West Virginia Landslide Risk Assessment

Cumberland Plateau and Mountains

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WEST VIRGINIA UNIVERSITY

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Landslides in the Cumberland Plateau and Mountains of West Virginia

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The area designated as the Cumberland Plateau and Mountains in southwestern West Virginia (Figure 1) is dominated by rugged topography, clastic sedimentary bedrock, and well-drained soils developed in colluvium, mining regolith, and residuum. Regolith (unconsolidated material) produced by mining is widely distributed and locally thick in the coal-bearing geologic settings that encompass over 90 percent of the area. A U.S. Geological Survey landslide overview map of the United States (Radbruch-Hall and others, 1978) shows high landslide incidence throughout the entire area. LiDAR-based mapping reveals the abundance of landslides in the Cumberland Plateau and Mountains is virtually the same as in the Southern Alleghenies, but over five times more abundant than in the Appalachian Ridges and Valleys (Figure 1).

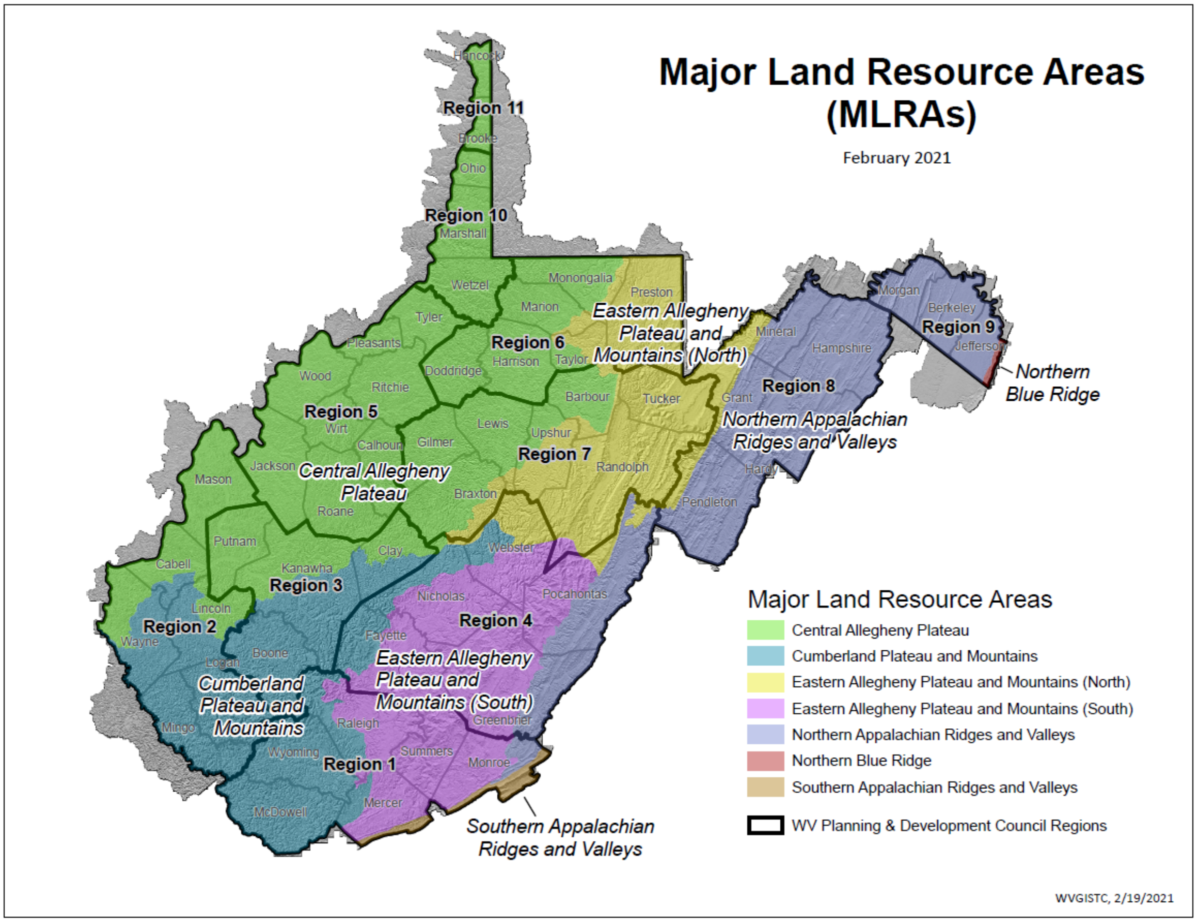

Figure 1: Map of Natural Resources Conservation Service Major Land Resource Areas (MLRAs), Planning and Development Regions, and county boundaries in West Virginia, shown on a shaded relief topographic base map.

In the West Virginia Landslide Risk Assessment natural regions were subdivided by U.S. Natural Resources Conservation Service (2006) Major Land Resource Areas (MLRAs), not by physiographic regions. West Virginia's physiography is coarsely mapped compared to detailed physiographic maps in adjacent states, whereas MLRAs are more precisely delineated and better capture regional variations in topography, geology, and soils than the state's established physiographic provinces and sections.

