Appalachian Ridges and Valleys MLRA

The Appalachian Ridges and Valleys have very diverse topography, geology, and soils. These factors contribute to more variability in landslide distribution and wider variety of landslides types than in any other Major Land Resource Area (MLRA) in West Virginia. The Appalachian Ridges and Valleys encompass most of the gentle topography in the state, and LiDAR-based mapping reveals the MLRA has fewer landslides.

Almost all of the area covered in this report lies within the US Natural Resource Conservation Service (NRCS) MLRA 147 Northern Appalachian Ridges and Valleys. Two small areas in other MLRAs along the West Virginia-Virginia border were combined with MLRA 147 for purposes of statistical analysis: (1) a 1 to 6 mile wide belt of MLRA 128 Southern Appalachian Ridges and Valleys in Mercer and Monroe counties and (2) a 1 to 2 mile wide strip of MLRA 130 Northern Blue Ridge in Jefferson County. Neither of the two small West Virginia portions of MLRA 128 and 138 have a sufficient number of inventoried landslides to allow robust stand-alone analyses of factors contributing to landslide susceptibility. These areas share many characteristics with MLRA 147 Northern Appalachian Ridges and Valleys, so all three areas were combined into a single "Appalachian Ridges and Valleys MLRA" for purposes of inventory and analysis in this project.

The Northern and Southern Appalachian Ridges and Valleys MLRAs generally correlate to the Valley and Ridge physiographic province as recognized by the U.S. Geological Survey (Fenneman and Johnson, 1946). The West Virginia Geological and Economic Survey (2020) assigns the Shenandoah Valley in Jefferson and Berkeley counties to the Great Valley subprovince, but that subdivision is not regularly followed by the U.S. Geological Survey. Many geological and topographic attributes support subdivision of the Appalachian Ridges and Valleys, but it is a moot issue for this project because the Great Valley lacks enough landslides in West Virginia to allow sound statistical analyses separate from the rest of the Appalachian Ridges and Valleys. The Northern Blue Ridge MLRA in West Virginia correlates to the widely recognized Blue Ridge physiographic province (Fenneman and Johnson, 1946; West Virginia Geological and Economic Survey, 2020).

Landscape Characteristics

The Appalachian Ridges and Valleys MLRA is an erosional landscape underlain by folded and faulted bedrock with varied resistance to weathering and erosion. Hard resistant bedrock units, primarily composed of quartz-rich sandstone, form parallel linear ridges, separated by valleys underlain by more erodible shales, siltstones, and limestones. Appalachian Ridges and Valleys slope failures are most common on the steep flanks of ridges, but less common on ridge crests, Landslides rarely initiate on flat land, but large landslides may extend from steep slopes onto valley bottoms.

Residuum (material weathered in place or nearly in place) and colluvium (material transported some distance by gravitational processes) are the dominant earth materials in which soils develop in the MLRA. Residuum depth varies with rock type and degree of weathering; limestones and very old stable surfaces typically develop thick residual soils. Colluvium, which includes landslide deposits, is generally thin close to ridgetops, increasing in thickness further downslope.

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. In spite of the broad scope of the project, there is no pretense that most landslides were identified and inventoried throughout the area. Head scarps on failures 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 10 meters (33 feet) wide were not mapped. The 10 meter minimum size avoided a multitude of false signatures due irregularities in LiDAR data, vegetation interference, and indiscernible anthropogenic or natural features that are not products of slope failure. Exploratory trial mapping indicated that attempting to map smaller features would cause 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.

The goal of this landslide risk assessment was to determine where landslides are apt to occur, not when, so ever-changing weather factors such as precipitation were not directly addressed. Slides and slumps, the most common landslide types in the area, tend to develop when soil moisture and pore pressure are highest. They are most problematic after prolonged wet seasons, particularly in later winter and early spring when ground-water tables usually are high over all of the MLRA.

Debris flows initiate as slumps or slides in residuum or colluvium on upper slopes, but may run downslope for a mile or more from their source. The most frequent causes of debris flows are heavy rains 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, Appalachians debris flows are infrequent, with recurrence intervals at the most vulnerable sites estimated to be hundreds or thousands of years.

Less common landslides types in the Appalachian Ridges and Valleys include multiple failures (tight clusters of small landslides and debris flows that tend to occur during debris flow events) and lateral spreads (clusters of large rock blocks that appear to rarely move).

