposition downslope by gravity (Abramson and others, 2002). Colluvium accumulates slowly to rapidly, forming veneers across slopes of varying thickness. When disturbed or loaded, these soils are susceptible to landslides. Figure 3 shows common terms used to describe the major features of landslides.

Geologists, engineers, soil scientists, and other professionals have varying definitions, landform terminology, and interpretations of landslide activity. Often, landslides are termed "slope failures" because of damage inflicted to roads, houses, or other infrastructure. Used in its engineering sense, "failure" is an undesired response in a material, in this case soil or rock on a hillside. Failure in a material can take the form of a clear break in rock or soil (a rupture), deformation of the soil (plastic behavior), flow of the soil (liquefaction), or combinations of these behaviors.

Why Slopes Fail

A stable slope is one that balances the stresses imposed (driving forces) with the strength of the rock or soil material (resisting forces) (Fig. 4). A slope will fail if those balanced conditions are disturbed by a change in loading that increases the stress, or a change in resistance, which decreases shear strength. Triggering mechanisms that coincide with preexisting causes create the potential for slope failure. Examples of load changes include:

- Increasing weight at the top of the slope by adding fill, building construction, or heavy precipitation
- Removing soil or rock at the toe of a slope by engineered cuts or natural stream erosion.

Examples of resistance changes include:

- Increasing internal pore-water pressure from rapid rainfall or, in stream banks, from rapid fall of water level in the stream (Fig. 5)

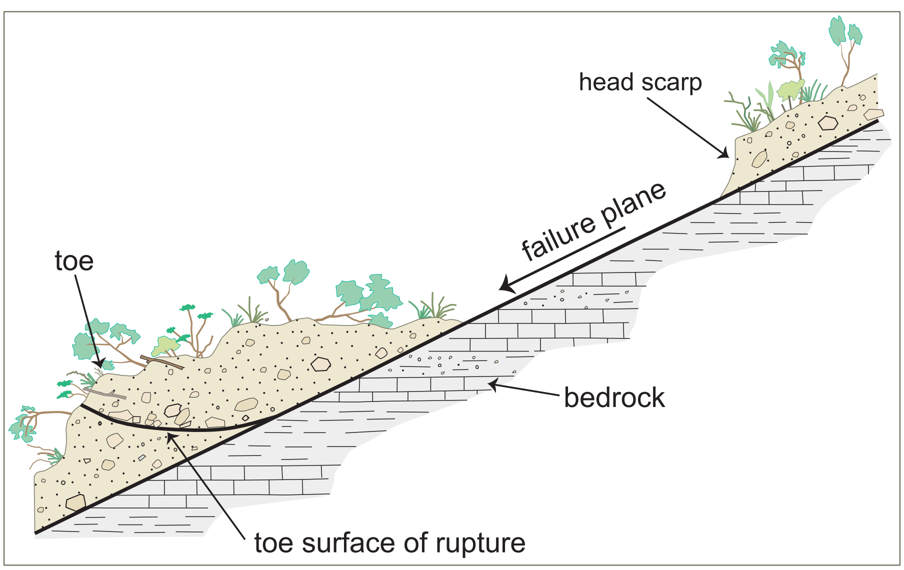

Figure 3. Common terms used to describe landslide features.

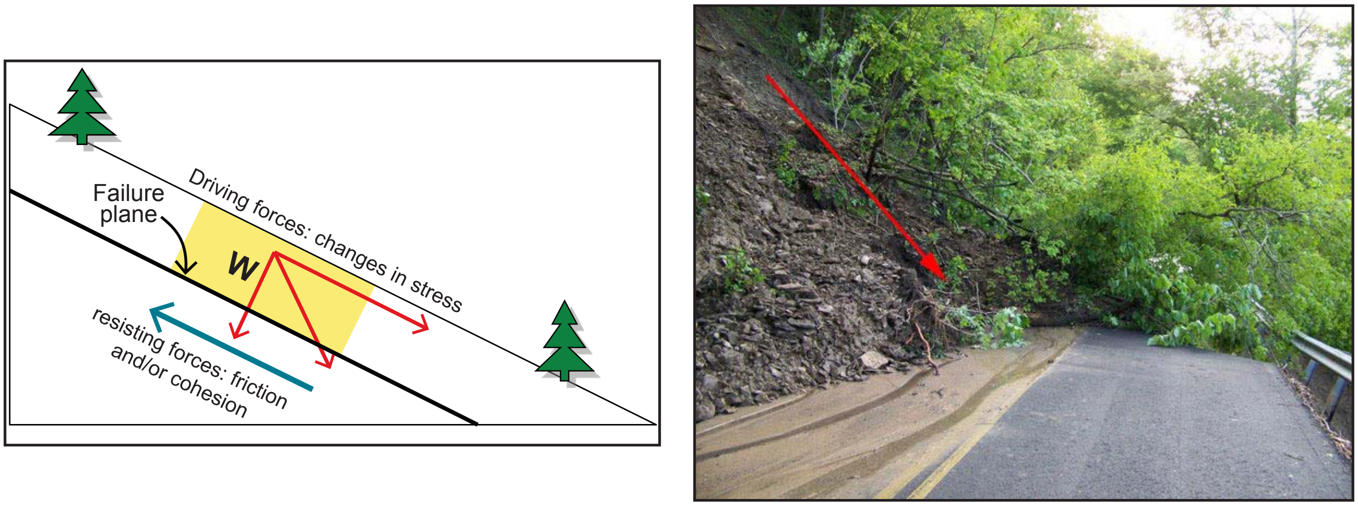

Figure 4. Left: The driving and resisting forces on a slope. W is the weight of the block. Right: A landslide along Big Eddy Road, Franklin County. This slide resulted from excess rainfall that increased the pore-water pressure, which decreased the strength of the material. The steep slope and clay-rich rocks were the underlying causes.

- Removing vegetation
- Expanding and contracting of swelling clay soils with wet-dry weather cycles
- Weathering of weak rocks (shales).

Causes of Landslides

Geology, Soils, Water, and Steep Slopes. Easily weathered rock types and soils, especially on steep slopes, are the underlying causes of landslides. Adding excess water makes the materials susceptible to sliding (Figs. 5–6). When these causes are combined with triggers, landslide hazards are likely.

