West Virginia Landslide Risk Assessment

Eastern Allegheny Plateau and Mountains (South)

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Landslides in the Southern Alleghenies of West Virginia, the Southern Portion of the Eastern Allegheny Plateau and Mountains MLRA

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The “Southern Alleghenies” in this report is comprised of the southern portion of the Eastern Allegheny Plateau and Mountains Major Land Resource Area (MLRA) in West Virginia (Figure 1). This area is dominated by rugged topography, clastic sedimentary bedrock, and well-drained soils developed in residuum and colluvium. Unconsolidated material produced by mining is locally significant in coal-bearing settings, and mining related-landslides are abundant, but some non-coal bearing units have high landslide susceptibility. LiDAR-based mapping reveals landslide abundance in the Southern Alleghenies and the adjacent Cumberland Plateau and Mountains are similar, but over five times greater than the abundance in the Appalachian Ridges and Valleys (Figure 1).

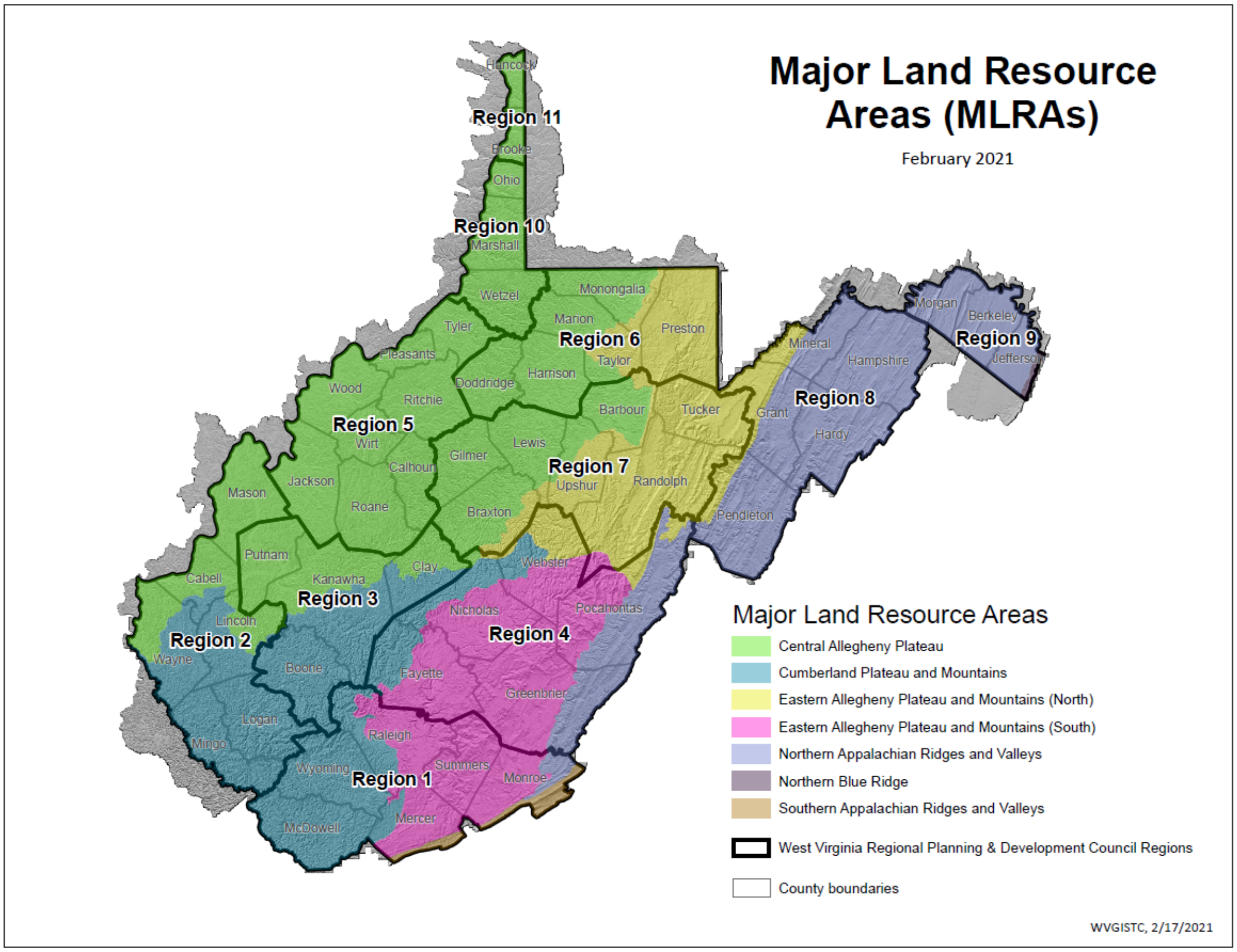

Figure 1: Map of Natural Resources Conservation Service Major Land Resource Areas (MLRAs), Planning and Development Regions, and county boundaries in West Virginia, shown on a shaded relief topographic base map.

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.

All of the area covered in this report lies within the U.S. Natural Resource Conservation Service (NRCS) MLRA 127: Eastern Allegheny Plateau and Mountains. The MLRA was divided into Southern and Northern portions for the West Virginia Landslide Risk Assessment (Figure 1). This division was necessitated by a much higher availability of high-resolution LiDAR-based DEMs in the southern portion at the time of analysis (Late 2020), but also reflects significant differences in topography and in the nature and thickness of bedrock geology map units from south to north across the whole MLRA. Landslides in the Northern Alleghenies portion of the MLRA are not included in this discussion, but will be addressed separately in another document. The Southern Alleghenies extent of MLRA 127 in West Virginia spans portions of 11 counties within Planning and Development Regions 1, 4, and 7 (Figure 1).

