West Virginia Landslide Risk Assessment

Eastern Allegheny Plateau and Mountains (North)

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

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The "Northern Allegheny Mountains" denote the northern part of the Eastern Allegheny Plateau and Mountains Major Land Resource Area (MLRA) (Figure 1), an area dominated by rugged topography, clastic sedimentary bedrock, and well-drained soils developed in residuum and colluvium. Two non-coal bearing bedrock units have the highest landslide susceptibility, but unconsolidated material produced by mining is locally significant and associated with landslides. Results of ongoing LiDAR-based mapping suggest landslide abundance is less in the Northern Allegheny Mountains than in the Southern Alleghenies and Cumberland Plateau and Mountains, but significantly greater than the abundance in the Appalachian Ridges and Valleys (Figure 1).

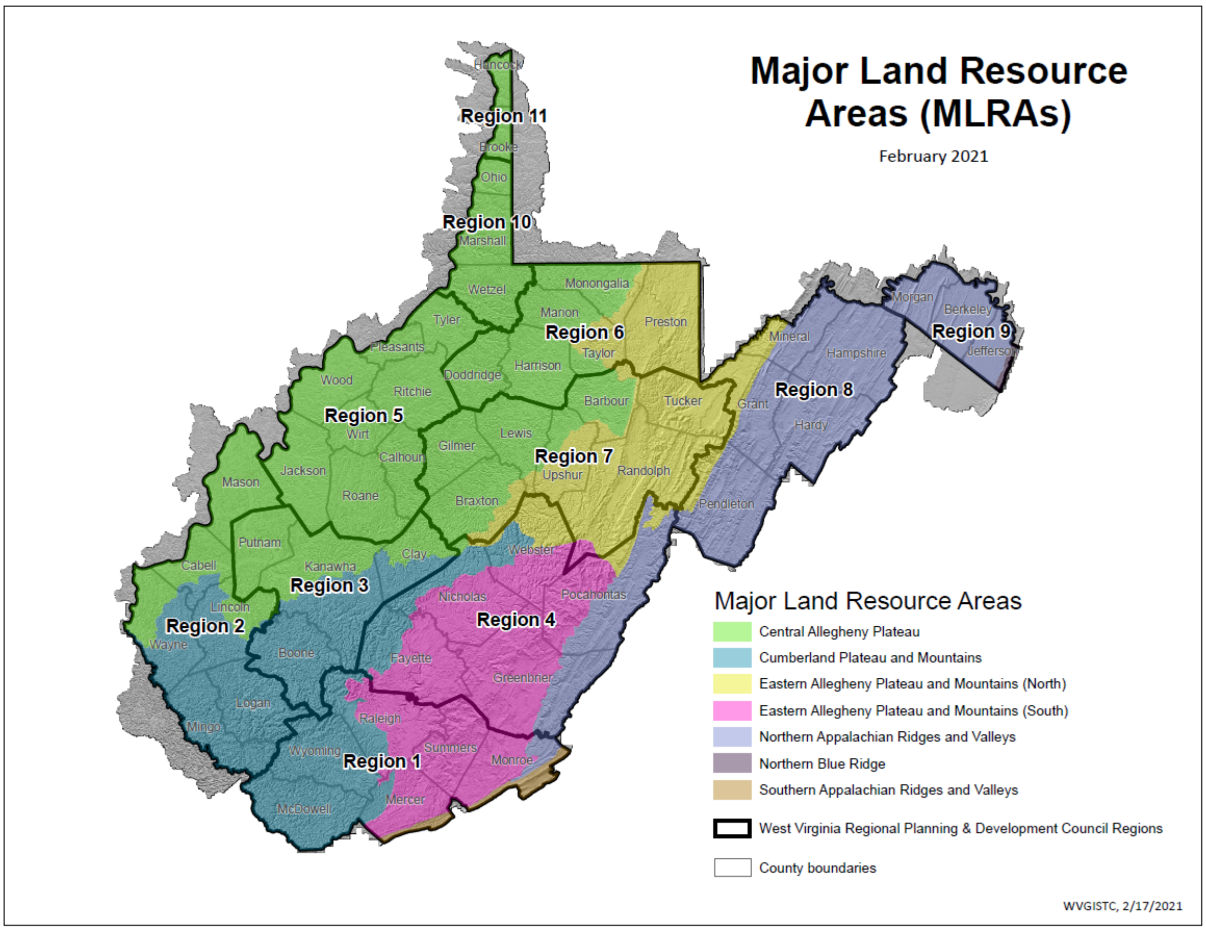

Figure 1: Map of Natural Resources Conservation Service Major Land Resource Areas (MLRAs), Planning and Development Regions, and county boundaries in West Virginia, shown on a shaded relief topographic base map.