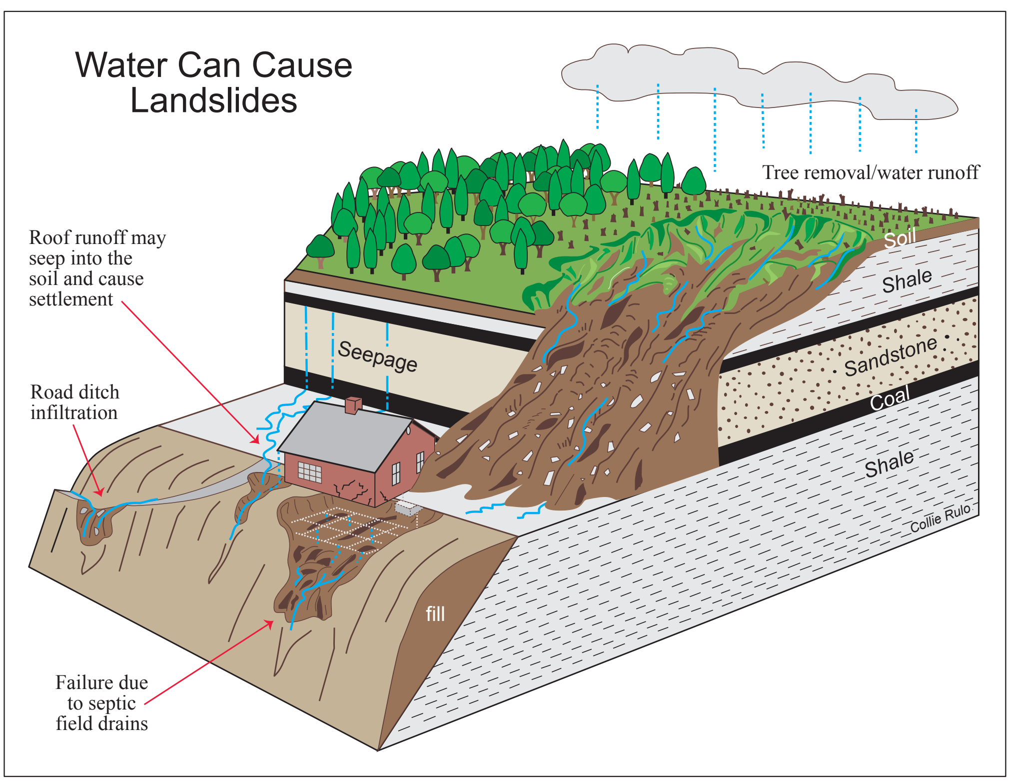

Figure 5. Multiple causes and triggers of landslides.

Triggers of Landslides

Intense Rainfall. High moisture levels increase pore-water pressure and decrease the strength of slope material. It is important to be aware of stormwater drainage near homes, offices, and other buildings.

Water-Level Change. Rapid lowering of groundwater against a slope can trigger landslides, especially along dams, coastlines, reservoirs, and rivers. The pore pressure in soil or rock material may not be able to adjust to a sudden drawdown of water, causing slope instability.

Erosion. Natural streamwater erosion can destabilize slopes and cause failure. This is common at the toe (bottom) of a slope, often along sharp bends in a stream.

Human Activities. Vegetation removal, excavation of toe slopes, loading on a slope, leakage from pipes, and surface and underground mining can trigger landslides.

Earthquakes. Ground shaking during earthquakes can cause landslides in many different topographic and geologic settings. The 1811-12 large earthquakes in the New Madrid Seismic Zone generated several hundred landslides along the Mississippi River.

Figure 6. Landslide-damaged home, Lawrence County.

Landslide Types

Cruden and Varnes (1996) created a classification system (Fig. 7):

- Translational slides—Material moves down a relatively planar surface. The sliding material can be composed of fine- to coarse-grained soils or rock. Slide planes typically occur at the soil-bedrock contact and are shallow (less than 3 m). Translational slides are very com-

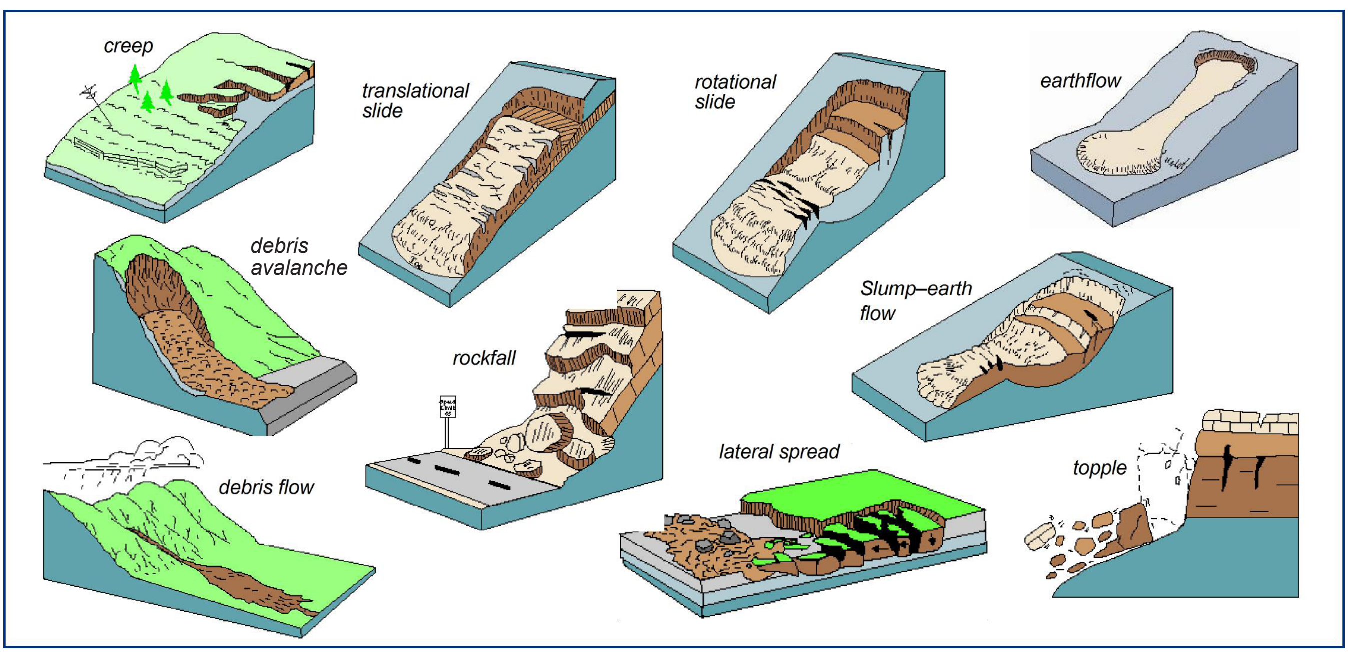

Figure 7. Classification of landslide types. Modified from Highland and Bobrowsky (2008).

mon, occurring in all physiographic regions. Their size can range from small (lengths less than 30 m) to very large (several kilometers wide along roadways or cutbanks in streams).

- Rotational slides—Also called slumps, these slides are distinguished by an upward-curved slide plane, causing rotational movement. Rotational slides can have multiple scarps, creating displacement that tilts back toward the head scarp and crown. Slumps often have a hummocky surface and thick toe. These slides usually occur in thick, unconsolidated soils, loess, and artificial fills, but also may occur in weathered rock masses. Rotational slide velocity ranges from slow (less than 0.3 m every 5 yr) to moderately fast (1.5 m per month) (Highland and Bobrowsky, 2008).
- Flows—This category consists of styles differentiated by velocity and material. The types of flows include debris flow, debris avalanche, and earthflow. Each type ranges from small to very large. Smaller earthflows are common in soils developed on shale, weathered clay-rich rocks, and fill. Debris flows and debris avalanches are rapid movements (up to 56 km/hr). They are most common on slopes where thick, coarse soils are deposited in concave parts of the slope or steep channels. Excessive water commonly triggers the movement of these flows.
- Creep—Creep is extremely slow earthflow (less than 1 m per decade) that can only be noticed by its effects (Highland and Bobrowsky, 2008). Shear stresses in the soil or rock are sufficient to cause movement, but soil or rock displacement is gradual. Typical damage is tilted or curved tree trunks, broken or tilted fences, tilted telephone poles, cracked foundations, and broken underground utilities. Creep can lead to more destructive, faster-moving slides or flows. Creep often occurs seasonally with changes in moisture content and temperature (Highland and Bobrowsky, 2008). Slopes with creep often have a complex system of slide planes. This is the most common landslide type and occurs statewide.
- Spreads—These usually occur on very gentle slopes where soft, clay-rich layers undergo lateral extension, spreading apart overlying firmer rocks and soil (Highland and Bobrowsky, 2008). Spreads can occur in clayey lacustrine and other glacial deposits in northern Kentucky and less commonly in thick, liquefiable soils of the Jackson Purchase Region.
- Rockfalls and topples—Rock material of varying size can free-fall through the air from cliffs, roadcuts, or steep slopes. These failures are more susceptible if rocks are dipping the same direction as the slope. Rocks can become detached from in-place bedrock by fracturing, weathering from freeze-thaw cycles, erosion of underlying material, and human activities such as road construction (Highland and Bobrowsky, 2008).