The area covered in this report lies within U.S. Natural Resource Conservation Service (NRCS) MLRA 125: Cumberland Plateau and Mountains, which extends from central West Virginia to northern Alabama, including portions of southwest Virginia, eastern Kentucky, and middle Tennessee. The extent of MLRA 125 in West Virginia includes all or portions of 15 counties distributed over West Virginia Planning and Development Regions 1, 2, 3 and 4 (Figure 1).

The MLRA extent in West Virginia generally matches the Logan Plateau delineated by William Outerbridge (1987) of the U.S. Geological Survey, who noted this region has steeper slopes than the Cumberland Plateau farther south. Although it is a valid concept, unfortunately the Logan Plateau has not been widely adopted and is not incorporated into NRCS MLRA designations.

The terms "Cumberland Plateau" and "Cumberland Mountains" are not commonly associated with West Virginia. A U.S. Geological Survey physiographic map by Fenneman and Johnson (1946) restricts the two units to the Southern Appalachians and did not extend either unit north as far as West Virginia. The U.S. Natural Resources Conservation Service (2006) description states the northern third of MLRA 125 is located primarily in Fenneman and Johnson's Kanawha Section of the Appalachian Plateaus Province, a varied physiographic region that also includes most of three other MLRAs. A West Virginia Geological and Economic Survey (2020b) map is less specific, showing the West Virginia portion of MRLA 125 within the vast Appalachian Plateau province.

The MLRA 125 description states clastic sedimentary rock types (sandstone, siltstone, claystone), and shale), interbedded with coal seams dominate the geology of the Cumberland Plateau and Mountains (U.S. Natural Resources Conservation Service, 2006). Limestone occurs only in geologic units in the lower and upper parts of the stratigraphic column. Relatively flat-lying bedding characterize the bedrock structure throughout the MLRA in West Virginia.

Landslide Characteristics and Contributing Factors

This project's definition of "landslide" encompasses all kinds of slope failures, except those arising from surface subsidence related to underground mines or caves and karst topography. Despite the broad scope of the project, there is no pretense that most landslides were identified and inventoried throughout the MLRA. Landslides scars developed in shallow soils may not be large enough or deep enough to be identified on the LiDAR-based imagery used for landslide mapping. Although Digital Elevation Models (DEMs) used in the project had 1 or 2 meter resolution, possible landslides features smaller than 33 feet (10 meters) wide were not mapped. The 33 feet minimum size avoided a multitude of false signatures due irregularities in LiDAR data, vegetation interference, and anthropogenic or natural features not produced by slope failure. Exploratory trial mapping indicated that attempts to map smaller features led to unacceptable increases in time and effort, while decreasing the accuracy and validity of map data that served as the basis for landslide susceptibility modeling and risk analysis. As a result of the 10 meter minimum width requirement, landslide susceptibilities shown in this study should be considered conservative, especially with regards to small failures.

The focus of the West Virginia landslide inventory has been to identify points where landslides initiate. Mapping the full extent of each landslide in the inventory would have required at least five times the effort required to map initiation points, so full-extent mapping could not be accomplished within the time allocated for the project. Comprehensive landslides mapping programs in other states have been underway for a decade or more but remain incomplete. It is hoped that this initiation-point inventory will be expanded into a long-term ongoing assessment of the full extent of landslides with the addition of new landslides occurrences in the future.

Colluvium (material transported some distance by gravitational processes), mining regolith, and residuum (material weathered in place or nearly in place) are the dominant earth materials in which soils develop in the MLRA. Colluvium, which includes landslide deposits, is generally thin near mountain tops, increasing in thickness farther downslope. Lenses of thick colluvium may accumulate in hillslope hollows, directly upslope from the beginnings of tiny ephemeral stream channels. The character and geometry of mine-related landforms has varied over the history of mining, reflecting the evolution of dominant extraction methods. Extensive valley fills created in recent decades locally exceed several hundred feet (100 meters) in thickness. Residuum depth varies with rock type and degree of weathering; most rock types in the area produce thin residual soils.

The West Virginia landslide risk assessment is focused on determining where landslides are apt to occur, not when, so ever-changing weather factors such as precipitation were not addressed. Constituting over 98 percent of mapped slope failures types in the area, 12,328 slides and slumps, are collectively classified as “slides” in this report. Slides tend to form when soil moisture and pore pressure are highest. They are most problematic after prolonged wet seasons, particularly in late winter and early spring when soils are saturated and ground-water tables usually are high throughout the MLRA.

Debris flows initiate as slumps or slides in residuum or colluvium on upper slopes, but may run long distances downslope from their source. MLRA 125 mapping revealed 178 debris flows. The most frequent cause of Appalachian debris flows is heavy rain associated with intense spring and early summer storms or late summer and early autumn remnants of tropical cyclones. The high-intensity rainfall events that trigger debris flows tend to produce numerous slope failures in local clusters. Fortunately, Appalachian debris flows are infrequent in relatively undisturbed areas, with recurrence intervals at vulnerable sites estimated to be hundreds or thousands of years. However, debris flows may be more much frequent in mining regolith and disturbed areas.

Rock fall failures are commonly reported in the MLRA, especially on disturbed slopes such as rock cuts along transportation corridors and mine highwalls, but the scope of rock fall susceptibility is not well shown by this landslide inventory. Fallen rock is unlikely to be caught on occasional LiDAR surveys because it is usually removed promptly and commonly too small to be resolved and identified using 1 or 2 m LiDAR-based DEMs.