In the West Virginia Landslide Risk Assessment natural regions were subdivided by U.S. Natural Resources Conservation Service (2006) Major Land Resource Areas (MLRAs), rather than physiographic regions. West Virginia's physiography is coarsely mapped compared to detailed physiographic maps in adjacent states. Throughout most of the state, MLRAs are more precisely delineated and better capture variations in topography, geology, and soils than traditional 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 Landslide Risk Assessment (Figure 1). Landslides in the Southern Alleghenies portion of MLRA 127 are not included in this discussion, but are addressed separately in another document. The subdivision of MLRA 127 was prompted by a lower availability of high-resolution LiDAR-based DEMs in the northern portion at the time of modeling analysis in 2020, but also reflects significant differences in topography, bedrock structure, and the nature and thickness of bedrock geology map units from north to south across the whole MLRA. The boundary between the northern and southern Allegheny areas was drawn to place the headwaters of the Cheat and Tygart Valley rivers, in Pocahontas and Randolph counties, into the northern area, then bending westward in Randolph County such that areas north of the Elk River in eastern Webster County also would be in the northern area. The Northern Allegheny Mountains area spans all or parts of 15 counties within West Virginia Planning and Development Regions 4, 6, 7 and 8 (Figure 1).

The "Northern Allegheny Mountains" discussed in this report align approximately with traditionally assigned limits of the Allegheny Mountain physiographic section in West Virginia, with significant differences of 25 miles or more in the location of the western boundary in Randolph, Upshur and Webster counties. A U.S. Geological Survey map by Fenneman and Johnson (1946) excludes most of the Tygart Valley River basin from the Allegheny Mountain section, and a map published by the West Virginia Geological and Economic Survey (2020b) excludes about half of the upper part of that river basin.

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, over two-thirds of the Northern Allegheny Mountains in West Virginia is underlain by substantially folded bedrock with gently to steeply dipping beds at many locations, including much of the Cheat and Tygart Valley river basins and the Allegheny Front along the eastern border of the MLRA. Visual survey of topography shown on LiDAR-based imagery suggests the West Virginia Geological and Economic Survey mapping of the Allegheny Mountain section more precisely delineates a cohesive physical entity, but wholesale redrawing of MLRA boundaries was beyond the scope of this project, so landslide mapping was in general accordance with NRCS-designated boundaries.

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 Northern Allegheny Mountains. 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 very 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 ephemeral stream channels. Mining regolith, unconsolidated material produced as a result of mining, is locally extensive within coal-bearing geologic units.

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 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, 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 cubic feet 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. Only one rock fall was identified in the Northern Alleghenies using LiDAR based DEMs.

Less common landslides types include eight features mapped as multiple failures: tight clusters of small landslides and debris flows known to occur during debris flow events elsewhere in West Virginia. One landslide could not be classified due to its unusual topographic features.

As of March 2021, 2,233 landslides have been identified through mapping on LiDAR-based DEMs constructed for the portions of the Northern Alleghenies; 2,211 of these were analyzed in mid-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).

Landslide mapping and analysis included only areas covered by 1 m or 2 m resolution LiDAR-based DEMs in March 2020 (Figure 2). Very few landslides can be resolved on DEMs with coarser resolution, so no landslides or non-landslide points were analyzed in areas lacking 1 m or 2 m LiDAR. Mapping included all of Preston County, all areas within Pocahontas, Pendleton, Grant, and Mineral counties that lie within the MLRA, and fractions of most other Northern Allegheny Mountain counties, but not the small portions of Lewis and Upshur counties lying in the MLRA. Hence, the discussion and data presented come from only 47.8 percent of the MLRA, a sample large enough to be representative, but less precise than those from most other MLRAs in the state.