Landslide Inventory Database

KGS began constructing the landslide inventory database in 2011. The database contains known landslide locations and associated data. Some important questions asked before designing the database were:

- What is the aim and scope?
- Who will be the users?
- Is the goal to understand specific landslide dynamics, gain a general understanding of their distribution, or model landslide susceptibility and risk?
- Can enough reliable landslide locations be gathered and attributed with the detail necessary to achieve the goals?

There is no best practice or standard methodology to develop such a database. Much depends on the ability to collect landslide locations and associated attributes. Access to geology, soils, and other geographic information system resources is very helpful in being able to put the slide locations in a geologic and geomorphic context, even if not much is known about the slide itself.

Methodology

Large amounts of data can be associated with landslides. It is unlikely that all pertinent data can be gathered for every documented landslide. One primary goal of constructing a landslide inventory database was to create an applied database, which facilitated adding, querying, and displaying data. In order to reduce complexity and size of the KGS database, other landslide inventory databases were analyzed, and common, relevant terminology was determined. Database fields and attributes from the North Carolina Geological Survey, Oregon Department of Geology and Mineral Industries, California Geological Survey, and Washington State Department of Natural Resources were evaluated. Major landslide categories common to all databases were

- Location
- Movement type
- Mechanism
- Dimensions
- Material
- Setting
- Trigger
- Damage/cost
- Source
- Repair activity.

Within each major category, specific data fields and attributes from each state were compiled in a Microsoft Excel[1] spreadsheet to visualize the different nomenclature and identify the most commonly used terms. For example, other states' databases used the category Type of Movement, which contained similar fields and attributes. But for the categories Location, Mechanism, Setting, and Source, there were many different fields and attributes that were pertinent to those areas. For the KGS database, a combination of the most common data fields and attributes was chosen, based on what is known about geology and landslides in Kentucky. In the spreadsheet, fields and attributes were color-coded to help visualize the most commonly used and similar attributes (Table 1).

Design

From the list of major categories and examination of the attribute spreadsheet (Table 1), 40 fields were chosen for the KGS database (Table 2). Many of the same fields from other states were used, as well as newly created or renamed fields. The fields contain variable landslide information while limiting the number of records to be able to effectively

Table 1. Example of the major category Setting and the different attributes associated with that category from the North Carolina and Oregon surveys. Each attribute is color-coded. This was done for each major category.

Categories	*North Carolina Fields*	*Attributes*	*Oregon Fields*	*Attributes*
Setting	Failed slope configuration, geomorphic position, geomorphic shape, geomorphic structure, source area vegetation	Roadcut, embankment (not road-related), road embankment, cut slope (not road-related), other, mid to upper slope, upper slope, toe slope, mid slope, mid to toe slope, upper slope/ridgetop, floodplain; planar, concave, hollow, convex, hummocky, convex to planar, planar to concave, concave to convex; oblique slope, scarp slope, dip slope, oblique to scarp slope, dip to oblique slope, oblique to dip slope, other; none, grass-shrub, deciduous forest, mixed forest, grass-shrub-tree, pavement or gravel road	Slope angle, landform, geomorphic shape V, geomorphic shape H, drainage setting, vegetation	Percent or degrees, avalanche chute, convergent headwall, flat plain, glacial moraine, hollow, inner gorge, ridge, river bank, river cutbank, scarp of landslide, swale, talus slope, terrace, toe of landslide; concave, convex, hummocky, planar; convergent, divergent, planar, U-shaped valley, V-shaped valley; anomalous drainage, stagnated drainage, interruption of drainage, springs and seeps; agricultural, clearcut, meadow, mature forest, partial cut, young stand

[1]The use of trade or product names is for descriptive purposes only and does not imply endorsement by the Kentucky Geological Survey.

Table 2. Landslide attributes and data types in the inventory database.

1	**ID**	*Number*	21	**Lithology**	*Text*
2	**SourceDesc**	*Text*	22	**Surficial_Geology**	*Text*
3	**SourceID**	*Text*	23	**Geomorphic_Position**	*Text*
4	**County**	*Text*	24	**Geomorphic_Shape**	*Text*
5	**24kQuad**	*Text*	25	**Failure_Location**	*Text*
6	**Latitude83**	*Number*	26	**Slope_Angle**	*Text*
7	**Longitude83**	*Number*	27	**Aspect**	*Text*
8	**Route**	*Number*	28	**Fractures**	*Text*
9	**DateObserved**	*Date/Time*	29	**Faults**	*Text*
10	**FailureDate**	*Date/Time*	30	**Water_Present**	*Text*
11	**General_Type**	*Text*	31	**Contributing_Factor**	*Text*
12	**FieldChecked**	*Text*	32	**Soil_Type**	*Text*
13	**Process**	*Text*	33	**Movement_Rate**	*Text*
14	**Material**	*Text*	34	**Damage**	*Text*
15	**Failure_Type**	*Text*	35	**New_or_Existing**	*Text*
16	**Track_Length**	*Number*	36	**Cost**	*Currency*
17	**Width**	*Number*	37	**Comments**	*Memo*
18	**Head_Scarp_Height**	*Number*	38	**Nearest_mp**	*Text*
19	**Slip_Surface_Depth**	*Number*	39	**Begin_mp**	*Text*
20	**GeologicUnit**	*Text*	40	**End_mp**	*Text*

populate the database. The database resides in a Microsoft Access database. The main advantages are easily facilitated queries, links to other KGS tabular data sets, and the capability to display the data in the online Kentucky Geologic Map Information Service. Access databases also allow for easy exporting and use in a GIS for spatial analysis.

Data Sources

An important and challenging factor in the landslide inventory database is the source of the data. Sources for landslide locations include KGS research and field work, published geologic maps, State and local government agencies, media reports, and the public (Table 3, Figs. 8–9). Compiling landslide locations from different sources makes choosing data fields and standard attributes a challenge. For example, landslides identified and mitigated by the Kentucky Transportation Cabinet may have a geotechnical report providing much related data, but slides identified by Kentucky Emergency Management may only have location data and no extensive records. Also, for road-related landslides that prompt a Transportation Cabinet response, the responsibility and documentation is divided up between many district and county maintenance offices, depending on the slide location. Is it worth the effort to reach out to all these potential sources and try to gather everything?

With such a wide variety of sources, the landslide inventory database must maintain a balance of necessary fields, but not be overwhelmed with too many fields that would most likely be unpopulated. Attributing every field for every slide located will not be possible, but if the source of the data has an accurate location (latitude-longitude, mile marker, anecdotal, etc.), then some fields such as Geologic Unit, Slope Angle, Aspect, Soil Type, and Mile Points can be populated later using GIS geoprocessing tasks.

Landslides and Related Features Maps

A series of 7.5-minute, 1:24,000-scale quadrangle maps showing landslides and related features was published in the late 1970's to early 1980's by the U.S. Geological Survey; they cover much of the Eastern Kentucky Coal Field (Fig. 10). The maps were interpreted from aerial photography, field

Table 3. Sources for landslide locations and data.