A randomly selected sample composed of 1799 of the 2066 Appalachian Ridges and Valleys landslides mapped in the project was analyzed to assess which contributing factors are best at predicting where landslides occur. The remaining 267 landslides were set aside as a data base to validate the predictive model results. The model analysis used a random forest model of 45 different attributes, as described at length in Maxwell and others (2020).

Slope: Analysis of the LiDAR-based landslide data from the 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 the locations of hillslope hollows (a predictor of where future landslides may develop) or may be an indicator of the scars of past slope failures. Almost 90 percent of mapped landslides occur on slopes greater than 20° (Figure 1). Excluding debris flows, median slope at landslide initiation sites is 30° and four out of five landslides initiated on 20° to 40° slopes.

Debris flows tend to initiate on even steeper slopes than other landslides, a trend that may reflect a tendency for landslides on steeper slopes to be more likely to have the momentum required to translate downslope into debris flows. The median slope at debris flow initiation sites is 35°, and four out of five debris flows initiated on 25° to 45° slopes (Figure 1).

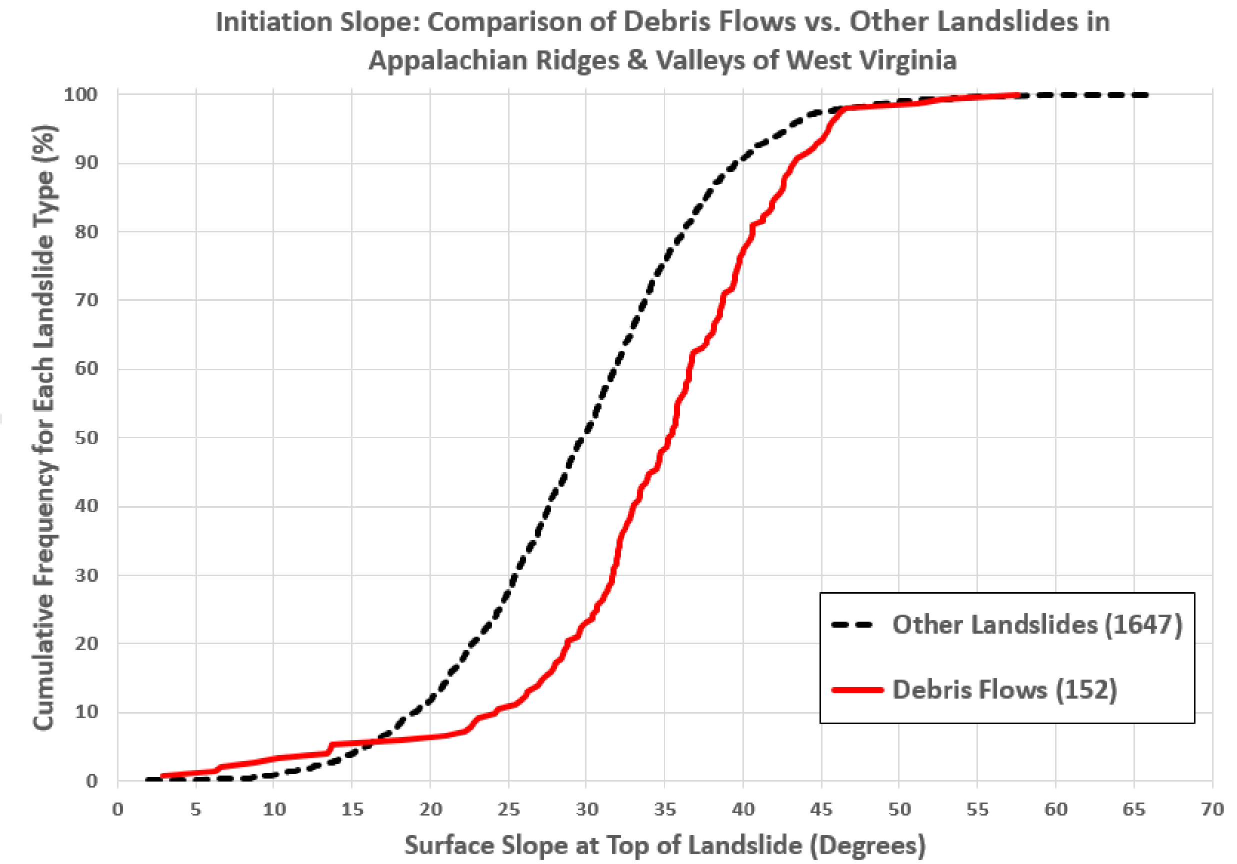

Figure 1. Comparison of initiation slope for debris flows with all other landslides in the Appalachian Ridges and Valleys MLRA of West Virginia.

