West Virginia Landslide Risk Assessment

Central Allegheny Plateau

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WEST VIRGINIA UNIVERSITY

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Landslides in the Central Allegheny Plateau MLRA of West Virginia

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The Central Allegheny Plateau is an extensive Major Land Resource Area (MLRA) (Figure 1) situated in an area dominated by rugged topography, nearly flat-lying clastic sedimentary bedrock (siltstone, shale, and sandstone) and well-drained soils formed in residuum and colluvium. The U.S. Geological Survey (USGS) has mapped high landslide incidence over the entire West Virginia portion of the MLRA (Radbruch-Hall and others, 1978). The Conemaugh Group, a bedrock unit with few mineable coal resources, has the highest landslide susceptibility, but unconsolidated material produced by mining in Monongahela Group bedrock unit is locally linked to abundant landslides. Preliminary results of ongoing LiDAR-based mapping suggest landslide abundance is greater in the Central Allegheny Plateau than in any other MLRA within West Virginia.

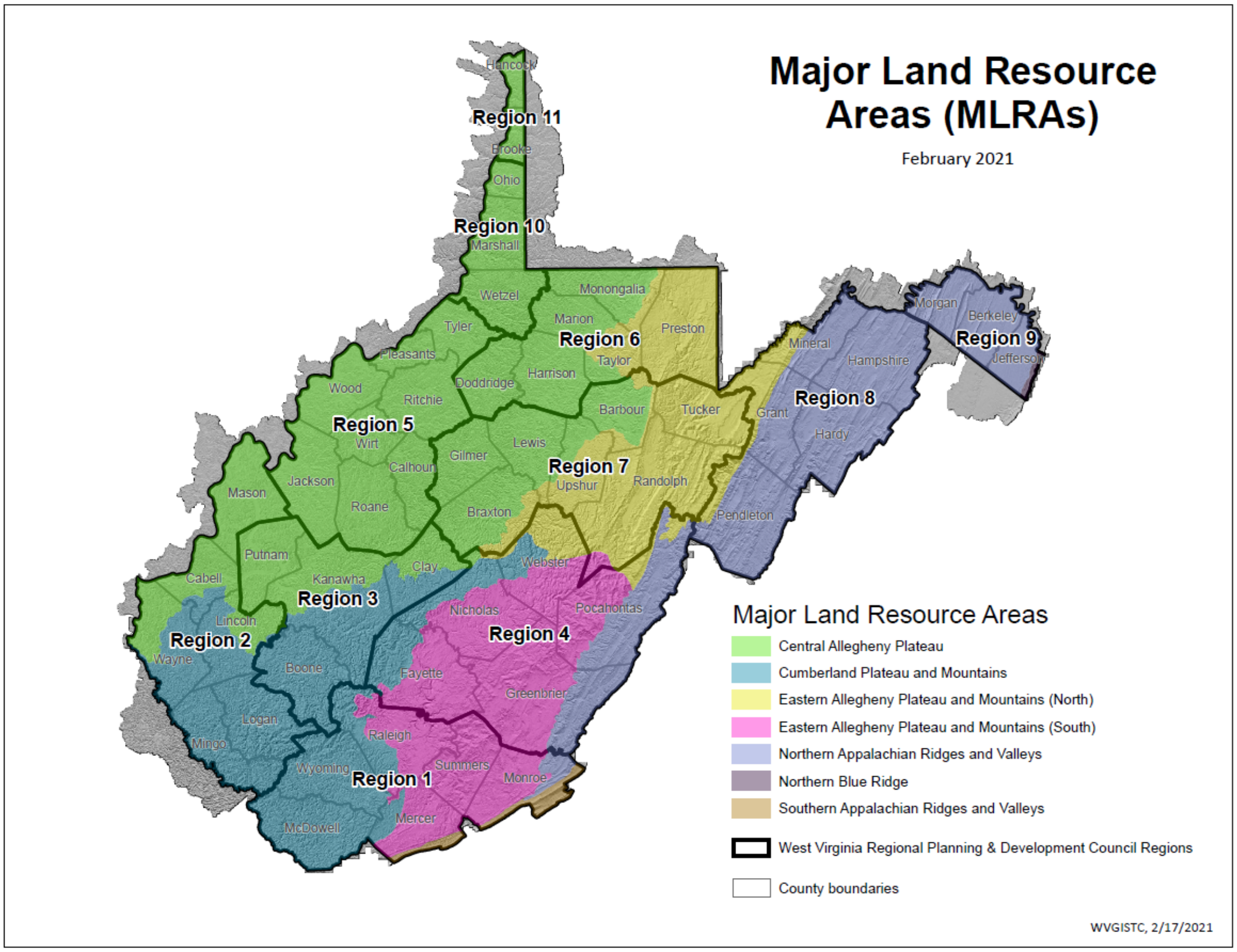

Figure 1: Map of Natural Resources Conservation Service (NRCS) Major Land Resource Areas (MLRA), Planning and Development Regions, and county boundaries in West Virginia, shown on a shaded relief topographic base map.

In the West Virginia Landslide Risk Assessment natural regions were subdivided using U.S. Natural Resources Conservation Service (2006) Major Land Resource Areas (MLRA), rather than physiographic regions. West Virginia's physiography is coarsely mapped compared to detailed physiographic maps in adjacent states. Throughout most of the state, MLRA 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 NRCS MLRA 126: Central Allegheny Plateau (Figure 1). The Central Allegheny Plateau spans all or parts of 29 of the 55 counties in the state, encompassing all of West Virginia Planning and Development Regions 5, 10, and 11 and parts of Regions 2, 3, 6, and 7 (Figure 1).

The Central Allegheny Plateau discussed in this report lies in the Kanawha Section of the Appalachian Plateaus physiographic province shown in a USGS map by Fenneman and

Johnson (1946) and the Allegheny Plateau province delineated in a map published by the West Virginia Geological and Economic Survey (WVGES) (2020b). However, the physiographic units shown in both of these maps also include substantial portions of the Cumberland Plateau MLRA and the Southern Portion of the Allegheny Mountains MLRA used in this project to divide the state into areas with similar geology and topography.