Less common landslides types include multiple failures: tight clusters of small landslides and debris flows that tend to occur during debris flow events; only 19 were mapped in MLRA 125. Lateral spreads, typically well-defined landforms called rock cities, are clusters of very large rock blocks that rarely move under modern conditions. Hundreds of rock cities have been mapped elsewhere in West Virginia, but only one was identified in LiDAR-based DEMs from the Cumberland Plateau and Mountains MLRA.

A total of 12,532 landslides were identified through LiDAR-based mapping on DEMs viewed at 1:3,900 screen scale. These landslides provided the basis for an analysis of 43 different attributes using a random forest model similar to one used for modelling landslide susceptibility in the Appalachian Ridges and Valleys and described in Maxwell and others (2020). Graphical output from this modelling is displayed as the Landslide Hazard Susceptibility layer on the West Virginia Landslide Tool. Ultimately, uncertainty in location or a lack of verification by a second mapper led to exclusion of six landslides, but 12,526 verified slope failures were analyzed in detail for this report to explain how four key factors contribute to where landslides occur.

Slope

Analysis of the LiDAR-based landslide mapping of the Cumberland Plateau and Mountains MLRA reveals that slope steepness may be the most important control over where landslides develop, especially in steep hillslope hollows that allow subsurface moisture, surface-water runoff, and unconsolidated material to accumulate. Slope area ratio, the only other variable with correlation strength comparable to surface slope, may indicate precise locations of hillslope hollows (a good predictor of where future landslides may develop) or may reflect the locations of scars from past slope failures.

The slopes of upland surfaces where slides (including slumps) and debris flows initiate are similar, with 90 percent of both types of failures occurring on slopes greater than 21° (Figure 2). Slides are by far the most common slope failure category, and the median slope for 12,328 slide initiation sites is 34° and four out of five slides initiated on 21° to 43° slopes. For comparison, a sample of 75,833 randomly selected non-landslide points throughout the MLRA have a median slope of 28°, with four out of five points having 8° to 38° slopes.

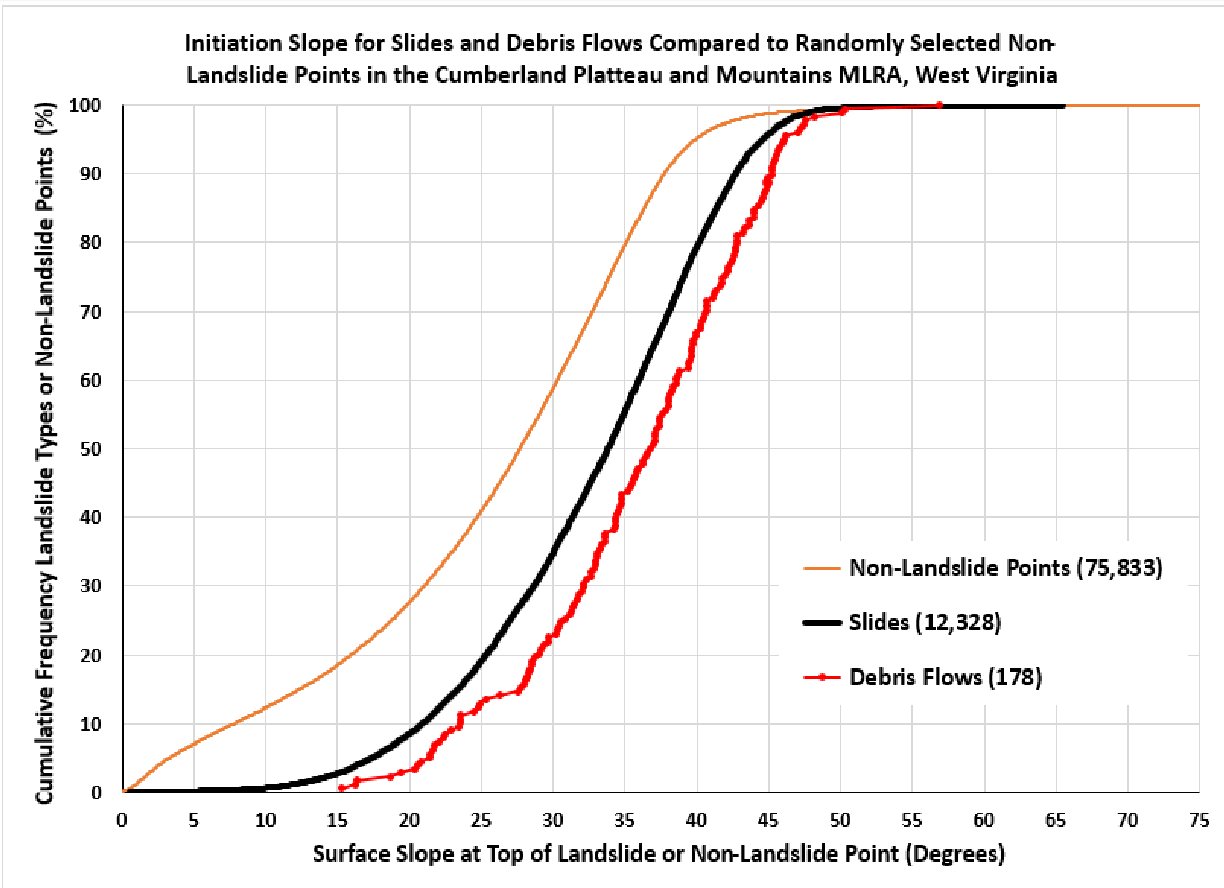

Figure 2. Comparison of initiation slopes for slides (including slumps) and debris flows with randomly selected non-landslide points in the Cumberland Plateaus and Mountains of West Virginia. Initiation slope was measured at the uppermost point on a landslide as mapped from the LiDAR-based DEMs.