Geology and Soils:

Primary Rock Type: Geology is a universally cited factor in landslide distribution, and this is the case in the Ridges and Valleys of eastern West Virginia. Much of role of geology on landslides is indirect. The distribution of resistant bedrock at the earth surface determines the location of ridge crests and steep adjacent side slopes. Weaker rock types on side slopes may be just as prone, or even more prone to failure as a resistant rock type responsible for the ridge.

Geologists make maps to decipher earth history. Varied events in earth history generally lead to a heterogeneous rock record. However, not all differences in rock type are reflected in the designation of map units. Geological maps are imperfect as proxies for the distribution of earth materials, but they are the only widely available resource to trace bedrock distribution for analyses of the role of geology on landslide susceptibility in the Ridges and Valleys area.

Table 1 shows how landslides are proportioned between primary "rock" types on the West Virginia Geological and Economic Survey (WVGES) state geological map (Cardwell and others, 1968). All four widespread rock types in MLRA 147 are significantly susceptible to landslides, with only a two-fold difference in landslide density. Two moderately common rock types appear less susceptible, but sample sizes may be too small to address susceptibility in the four least common rocks.

Dominant "Rock" Type	Landslide Count	% of All Landslides	Rock Type Area Mi^2	Est. Slides /100 Mi^2
shale	918	51.0	1890.3	56
siltstone	210	11.7	719.6	34
sandstone	423	23.5	717.4	68
limestone	231	12.8	630.5	42
alluvium	10	0.6	105.1	11
dolomite	3	0.2	62.6	6
phyllite	0	0.0	13.2	0
black shale	4	0.2	9.8	47
quartzite	0	0.0	6.8	0
greenstone	0	0.0	0.2	0
Ridges & Valleys Total	1,799	100.0	4155.5	50

Table 1. Primary "rock" types listed on the WVGES state geological map and associated landslide initiation point data. Estimated landslides/100 mi^2 are proportionally adjusted to compensate for 267 mapped points excluded from the 1799 landslides used for model input.

Table 1 shows shale is the primary rock type in geological units covering over 45 percent of the Ridges and Valleys MLRA, providing initiation sites for 51 percent of landslides. Siltstone, sandstone, and limestone are each the primary rock type in about 1/6th of the MLRA, but sandstone units are more strongly associated with landslides. Alluvium (unconsolidated floodplain and river terrace deposits) and dolomite cover smaller fractions of the MLRA, and are host to even smaller fractions of landslides. Black shale dominates a very limited extent where 4 landslides were mapped. Phyllite, quartzite, and greenstone occur only in narrow outcrop belts in Jefferson County, where no landslides were mapped from the best available LiDAR.

Sandstone-dominated units have landslides/square mile densities 36 percent higher than the whole MLRA. Shale unit landslide densities are 12 percent above the overall MLRA, whereas limestone (15 percent) and siltstone (33 percent) are underrepresented. Alluvium and dolomite have landslide densities below average by 78 and 89 percent, respectively, and their areal extents are adequate to indicate these under-representations are meaningful. Despite similarities in weathering and erosion resistance, limestone-dominated units have a landslide density nearly eight times that of dolomite-dominated units, suggesting other factors partly eclipse the complex role primary rock types play in slope stability.

The extents of four of the 10 primary rock types are too small to allow confident conclusions. The absence of mapped landslides in phyllite, quartzite, and greenstone may be spurious and appears to contradict field observations and local knowledge. Landslide modelling results displayed in the West Virginia Landslide Tool show significant landslide susceptibility in the Blue Ridge Mountains, suggesting landslides formed on these three metamorphic rock types may have gone unrecognized in LiDAR-based mapping because their morphology differs from landslides on sedimentary units that extend across more than 99.9 percent of West Virginia. More reliable analysis of the factors associated with Blue Ridge landslides would require collection of extensive data from adjacent states, an effort beyond the scope of this project.