KGS Data	*External*
• 1:24,000-scale geologic maps • 1:24,000-scale landslide and related features maps • Light Detection and Ranging (LiDAR) mapping—Kenton and Campbell Counties only	• Kentucky Transportation Cabinet • Division of Abandoned Mine Lands • Kentucky Emergency Management • Natural Resources Conservation Service • Kentucky Department for Natural Resources—Mine Reclamation and Enforcement • Northern Kentucky Area Planning Commission • Aerial photography—Google, Bing, National Agriculture Imagery Program • Media alerts (Internet, Twitter, newspaper, television) • Public/personal communication

evidence, and other historical records, and depict generalized slope-stability conditions at the time the maps were field checked (1977–81). The types of slides are variable and consist of earthflow, translational, slump, and complex composite. The areas susceptible to debris flows are primarily shallow, narrow ravines that have thick colluvial soil deposits (approximately 3 m or less) or have the potential to accumulate soil that is susceptible to movement. Many of these features have not been confirmed or field-checked.

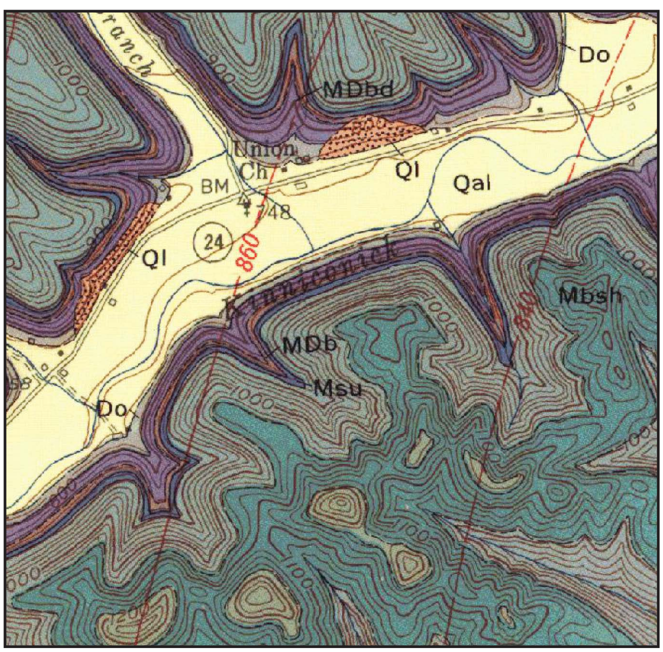

Figure 8. Landslide deposits (orange) on the Stricklett 7.5-minute quadrangle map, Lewis County (Morris, 1965).

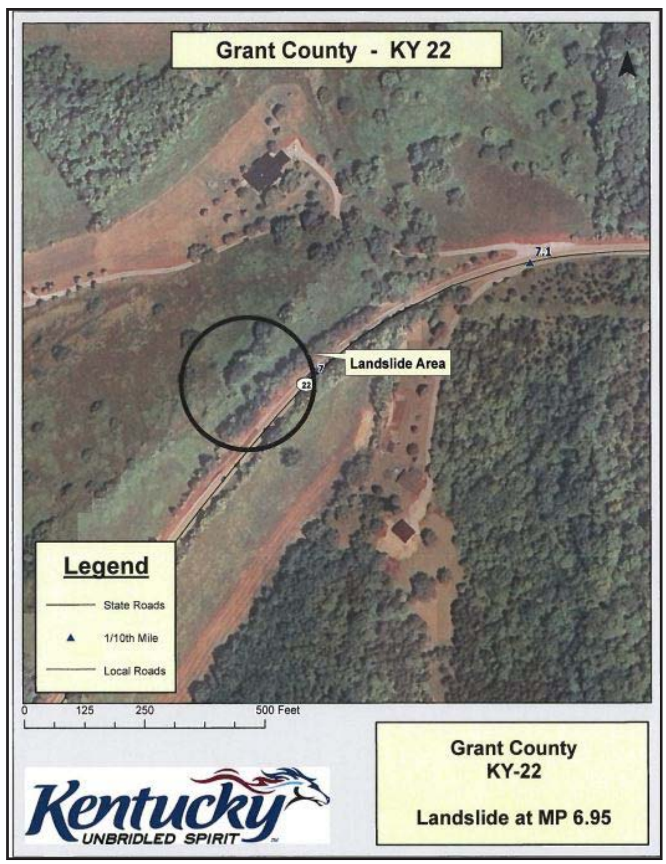

Figure 9. Example page from Kentucky Transportation Cabinet landslide geotechnical report (Beckham, 2013). Used with permission.

Figure 10. Screenshot of a landslides and related features map. The black ovals are landslides and the arrows are areas susceptible to debris flows. Other map symbology indicates colluvial slopes, old landslides, or soil susceptible to landsliding. Image from Outerbridge (1979).

From these maps, 13,516 landslide locations and 60,067 areas susceptible to debris flows have been digitized as polygons and arcs, respectively. These features are maintained in an ArcGIS geodatabase and displayed in the interactive KGS Landslide Information Map Service (see next section). The original landslides and related features maps can be downloaded from the KGS publications webpage: kgs.uky.edu/kgsweb/PubsSearching/PubResults.asp?pubtype=Landslide+Map&searchtype=typeofpub.

Inventory Statistics

As of August 20, 2014, the KGS landslide inventory database has 2,302 documented landslides (Table 4). The landslides are depicted by points, lines, and polygons, the former two features representing larger landslide areas, many of which have

Table 4. Count of landslides from the landslide inventory database by source. Because many of the Kentucky Transportation Cabinet reports contain more than one landslide, the count in this table does not add up to 2,302. Features digitized from the landslide and related features maps are not included.

Source Description	*Count*
Kentucky Transportation Cabinet	870
Division of Abandoned Mine Lands	697
Kentucky Geological Survey	458
LiDAR (two counties)	234
Kentucky Emergency Management	35
Natural Resources Conservation Service	35
Public	29
Media alert	27
Kentucky Department for Natural Resources–Mine Reclamation and Enforcement	24
Northern Kentucky Area Planning Commission	15

not been mapped in detail. The features digitized from the landslide and related features maps have not been combined with the landslide inventory database. The variety of sources makes the spatial accuracy and attributed fields highly variable. All landslide types and sizes are represented and are active or have historically been active.

Figure 11 shows the number of landslides in the database per county for those counties with 10 or more landslides. Although these landslides come from a variety of sources, which can locally bias the distribution, the data reflect Kentucky's geology, slope, and urbanization and highlight counties that have high incidence of landslides. Many landslides in Kentucky occur in colluvium, but the underlying bedrock influences the composition and thickness of the colluvial soil, slope morphology, and hydrogeologic conditions. Landslides per mapped geologic formation are shown in Table 5. The three formations highlighted in yellow indicate landslide deposits and alluvial fans mapped on the 1:24,000-scale geologic quadrangle maps; many of these deposits are large and have not been attributed with a particular underlying bedrock formation (Fig. 12).

The slope angle associated with each point in the database was documented using an ArcGIS geoprocessing task. Using the Extract Values to Points tool in ArcGIS, slope values (raster cell values) from a statewide 10-m digital elevation model were extracted for each landslide (point). A bilinear interpolation method used adjacent cells in a digital elevation model around the landslide location to calculate the slope value. Most landslides fell within the 6 to 15° range (Fig. 13). Different landslide types vary with slope angle and underlying geologic materials (Potter, 2007). Several studies (Froelich, 1970; Davies, 1973; Gray and others, 1978; Fleming and Johnson, 1994) discuss the occurrence of landslides across Kentucky that fall within this slope range. Many slides near roads rupture in a steeper part of the slope (above or below a road), but the source and location method used put the landslide point along the road closer to the valley bottom where the slope is gentle. Slope values and associated geologic formations provide insight into water infiltration and material strength. Saturated colluvial slopes and roadway embankments weaken soil and rock shear strength, potentially triggering landslides.