The "Southern Alleghenies" discussed in this report (the southern extent of the Eastern Allegheny Plateau and Mountains MLRA) do not align with traditionally assigned physiographic provinces in West Virginia. The Southern Alleghenies lie within eastern portions of the large Kanawha Section of the Appalachian Plateaus physiographic province shown in a U.S. Geological Survey map by Fenneman and Johnson (1946), and within the even-larger Appalachian Plateau province mapped by the West Virginia Geological and Economic Survey (2020b).

Despite the use of similar terms, the Southern Alleghenies in this report do not lie within the Allegheny Mountain Section of the Appalachian Plateaus shown by Fenneman and Johnson (1946) and the West Virginia Geological and Economic Survey (2020b). The southwestern borders of the Southern Alleghenies do approximately match with the western borders of the Allegheny Plateau province shown in a noteworthy U.S. Geological Survey map by Outerbridge (1987, Plate 1), but Outerbridge's perceptive map does not cover the full extent of the MLRA.

The NRCS description of MLRA 127 Eastern Allegheny Plateau and Mountains states the geology is characterized by mostly flat-lying sedimentary beds (U.S. Natural Resources Conservation Service, 2006). However, two small areas are underlain by steeply dipping beds and would be more inappropriately assigned to the Southern Appalachian Ridges and Valleys: a 1 mile wide, 20 mile long belt along Middle Mountain in Monroe County and a 1 mile wide, 12 mile long belt encompassing Stoney Ridge in Mercer County. Redrawing MLRA boundaries was beyond the scope of this project, so landslides in these locations near the Virginia border are included in the Southern Alleghenies landslide assessment.

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 Southern Alleghenies. 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 attempting 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 in this study should be considered conservative, especially with regards to small slope 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.

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; most rock types in the area produce thin residual soils, but limestone units throughout the area and sandstones on stable low-relief upland surfaces typically develop thick residual soils. Colluvium, which includes landslide deposits, is generally thin close to mountain tops and ridge lines, increasing in thickness farther downslope. Lenses of thick colluvium may accumulate in hillslope hollows, directly upslope from the beginnings of tiny ephemeral stream channels. Mining regolith, unconsolidated material produced as a result of mining, is locally extensive in areas of coal-bearing bedrock.

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. 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 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. 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, like those that occurred in Greenbrier County in 1969 (Schneider, 1973). Fortunately, Appalachian debris flows are infrequent, with recurrence intervals at the most vulnerable sites estimated to be hundreds or thousands of years.

Lateral spreads, including well-defined landforms called rock cities, are clusters of very large (~500 ft^3 or more) rock blocks that rarely move under modern conditions. Rock cities elsewhere in the Appalachians have been interpreted as relict Pleistocene Ice Age features or the product of ancient earthquakes, but enough individual sandstone blocks in lateral spreads have moved significantly in historic times to suggest lateral spreads may be on-going failures formed over thousands of years.

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 mapped using LiDAR-based imagery.

Less common landslides types include multiple failures: tight clusters of small landslides and debris flows that tend to occur during debris flow events. A few landslides could not be classified due to their unusual topographic features.

As of November 2020, 10,306 landslides have been identified through mapping on LiDAR-based DEMs constructed for the Southern Alleghenies; 10,220 of these were analyzed in September 2020 to assess which contributing factors best predict where landslides occur. The analysis of 43 different attributes used a random forest model similar to one used for modelling landslide susceptibility in the Appalachian Ridges and Valleys described in Maxwell and others (2020).

Slope

Analysis of the LiDAR-based landslide data from the Southern Alleghenies 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 on upland surfaces where slides (including slumps) and debris flows initiate are steeper than most of the nearby landscape, with 90 percent both types of failures occurring on slopes greater than 20° (Figure 2). Slides are by far the most common type of slope failure, and the median slope for 9691 slide initiation sites is 32° and four out of five slides initiated on 21° to 41° slopes. For comparison, a sample of 96,236 randomly selected non-landslide points throughout the Southern Alleghenies have a median slope of only 15°, with four out of five points having 3.5° to 30° slopes.

Debris flows tend to initiate on slightly 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 248 debris flow initiation sites is 34°, and four out of five debris flows initiated on 22° to 43° slopes (Figure 2).

Slopes at the uppermost points on 247 laterals spreads are typically gentler and much more varied than the uppermost points on slides or debris flows (Figure 2). The median slope of the uppermost points on lateral spreads is only 21°, while 45 percent are under 20°. Four out of five lateral slides head on 6° to 44° slopes. At the steep end of the lateral spread spectrum, 5 percent head on slopes over 50°, a higher proportion than mapped for other landslide types. The wide variability in slope of the uppermost points on lateral spreads may stem partly from the topography of the landforms, where a nearly flat surface adjacent to a rock city may lie right next to 30 foot high cliff within the feature. A 10 foot (3 m) difference in mapping the location of the uppermost point on a lateral spread may translate into a great difference in slope value. Mapping precision aside, the wide variation in slope observed on lateral spreads demonstrate these are very different types of landslides than common slope failures in West Virginia, and they need to be regraded accordingly.