Rock Resistance Groups: To better understand variations in landslide susceptibility not fully explained by a single primary "rock" type, WVGES geological units were categorized into eight groups based on how well their first three listed "rock" types collectively resist weathering and erosion in the Central Appalachians (Table 2). Resistance groups range from very resistant ridge-forming bedrock, primarily sandstone, to weakly resistant units common on valley bottoms: alluvium and carbonate or shale units lacking hard interbedded layers. Intermediate units include sedimentary units with sandstone or chert in secondary or tertiary abundance, and variable units that are ridge formers at some localities, but not others.

Resistance groups were selected so rock units with similar properties (such as sandstone and quartzite, or limestone and dolomite) are classified in the same group. Grouping allowed the areal disproportion between geological categories to decrease from a factor of 1,000 in Table 1 to a factor of 12 in Table 2. This closer proportionality reduces apparent differences between groups, but allows more confidence in the robustness of interpretations from the data.

Table 2 shows landslides are unequally distributed between different "rock" weathering and erosion resistance groups, but a mere six-fold variation in landslide density data suggest other factors, such as slope, attenuate the significance of resistance in slope stability. Resistance grouping approach is a novel approach to West Virginia landslide susceptibility research, and its potential power many not have been realized if one or more WVGES map units were assigned to inappropriate groups,

"Rock" Resistance Groups Based on WVGES Listed "Rock" Types	Landslide Count	% of All Landslides	Group Area Mi^2	Est. Slides /100 Mi^2
Moderately Resistant Clastic Sed. Rock	359	20.0	614	.67
Major Ridge Formers	163	9.1	313	.60
Shaley Units & Interbedded Sandstone	454	25.2	997	52
Variably Resistant Ridge Formers	470	26.1	1,144	47
Weakly Resistant Shaley Units	109	6.1	289	43
Variably Resistant Carbonates	221	12.3	593	43
Weakly Resistant Carbonates	13	0.7	100	15
Alluvium (Weakly Resistant)	10	0.6	105	11
Ridges & Valleys Area Total	1799	100.0	4,155	50

Table 2. Weathering and erosion resistance groups, inferred from 1st three "rock" types listed on the WVGES state geological map, and associated landslide mapping data. Estimated landslides/100 m^2 are proportionally adjusted to compensate for 267 mapped points excluded from 1799 landslides used for model input.

Just over half of sampled landslides tallied in Table 2 occur in variably resistant quartz-rich ridge formers or shaley units with interbedded sandstone, but this abundance can be explained by the fact that these two resistance groups cover just over half of the project area. The landslide densities on major ridge formers and moderately resistant clastic sedimentary rocks are over-represented compared to the whole project area by 20 percent and 35 percent, respectively. The higher landslide density in the latter group probably stems from the fact that moderately resistant clastic sedimentary rocks commonly occur on mountain sides adjacent to major ridge formers; the extremely resistant quartz-rich ridge-forming bedrock create a mountainous topography in which weaker neighboring rocks are inherently unstable. Weakly resistant shaley units and variably resistant carbonates are 13-14 percent under-represented, a number that qualitative map inspection suggests would be more pronounced if not for the influence of topography formed by more resistant neighboring rock types.

A conspicuous tendency revealed in Table 2 is the fact that alluvial deposits and weakly resistant carbonates are under-represented by 70 to 80 percent. Unfortunately from a risk perspective, these two relatively stable groups make up only 5 percent of the Appalachian Ridges and Valleys area. Weakly resistant limestone and dolomite bedrock units are prominent in the Shenandoah Valley of Jefferson and Berkeley counties, whereas alluvial deposits are concentrated in valley bottoms of Hardy, Grant, Hampshire, and Grant counties. The low relief in these settings reflects underlying geology, so the low landslide susceptibility may be more a consequence of role of bedrock resistance on topography than the strength inherent to earth materials in these two resistance groups.

Geological Map Units: The WVGES West Virginia geological map shows 44 different map units in the Ridges and Valleys, with extents ranging from 0.18 to 720 square miles. Lidar-based mapping revealed no landslides in 15 of these units, but 12 of these have extents of less than 20 square miles. As is the case for primary rock type, wide differences in unit extents and landslide counts create problems for meaningful statistical analysis, not to mention that a table of attributes from each of the 44 units would be a lot for any reader to absorb. However, significant trends do emerge from a simplified table where very similar geological units are combined and minor units are omitted. Table 3 provides a summary of landslide-related attributes for 15 geological units and unit combinations. Units listed in Table 3 cover 4063 square miles, almost 98 percent of the MLRA, but exclude 13 WVGES map units with individual extents of less than 15 square miles. The most notable omissions are four very old Precambrian metamorphic rock units in the Blue Ridge Mountains and six relatively young Mississippian units on the western side of the MLRA.