Although it does not extend into West Virginia, the most recent physiographic map of Pennsylvania (Sevon, 2000) subdivides nearby areas in the Kanawha Section into the Pittsburgh Low Plateau and the Waynesburg Hills. The topography of northern West Virginia suggests these two subdivisions used in Pennsylvania could be extended throughout the Central Allegheny Plateau as far south as the Kanawha River, potentially providing clearer insights into landslides. However, delineation and characterization of new physiographic regions in West Virginia are beyond the scope of this project.

Description of MLRA 126 Central Allegheny Plateau states the geology is characterized by mostly horizontally bedded Pennsylvanian-age sandstone, siltstone, shale, coal, and some limestone (U.S. Natural Resources Conservation Service, 2006). River valleys have significant alluvial deposits ranging from coarse gravel in steep upland river channels to fine silt and clay on broad low-gradient river bottoms. Fine-grained Pleistocene lake sediments and eolian (wind-blown) sands and silts have been locally documented on relatively flat slopes, but these deposits are less common in West Virginia than in Pennsylvania and Ohio portions of MLRA 126.

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 Central Allegheny Plateau. 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 landslide 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 timeframe 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 and ballpark volume of landslides, supplemented by the addition of new landslide 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, although sandstones on stable low-relief upland surfaces and thin calcareous sandstones dispersed throughout the area typically develop moderately deep 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 extraction, is locally extensive within coal-bearing bedrock units and adjacent terrain.

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 considerable distances downslope from their source. The most frequent cause of debris flows is heavy rain associated with intense spring and 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, large debris flows are uncommon in the Central Allegheny Plateau, and they are infrequent even at the most vulnerable Appalachian sites, with recurrence intervals estimated to be hundreds or thousands of years.