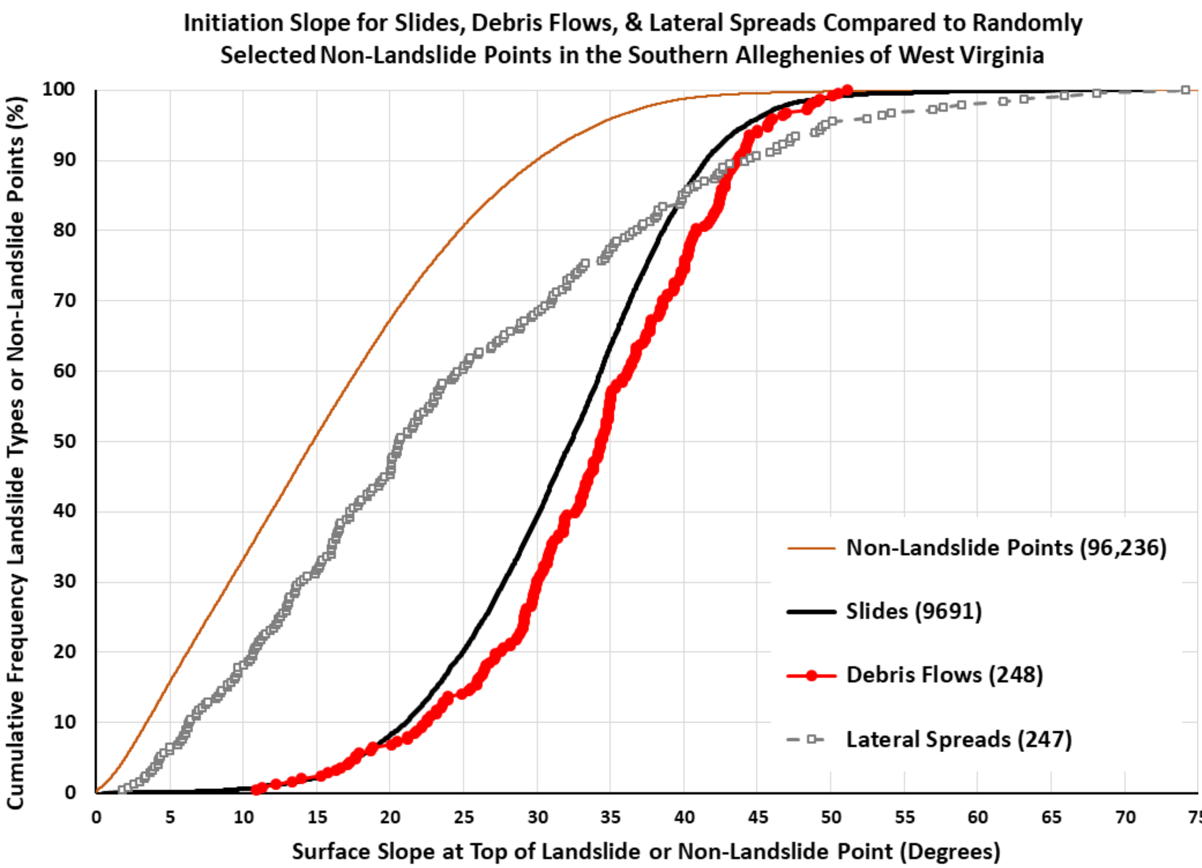

Figure 2. Comparison of initiation slopes for slides (including slumps), debris flows, and lateral spreads (rock cities) with randomly selected points in the Southern Alleghenies of West Virginia. Initiation slope was measured at the uppermost point on a landslide as mapped from the LiDAR-based DEMs.

Geology

Geology is a universally cited factor in landslide distribution, and this is the case in the Southern Alleghenies of West Virginia. 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 region, generally are responsible for the highest-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 canyon 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 tends to be less rugged than the landscapes dominated by weaker shale or siltstone. On the almost ubiquitous steep slopes that extend across most of the Southern Alleghenies, 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.

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. Geologic 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 area.

Geologic Map Units and Landslide Susceptibility: The West Virginia Geological and Economic Survey (WVGES) state geologic map (Cardwell and others, 1968) shows 20 different map units in the Southern Alleghenies, with individual extents ranging from 0.02 to 522 square miles. Eighteen units show bedrock geology; the other two denote alluvial deposits and water. Some overlapping and redundant WVGES bedrock map units were combined; for example, the “Maccrady Formation”, the “Pocono Group” and the “Maccrady Formation & Pocono Group, undivided” were analyzed as a single entity because the “undivided” map polygons could not be subdivided without revising the WVGES map. Five Devonian clastic bedrock units were combined because they cover very small areas that include only 0.2 % of all landslides. These combinations reduced the analysis to 14 separate geologic units (Table 1). Lidar-based mapping revealed no landslides in two of these units, each with an extent of 0.03 square miles or less. Moreover, no geologic unit was assigned for two landslides.

Wide differences in unit extents and landslide counts create problems for meaningful statistical analysis; however, significant trends do emerge from a summary of landslide-related attributes for 14 separate geologic units and unit combinations (Table 1).

WVGES Geologic Map Unit	Geologic Period	Mapped Landslide Count	% of All Failures	Unit Area Mi^2	Mapped Failures /100 Mi^2
Water (perennial or episodic)	Quaternary	33	0.32	15	213
Alluvium	Quaternary	2	0.02	22	9
Conemaugh Group	Pennsylvanian	0	0.00	0.03	0
Allegheny Formation	Pennsylvanian	92	0.90	15	631
Kanawha Formation	Pennsylvanian	1180	11.55	523	226
New River Formation	Pennsylvanian	1864	18.25	1121	166
Pocahontas Formation	Pennsylvanian	673	6.58	138	488
Bluestone & Princeton Formations	Mississippian	1641	16.05	382	430
Hinton Formation	Mississippian	3026	29.61	508	596
Bluefield Formation	Mississippian	1348	13.18	477	283
Greenbrier Group	Mississippian	245	2.40	308	80
Maccrady Fm. & Pocono Group (3 units)	Mississippian	95	0.93	98	97
Devonian Clastic Bedrock (5 units)	Devonian	19	0.19	9	222
Ordovician Carbonates	Ordovician	0	0.00	0.02	0
Geology unassigned	?	2	0.02	---	---
Overall Southern Alleghenies		10220	100.00	3616	283

Table 1. Simplified list of Southern Alleghenies geologic map units, show in stratigraphic order, and associated data for all landslides. Slope failures counted in the "water" unit would be more accurately assigned to other geologic units.