WVGES Geological Map Unit	Geologic Period	Landslide Count	Unit Area Mi^2	Debris Flow %	Est. Slides /100 Mi^2
Alluvium	Quaternary	10	105	0	11
Price = Pocono Group	Mississippian	67	219	4	35
Hampshire Fm.	Devonian	107	560	3	22
Chemung Group	Devonian	210	720	2	34
Brallier Fm. & Harrell Shale (3 units)	Devonian	228	470	0	56
Middle Devonian shale (4 units)	Devonian	140	480	1	34
Oriskany Sandstone & Huntersville Chert	Devonian	210	320	11	75
Oriskany & Helderberg, undivided	Devonian	23	39	4	68
Helderberg Group	Devonian	79	115	23	79
Tonoloway, Wills Crk. & Williamsport fm.	Silurian	130	205	11	73
McKenzie Fm. & Clinton Group	Silurian	301	181	5	191
Tuscarora Sandstone	Silurian	96	82	34	134
Juniata & Oswego Fm.	Ordovician	27	52	48	59
Martinsburg & Reedsville Fm.	Ordovician	139	156	14	102
Cambro-Ordovician carbonates (12 units)	Cambrian & Ordovician	20	359	0	6
Overall Ridges & Valleys (all 44 units)		1799	4155	8	50

Table 3. Simplified stratigraphic column of WVGES map units and associated overall landslide and debris flow data. Listed in stratigraphic order, landslide count and area data for individual units do not equal overall totals because minor units are not listed in the table. Estimated landslides/100 mi^2 are proportionally adjusted to compensate for 267 mapped points excluded from 1799 landslides used for model input.

Most WVGES geological units have significant landslide susceptibility, but landslide densities in three units stand out. The McKenzie Formation and Clinton Group map unit contains 16.7 percent (301 of the 1799) slope failures in the landslide model data base: more than any other unit; its landslide density is almost four times the 50 failures/100 square miles calculated for the whole MLRA. This shale-dominated map unit is inter-bedded with resistant sandstone, and occurs stratigraphically immediately above, and in very close proximity to, the Tuscarora Sandstone, the dominant ridge-forming unit in the MLRA. Best known from picturesque Seneca Rocks, the Tuscarora is typically only a few hundred feet thick, but hosts 5.3 percent of all landslides within only 2.3 percent of the MLRA: a landslide density 2.7 times that of the whole area. Martinsburg and Reedsville formations map polygons encompass areas with a landslide density twice the MLRA average, in spite of the fact that these formations are shale dominated.

Both the Oriskany Sandstone and Huntersville Chert unit and the Chemung Group unit contain nearly 1/8th of mapped landslides, but the Chemung covers a much larger area. The Chemung has a 33 percent lower landslide density than the whole MLRA, whereas the Oriskany has 52 percent more. The Tonoloway, Wills Creek, and Williamsport formations map unit and the Helderberg Group are primarily limestone, yet both have usually high landslide densities, possibly influenced by resistant sandstone and chert secondary constituents. In contrast, the 12 Cambrian and Ordovician limestone and dolomite units, which include little interbedded sandstone, have very few mapped landslides, although the landslide scarcity may be heavily influenced by the low relief of the Great Valley where these units are most common. Alluvium, the only map unit composed of unconsolidated sediments, shows low landslide susceptibility despite its low inherent strength. The apparent stability is a result of the low-relief bottomland topography where alluvium occurs.

Debris flows make up 1/12th of landslides in the inventory, but their potential far-reaching risks warrant a look at the geology in which they occur (Table 3). No landslide age assignments were made in mapping, but many of the debris flows appear related to two remarkable events on North Fork Mountain in 1949 (Stringfield and Smith, 1956) and 1985 (Jacobson and others, 1991). Debris flows were mapped in only 14 of the 44 geological units mapped in the region. Nearly half of 15 geologic map units and combined units listed in Table 3 show little or no evidence of debris flow.