Less common landslides types include three individual features mapped as multiple failures: tight clusters of small landslides and debris flows known to occur during debris flow events elsewhere in West Virginia. Only two lateral spreads were identified using LiDAR based DEMs from the Central Allegheny Plateau. Lateral spreads, or rock cities, are clusters of very large (~500 cubic feet or more) rock blocks that move infrequently in historic times, but just often enough to suggest they are 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 high walls. However, the scope of rock fall susceptibility is poorly shown by this landslide inventory. Fallen rock is unlikely to be recorded on occasional LiDAR surveys because it is usually removed promptly and is commonly too small to be resolved and mapped using LiDAR-based imagery. Only two rock falls have been identified from LiDAR-based DEMS in MLRA 126.

A total of 29,747 landslides were mapped in this project using LiDAR-based DEMs in the Central Allegheny Plateau MLRA by September 2020. However, the statistical analysis run in spring 2020 to assess which factors best predict where landslides occur included only 14,974 landslides within an area covering only about 41.95 percent of the Central Allegheny Plateau MLRA. 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).

An additional 1,079 Central Allegheny Plateau landslides mapped in earlier projects by other means are included in the landslide data base. A few dozen of these of these were identified from field observations or landslide reports, but the vast majority were digitized from maps of landslides and slide-prone areas published by the West Virginia Geological and Economic Survey (Lessing and others, 1976). The WVGES mapping relied heavily on traditional stereoscopic air-photo interpretation, supplemented by field observations. The WVGES maps do not differentiated debris flows, lateral spreads, and multiple failures from other landslides.

As part of this project, the locations of likely initiation points within 220 WVGES mapped slide and slide-prone area polygons in Monongalia County were verified using the 1 and 2 meter LiDAR-based DEMs. These included 120 older landslides, 42 recent landslides, and 58 areas of rock fall risk. Analysis of the attributes for the WVGES mapped features provides insight into how other mapping methods by yield interpretations differing form the LiDAR-based approach.

Landslide mapping and analysis included only areas covered by 1 or 2 meter resolution LiDAR-based DEMs in March 2020 (Figure 2). Very few landslides can be resolved on DEMs with coarser resolution, so no inventoried landslides in areas lacking 1 or 2 meter LiDAR were subject to analysis. The availability of 1 meter LiDAR mapping at the time of analysis was limited to portions of Wayne, Lincoln, Putnam, Mason, Kanawha, Roane, and Monongalia counties. As shown in Figure 2, mapping using publicly available 2 meter LIDAR data included all of Gilmer and Cabell counties, all of Marion County within the MLRA, and portions of Lincoln, Putnam, Mason, Kanawha, Roane, Clay, Braxton, Barbour, and Monongalia counties. Proprietary LiDAR data for Ohio and Doddridge counties were used for mapping and analysis, but not shown in figure 2. Collectively, the following discussion and data come from just under 42 percent of the MLRA, a sample large enough to be generally representative, but less precise and possibly less accurate than those from other MLRA in the state.