Temporal data associated with landslides is also needed for hazard analysis and relating landslides to particular storms or rainfall levels. For the landslide locations from the Kentucky Transportation Cabinet geotechnical reports, the year of failure has been correlated with rainfall across the state (Fig. 14). Generally, years with high incidence

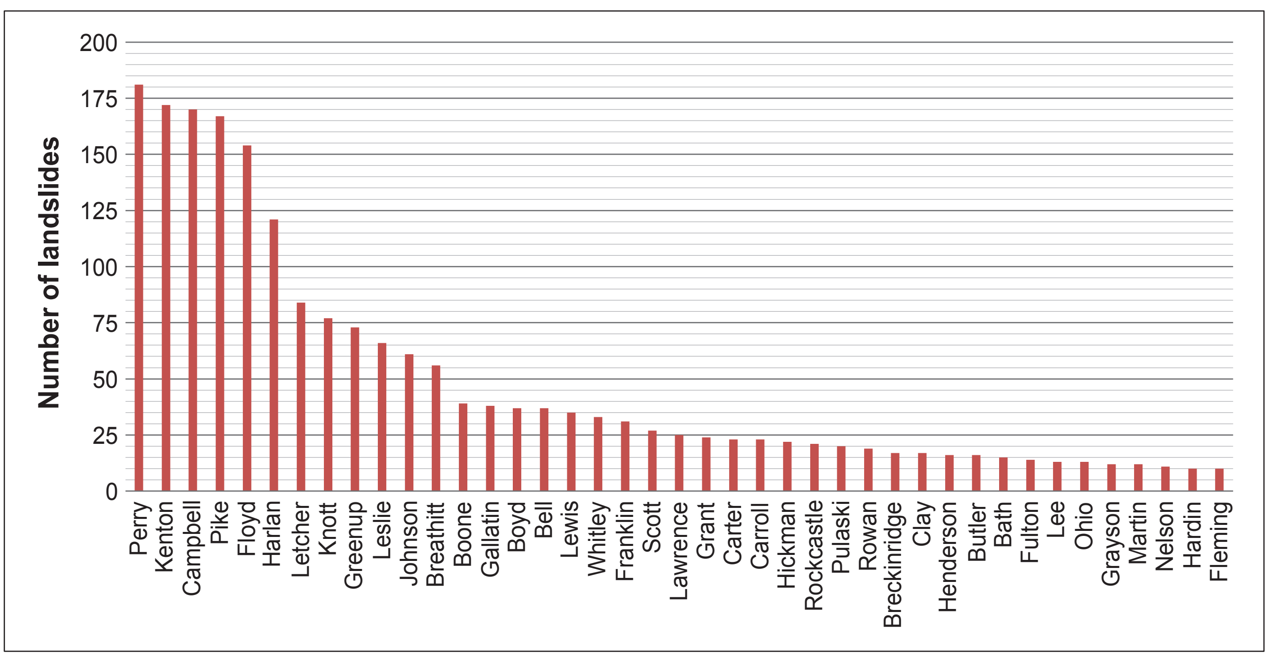

Figure 11. Distribution of landslides by county (10 or more landslides).

Table 5. Landslide inventory by geologic formation (five or more). The highlighted records are deposits mapped on the 1:24,000-scale geologic quadrangle maps and have not been associated with a particular bedrock formation in the database. Often, these are large landslides that span several bedrock formations.

Geologic Formation	Landslides		Geologic Formation	Landslides
Pikeville Formation	474		Carbondale Formation	14
Kope Formation	334		Conemaugh Formation	14
Hyden Formation	285		Tradewater Formation	13
Landslide deposits	186		Shelburn Formation	11
Four Corners Formation	156		Grant Lake Limestone	11
Grundy Formation	67		Alvy Creek Formation	9
Fairview Formation	62		Buffalo Wallow Formation	8
Alluvium	57		Drakes Formation	8
Alluvial fan deposits	54		Middle Part of Breathitt Group	8
Princess Formation	53		Tyrone Limestone	8
Clays Ferry Formation	43		Ste. Genevieve Limestone	7
Landslide deposits and colluvium	41		Ohio Shale	7
Bull Fork Formation	27		Alger Shale	6
Borden Formation	21		Beech Creek Limestone Member	6
Paragon Formation	19		Borden Formation, Cowbell Member	6
St. Louis Limestone	18		Borden Formation, Nancy Member	6
Tradewater and Caseyville Formations	17		Estill Shale of Crab Orchard Group	6
Artificial fill	17		Point Pleasant Tongue of Clays Ferry Formation	6
Kope and Clays Ferry Formations	16		Big Clifty Sandstone Member	5
Terrace deposits	15		Fort Payne Formation	5
Corbin Sandstone Member	15		Glen Dean Limestone	5
Lower Part of Lexington Limestone	15		Leitchfield Formation	5
Loess	15		New Albany Shale	5

of landslides occurred during or just after years of high rainfall. There are a few anomalies in which there are years of peak rainfall and low incidence of landslides or vice versa. The more temporal data collected with each landslide location, the more of these types of correlations with weather can be made, although it is not always possible to gather temporal data.

Application: Landslide Information Map

The landslide inventory database was used to create an online, interactive landslide information map, which provides an overall view of landslide hazards across the state and shows locations of known landslides and areas susceptible to debris flows in a geologic and geomorphic context (Figs. 15–17). Five landslide data layers were created, represented as points, lines, and polygons. These layers were taken from the landslide inventory database and best represent the variety of sources and feature types in the database. The layers on the map are:

Layer Name	*Description*
Landslide Inventory Data (points)	Known landslide locations from different sources in the database
1:24,000-Scale Geologic Map Landslides (polygons)	Mapped on the 7.5-minute geologic quadrangle maps published jointly by the Kentucky Geological Survey and U.S. Geological Survey from 1960 to 1978
Landslide Areas Derived from LiDAR	Mapped and digitized using 1-m resolution