The role of geological map units appears critical to debris-flow distribution, and the most prominent ridge-forming unit in the MLRA, the exceptionally resistant Tuscarora Sandstone, is central to this role. The Tuscarora has both the highest number and highest density of debris-flow initiation sites. All other units in Table 3 with a dozen or more debris flows are all in close proximity to the Tuscarora: Juniata and Oswego formations (where debris flows make up almost half of all landslides) and the Martinsburg and Reedsville formations lie immediately below the Tuscarora, whereas the Oriskany Sandstone and Huntersville Chert; Helderberg Group; Tonoloway, Wills Creek, and Williamsport formations; and McKenzie Formation and Clinton Group occur immediately above the Tuscarora.

A noteworthy facet of units containing numerous debris flows is their wide diversity of bedrock types: sandstone, siltstone, shale, limestone, chert, and dolomite. This host rock diversity supports a conclusion similar to that demonstrated by computer modelling of overall landslide susceptibility and noted previously for landslides in general; debris-flow distribution in the Ridges and Valleys MLRA is strongly correlated with slope characteristics, which are associated with underlying geology. The distribution of resistant bedrock, such as Tuscarora Sandstone, determines the location of ridges and adjacent steep sideslopes. Less resistant rock types on the sideslopes appear only slightly less prone to debris flow as the ridge forming cap rock.

Soils: USDA Natural Resource Conservation Service (NRCS) SSURGO data show that soil parent material and drainage class influence landslide susceptibility in the Ridges and Valleys area. However, the broad resolution of soils maps and limited number of parent material categories restrict interpretations to a few important general interpretations about relationships between soils and where slope failures initiate.

Over 3/4th of soils in the area are developed predominantly in residuum parent material and over 90 percent of landslides initiated in these residual soils (Table 4). The dominance of residual soils suggest trends in parent material and landslides shown in Table 4 should reinforce geological trends shown in Table 1, 2, and 3. This expected concordance is generally, but not universally, the case.

The NRCS recognizes four residuum categories in the study area, differentiated by the underlying bedrock from which the soil was derived. Acid clastic residuum forms on sedimentary bedrock (shale, siltstone, or sandstone) lacking significant amounts of carbonate minerals, whereas calcareous clastic residuum develops from sedimentary bedrock that is either admixed with calcareous layers, or bound together by calcium carbonate cement. Limestone residuum in the Ridges and Valleys forms from either limestone or dolomite. Metamorphic rock residuum in West Virginia is limited to phyllite, quartzite, and greenstone bedrock in the Blue Ridge Mountains of eastern Jefferson County. NRCS designations of non-residual parent material focus on sediment transport processes, rather than initial source rock type. Nonetheless, associations exist between transported soil parent material and underlying geology, such as the case of marl in West Virginia, which only occurs in association with limestone or other carbonate bedrock.

Soil Parent Material	Approx. % of Area	Landslide Count	Approx. % of All Landslides
Residuum, acid clastic	62.6	1,400	77.8
Colluvium	14.3	157	8.7
Residuum, limestone	8.9	154	8.6
Residuum, calcareous clastic	4.0	73	4.1
Recent alluvium	5.6	11	0.6
Disturbed areas	0.4	3	0.2
Old terrace alluvium	3.1	1	0.1
Water	0.6	0	0.0
Residuum, metamorphic rock	0.3	0	0.0
Mining regolith	0.1	0	0.0
Marl	0.1	0	0.0
Ridges & Valleys Area Total	100.0	1,799	100.0

Table 4. Dominant parent material for soils mapped by the USDA NRCS and relative landslide abundance in the Ridges and Valleys area.

Six of the 11 parent materials listed in Table 4 are extensive enough to conclude that landslide initiation is heavily influence by soil parent material. Acid clastic residuum, the most widespread category, has significantly more landslides than would be expected based on the extent of this parent material. The count of landslides initiating on limestone residuum or calcareous clastic residuum appears more or less proportional to the extent of these residual soils; however, these counts may be a deceptive composite of very few landslides on Cambro-Ordovician carbonate and shale bedrock in the Great Valley combined with very many landslides on Silurian and Devonian carbonate and shale bedrock elsewhere.

The association of colluvium with only 60 percent of landslide density its extent would predict presents a somewhat surprising observation. Colluvium includes landslide deposits, so a weak association seems counter-intuitive except for the fact that landslide mapping in this project focused on the points of landslide initiation, not the full extent of landslides polygons. Colluvium records the destination of landslides that typically initiate in residuum farther up slope.