Debris flows tend to initiate on steeper slopes than other landslides, a trend that may reflect a tendency for landslides on steeper slopes to have enough momentum required to translate downslope into debris flows. The median slope at 178 debris flow initiation sites is 37°, and four out of five debris flows initiated on 23° to 45° slopes (Figure 2).

Geology

Geology is a universally cited factor in landslide distribution, and this is the case in the Cumberland Plateau and Mountains MLRA. The role of geology on landslides may be complex, indirect, and somewhat counter-intuitive. Bedrock units heavily dominated by sandstone, the hardest and most resistant rock type in the area, generally are responsible for higher-elevation topography in the area and numerous cliffs along major river valleys. An intuitive assumption that heavily sandstone-dominated bedrock slopes should host more landslides than other geologic units may seem apparent on the steep valley walls, but the inherent strength of thick sandstone layers makes them more stable than other rock types at any given slope angle. Away from river valleys, upland landscapes associated with heavily sandstone-dominated units tend to be less rugged than landscapes dominated by weaker shale, claystone, or siltstone. On the almost ubiquitous steep slopes that extend across most of the Cumberland Plateau and Mountains, weaker bedrock units tend to be more deeply incised and more prone to failure than resistant units, even if the weak units contain some significant sandstone beds. The importance of bedrock geology in the MLRA is further complicated by the role of mining and its resulting regolith. The inherent strength of coal-bearing bedrock units may be less significant to slope stability than the properties and behavior of unconsolidated material left on the landscape by mining and related activities.

Geologists make maps to decipher earth history. The varied events in earth history lead to a heterogeneous rock stratigraphic record. However, not all differences in rock type are reflected in the designation of formations and groups that serve as basic map units. Geologic maps are imperfect as proxies for the distribution of earth materials, but these maps are the best widely available resource to trace bedrock distribution for analyses of the role of geology on landslide susceptibility in the area.

Digital layers created from the West Virginia Geological and Economic Survey (WVGES) state geologic map (Cardwell and others, 1968) are the source for the distribution of geologic units and descriptions of rock types used in this report. Although this map is an often-used valuable resource, it has imprecisions and inaccuracies in map unit boundaries that create potential uncertainties in the links between geology and landslide susceptibility. Problems of scale-related resolution or error in map compilation and reproduction exist. Inaccuracies in the original 1:250,000 scale geologic map may have been compounded when a paper copy was scanned and digitized by the West Virginia Division of Environmental Protection in 1998. The issues of inaccuracy and imprecision emphatically reiterate the warning that this report and the West Virginia Landslide Tool should not be used to substitute for site-specific analysis by landslide experts and geotechnical engineers.

Geologic Map Units and Landslide Susceptibility: The WVGES state geologic map (Cardwell and others, 1968) shows nine different map units in the Cumberland Plateau and Mountains, with individual map area extents ranging from 0.1 to 2383 square miles (Table 1). Eight units show bedrock geology; the other unit denotes alluvial deposits on river terraces and floodplains.

LiDAR-based mapping revealed no landslides in three geologic units, each having an extent less than 24 square miles. Wide differences in unit map area extent and landslide count create problems for detailed statistical analysis. However, meaningful trends do appear in a tabulation of landslide attributes for each geologic unit (Table 1). All Cumberland Plateau and Mountains bedrock units occupying over 24 square miles reveal significant susceptible to failure, but Table 1 shows landslide densities (failures/100 mi^2) in these six landslide bearing units vary by a factor of eight.

WVGES Geologic Map Unit	Geologic Period	Mapped Landslide Count	% of All Landslides	Unit Area mi^2	Mapped Landslides /100 mi^2
Alluvium	Quaternary	0	0.0	15.9	0
Monongahela Group	Pennsylvanian	0	0.0	23.2	0
Conemaugh Group	Pennsylvanian	198	1.6	406.9	49
Allegheny Formation	Pennsylvanian	993	7.9	654.3	152
Kanawha Formation	Pennsylvanian	10,146	81.0	2382.3	426
New River Formation	Pennsylvanian	642	5.1	776.3	83
Pocahontas Formation	Pennsylvanian	509	4.1	200.2	254
Bluestone & Princeton Formations	Mississippian	38	0.3	33.1	115
Hinton Formation *	Mississippian	0	0.0	0.1	*
Overall MLRA 125		12,526	100.0	4492.3	279

*Table 1. Landslide data associated with Cumberland Plateau and Mountains geologic map units, listed in stratigraphic order. Data include all types of landslides, including debris flows. Note * extent of the Hinton Formation is too small for meaningful calculation of failures/100 mi^2.*

The Pocahontas, New River, Kanawha, and Allegheny formations collectively constitute the major coal-bearing bedrock units in the study area (West Virginia Geological and Economic Survey, 2020a), which lies in the heart of the central Appalachian coal fields. Southern West Virginia has experienced exceptionally high coal production during the last four decades particularly from the upper part of the Kanawha formation (Fedorko and Blake, 1998). Much of this coal was extracted through surface mining methods, especially mountaintop removal and associated deep valley fills. The relationships between mined lands and landslide susceptibility is more precisely addressed in subsequent discussion of soil parent materials.