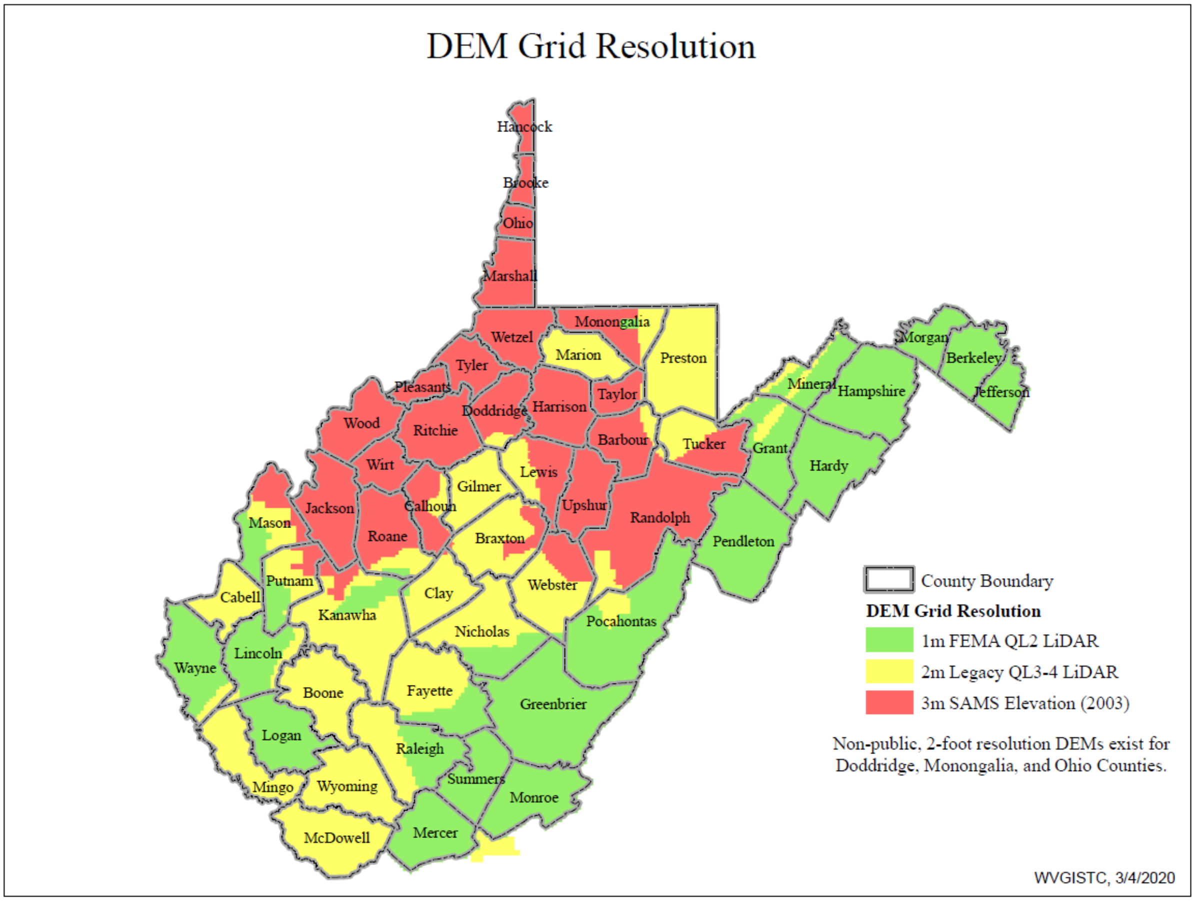

Figure 2: Map of Digital Elevation Models (DEM) availability for West Virginia at the onset of landslide analysis in March 2020. Analysis focused on areas with 1 m or 2 m DEMs.

Slope

Analysis of the LiDAR-based landslide data from the Northern 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 significantly steeper than most of the nearby landscape (Figure 3). Slides are by far the most common type of slope failure, and the median slope for 2,129 slide initiation sites is 31° and four out of five slides initiated on 21° to 40° slopes. For comparison, a sample of 47,315 randomly selected non-landslide points throughout the Northern Alleghenies have a median slope of only 13°, with four out of five points having 3° to 28° slopes.

Elsewhere in West Virginia, 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. However, the statewide tendency is not shown by 30 debris flows documented in the Northern Alleghenies, an anomaly that may stem from the small number of mapped debris flows. The median slope at debris flow initiation sites is 29°, and four out of five debris flows initiated on 17° to 46° slopes (Figure 3).

Slopes at the uppermost points on 52 laterals spreads are typically gentler and much more varied than the uppermost points on slides or debris flows (Figure 3). The median slope of the uppermost points on lateral spreads is only 22.5°, while 33 percent are under 15°. Four out of five lateral slides head on 6° to 38° slopes. At the steep end of the lateral spread spectrum, 10 percent head on slopes over 46°, 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 more common slope failures in West Virginia; they need to be regraded accordingly.