Most Southern Alleghenies bedrock is highly susceptible to failure, but Table 1 shows landslide densities in several units are more 50 percent higher than the area's overall average. The Hinton Formation is predominantly shale alternating with sandstone and contains almost 30 percent of mapped landslides in the entire area. Deeply dissected topography is associated with much of the Hinton outcrop belt, which is most extensive in the southeastern portion of the Southern Alleghenies. This steep topography and the Hinton's relatively unstable bedrock material are responsible for a landslide density (number of landslide per 100 mi^2) that is 2.1 times the overall area average. Above the Hinton, the combined Bluestone and Princeton formations map unit has a landslide density 1.5 times the overall Southern Alleghenies. Its geology includes locally thick sandstone beds and significant interlayers of shale, and it is deeply dissected throughout most of its extent. Below the Hinton, the Bluefield Formation has the same landslide density as the area as a whole. Shale and sandstone dominated, the Bluefield includes the Droop Sandstone, a conspicuous thick-bedded caprock in Greenbrier and southern Pocahontas counties.

Collectively the Bluestone, Princeton, Hinton, and Bluefield formations make up the Mauch Chunk Group, a geologic map unit widely used in northern West Virginia. Almost 59 percent of all Southern Alleghenies landslides occur in the formations within the Mauch Chunk, even though the group covers only 38 percent of the area. Considered as a whole, the deeply incised Mauch Chunk Group provides a good example of failure-prone, shale-dominated bedrock lacking the inherent stability of heavily sandstone-dominated units. A widely used U.S. Geological Survey landslide overview map of the conterminous United States (Radbruch-Hall and others, 1978) shows low landslide incidence throughout much of the Mauch Chunk outcrop belt, but this interpretation is inaccurate.

The Pocahontas Formation, the lowest coal-bearing unit in the Southern Alleghenies sequence, has a landslide density 1.7 times the overall area. The unit includes thick sandstone beds and significant interlayers of shale, and is deeply dissected throughout much of its extent.

The two most extensive bedrock units cover 45 percent of the area, but contain only 30 percent of the landslides. The New River Formation has the second highest number of slides, but a landslide density less than 60 percent of the whole area. The Kanawha Formation has a landslide density less than 80 percent of average. Rock type abundance lists for the New River and Kanawha are similar: sandstone, shale, siltstone, and coal. The New River is mostly sandstone, while the Kanawha is approximately 50 percent sandstone. Some of the most rugged topography in West Virginia is formed on these two heavily sandstone-dominated units, such as the steep valley walls of the New and Gauley river gorges. Elsewhere, these same rocks are the caprock forming broad realtively undissected areas that are “flat” by Mountain State standards. The overall low landslide density for the two units reflects the fact that broad sandstone uplands in Raleigh, Fayette, Nicholas, and Webster counties cover a much larger total area than the steep landslide-prone canyons rivers have carved into the highly resistant formations.

The Allegheny Formation has the highest landslide density of any unit, 2.2 times the area as a whole. The formation chiefly consists of interlayered sandstone, siltstone, and shale, but is limited to small mountain-top areas in the westernmost portions of the

Southern Alleghenies.

Coal beds are not shown on the Cardwell and others (1968) map used to assess landslide susceptibility in geologic units. Only three Pennsylvanian-aged bedrock units, the Pocahontas, New River and Kanawha formations, contain significant mined coal beds in the Southern Alleghenies (West Virginia Geological and Economic Survey, 2020a). The Allegheny Formation is heavily mined elsewhere in West Virginia, but its mined coals do not extend into this area.

Mining and related activities, such as overburden disposal and haul road construction, can considerably increase landslide susceptibility, although reclamation may reduce susceptibility or obscure landslide evidence on LiDAR-based DEMs. It is noteworthy that the combined landslide density in the three formations with significant coal mining is only 209 slides per 100 square miles, about 3/4ths of the Southern Alleghenies average. However, this realtively low landslide density most likely reflects the inherent strength of heavily sandstone-dominated bedrock, rather than impacts on slope stability from mining or reclamation. The relationships between mined lands and landslide susceptibility is more precisely addressed in subsequent discussion of soil parent materials.

The limestone-dominated Greenbrier Group, shale-dominated Maccrady Formation, and sandstone-and-shale-dominated Pocono (a.k.a. Price) Group have landslide densities only 28 to 34 percent of the area average. These units occur in realtively low relief topography in Greenbrier, Monroe, and Pocahontas counties, a landscape differing from the almost ubiquitous steep slopes typical of the Southern Alleghenies. Numerous landslides formed on these geologic units as a result of a torrential June 2006 storm, a reminder that substantial landslide risks exist even in less susceptible portions of the Southern Alleghenies.

The five combined Devonian clastic bedrock units are made up of interbedded sandstone, siltstone, and shale in varying proportions. The overall landslide density of the combined units is about 80 percent of the whole area, although the small total extent of these units and their small number of landslides raise questions about the accuracy and precision of this density estimate.