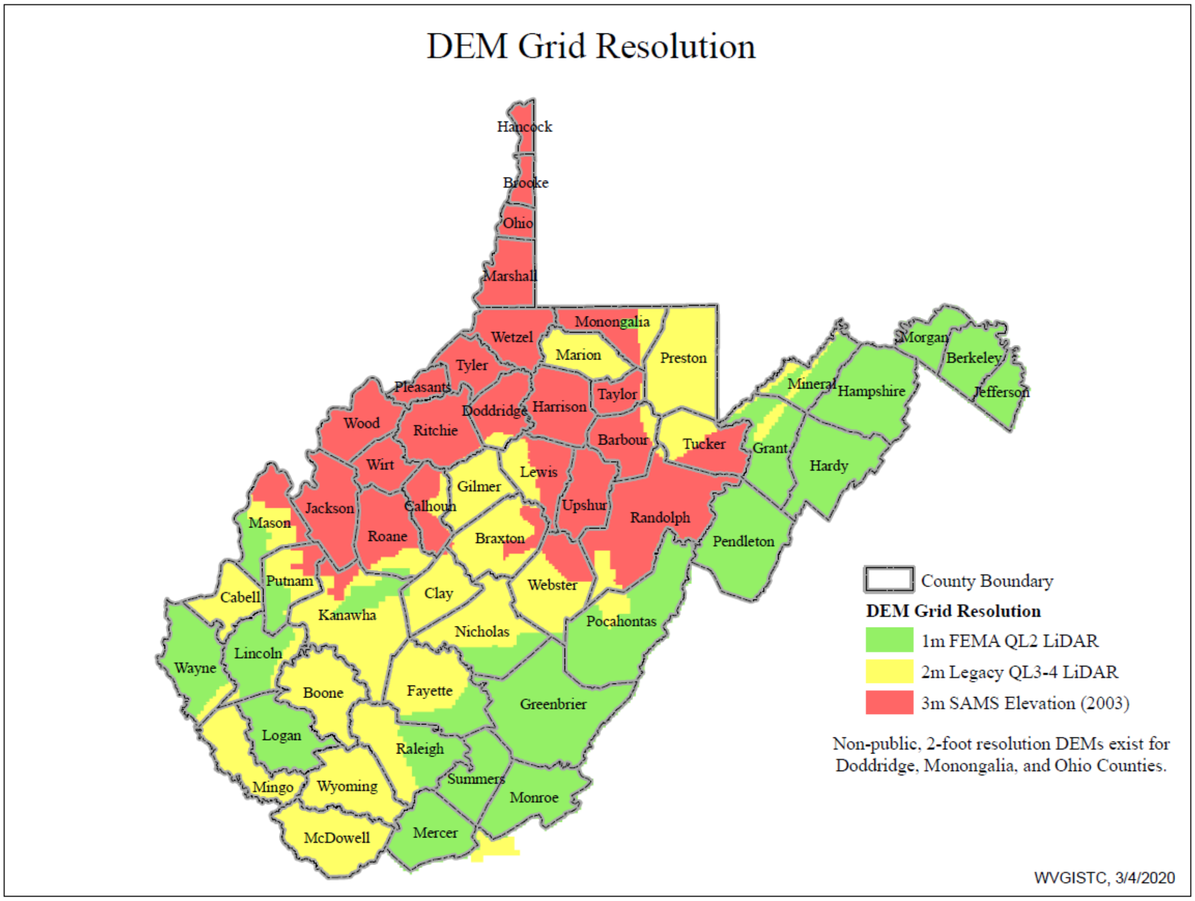

Figure 2: Map of Digital Elevation Models (DEM) availability for West Virginia at the onset of landslide analysis in March 2020. Analysis focused on areas with 1 or 2 meter DEMs.

Slope

Analysis of the LiDAR-based landslide data from West Virginia 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 either 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 widespread unfamiliarity with slope-area ratio and uncertainly over how to interpret the variable suggests a focus on slope steepness, measured in degrees, is more useful in discussing of 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, with a median slope for 14,927 slide initiation sites of 27.5°. Four out of five slides initiated on 17° to 39° slopes. In contrast, 142,774 randomly selected non-landslide points in the Central Allegheny Plateau have a median slope of only 18°, with approximately four out of five points having 5° to 30° slopes.