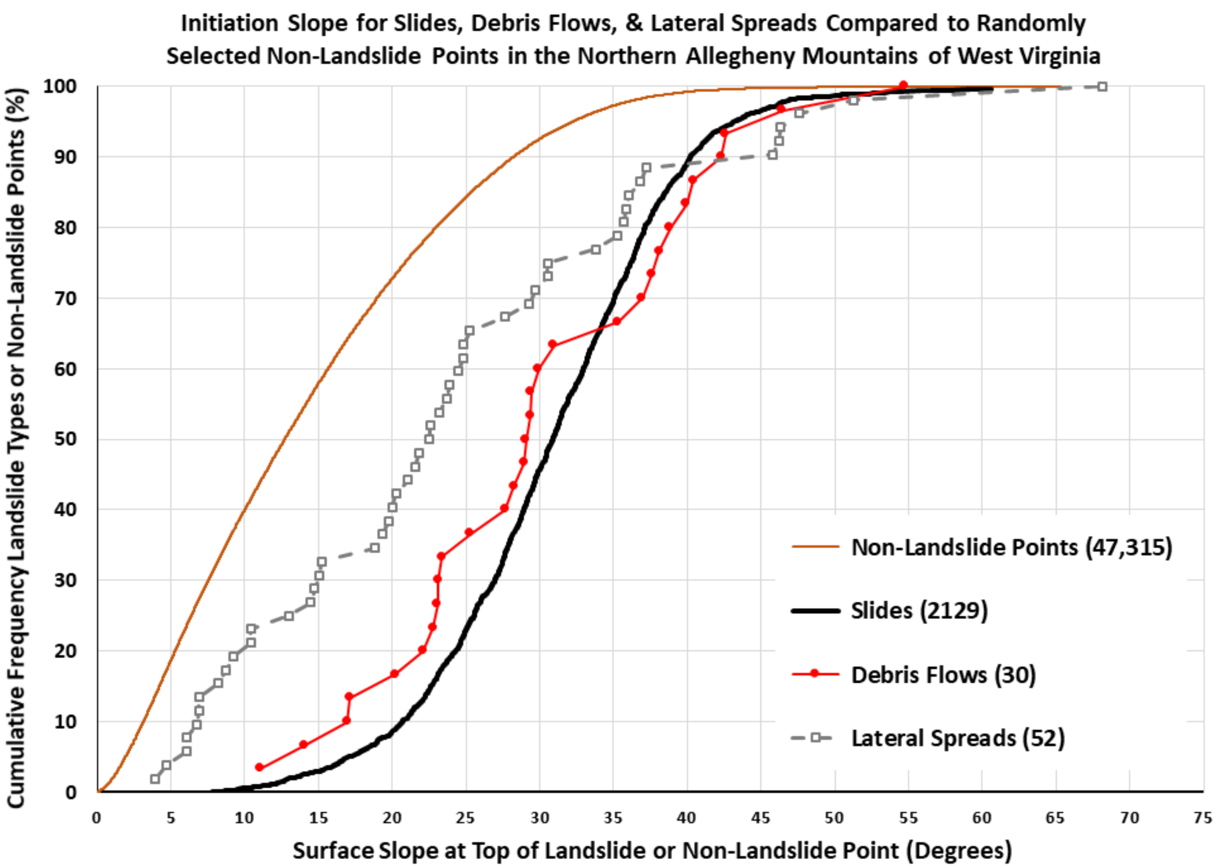

Figure 3. Comparison of initiation slopes for slides (including slumps), debris flows, and lateral spreads (rock cities) with randomly selected points in the Northern Allegheny Mountains of West Virginia. Initiation slope was measured at the uppermost point on a landslide as mapped from the LiDAR-based DEMs.

Geology

Geology is a universally cited factor in landslide distribution, and this is the case in the Northern Allegheny Mountains 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 cliffs along waterways. An assumption that sandstone-dominated bedrock should host more landslides than other geologic units may seem intuitive if one compares steep sandstone canyon walls to broad low-relief bottomlands underlain by weaker bedrock types. However, the inherent strength of thick sandstones makes them more stable than other rocks at any given slope angle. Except for steep narrow canyons, topography formed on sandstone-dominated units tends to be less rugged than landscapes dominated by weaker shale or siltstone. On the steep uplands across the Northern Alleghenies, weaker bedrock units tend to be more deeply incised and more prone to failure than resistant units, even where the weaker units contain some significant sandstone beds.

Geologists make maps to decipher earth history. Varied events in earth history lead to a heterogeneous rock record. However, not all differences in rock type are reflected in designating 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.

This project used a West Virginia Geological and Economic Survey (WVGES) geologic map of West Virginia (Cardwell and others, 1968) as the exclusive source of spatial geologic data. There is significant uncertainty in the WVGES 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 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 22 different map units in the Northern Allegheny Mountains, with individual extents ranging from 0.06 to 691 square miles. Twenty 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 “Pocono Group” and the “Maccrady Formation & Pocono Group, undivided” were analyzed as a single entity because the “undivided” map polygons can’t be subdivided without revising the WVGES map. The Mauch Chunk and Pottsville groups are each treated as single geologic units; though they are subdivided into constituent formations in Upshur, Randolph, and counties farther to the southwest, the two groups are undivided in Pendleton, Tucker, Barbour, and counties farther to the northeast because of geographic changes in unit thickness and character. Five fine-grained clastic bedrock units of Devonian age were combined because they each encompass a very small total area and collectively include only two landslides. These groupings reduced analysis of geology and landslides to 12 separate geologic units and unit combinations (Table 1).

WVGES Geologic Map Unit	Geol. Period	Mapped Land-slides Count	Mapped Land-slides in Unit %	Random Points in Unit %	Meas. Unit Area Mi^2	Meas. Unit Area %	Estimated Failures /100 Mi^2
Water	Quat.	0	0.0	0.00	0.3	0.01	**
Alluvium	Quat.	0	0.0	0.45	41.5	1.24	0
Monongahela Formation	Penn.	2	0.1	0.25	4.4	0.13	50
Conemaugh Group	Penn.	535	24.2	29.20	690.7	20.58	114
Allegheny Formation	Penn.	269	12.2	16.15	497.5	14.83	104
Pottsville Group (3 units)	Penn.	259	11.7	12.83	823.5	24.25	126
Mauch Chunk Group (4 units)	Miss.	281	12.7	8.52	304.4	9.07	206
Greenbrier Group	Miss.	67	3.0	3.45	120.4	3.59	121
Pocono & Maccrady fm. (2 units)	Miss.	63	2.8	4.83	123.7	3.69	81
Hampshire Group	Devon.	134	6.1	8.11	283.3	8.44	103
Chemung Group	Devon.	599	27.1	15.92	412.7	12.30	235
Fine-grained clastic rock (5 units)	Devon.	2	0.1	0.29	53.6	1.60	43
Overall Northern Allegheny Mtns.		2211	100.0	100.00	3356.0	100.00	138