Neither the lowermost nor uppermost bedrock units include mapped landslides, but the extent of these units is so small that this absence may not be significant. The Pennsylvanian Conemaugh Group is restricted to two mountain tops lacking landslides in Nicholas County, but the unit is a notorious landslide source elsewhere in West

Virginia. The limestone-dominated Ordovician carbonates crop out in a narrow heavily faulted belt in Monroe County underlain by steeply dipping beds that should be assigned to the Southern Appalachian Ridges and Valleys. Few landslides have been mapped in Ordovician carbonates in eastern West Virginia, where similar limestones are extensive, but the topographic settings are not identical.

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.

The geologic map unit "water" warrants detailed discussion. The "water" unit polygons encompassed 33 landslides within 15.5 square miles, including one debris flow and one lateral spread. These values suggest a landslide density about 3/4ths of the area average. However, the red laser light used to generate LiDAR data is reflected by water, making water surfaces appear flat on LiDAR-based DEMs. Worded in human terms, the type of LiDAR used in this project can't "see" landslides features submerged under water. The expected landslides density in "water" polygons should be essentially zero, an expectation consistent with the fact that none of these landslides are mapped within NRCS digital soil survey "water" polygons.

Examination of best available LiDAR-based DEMs shows the landslides that plot within geologic map "water" polygons actually occur on ground above normal water levels on nearby lakes. Thirty of these are near Bluestone Lake in Summers County; three are near Summersville Lake in Nicholas County. The portrayal of these two flood-control reservoirs on the geologic map (Cardwell and others, 1968) shows the extent of the water bodies at exceptionally high water levels, tens of feet higher than normal water levels that existed when LiDAR data were collected. The lake polygons were inherited from 1:250,000 scale topographic maps used as the base for the original 1968 geologic map.

These "water" landslides would be more accurately assigned to the geologic units that actually crop out within the water body polygons, but map revisions are beyond the scope of this project. It is possible that episodic inundation of these surfaces after creation of these man-made lakes has contributed to slope failures, but it is also possible that the mapped landslides developed before, or independent of, lake impoundment.

The "water" boundary issues may not be the only significant uncertainty in geologic map polygons. Problems of scale-related resolution or error in map compilation and reproduction cannot be discounted. 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. These issues emphatically reiterate the warning this report and the West Virginia Landslide Tool should not be used to substitute for site-specific analysis by landslide experts and geotechnical engineers.

Debris Flows and Lateral Spreads: Although each makes up only 2.4 percent of landslides in the Southern Alleghenies inventory, the distinctive characteristics of debris flows and lateral spreads, as well as their exceptional potential risks to safety and civil infrastructure warrant examination how they relate to geology (Table 2). Susceptibility to the two types of slope failures varies greatly between different geologic map units, and both have geologic distributions dissimilar from overall landslides in the area.

WVGES Geologic Map Unit	Debris Flow Count	% of Debris Flows	Debris Flows /100 Mi^2	Lateral Spread Count	% of Lateral Spreads	Lateral Spreads /100 Mi^2
Water (perennial or episodic)	1	0.4	6.5	1	0.4	6.5
Alluvium	0	0.0	0.0	0	0.0	0.0
Conemaugh Group	0	0.0	0.0	0	0.0	0.0
Allegheny Formation	0	0.0	0.0	0	0.0	0.0
Kanawha Formation	8	3.2	1.5	27	10.9	5.2
New River Formation	26	10.5	2.3	129	52.2	11.5
Pocahontas Formation	20	8.1	14.5	12	4.9	8.7
Bluestone & Princeton Formations	48	19.4	12.6	7	2.8	1.8
Hinton Formation	118	47.6	23.2	3	1.2	0.6
Bluefield Formation	24	9.7	5.0	68	27.5	14.3
Greenbrier Group	0	0.0	0.0	0	0.0	0.0
Maccrady Fm. & Pocono Group (3 units)	3	1.2	3.0	0	0.0	0.0
Devonian Clastic Bedrock (5 units)	0	0.0	0.0	0	0.0	0.0
Ordovician Carbonates	0	0.0	0.0	0	0.0	0.0
Overall Southern Alleghenies	248	100.0	6.9	247	100.0	6.8

Table 2. Frequency of debris flows and lateral spreads in Southern Alleghenies geologic map units, show in stratigraphic order. Slope failures counted in the "water" unit would be more accurately assigned to other geologic units. Sum of percentages do not add up to 100.0 percent because of rounding.

Debris flows were mapped in only eight the 14 geologic units. Nearly half were mapped in the Hinton Formation, the unit with the highest density of debris flows. Over 3/4ths of all debris flows occur in the bedrock units that comprise the Mauch Chunk Group: the Bluestone, Princeton, Hinton, and Bluefield formations. Landslide age assignment was not attempted during mapping, but some of the Mauch Chunk debris flows were recognized in Schneider's 1973 study of slope failures in Greenbrier County in the aftermath of Hurricane Camille during 1969.

The second highest debris flow density was recorded in the Pocahontas Formation. Almost 22 percent of debris flows were mapped in the three sandstone-dominated coal-bearing units, the Pocahontas, New River, and Kanawha formations.

A lack debris-flow initiation points in the Greenbrier Formation is telling, since that limestone-dominated unit covers 8.5 percent of the study area. On the other hand, the absence of evidence is not the same as the evidence of absence, so the lack of mapped debris flows in other units that cover tiny areas may or may not be significant. 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 distribution of mapped lateral spreads is strongly associated with geology. Over half of all lateral spreads are associated with the New River Formation, which has more massive sandstone layers than any other unit. This formation has the second highest number of lateral spreads per 100 mi^2 and the Pocahontas Formation and Kanawha Formation rank third and fourth respectively. These three coal-bearing units have over 2/3rds of the lateral spreads mapped in the Southern Alleghenies.