The Kanawha Formation is more susceptible to landslides than any other geologic unit, containing 81 percent of mapped landslides while encompassing just 53 percent of the study area. Accordingly, the number of landslides per 100 mi^2 in the Kanawha Formation is over 67 percent more than any other unit. The Pocahontas Formation is the only other unit with a landslide density approaching the MLRA average, although it ranks only fourth in total landslide count. Landslide counts in Allegheny and New River formations rank second and third, respectively. Although sandstone is the most common bedrock type in all four coal-bearing units, the New River Formation is the only unit with more than half of its thickness made up of inherently resistant thick sandstone beds, commonly 60 to 100 feet thick. Sandstone beds in the other three coal-bearing units are interbedded with voluminous interlayers of shale and siltstone. In McDowell, Wyoming, Raleigh and Mercer counties, the New River Formation serves as a caprock underlying broad undissected uplands that are “flat” by Mountain State standards. This topographic setting and the inherent strength of its sandstone layers appear to contribute to a New River Formation landslide susceptibility that is only 30 percent of the overall MLRA average.

The significant extent of the Conemaugh Group in the MLRA suggests its relatively low landslide susceptibility is meaningful, but this interpretation should be tempered by the fact that this level of susceptibility is significant and the formation has a “reputation” as an unstable bedrock unit among geoscientists in the region. Few conclusions should be drawn from the lack of landslides in the Pennsylvanian Monongahela Group, which is restricted to mountain tops the western portions of the MLRA, but hosts many landslides in northern and central West Virginia. Alluvium, the only map unit composed of unconsolidated sediments, shows no landslide susceptibility despite its low inherent strength. The apparent very low susceptibility is likely a result of both small sample size and the low-relief bottomland topography where alluvium occurs.

The two Mississippian units at the bottom of the area's stratigraphic column are within the Mauch Chunk Group, which is highly susceptible to landslides elsewhere in West Virginia, but not clearly so in the this study area. The low landslide susceptibility in Cumberland Plateau and Mountains could possibly reflect variations in the units across the state or be a spurious result of the small extent of these units in the MLRA. The 115 landslides/100 mi^2 in the combined Bluestone and Princeton unit may understate its susceptibility; this unit has nearly four times this density over a much larger extent in the adjacent Southern Alleghenies. The complete lack of landslides in the Hinton Formation is almost certainly a sampling artifact of the unit's tiny area exposed within the MLRA boundaries, so inherent stability should not be inferred for the unit, which contains almost 30 percent of all landslides mapped in the adjacent Southern Alleghenies.

Debris Flows: Although they make up only 1.4 percent of landslides in the Cumberland Plateau and Mountains inventory, the distinctive characteristics of debris flows and their exceptional potential risks to safety and civil infrastructure warrant examination how they relate to geology (Table 2). Susceptibility to debris flows varies greatly between different geologic map units, with geologic distributions similar to overall landslides in the area, including maximum high susceptibility in the Kanawha Formation.

WVGES Geologic Map Unit	Geologic Period	Debris Flow Count	% of Debris Flows	Unit Area mi^2	Debris Flows /100 mi^2
Alluvium	Quaternary	0	0.0	15.9	0.0
Monongahela Group	Pennsylvanian	0	0.0	23.2	0.0
Conemaugh Group	Pennsylvanian	4	2.3	406.9	1.0
Allegheny Formation	Pennsylvanian	18	10.1	654.3	2.8
Kanawha Formation	Pennsylvanian	150	84.3	2382.3	6.3
New River Formation	Pennsylvanian	6	3.4	776.3	0.8
Pocahontas Formation	Pennsylvanian	0	0	200.2	0.0
Bluestone & Princeton Formations	Mississippian	0	0	33.1	0.0
Hinton Formation *	Mississippian	0	0	0.1	*
Overall MLRA 125		178	100.0	4492.3	4.0

*Table 2. Debris flow data associated with Cumberland Plateau and Mountains geologic map units, listed in stratigraphic order. Note * extent of the Hinton Formation bedrock is too small for meaningful calculation of debris flows/100 mi^2. Sum of percentages do not add up to 100.0 percent because of rounding.*

The overall debris flow density in MLRA 125 is lower than in the adjacent Southern Alleghenies area (6.8/100 mi^2), but virtually identical to overall debris flow density in the Appalachian Ridges and Valleys of eastern West Virginia (4.0/100 mi^2). Debris flow initiation points were mapped in only four of the nine geologic units, but these four units cover 94 percent of the area. Debris flows may have notoriously long run outs of a mile or more, so some locations in geologic units with few mapped debris-flow initiation points may be at risk due to geology and topographic conditions far upslope.