*Table 1. Simplified list of Northern Allegheny Mountains geologic map units, show in stratigraphic order, and associated data for 2211 landslides and 47,315 randomly generated points in the area. Sum of percentages and unit areas do not equal overall totals because of rounding. Some insignificant digits are shown so that very small values don't appear as zero. Note * extent of water in the area is too small for meaningful estimation of failures/100 mi^2.*

Data in Table 1 are complicated by the fact that incomplete high-resolution LiDAR coverage allowed only 47.8 percent of the MLRA in West Virginia to be mapped. Fortunately, modelling by Maxwell and others (2020) created geologic and soils data at randomly sampled 47,315 points in the same locations where landslides were mapped. The surface area actually covered by each geologic unit was calculated independently, and the proportion of each unit in which landslides were mapped can be inferred from the proportion of randomly generated points in the unit.

The Pottsville Group provides an illustrative example of how point data were used. Mapping revealed 259 landslides in the group, which covers 823.5 mi^2, 24.25 percent of the area. A simple mathematical adjustment of the number of slides based on 47.8 percent mapping coverage (n = 259/0.478) would result in a prediction of 542 Pottsville Group landslides in the whole MLRA and a landslide susceptibility of 66 failures/100 mi^2. However, the randomly generated point counts shows that the Pottsville unit comprised only 12.83 percent of the area actually mapped in the MLRA. The Pottsville was under-sampled because it is more dominant in areas of Randolph, Upshur and Webster counties that lacked high resolution LiDAR than in other areas in the MLRA where high-resolution LiDAR allowed landslide mapping. Adjustment to the landslide susceptibility through multiplying by (measured unit area % / random points in unit %) yields an approximate susceptibility estimate of 126 failures/100 mi^2. This value is much closer to that calculated for formations within the Pottsville Group elsewhere in West Virginia, and provides an estimate of over 1000 Pottsville Group landslides within the MLRA.

The overall Northern Allegheny Mountains estimate of 138 failures/100 mi^2 is more than twice the 50 failures/100 mi^2 estimate for Appalachian Ridges and Valleys, but only half the 283 and 279 failures/100 mi^2 estimates for the Southern Alleghenies and the Cumberland Plateau, respectively. Although these relative abundances likely reflect conditions on the ground to some degree, the Northern Allegheny estimate may be low because a large proportion of mapping relied on DEMS based on 2 m LiDAR, rather than higher resolution 1 m LiDAR. No significant difference in the ability to identify landslides was perceived during mapping, but it is likely more landslides would have been discerned if higher resolution DEMs had been available.

Most bedrock in the Northern Allegheny Mountains is highly susceptible to failure, but to varying degrees. Table 1 shows the estimated failures/100 mi^2 in two units are more than 50 percent higher than the area's overall average. Two bedrock units and alluvium have estimated susceptibilities more than 60 percent lower than the MLRA average.

The Chemung Group has both more mapped landslides and the highest susceptibility to failure (235/100 mi^2) of any unit. The Chemung is comprised of layers of siltstone and relatively thin (< 5 feet thick) sandstone, with interbedded shale. The shale layers can be incompetent and serve as slip surfaces, initially under tectonic forces many millions of years ago that produced highly deformed zones of complex weak bedrock amidst zones of relatively uniformly dipping competent bedrock. On today's landscape, dipping Chemung shale layers may serve as shear zones at the base of large landslides, including failures of mostly intact blocks covering tens of acres. The unpredictable complexity of bedrock structure within Chemung bedrock and the inordinate role that a < 1 foot shale layer may play in the stability of otherwise competent bedrock makes it very difficult to predict where landslides are apt to occur without comprehensive slope stability assessment, including extensive closely-spaced test borings, field investigation, and detailed geotechnical analysis.

The Mauch Chunk Group has the third highest number of landslides in the area and second highest estimate of landslides/100 mi^2. The Mauch Chunk is subdivided into three map units over most of the whole Eastern Allegheny Plateau and Mountains Major Land Resource Area (MLRA 127), including roughly half of Northern Alleghenies counties and all of the Southern Alleghenies, which is covered in a separate report (Figure 1). From bottom to top these geologic units are the Hinton Formation (predominantly shale alternating with sandstone), the Bluestone and Princeton formations (locally thick sandstone beds and significant interlayers of shale), and the Bluefield Formation (shale and sandstone). The estimated Mauch Chunk Group landslide susceptibility of 206 failures/100 mi^2 in the Northern Alleghenies is less than half of the 440 failures/100 mi^2 calculated for the group in the Southern Alleghenies, but the 49 percent above overall Northern Alleghenies susceptibility is close to the 56 percent above overall Southern Alleghenies susceptibility determined in southern West Virginia.