The Bluefield Formation has the highest concentration of lateral spreads, many formed of large Droop Sandstone blocks on Droop Mountain, including a very popular rock city in Beartown State Park. Lateral spreads also occur in the other formations of the Mauch Chunk Group, and collectively the group contains nearly 1/3rd of mapped Southern Alleghenies lateral spreads.

Lateral spreads are mapped in all of the geologic map units that contain significant thick massive sandstone layers, except for one: the Allegheny Formation. Allegheny Formation lateral spreads are mapped elsewhere in West Virginia, so their absence in the area may reflect the formation's position at the top of highly weathered mountain tops or its limited extent of less than 15 mi^2. With the exception of one site assigned within a "water" polygon, no other geologic map units contain mapped lateral spreads, an absence that is consistent with their lack of resistant massive sandstone layers that break down into the large blocks required to create this type of slope failure.

The potential risks presented by lateral spreads is unclear because the processes and circumstances in which they form is uncertain. A few instances of individual blocks moving significant distances have been documented in West Virginia, and such movement can lead to substantial rockfall hazard down slope from lateral spreads. If, as some geologists have suggested, these features are relic from intense ground-ice dynamics under exceptionally cold Ice Age climates, most lateral spreads may have experienced little movement since the end of the Pleistocene Epoch, 11,700 years ago. No matter what natural processes have led to their development, human disturbance of nearby slopes and drainage may increase the risk presented by the huge blocks in these curious landforms.

Soils

Analysis of mapped landslides and the NRCS Soil Survey Geographic database (SSURGO) indicate soil parent material and drainage class influence landslide susceptibility in the Southern Alleghenies. The SSURGO digital database 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. Soil series provide the basic units of soils 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 soils map polygons used for 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 typical situations where multiple soil series exist within a soil survey map unit. The inexactness of soils maps and the dominance of only five parent materials and five drainage classes limit this analyses to general interpretations about soils and where landslides initiate in the Southern Alleghenies.

Soil Parent Material: SSURGO data provide the basis for 10 different soil parent materials in the Southern Alleghenies area, and an eleventh category addresses soils covering small areas where no parent material has been assigned (Table 3). Water is not true soil parent material, but is included in SSURGO data and Table 3. The category “old terrace alluvium” is a combination of “old alluvium” and “lacustrine deposits” into a single category because significant lacustrine deposits are not known in the Southern

Alleghenies, and some soil series that form elsewhere on old fine-textured lake deposits also form on old fine-textured alluvium. Across the area, three widespread parent materials have high susceptibility to landslides, one has exceptionally high susceptibility, two have moderate susceptibility, and the other five categories appear to have low susceptibility (Table 3).

NRCS Soil Parent Material	Mapped Landslide Count	% of All Failures	Unit Area Mi^2 (Approx.)	Mapped Failures /100 Mi^2
Residuum, Acid Clastic	5240	51.27	1740.9	301
Colluvium	3508	34.32	1160.9	302
Mining Regolith	801	7.84	93.3	858
Residuum, Calcareous Clastic	428	4.19	146.1	293
Residuum, Limestone	210	2.05	244.9	86
Disturbed Areas	19	0.19	24.7	77
Recent Alluvium	9	0.09	116.0	8
Old Terrace Alluvium	3	0.03	46.6	6
Parent Material Not Assigned	2	0.02	14.8	14
Water	0	0.00	27.6	0
Organic Material	0	0.00	0.3	0
Southern Alleghenies Total	10220	100.00	3616.0	283

Table 3. Dominant soil parent materials for landslides of all types in the Southern Alleghenies area. Materials are listed in decreasing order for percentage of all landslides. Sum of unit areas does not equal overall MLRA totals because of rounding.

Acid clastic residuum, colluvium, and calcareous clastic residuum parent material are highly prone to landslides, with 293 to 302 landslides per 100 mi^2, slightly higher than the Southern Alleghenies average of 283. Collectively, these three parent materials cover almost 90 percent of the area, so they contribute significantly to the high regional landslide density. Over 55 percent of soils in the area are developed in residuum derived from clastic sedimentary rocks, such as sandstone, siltstone, and shale: parent materials that cover about 52 percent of the area. Most of the clastic parent material is “acid”, lacking limestone beds or calcite cement to buffer soil pH. Clastic sedimentary rocks in the Pennsylvanian-aged coal-bearing units are likely sources of acid residuum, but so are portions of other sandstone- or shale-dominated units. Clastic bedrock with interbedded limestone or calcite cement is "calcareous" and generally more fertile for plant growth. Formations in the Mauch Chunk formation are the most likely sources of calcareous clastic residuum. Approximately 34 percent of landslides developed from colluvium, which covers about 32 percent of the area and derived from any bedrock unit.

The 858 landslides per 100 mi^2 in mining regolith parent material is nearly three times higher than the Southern Alleghenies average. Mapping projects in the New River Gorge have identified many landslides associated with old unreclaimed coal strip mine benches and haul roads (Remo, 1999; Yates and others, 2016), but landslides also have occurred on reclaimed mines that postdate the 1977 Surface Mining Control and Reclamation Act (SMCRA). 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 is relic from old mining practices or an issue common to mined lands of all generation.

Limestone residuum parent material is associated with only 86 landslides per 100 mi^2, a value very similar to the susceptibility in the Greenbrier Group geologic unit. Greenbrier bedrock in realtively low-relief topography is the source for most limestone residuum in the Southern Alleghenies.