The Kanawha Formation encompasses 150 of 178 mapped debris flows initiation points, and is the only geological map unit in which debris flows/100 mi^2 is greater than the overall MLRA average. The Allegheny Formation ranks second in debris flow count, followed by the New River Formation. All three of these units are sandstone-dominated coal-bearing units. In contrast, the Conemaugh Group, the only other unit with debris flows, is dominantly shale and siltstone with much less sandstone and no significant coal (West Virginia Geological and Economic Survey, 2020a).

The Pocahontas Formation is the only sandstone-dominated coal-bearing unit lacking mapped debris flows. It is also the only unit lacking debris flows that covers an area large enough that their absence is difficult to dismiss as a mere reflection of a small sample size. Remarkably, three units lacking any debris flows in the Cumberland Plateau and Mountains are the units with the most debris flows in the adjacent Southern Alleghenies: the Hinton Formation (23.2/100 mi^2 in the Southern Alleghenies), Bluestone & Princeton formations (12.6/100 mi^2), and Pocahontas Formation (14.5/100 mi^2). All three of these units are concentrated along or near valley bottoms in Cumberland Plateau and Mountains MLRA 125, whereas the same units tend to occur higher on the dissected topography of the Southern Allegheny Mountains. The role of topographic position of a geologic unit may partly explain why the New River Formation has fewer debris flows than the overlying Kanawha, Allegheny, and Conemaugh map units in MLRA 125, but more debris flows than the same three units in the Southern Alleghenies.

At the top of the stratigraphic section, Quaternary alluvium occurs on low slopes that are not conducive to debris flow anywhere. The Monongahela Group is restricted to a few mountain tops the western portions of the MLRA, and hosts some debris flows elsewhere in West Virginia.

<u>Minor Landslide Types:</u> Nineteen landslides were mapped as multiple failure complexes. Sixteen of these occur in the Kanawha Formation, two in the Allegheny Formation, and one in the New River Formation. All three of these Pennsylvanian units are coal-bearing.

Only one lateral spread was identified in MLRA 125; it lies in the Kanawha Formation. This solitary Cumberland Plateau and Mountains occurrence contrasts sharply with the 247 lateral spreads mapped in the Southern Alleghenies, particularly since over 2/3rds of those spreads were identified in the Pocahontas, New River, and Kanawha formations. Mappable lateral spreads, such as rock cities, require large blocks that develop from thick beds of resistant rock; hence, the difference in lateral spreads between the two areas may relate to westward thinning of sandstone beds within these sandstone-dominated units, and an associated westward decrease in size and abundance of sandstone blocks across southern West Virginia.

Soils

NRCS Soil Survey Geographic (SSURGO) data provide a tool to assess how soil parent material and drainage class relate to landslide susceptibility. The SSURGO digital database for West Virginia was created from maps at 1:24,000 or finer scale during the 1990s and early 2000s, and is revised when new soil mapping is completed. In spite of the detail theoretically possible at fine scales, the complex and intermixed nature of soils make their identification and delineation an inexact science constrained by limited NRCS budgets and practicable schedules.

Soil series provide the basic units of soil survey mapping, and most soil series develop from a dominant parent material and have a dominant drainage classification. In mountainous landscapes, few sizeable landforms contain only one soil series. Most soil map polygons underlying this analysis were assigned based on one or two dominant soil series in a tract, while acknowledging that other series exist as inclusions. Parent material and drainage class may differ throughout individual polygons in the very common practice in which two or more soil series are grouped together as a single soil survey map unit.

Analysis of mapped landslides indicate that interpretations about soils and where landslides initiate can be drawn from SSURGO from West Virginia. However, the inexactness of soils maps and the dominance of only four parent materials and one drainage class in the Cumberland Plateau and Mountains limit interpretations from this area to broad generalizations.

Soil Parent Material: SSURGO data provide the basis for 8 different soil parent materials in the Cumberland Plateau and Mountains area (Table 3). Water is not true soil parent material, but is included in SSURGO data and Table 3. Across the area, four widespread parent materials have moderately high to exceptionally high susceptibility to landslides. One widespread material appears has low susceptibility, while data from the three less extensive material warrant caution because of their tiny areal extent, small landslide count, or both.

NRCS Soil Parent Material	Mapped Landslide Count	% of All Failures	Unit Area mi^2 (Approx.)	Mapped Failures /100 mi^2
Colluvium	7598	60.66	3089.0	246
Mining Regolith	3047	24.33	403.5	755
Residuum, Acid Clastic	1458	11.64	729.8	200
Disturbed Areas	406	3.24	99.7	407
Recent Alluvium	13	0.10	114.2	11
Residuum, Calcareous Clastic	2	0.02	0.4	482
Old Terrace Alluvium	1	0.01	35.7	3
Water	1	0.01	20.1	5
Overall MLRA Total	12,526	100.00	4492.3	279

Table 3. Dominant soil parent material for all landslides mapped in the Cumberland Plateau and Mountains. Materials are listed in decreasing order by number of landslides of all types. Sum of percentages and unit areas do not equal overall MLRA totals because of rounding.