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. The most important point may be that the Mauch Chunk is very susceptible to landslides, contrary to a widely used U.S. Geological Survey landslide overview map of the conterminous United States (Radbruch-Hall and others, 1978), which incorrectly shows low landslide incidence throughout much of the Mauch Chunk outcrop belt.

Five geologic units have estimated susceptibilities of 103 to 126 failures/100 mi^2, values 8 to 25 percent below the Northern Alleghenies average. The predominant rock types within the geologic units differ greatly, ranging from sandstone-dominated Pottsville Group and Allegheny Formation, through shale-dominated Hampshire Formation and Conemaugh Group, to limestone-dominated Greenbrier Group. All of the units contain sequences of potentially incompetent shale and other fine-grained rocks interbedded with generally competent sandstone or limestone. Possibly the most surprising unit in this group is the Greenbrier Group, which is associated with low relief valley bottoms where there are very few landslides, such as Canaan Valley, whereas elsewhere the limestone units occurs on the flanks of Pottsville sandstone-capped mountains where slopes are steep and landslides common. Although speculation as to why landslide susceptibility in the units differ slightly might be a useful intellectual exercise, the differences in susceptibility are so slight that factors such as bedrock structure, landscape position, or the regional Quaternary history of hillslopes and streams may overwhelm differences arising from the rock constituents of the units.

The sandstone-and-shale-dominated Pocono (a.k.a. Price) Group and comingled shale-dominated Maccrady Formation have landslide susceptibilities of 81 failures/100 mi^2, only 59 percent of the Northern Alleghenies average. Sandstone beds within the Pocono are commonly quartz-rich and more resistant than stratigraphically adjacent rocks a forming widespread benches and local ridges. It is possible this inherent resistance explains the Pocono Group's relatively low landslide susceptibility, which also is apparent in Southern Allegheny data. The Maccrady extent is minor in this area, being limited to Pendleton County and farther south (Cardwell and others, 1968).

The uppermost bedrock unit, the Pennsylvanian Monongahela Group, includes only two mapped landslides, and the mapped extent of the diverse sedimentary rock unit is so small that the 37 percent of average susceptibility estimate for the unit may not be significant. The five combined Devonian clastic bedrock units at the bottom of the stratigraphic column are made up of interbedded sandstone, siltstone, and shale in varying proportions. The overall landslide susceptibility estimate for the combined units is only 31 percent of the whole area, a reasonable number for units generally found on valley bottoms, but the small total extent of these units and their two mapped landslides raise questions about the accuracy and precision of this estimate.

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. Lidar-based mapping revealed no landslides in water polygons, which have a total extent of only 0.3 square miles, and whose expected landslides count should be essentially zero because the red laser light used to generate LiDAR data is reflected by water obscuring any underwater landslides.

Coal beds are not shown on the Cardwell and others (1968) map used to assess landslide susceptibility in geologic units. The Allegheny Formation and Monongahela Group have been heavily mined for coal in the Northern Alleghenies, and minor coal seams also exist in the Conemaugh and Pottsville Groups (West Virginia Geological and Economic Survey, 2020a). Greenbrier Group limestone has been mined at widespread locations. Both coal and limestone have been extracted from both surface and deep mines; historically sandstone was surface mined for sand and building materials.

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. The role of mining on slope stability is not apparent from geologic data alone, but it is noteworthy that landslide susceptibility is greatest on two geologic units that have experienced little mining. The near-average to relatively low landslide susceptibility in units subject to mining may reflect the inherent strength of bedrock dominated by competent sandstone or limestone, rather than impacts on slope stability from mining or reclamation. The relationships between mined lands and landslide susceptibility is more precisely addressed through discussion of soil parent materials.

Debris Flows and Lateral Spreads: Although each makes up a small fraction of landslides in the Northern Allegheny inventory, the distinctive characteristics of debris flows and lateral spreads and their unusual risks to safety and civil infrastructure warrant examination how they relate to geology (Table 2). Susceptibility to the two types of slope failures varies 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	0	0.0	0.0	0	0.4	0.0
Alluvium	0	0.0	0.0	0	0.0	0.0
Monongahela Group	0	0.0	0.0	0	0.0	0.0
Conemaugh Group	5	16.7	1.1	0	0.0	0.0
Allegheny Formation	4	13.3	1.5	8	15.4	3.1
Pottsville Group (3 units)	4	13.3	1.9	34	65.4	16.5
Mauch Chunk Group (4 units)	6	20.0	4.4	10	19.2	7.3
Greenbrier Group	2	6.7	3.6	0	0.0	0.0
Pocono Group & Maccrady Fm. (2 units)	2	6.7	2.6	0	0.0	0.0
Hampshire Formation	3	20.0	2.3	0	0.0	0.0
Chemung Group	4	13.3	1.6	0	0.0	0.0
Devonian Clastic Bedrock (5 units)	0	0.0	0.0	0	0.0	0.0
Overall Northern Allegheny Mountains	30	100.0	1.9	52	100.0	3.2

Table 2. Frequency of debris flows and lateral spreads in Northern Allegheny Mountains geologic map units, show in stratigraphic order.