The SSURGO data suggest disturbed land has moderate landslide susceptibility, a surprising relationship in light of the more than ten-fold higher vulnerability calculated in mining regolith. Disturbed parent material is unlikely to have high inherent strength, suggesting the moderate susceptibility may stem more from the morphology of slopes on which the material occurs rather than from material properties. Cursory examination of soils maps covering disturbed land near Summersville Lake suggests much of the material has been graded into relatively flat man-made landforms.

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 22 mi^2 in the Southern Alleghenies, whereas NRCS soil parent material data suggest the two alluvium categories, when combined, cover over 162 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.

As noted in the geology section, no landslides are mapped within water soil parent material polygons. None were mapped on organic material, a finding that lacks statistical significance because of the tiny area in covered by the parent material, but is to be expected because of the low relief in which organic soils accumulate.

Tabulation of debris flows within the Southern Alleghenies shows that these long-runout failures initiate in only five parent materials (Table 4). Most debris flows were mapped in acid clastic residuum, which has more debris flows per 100 mi^2 than the regional average colluvium. However, the concentration of debris flows in mining regolith is 85 percent higher than any other parent material, consistent with overall landslide data that indicate this parent material is more problematic than others. Colluvium and calcareous clastic residuum are slightly less prone to debris flows than the area as a whole. Debris flow susceptibility appears low to exceptionally low in other parent materials, but the small extent and sample size for four or five of these materials raise concerns that numbers may be misleading, particularly for disturbed areas.

NRCS Soil Parent Material	Mapped Debris Flow Count	% of All Debris Flows	Unit Area Mi^2 (Approx.)	Mapped Debris Flows /100 Mi^2
Residuum, Acid Clastic	160	64.5	1740.9	9.2
Colluvium	64	25.8	1160.9	5.5
Mining Regolith	16	6.5	93.3	17.1
Residuum, Calcareous Clastic	7	2.8	146.1	4.9
Residuum, Limestone	1	0.4	244.9	0.4
Disturbed Areas	0	0.0	24.7	0
Recent Alluvium	0	0.0	116.0	0
Old Terrace Alluvium	0	0.0	46.6	0
Parent Material Not Assigned	0	0.0	14.8	0
Water	0	0.0	27.6	0
Organic Material	0	0.0	0.3	*
Southern Alleghenies Total	248	100.00	3616.0	6.9

*Table 4. Dominant soil parent materials for debris flows mapped in the Southern Alleghenies. Materials are listed in decreasing order for percentage of all landslides shown in Table 3. Note * extent of organic material is too small for meaningful calculation of debris flows/100 mi^2. Sum of unit areas does not equal overall MLRA totals because of rounding.*

Lateral spreads have been mapped in only four parent materials within the Southern Alleghenies (Table 5). Most lateral spreads lie within acid clastic residuum, which has more than twice the number of spreads per 100 mi^2 than any other parent material. Colluvium and calcareous clastic residuum are slightly less likely to have spreads than the whole the Southern Alleghenies. Except for one spread in mining regolith, no other parent material encompasses any lateral spreads.

NRCS Soil Parent Material	Lateral Spread Count	% of All Lateral Spreads	Unit Area Mi^2 (Approx.)	Lateral Spreads /100 Mi^2
Residuum, Acid Clastic	160	64.5	1740.9	9.2
Colluvium	64	25.8	1160.9	5.5
Mining Regolith	16	6.5	93.3	17.1
Residuum, Calcareous Clastic	7	2.8	146.1	4.9
Residuum, Limestone	1	0.4	244.9	0.4
Disturbed Areas	0	0.0	24.7	0
Recent Alluvium	0	0.0	116.0	0
Old Terrace Alluvium	0	0.0	46.6	0
Parent Material Not Assigned	0	0.0	14.8	0
Water	0	0.0	27.6	0
Organic Material	0	0.0	0.3	*
Southern Alleghenies Total	247	100.00	3616.0	6.9

*Table 5. Dominant soil parent materials for lateral spreads mapped in the Southern Alleghenies. Materials are listed in decreasing order for percentage of all landslides shown in Table 3. Note * extent of organic material is too small for meaningful calculation of lateral spreads/100 mi^2. Sum of unit areas does not equal overall MLRA totals because of rounding.*

<u>Soil Drainage Classification</u>: The NRCS recognizes seven different drainage classes for soil series (Table 6). Drainage classes are assigned under normal moisture conditions, and vary depending on soil material infiltration capacity, water table depth, and surface topography. Two additional rows are shown in Table 6: “water” and “drainage class not assigned”.

NRCS Soil Drainage Classification	Mapped Landslide Count	% of All Failures	Unit Area Mi^2 (Approx.)	Mapped Failures /100 Mi^2
Excessively Drained	175	1.71	103.0	170
Somewhat Excessively Drained	61	0.60	14.5	421
Well Drained	9577	93.71	3018.7	317
Moderately Well Drained	161	1.58	203.8	79
Somewhat Poorly Drained	241	2.36	175.8	137
Poorly Drained	3	0.03	57.6	5
Very Poorly Drained	0	0.00	0.3	0
Water	0	0.00	27.6	0
Drainage Class Not Assigned	2	0.02	14.8	14
Southern Alleghenies Total	10220	100.00	3616.0	283

Table 6. Drainage classes for soils and relative landslide abundance in Southern Alleghenies area. Classes are listed in order from most drained to least drained. Sum of percentages do not add up to totals because of rounding.