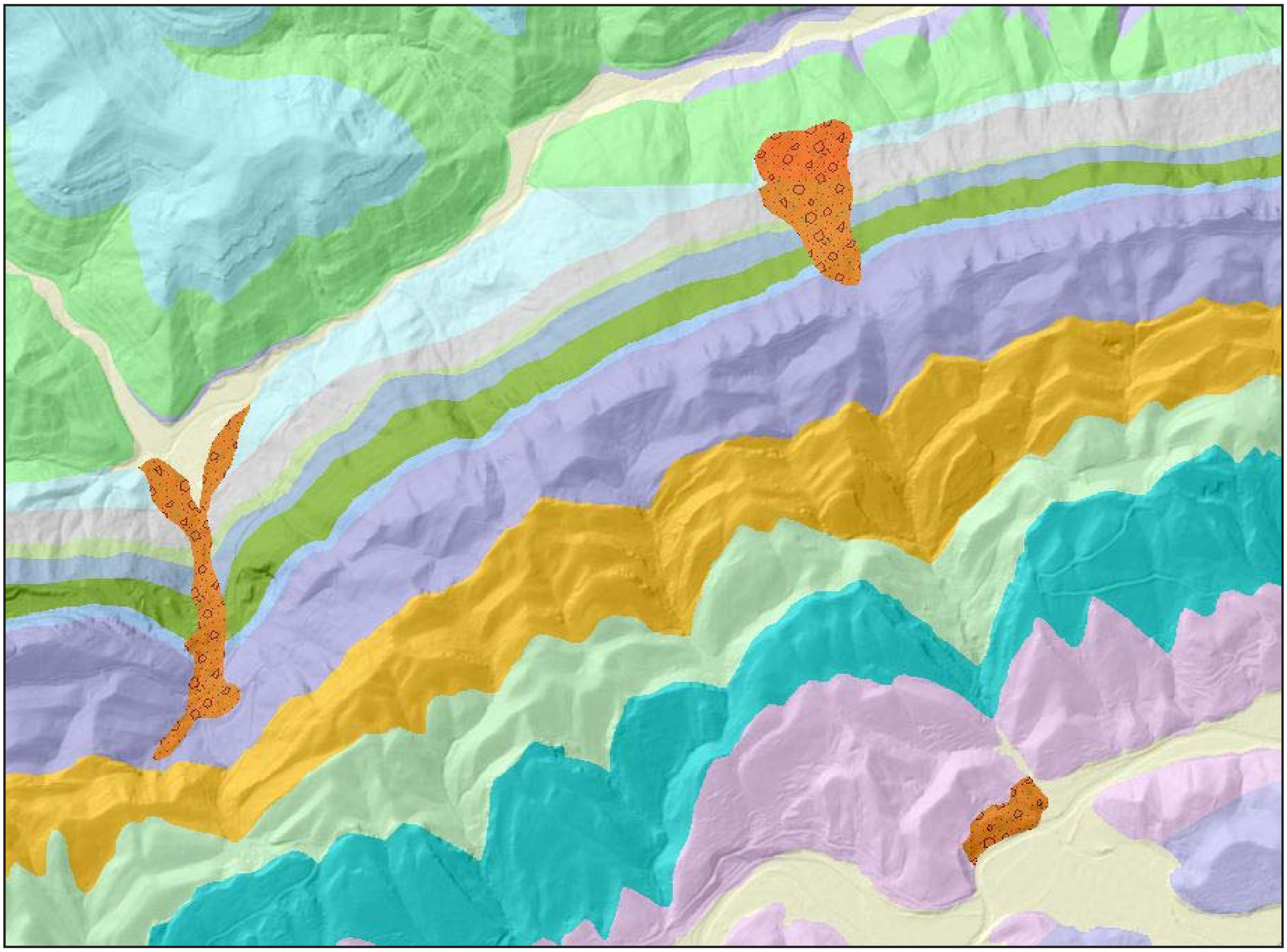

Figure 12. Example of landslide deposits (stippled orange) mapped on the 1:24,000-scale geologic quadrangle maps. The geology is draped over a 5-ft horizontal-resolution LiDAR hillshade base.

(polygons)	(horizontal) LiDAR data
Landslide Areas Derived from Aerial Photography (polygons)	Digitized from landslide and related features maps
Areas Susceptible to Debris Flows (lines)	Digitized from landslide and related features maps.

The data are served as an ESRI Internet map service through KGS Web and GIS servers. The landslide layers were compiled into an ESRI geodatabase, reviewed and symbolized in an ESRI ArcMap project, and then published via ESRI ArcGIS Server 10.1 as an ArcGIS Map Service. The online service is made to be a standalone service with capability for connections in ArcMap, ArcGIS.com, and Google Earth. Accompanying LiDAR data (5-ft hillshade base), also a layer in the service, are made available as an ArcGIS Image Service from the Kentucky Office of Geographic Information.

The landslide map and data can be accessed and viewed on a themed layout, but are also embedded in the KGS Geologic Map Information Service, which offers the capability of creating highly customized maps. Other available layers include topographic map imagery, aerial photography, boundary index maps, roads, mile markers, 1:24,000-scale geology, 1:24,000-scale faults, coal beds, structural contours, oil and gas data, quarries, sinkholes, water wells, springs, and slope (from 10-m digital elevation models). A sliding transparency tool is available for many of the base and raster layers, providing functionality to view multiple layers. A help file accompanies the map

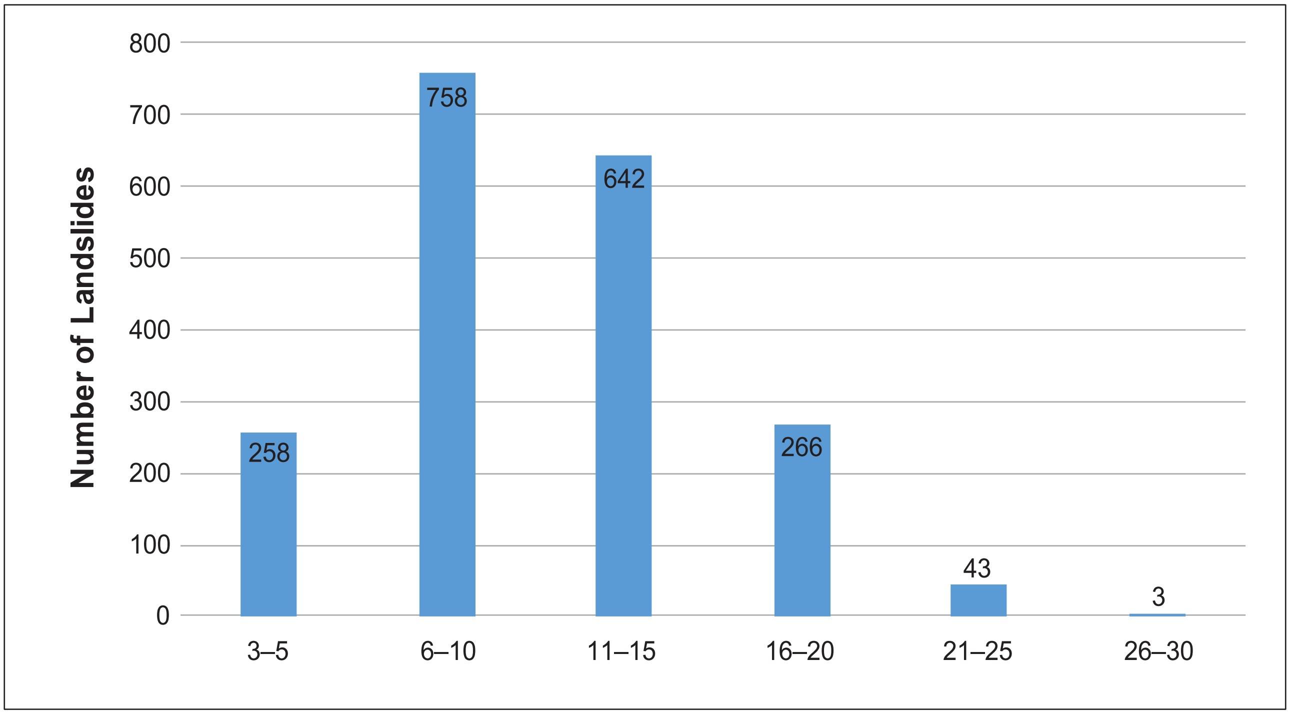

Figure 13. Distribution of landslides by slope angle. Slopes less than 3° not shown.