Although the two most common parent materials have moderately high landslide susceptibility and cover 85 percent of the MLRA, the 246 landslides/100 mi^2 identified in colluvium and the 200 landslides/100 mi^2 in acid clastic residuum is less than the overall MLRA average. The highest concentrations of landslides occur in mining regolith (755 landslides/100 mi^2) and disturbed areas (400 landslides/100 mi^2). Both of these young unconsolidated parent materials have low inherent strength, and may have not been in place on the landscape long enough to reach slope equilibrium. Unless disturbed by human activities or truly exceptional natural events, colluvium and residuum have developed over thousands of years or more, providing more opportunity to adjust to conditions on this steep rugged landscape.

The parent material data convey a clear message that human disturbance, especially coal mining, contributes heavily to landslide susceptibility. Mapping projects in the adjacent Southern Allegheníes area have identified many landslides associated with old unreclaimed strip mine benches and haul roads that predate the 1977 Surface Mining

Control and Reclamation Act (Remo, 1999; Yates and others, 2016), but landslides and other instabilities have been documented on reclaimed mines that operated after 1977 (Reed and Kite, 2020). SSURGO data do not differentiate "pre-law" mining regolith from post-SMCRA regolith, so it is unclear the degree to which exceptionally high landslide susceptibility in mining regolith relates to past mining practices or more recent methods such as mountain-top mining and valley filling.

Table 3 suggests calcareous clastic residuum is very highly susceptible to landslides; however, the 482 landslides/100 mi^2 value in the table is based on only two landslides in a very small area. A much larger area of calcareous clastic residuum in the Southern Allegheniess contained 293 landslides/100 mi^2, so this parent material should be regarded accordingly.

Recent alluvium and old terrace alluvium are underrepresented in landslides per 100 mi^2 by an order of magnitude or more; a slightly lower susceptibility than indicated for the alluvium geologic map unit in Table 1. It is revealing to note that the WVGES geologic map shows alluvium covers only 15.9 mi^2 in the Cumberland Plateaus and Mountains, whereas NRCS soil parent material data suggest the two alluvium categories, when combined, cover 149.8 mi^2. The state geologic map is very conservative in portrayal of non-bedrock geologic units, so the larger percentage indicated by soil parent material is almost certainly more accurate.

Water is not soil parent material, but covers almost 0.5 percent of MLRA 125. Tables 3 and 4 both include one landslide adjacent to a river that was assigned erroneously as "water" because of imprecise polygon boundaries. The LiDAR used to create the elevation data used to create the DEMs used in mapping landslides cannot significantly penetrate water, so it is not possible to map underwater landslides using the methods of this study.

Tabulation of debris flows within the Cumberland Plateau and Mountains shows that these long-runout failures initiate in only four parent materials (Table 4). Debris flows were mapped in the two most widespread units, colluvium and acid clastic residuum, but with frequencies much lower than in mining regolith and disturbed areas. These debris flow statistics reinforce the message that human disturbance contributes heavily to slope instability in the Cumberland Plateau and Mountains.

NRCS Soil Parent Material	Debris Flow Count	% of Debris Flows	Unit Area mi^2 (Approx.)	Debris Flows /100 mi^2
Colluvium	92	51.7	3089.0	3
Mining Regolith	64	36.0	403.5	16
Residuum, Acid Clastic	10	5.6	729.8	1
Disturbed Areas	12	6.7	99.7	12
Recent Alluvium	0	0.0	114.2	0
Residuum, Calcareous Clastic	0	0.0	0.4	0
Old Terrace Alluvium	0	0.0	35.7	0
Water	0	0.0	20.1	0
Overall MLRA Total	178	100.00	4492.3	4

Table 4. Dominant soil parent materials for debris flows mapped in the Cumberland Plateau and Mountains. Materials are listed in decreasing order by number of landslides of all types shown in Table 3. Sum of unit areas does not equal overall MLRA totals because of rounding.

Soil Drainage Class: The NRCS recognizes seven drainage classes for soil series (Table 5). Drainage classes are assigned under normal moisture conditions, and vary depending on soil material infiltration capacity, water table depth, and surface topography. Although not considered a soil drainage class, a "water" row is shown in Table 5 and includes one landslide adjacent to a river that was assigned erroneously because of imprecise polygon boundaries.

Soil Drainage Class	Mapped Landslide Count	% of All Failures	Unit Area mi^2 (Approx.)	Mapped Failures /100 mi^2
Excessively Drained	14	0.11	19.0	74
Somewhat Excessively Drained	31	0.25	40.5	77
Well Drained	12,380	98.83	4316.5	287
Moderately Well Drained	33	0.26	246.6	71
Somewhat Poorly Drained	67	0.53	44.7	150
Poorly Drained	0	0.00	5.1	0
Very Poorly Drained **	0	0.00	0.0	**
Water	1	0.01	20.1	5
Overall MLRA 125 Total	12,526	100.00	4492.3	279

*Table 5. NRCS Drainage classes and relative abundance of all landslide types for soils mapped in MLRA 125. Classes are listed from most to least drained. Note ** NRCS data do not show any very poorly drained soils in the MLRA. Sum of percentages and unit areas do not equal overall MLRA totals because of rounding.*

Soil polygons assigned as “well drained” cover about 96 percent of the Cumberland Plateau and Mountains landscape and account for almost 99 percent of landslide initiation points. The overwhelming preponderance of well drained soils dominates the overall MLRA 125 statistics, leaving other classes with such small areas and numbers of landslides that the validity of landslide statistics in these classes may not be robust. However, it is meaningful that the density of landslides at well drained sites is nearly twice that of the next highest drainage class, somewhat poorly drained soils. Somewhat well drained soils also host the second highest number of landslides (67), but that number is only 0.5 percent of the MLRA total. All of the failures on somewhat poorly drained slopes are developed on colluvium parent material, suggesting these slides may be reactivations of older landslides.