Soil polygons assigned as "well drained" cover about 83 percent of the Southern Alleghenies landscape and account for almost 94 percent of landslide initiation points, which occur in all five common parent materials. The small sample of somewhat excessively drained soils shows this drainage class has the highest landslide susceptibility, a trend consistent with the fact that somewhat excessively drained soils are common in mining regolith but uncommon in other soil parent material. Both of these drainage classes commonly occur on steep slopes, so the over-representation of landslides in these two classes may reflect the important role of slope as a control of both soil drainage and landslide initiation.

Soils in the other seven drainage classes have fewer landslides per 100 mi^2 than the regional average. Landslide susceptibility is moderate to moderately high on excessively drained, moderately well drained, and somewhat poorly drained soils. Almost all of the failures on somewhat poorly drained slopes are developed on colluvium, suggesting these slides may be reactivations of older landslides. Poorly drained and very poorly drained may have few landslides because these soils occur on very low slopes, The absence of landslides of in water polygons is an intrinsic artifact of the LiDAR-based mapping used to identify and map the surface expression of slope failures.

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 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 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 relies 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 somewhat-excessively or well-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. According to this model landslides would 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 Southern Alleghenies differ from other areas in West Virginia. Anthropogenic disturbance is significant, especially 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 Southern Alleghenies. 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. Ill-designed 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 Southern Alleghenies 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 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 Southern Alleghenies 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 Southern Alleghenies and elsewhere in the state may become more frequent with ongoing changes in climate.

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

References Cited

Cardwell, Dudley H., Erwin, Robert B., and Woodward, Herbert P., 1968, Geologic map of West Virginia: West Virginia Geological and Economic Survey, Map-1, 1;250,000 scale, 2 sheets.

Fenneman, N.M., and Johnson, D.W., 1946, Physiographic divisions of the conterminous U. S., U.S. Geological Survey, 1:7,000,000 scale map, https://store.usgs.gov/assets/MOD/StoreFiles/PDFs_2013/101215_US_Physical_Divisions_7MM_1946.pdf.

Hack, J. T., and Goodlett, J. C., 1960, Geomorphology and forest ecology of a mountain region in the central Appalachians: U.S. Geological Survey Professional Paper 347, 66 p., 1 plate. https://pubs.usgs.gov/pp/0347/report.pdf

Jacobson, Robert B., Cron, Elizabeth D., McGeehin, John P., Carr, Carolyn E., Harper, John M., and Howard, Alan D., 1993, Landslides triggered by the storm of November 3-5, 1985, Wills Mountain anticline, West Virginia and Virginia, in Jacobson, Robert B., editor, Geomorphic studies of the storm and flood of November 3-5, 1985, in the upper Potomac River basin: U.S. Geological Survey Bulletin 1981, p. C1-C33.

Maxwell, Aaron E., Sharma, Maneesh, Kite, James S., Donaldson, Kurt A., Thompson, James A., Bell, Matthew L., and Maynard, Shannon M., 2020, Large-Area Slope Failure Prediction Using Random Forest Machine Learning and LiDAR: Findings and Recommendations: Remote Sensing, v. 12, no. 486; doi:10.3390/rs12030486 https://www.mdpi.com/2072-4292/12/3/486/pdf

Outerbridge, William F., 1987, The Logan Plateau, a young physiographic region in West Virginia, Kentucky, Virginia, and Tennessee; U.S. Geological Survey Bulletin 1620, 19 p., 6 plates, https://pubs.usgs.gov/bul/1620/report.pdf

Radbruch-Hall, D.H., Colton, R.B., Davies, W.E., Lucchitta, I., Skipp, B.A., and Varnes, D.J., 1978, Landslide overview map of the Conterminous United States: U.S. Geological Survey Professional Paper 1183, 25 p. and 1 plate. https://pubs.usgs.gov/pp/p1183/

Remo, Jonathan W.F., 1999, Geologic controls on mass-movements in the New River Gorge, West Virginia (M.S. thesis): Morgantown, West Virginia University, 107 p. URL: http://157.182.199.25/etd/templates/showETD.cfm?recnum=789

Schneider, R. H., 1973, Debris slides and related flood damage resulting from Hurricane Camille 19–20 August, and subsequent storm, 5–6 September, 1969 in the Spring Creek drainage basin, Greenbrier County, West Virginia (Ph.D. dissertation), University of Tennessee, Knoxville, Tennessee, 131 p.

Stringfield, V. T., and Smith, R. C., 1956, Relation of geology to drainage, floods, and landslides in the Petersburg area, West Virginia: West Virginia Geological Survey Report of Investigations 13, 19 p.

U.S. Natural Resources Conservation Service, 2006, Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. U.S. Department of Agriculture Handbook 2, 672 p. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050898.pdf

West Virginia Geological and Economic Survey, 2020a, Interactive Coal Maps, http://www.wvgs.wvnet.edu/www/coal/cbmp/coalimsframe.html, revised 10 February 2020.

West Virginia Geological and Economic Survey, 2020b, Physiographic Provinces of West Virginia, https://www.wvgs.wvnet.edu/www/maps/pprovinces.htm, revised January 6, 2020.

Yates. M.K., Kite, J.S., and Gooding, S., 2016, Digital Surficial Geologic Map of New River Gorge National River, West Virginia (NPS, GRD, GRI, NERI, NERS digital map) adapted from a West Virginia University and West Virginia Geological and Economic Survey Open File Report map by Yates and Kite (and Gooding) (2015). National Park Service (NPS) Geologic Resources Inventory (GRI) program. https://irma.nps.gov/DataStore/Reference/profile/2229551