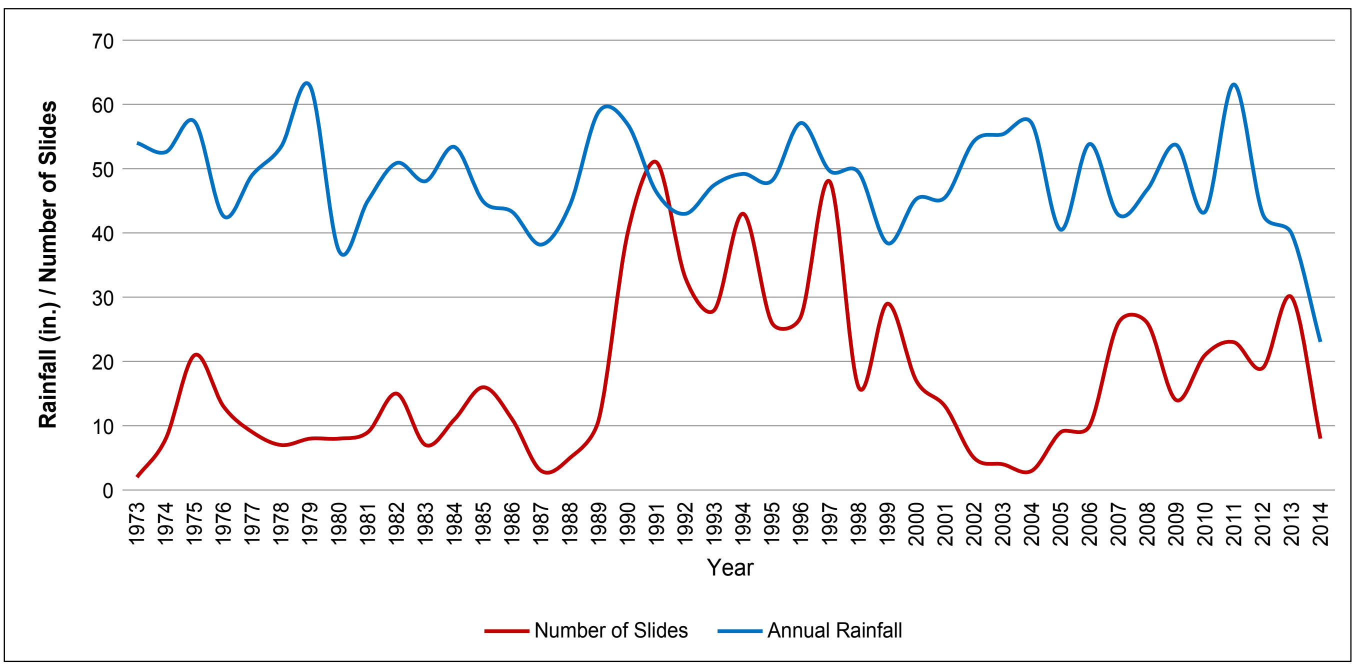

Figure 14. Landslides documented by Kentucky Transportation Cabinet compared with annual rainfall across Kentucky.

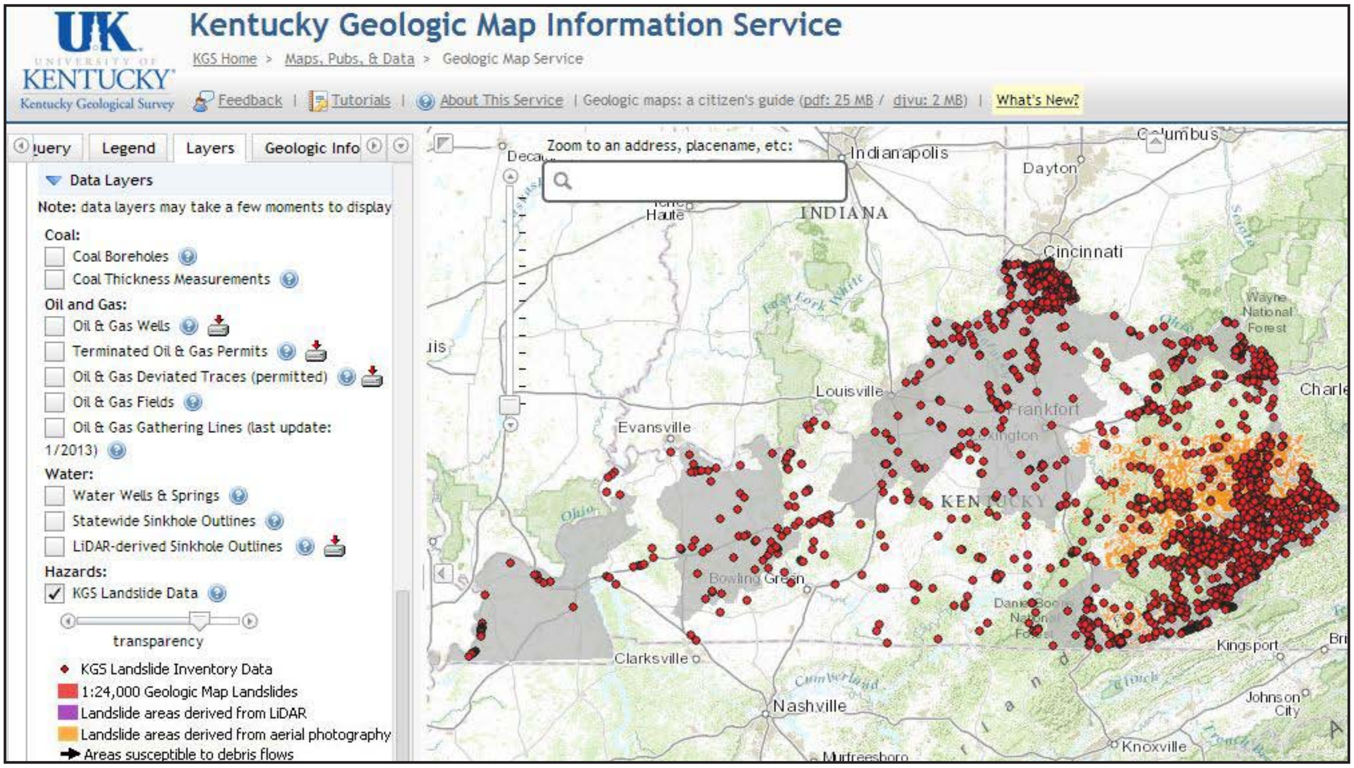

Figure 15. Screenshot of the KGS landslide information map (kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp?layoutid=25).