Debris flows were mapped in all eight of the 12 most extensive geologic units, but in no units covering less than 120 mi^2. The overall mean of 1.9 debris flows/100 mi^2 is smaller than the 4.0 debris flows/100 mi^2 calculated for both the Ridges and Valleys and the Cumberland Plateau, and the 6.9 debris flows/100 mi^2 determined from the Southern Alleghenies. The relatively low number may reflect the Northern Allegheny Mountains' greater distance from the Gulf of Mexico and Atlantic moisture sources that provide the levels of moisture required for the intense rainfall that triggers debris flow events.

One fifth of the 30 debris flows were mapped in the Mauch Chunk Group, the unit with the highest debris flow susceptibility. The small total of debris flows does not allow many other inferences from the data. Debris flows may have long run outs of a mile or more, so some locations in geologic units with no debris-flow initiation points or low susceptibility may be at risk due to geology and topographic conditions far upslope.

Mapped lateral spreads are limited to three geologic units. Nearly two thirds of lateral spreads are associated with the Pottsville Group, which has more massive sandstone layers than any other unit. The best known lateral spreads in northern West Virginia may be the twenty rock cities in Coopers Rock State Forest. The other two geologic units containing lateral spreads, the Mauch Chunk Group and Allegheny Formation, also contain significant thick massive sandstone layers. No other geologic map units contain lateral spreads. Except possibly the Pocono and Chemung groups, the absence of lateral spreads in most units is consistent with a lack of massive sandstone beds 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 their formation processes 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 downslope 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 correlate with landslide susceptibility in the Northern Allegheny Mountains. 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, very 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 two parent materials and three drainage classes limit this analyses to general interpretations about soils and where landslides initiate in the Northern Allegheny Mountains.

Soil Parent Material: SSURGO data provide the basis for 10 different soil parent materials in the Northern Allegheny Mountains (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 Northern Allegheny Mountains, and some soil series that form elsewhere on old fine-textured lake deposits also form on old fine-textured alluvium.

NRCS Soil Parent Material	Mapped Landslide Count	% of All Failures	% Non-Landslide Points	Approx. Mapped Area Mi^2	Approx. Failures /100 Mi^2
Residuum, Acid Clastic	1160	52.46	60.05	963.2	120
Colluvium	842	38.08	28.78	461.7	182
Mining Regolith	127	5.74	3.16	50.7	250
Residuum, Limestone	35	1.58	2.45	39.2	89
Residuum, Calcareous Clastic	26	1.18	0.68	11.0	237
Disturbed Areas	18	0.81	0.78	12.5	143
Recent Alluvium	3	0.14	2.83	45.3	7
Water	0	0.00	0.77	12.3	0
Old Terrace Alluvium	0	0.00	0.50	8.0	0
Organic Material	0	0.00	0.01	0.1	0
Overall Northern Alleghenies	2211	100.00	100.00	1604.2	138

Table 3. Dominant soil parent materials for landslides of all types in the Northern Allegheny Mountains. Parent materials are listed in decreasing order of number of landslides. Sum of columns may not equal overall MLRA totals because of rounding.

Over 90 percent of landslides were mapped in either residuum developed from acid clastic sedimentary bedrock or from colluvium, two units that cover almost 90 percent of the study area. Although most landslides occur in acid clastic residuum, the unit's 120 landslides/100 mi^2 indicate it is slightly less susceptibility to failure than the Northern Allegheny Mountains as a whole. Colluvium hosts the second highest number of landslides and a susceptibility of 182 landslides/100 mi^2 that is about 1/3rd higher than the mean for the whole area.

Two parent materials appear particularly landslide prone: mining regolith and calcareous clastic residuum. Mapping projects in the Southern Alleghenies 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 the unusually high landslide susceptibility in mining regolith is relic from old mining practices or an issue common to mined lands of all generations. Calcareous clastic residuum is commonly developed on Mauch Chunk Group bedrock, which has similarly high landslide susceptibility.

Limestone residuum parent material is associated with an estimated 89 landslides/100 mi^2, a value somewhat lower than the susceptibility in the Greenbrier Group geologic unit that is the source for most limestone residuum in the Northern Alleghenies. The mismatch may stem from colluvium derived from nearby clastic bedrock units that commonly extend downslope into the Greenbrier outcrop belt.