Recent alluvium and old terrace alluvium are underrepresented in landslides by an order of magnitude or more; a slightly higher under-representation than indicated for the alluvium geologic map unit in tables 1, 2, and 3. It is revealing to note that the WVGES geological map shows alluvium covers only 2.5 percent of the area, whereas NRCS soil parent material data suggest the two alluvium categories, when combined, cover 8.7 percent of the project area. The state geological map is known to be very conservative in portrayal of non-bedrock units, so the larger percentage indicated by soil parent material is almost certainly more accurate.

None of the other five parent material categories cover more than 0.6 percent of the_Ridges and Valleys area. In light of their small sample size, the fact that only one of the five, disturbed areas, is associated with any mapped landslides may not be significant or valid.

The NRCS recognizes seven different 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.

Soil Drainage Class	Approx. % of Area	Landslide Count	Approx. % of All Landslides
Excessively drained	4.2	11	0.6
Somewhat excessively drained	84.9	1704	94.7
Well drained	1.2	0	0.0
Moderately well drained	5.8	19	1.1
Somewhat poorly drained	0.6	0	0.0
Poorly drained	1.8	62	3.4
Very poorly drained	1.5	3	0.2
Ridges & Valleys Area Total	100.0	1799	100.0

Table 5. Drainage classes for soils mapped by the USDA NRCS and relative landslide abundance in the Ridges and Valleys area.

Soil polygons assigned as somewhat excessively drained cover about 85 percent of the Ridges and Valleys landscape, and account for almost 95 percent of landslide initiation points; this over-representation reflects the importance of slope to both soil drainage class and landslide initiation. Near the opposite end of the drainage spectrum, poorly drained soils are also over-represented with landslides. Over 99 percent of poorly drained soils are developed from acid clastic residuum or colluvium, the two parent materials with the highest landslide counts.

Soils in the other five drainage classes appear underrepresented although interpretation of these data may not be robust because of small landslide counts and limited extents of some units. The reason landslides are proportionally uncommon in excessively drained soils may be related to parent material associations. Half of excessively drained soils are developed in colluvium, and over a quarter are formed in recent or old alluvium. All three of these parent materials have proportionally fewer landslides than would be expected from their extent.

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

Compared to geological maps, soil maps are more accurate proxies for the distribution of unconsolidated earthy materials. However, soil map polygons in mountain areas are commonly huge: orders of magnitude larger than the dimensions of landslide initiation scars. Many soil map units in mountain landscapes contain associations of two soil series, interposed with inclusions of other soil series. Soil series descriptions indicate the primary soil in a soil survey map unit (for which data used in this analysis are derived) commonly have different parent material or drainage class than its secondary associated soil or other soil inclusions. A globally accepted landslide initiation model developed by Hack and Goodlett (1960) from detailed study of 1949 debris flows on Shenandoah Mountain along the West Virginia-Virginia border suggests that a typical mountainside would be dominated by 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 colluvium. 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 Ridges and Valleys area differ from elsewhere in West Virginia. Anthropogenic disturbance is locally significant, but generally not as problematic as in more-densely populated areas or coalfields farther west. Limestone quarries present local rock-fall susceptibility, but elsewhere in the area falls are most commonly associated with over-steepened road cuts, particularly where dipping bedrock layers have been undercut. The scope of rock fall susceptibility in the Ridges and Valleys roads is not well illuminated by the 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.

Forest products are a major part of the economy of most West Virginia counties in the Ridges and Valleys area. Hillslopes underlain by weak bedrock or soil may get 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. Ill-designed or poorly constructed skidder trails and timber haul roads may lead to surface drainage disruptions that causes unprecedented soil saturation and abnormal slope destabilization.

Urban and suburban 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, occasionally including farm land. Outside of the Great Valley, the intensity of property development is limited in the Ridges and Valleys, but 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 the Ridges and Valleys. 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). Many scores of landslides developed in response to short-lived deluges centered along the boundary between the Ridges and

Valleys and Southern Allegheny Plateaus in August 1969 and June 2016. **Cataclysmic landslide swarms develop when six or more inches of rainfall occur in 24 hours or less**, as transpired in these four events and are always associated with severe floods.

Some landslide swarms have been associated with hurricane remnants, 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, and may be increase with proximity to the Atlantic Ocean. This pattern suggest a slightly higher probability of swarms of debris flows and other landslides occurring in mountains of the Ridges and Valleys than in other areas in 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 their frequency is likely to increase with ongoing climate change.

This assessment is targeted toward outlining the geographic distribution of landslide susceptibility and associated risk. 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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