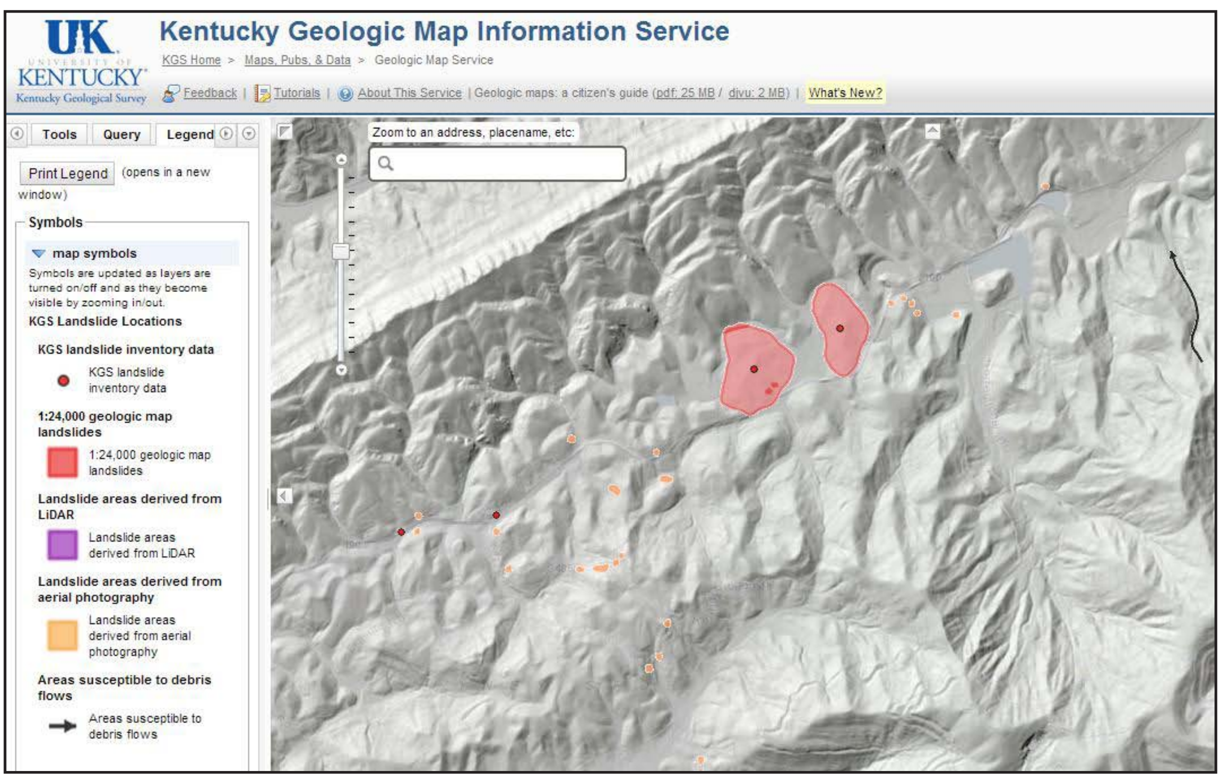

Figure 16. An enlarged section of the landslide information map. Note map legend on the left.

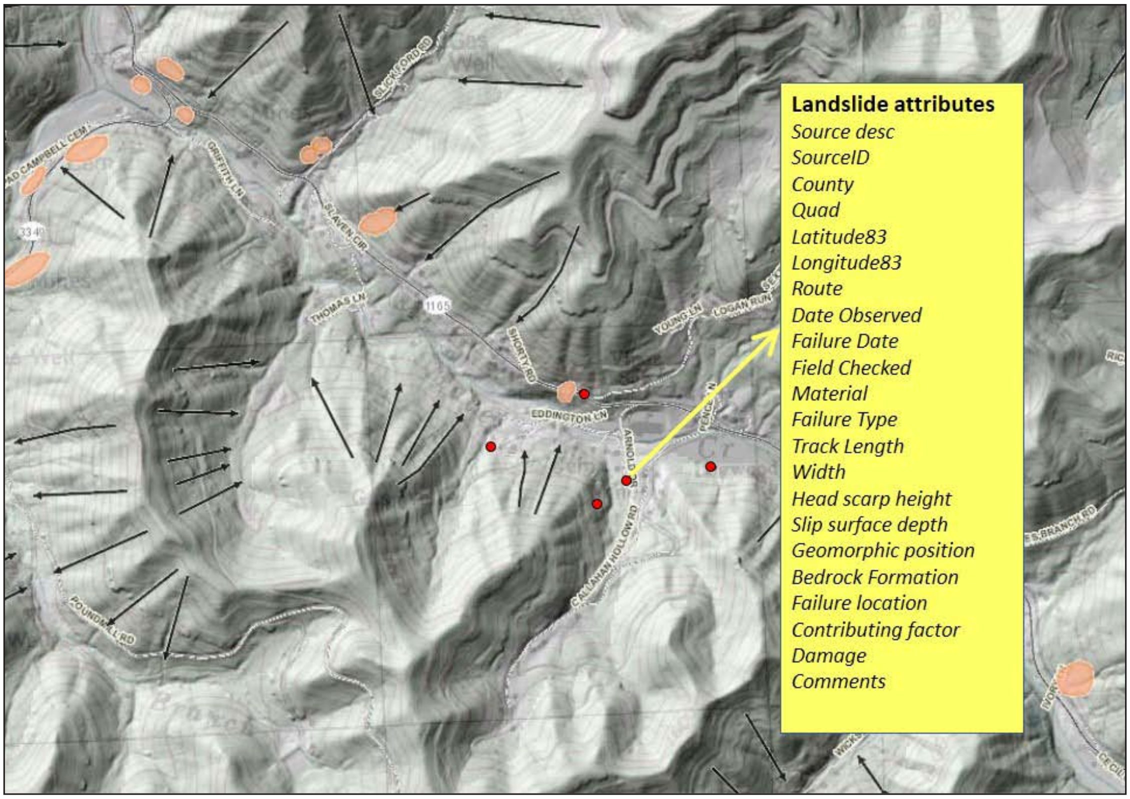

Figure 17. Enlarged view of a section of the landslide information map showing the fields and data from the landslide inventory database a user can access.

that explains the data layers and sources of the landslide information.

The landslide information map can be used to identify preexisting landslide locations and serve as a basis for landslide hazard assessment. The absence of landslides in an area does not imply that there is no landslide or that the ground is stable. Although not intended for site-specific investigations, this interactive map showing landslide locations in a geologic context in conjunction with topography, geology, slope, roads, and streams can be a powerful tool for trained persons to use to recognize landslide susceptibility and slope stability. A professional geologist or geotechnical engineer should be consulted for site-specific investigations of control and mitigation efforts for existing slides.

Summary and Impact

Landslide inventories create a foundation for assessing landslide hazard and risk reduction (Sarikhan and Stanton, 2009; Mazengarb and others, 2010; Foster and others, 2012). An inventory database allows spatial, temporal, and geologic data to be populated in a standard format. In addition, the database allows easy access, data delivery, and map creation, thereby highlighting the information needed for landslide hazard awareness. Maintaining the landslide inventory and creating the landslide information map has helped land-use planners, transportation personnel, emergency managers, meteorologists, geotechnical engineers, and the general public. Kentucky Emergency Management, the Natural Resources Conservation Service, and other government agencies have requested KGS assistance at several landslides, and the inventory and landslide information map have facilitated their job responsibilities and assisted with mitigation.

Most planners or local government officials do not have the resources to properly address landslides. Providing these agencies access to a landslide inventory in a geospatial context will complement any geotechnical site analysis, building and zoning regulations, and residential property assessment needed to minimize slope failure. A landslide inventory can serve as a standard place to document landslides, helping to facilitate cooperation among the various entities that deal with landslides. Although there is no best practice for landslide inventory development or maintenance, standardizing a database and making it available is a first step to best practices. Networking and communicating with officials who deal with landslides and are stakeholders in research is the challenge to support the need for landslide inventories.

Helpful Resources

- Crawford, M.M., 2012, Using LiDAR to map landslides in Kenton and Campbell Counties, Kentucky: Kentucky Geological Survey, ser. 12, Report of Investigations 24, 12 p.
- Highland, L.M., and Bobrowsky, P., 2008, The landslide handbook—A guide to understanding landslides: U.S. Geological Survey Circular 1325, 129 p. (available online at landslides.usgs.gov)
- KGS Landslide Information Map: kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp?layoutid=25
- KGS Landslides: www.uky.edu/KGS/geologichazards/landslide.htm
- KGS Report a Landslide form: kgs.uky.edu/kgsweb/KGSWEB/landslide.asp
- Potter, P.E., Bowers, M., Maynard, J.B., Crawford, M.M., Weisenfluh, G.A., and Agnello, T., 2013, Landslides and your property: Indiana Geological Survey, kgs.uky.edu/kgsweb/pubs/MoreInfo.asp?titleInput=17740&map=0 [accessed 06/10/2014].
- U.S. Geological Survey Landslide Inventory Project: landslides.usgs.gov/research/inventory

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