The SSURGO data suggest disturbed land has near average landslide susceptibility, a surprising relationship in light of the 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 the engineered slopes on which the material occurs rather than from material properties. Many areas of disturbed land have been graded into relatively flat man-made landforms.

Recent alluvium and old terrace alluvium are underrepresented in landslides/100 mi^2 by an order of magnitude or more, consistent with a miniscule to nonexistent susceptibility indicated for the alluvium geologic map unit in Table 1. It is revealing that the WVGES geologic map shows alluvium covers only 41.5 mi^2 in the whole (= 100%) Northern Alleghenies, whereas NRCS soil parent material data suggest the alluvium categories, when combined, cover more than 53 mi^2 in just the 47.8 percent of the MLRA that had high-resolution LiDAR that allowed detailed landslide mapping and analysis. The state geologic map is very conservative in portrayal of non-bedrock geologic units, so the larger percentage indicated by soil parent material is undoubtedly more accurate.

As noted in the geology section, no landslides are mapped within water "parent material" polygons. None were mapped on organic material, a finding lacking statistical significance because of the tiny area covered by the parent material, although landslides would not be expected because of the low relief in which organic soils accumulate.

Tabulation of debris flows within the Northern Alleghenies shows these long-runout failures initiate in five different parent materials (Table 4). Half of the debris flows were mapped in acid clastic residuum and nearly a quarter were identified in colluvium. The small total number of debris flows prevents meaningful statistical analysis, but one unit, limestone residuum, which includes 17 percent of debris flows within less than 3 percent of the mapped area, does seem heavily over-represented.

NRCS Soil Parent Material	Mapped Debris Flow Count	% of All Debris Flows	Lateral Spread Count	% of All Lateral Spreads
Residuum, Acid Clastic	15	50	49	9.2
Colluvium	7	23	3	5.5
Mining Regolith	2	7	0	17.1
Residuum, Calcareous Clastic	1	3	0	4.9
Residuum, Limestone	5	17	0	0.4
Disturbed Areas	0	0	0	0
Recent Alluvium	0	0	0	0
Old Terrace Alluvium	0	0	0	0
Water	0	0	0	0
Organic Material	0	0	0	0
Northern Allegheny Mountains Total	30	100	52	100

Table 4. Dominant soil parent materials for debris flows and lateral spreads mapped in the Northern Allegheny Mountains. Materials are listed in decreasing order of the number of all landslides shown in Table 3. Sum of columns may not equal overall MLRA totals because of rounding.

Lateral spreads were mapped in only two parent materials within the Northern Alleghenies (Table 4). Forty-nine of 52 lateral spreads are within acid clastic residuum, the soil parent material expected on thick quartz-rich sandstone beds. The other three were mapped in colluvium parent material.

Soil Drainage Classification: 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. An eighth class of "water" is assigned by the NRCS and shown in Table 5.

NRCS Soil Drainage Classification	Mapped Landslide Count	% of Mapped Landslides	% Non-Landslide Points	Approx. Mapped Area Mi^2	Approx. Failures /100 Mi^2
Excessively Drained	274	12.4	10.0	160.3	170
Somewhat Excessively Drained	0	0.0	0.2	2.8	0
Well Drained	1813	82.0	66.9	1073.2	169
Moderately Well Drained	105	4.7	14.4	231.2	45
Somewhat Poorly Drained	16	0.7	5.1	82.3	19
Poorly Drained	3	0.1	2.2	34.6	59
Very Poorly Drained	0	0.0	0.5	7.4	0
Water	0	0.0	0.8	12.3	0
Northern Allegheny Mountains Total	2211	100.0	100.0	1604.2	138

Table 5. Drainage classes for soils and relative landslide abundance in Northern Allegheny Mountains. Classes are listed in order from most drained to least drained. Sum of columns may not equal totals because of rounding.

Soil polygons assigned as "well drained" cover about 67 percent of the Northern Allegheny Mountains, account for almost 82 percent of landslide initiation points, and have the second highest landslide susceptibility. Excessively drained soils cover 10 percent of the area and contain the second highest number of landslides and the highest landslide susceptibility of any class. Both of these drainage classes commonly occur on steep slopes, so their over-representation in landslides may reflect the important role of slope as a control of both soil drainage and landslide initiation.

Soils in the other drainage classes have significantly fewer landslides/100 mi^2 than the Northern Allegheny Mountains average. Landslide susceptibility is moderate on moderately well drained, somewhat poorly drained, and poorly drained soils. No landslides were mapped on soils in three drainage classes. Somewhat excessively drained and very poorly drained soils are so uncommon in the area that the lack of slides could partly be a statistical artifact of their small sample size. 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 mountainsides could be dominated by excessively drained 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 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 Northern Allegheny Mountains 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 counties in the Northern Allegheny 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. 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 property development in the Northern Allegheny Mountains is increasing, so 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 or Atlantic moisture sources. This pattern suggest a lower probability of swarms of debris flows and other landslides in the Northern Allegheny Mountains than in southern and eastern 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 Northern Allegheny Mountains 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

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

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