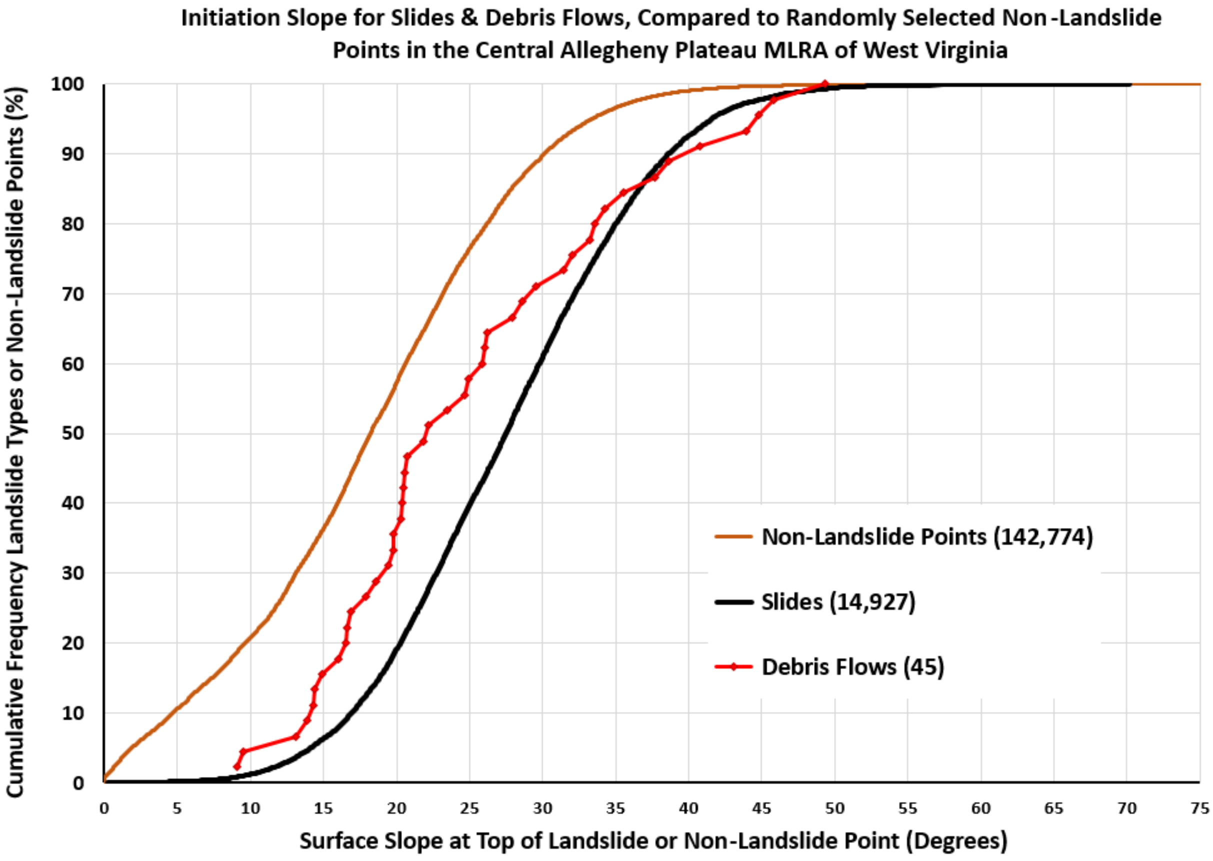

Figure 3. Comparison of initiation slopes for slides (including slumps) and debris flows with randomly selected points in the Central Allegheny Plateau of West Virginia. Initiation slope was measured at the uppermost point on a landslide as mapped from LiDAR-based DEMs.

In eastern West Virginia, where they are much more common, debris flows tend to initiate on somewhat steeper slopes than other landslides. However, the general statewide tendency is not shown by 45 debris flows documented in the Central Allegheny Plateau, a dissimilarity that may stem spuriously from the small number of mapped debris flows in the MLRA. The median slope at Central Allegheny debris flow initiation sites is 22°, and four out of five debris flows initiated on 14° to 40° slopes (Figure 3).

The numbers of multiple failures (3), laterals spreads (2) and falls (2) identified in the Central Allegheny Plateau using LiDAR-based DEMS are insufficient to draw significant conclusions. These landslide types are more common in other MLRA in the state.

Figure 4 is a graphical treatment of slope angle for LiDAR-based landslide mapping, WVGES mapped landslides and areas of rock fall risk (Lessing and others, 1976), and randomly generated non-landslide points. Differences between the WVGES failures and the LiDAR mapped landslides are striking, but without clear undisputable explanation.