Soils in all other drainage classes have less than 28 percent of the MLRA average number of landslides per 100 mi^2. Landslide susceptibility on excessively drained, somewhat excessively drained, and moderately well drained soils are similar, with 71 to 77 landslides/100 mi^2. NRCS SSURGO data for MLRA 125 show no very poorly drained soils and few polygons of poorly drained soils, which may host few landslides because these soils occur on very low slopes.

Soil moisture is a transient characteristic. Drainage classes are assigned under normal moisture conditions, but most landslides fail under abnormal circumstances. Regardless of drainage classification, almost any earth material can fail under unfavorable conditions, such as extremely intense rainfall, prolonged seasonal wetness, artificial increases in water table, improper surface drainage alterations, or failure of waterlines.

Compared to geologic maps, soil maps are more accurate proxies for the distribution of unconsolidated earthy materials. However, soil map polygons in mountain areas commonly are orders of magnitude larger than the dimensions of landslide initiation scars. Most soil map units in mountain landscapes are associations of two or more soil series and the descriptions of almost all map units recognize inclusions of other soil series. Data used in this analysis relie on descriptions of the primary soil in a map unit, which commonly has different parent material or drainage class than the unit's associated or included soils. One widely accepted landslide initiation model developed by Hack and Goodlett (1960) from detailed study of 1949 debris flows on along the West Virginia-Virginia border suggests typical mountainsides are dominated by well-drained or somewhat-excessively drained residuum, but landslide initiation points therein are usually concentrated in hillslope hollows, where moisture is relatively high and parent material is likely to be local accumulations of thick colluvium. This model suggests landslides tend to initiate in local inclusions of soils that are more poorly drained than the adjacent soils that dominate map polygons. Soil scientists are aware of the issue of polygon scale in mapping mountain soils, and future landslide research may have more precise soil-landscape data for susceptibility modelling.

Other Landslide Factors

Although many factors influencing slope stability are universal, some aspects of slope stability in the Cumberland Plateau and Mountains differ from other areas in West Virginia. Anthropogenic disturbance is particularly significant in landscapes underlain by coal-bearing bedrock. Unreclaimed mine high walls have local rock-fall susceptibility, but falls elsewhere in the area are most commonly associated with over-steepened road and railroad cuts, particularly on over-dip slopes where undercut bedrock layers dip in the downslope direction at angles less than the topographic slope angle.

Forest products are part of the economy of most West Virginia counties in the Cumberland Plateau and Mountains. Hillslopes underlain by weak bedrock or soil may obtain a significant fraction of their shear strength from tree roots, so intensive timber clearing may lessen slope strength for decades until new root systems develop. Illdesigned or poorly constructed haul roads and skidder trails may lead to surface drainage disruptions that causes unprecedented soil saturation and abnormal slope destabilization.

Urban, suburban, and rural development share many of the landslide issues characteristic of timber operations. Foundation excavations and inadequate retaining walls are additional contributors to slope failure on developed land, sometimes including farm land. The intensity of new property development in the Cumberland Plateau and Mountains is less than what is being experienced in rapidly growing areas in West Virginia; nonetheless, the importance of good engineering design, based on slope-stability site analysis by professional geologists and certified civil engineers, cannot be over-emphasized.

Extremely intense rainfall may create exceptionally high soil moisture content, high soil and bedrock pore pressure, and short-lived abnormal drainage conditions, all factors that have triggered widespread landsides over multiple-county expanses in West Virginia. Many scores of landslides developed in response to short-lived deluges centered along the boundary between the Southern Alleghenies and Appalachian Ridges and Valleys in summer 1969 (Schneider, 1973) and June 2016. Two dramatic historic rainfall events spawned hundreds of debris flows and other types of landslides in the Potomac Highlands in June 1949 and November 1985 (Stringfield and Smith, 1956; Jacobson and others, 1991). Cataclysmic landslide swarms develop when six or more inches of rainfall occur in 24 hours or less, as happened in these four events, which were all associated with severe floods.

Some landslide swarms have been associated with remnants of hurricanes and other tropical cyclones, but thunderstorm complexes in late spring and early summer present an equal or greater threat. Regional trends across the Appalachians suggest the frequency of these landslide events increases with nearness to Gulf of Mexico moisture sources. This pattern suggest a slightly higher probability of swarms of debris flows and other landslides in the Cumberland Plateau and Mountains than in northern areas of West Virginia. Historically, rainfall intensities sufficient to cause landslide swarms have had a more-than-once-in-a-lifetime chance of occurring at any given Mountain State locality, but local rainfall-induced landslide events in the Cumberland Plateau and Mountains and elsewhere in the state may become more frequent with ongoing changes in climate.

This assessment is targeted toward outlining the geographic distribution of landslide susceptibility and associated risk. Trustworthy prediction of how susceptibility and risk might change under future climates would be a laudable goal; so would a landslide warning map based on real-time weather. However, such tools are beyond the scope of this assessment.

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