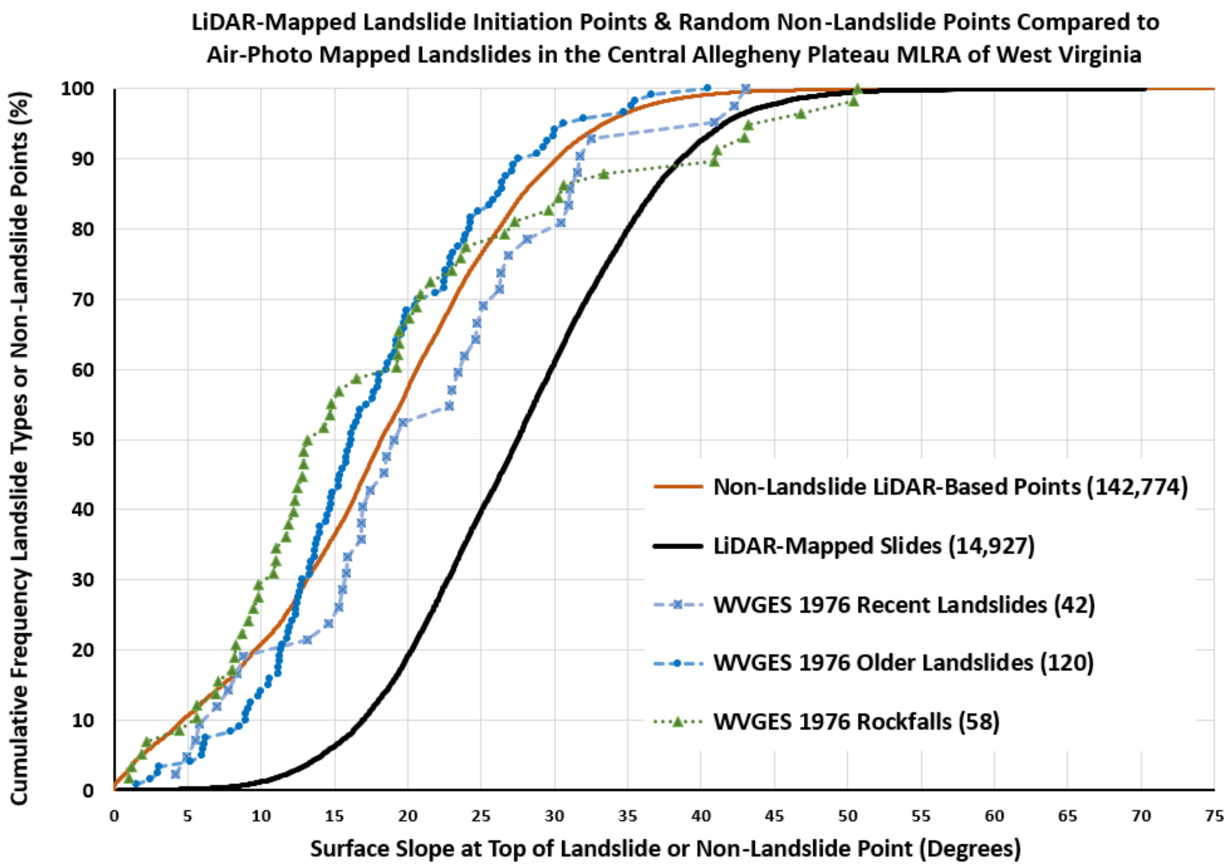

Figure 4. Comparison of initiation slopes for LiDAR-mapped landslides (including debris flows) identified in this project and air-photo-mapped landslides identified by the West Virginia Geological & Economic Survey (Lessing and others, 1976) with randomly selected points in the Central Allegheny Plateau. Initiation slope was measured at the uppermost point on a landslide or the most apparent initiation feature in a WVGES landslide polygon.

Although the 14,927 landslides mapped using LiDAR based DEMS tended to be on noticeably steeper slopes than randomly selected points, the WVGES mapped landslides showed complex slope trends that don’t differ greatly from the population of random points (Figure 4). Median slope angles for WVGES areas of rock fall risk (13°) and older landslides (16°) are less than the median for randomly selected points (18°). Even, the higher median slope for recent landslides (19°) may not be truly significant because of small landslide sample size.

Differences in slope angle trends between the WVGES mapped landslides and those mapped using LiDAR in this project may arise from differences in precisely what types of landslide features were mapped. Exploratory field landslide verification efforts at scattered sites throughout the Mountain State suggest inevitable differences in what types of features are apparent to a mapper using air photos, such as the WVGES efforts, versus what is apparent on LiDAR-based DEMs. Notably, the polygon- and line-based WVGES mapping was focused on landslide deposits, which may occur well downslope from the initiation sites that are the focus of point-based mapping in this project. Initiation points for WVGES landslide verification were selected only from within or at the edges of WVGES features, but an unknown number of initiation points may lie on steeper slopes above WVGES polygon boundaries.

It also is possible that some differences in slope trends stem from the fact that the relatively urban Monongalia County area in which WVGES landslides were verified was a small subset of the larger area for which the landslides and random points were located and two areas may differ significantly enough to weaken any comparison of these data.

Although the WVGES landslide maps represent a resource that warrant additional investigation, they are a geographically and land-use biased sample of the Central Allegheny Plateau MLRA. Moreover, WVGES mapping was not completed in other West Virginia MLRA. Accordingly, time constraints and uncertainties put these maps at a low priority and not investigated comprehensively in this project, so further discussion will be restricted to LiDAR-based landslide mapping and analysis.

Geology

Geology is a universally cited factor in landslide distribution, and this is the case in the Central Allegheny Plateau 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 MLRA. An assumption that sandstone-dominated bedrock should host more landslides than other geologic units may seem intuitive if one compares steep sandstone slopes to 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. Across the Central Allegheny Plateau, weaker bedrock units containing significant amounts of shale and siltstone tend to be more deeply incised and more prone to failure than resistant units, even if the weaker units contain some 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 use 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. The map is dated and does not differentiate some large geologic units (groups) into smaller mappable units (formations) that would allow more precise assessment of landslide susceptibility and risk in the Central Allegheny Plateau. 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 neither this report nor the West Virginia Landslide Tool should be used to substitute for site-specific analysis by landslide experts and geotechnical engineers.

<u>Geologic Map Units and Landslide Susceptibility</u>: The state geologic map (Cardwell and others, 1968) shows 9 different map units in the Central Allegheny Plateau, with individual extents ranging from 0.2 to 3930.8 mi^2. Seven units show bedrock geology; the others denote alluvial deposits and water. Two Pennsylvanian-aged WVGES bedrock map units overlap: the Kanawha Formation and the Pottsville Group. The Kanawha is the uppermost Formation in the Pottsville Group and mapped as a distinct unit covering 60 mi^2 throughout the MLRA, but Cardwell and others (1968) did not differentiate the Kanawha from the rest of the Pottsville in just over 13 mi^2 of Barbour and Monongalia counties. Most, if not all, of the Pottsville Group in the two counties is correlative to Kanawha Formation elsewhere, so data from the Pottsville Group were combined with the Kanawha Formation. This combination reduced the analysis of geology and landslides to 8 separate geologic units (Table 1).

WVGES Geologic Map Unit	Geologic Period	Mapped Land-slides Count	% Land-slides Mapped in Unit	% Random Points in Unit	Meas. Unit Area Mi^2	Meas. Unit Area %	Approx % of Unit Mapped	Estimate Failures /100 Mi^2
Water	Quat.	0	0.0	0.00	5.6	0.07	**	**
Alluvium	Quat.	149	1.0	5.86	435.0	5.06	48	71
Dunkard Group	Perm./Penn.	1489	10.0	20.12	3930.8	45.73	18	205
Monongahela Group	Penn.	3962	26.5	31.21	1842.6	21.44	61	352
Conemaugh Group	Penn.	8668	58.1	34.04	2021.1	23.52	61	706
Allegheny Formation	Penn.	508	3.4	6.88	299.4	3.48	83	205
Kanawha Formation	Penn.	151	1.0	1.87	60.0	0.70	100	224
Mauch Chunk Group	Miss.	0	0.0	0.01	0.2	0.003	100	**
Overall MLRA		14,927	100.0	100.00	8594.7	100.00	42	414

*Table 1. Simplified list of Central Allegheny Plateau geologic map units, show in stratigraphic order, and associated data for 14,927 landslides and 142,756 randomly generated points in the area. Sum of percentages may not equal overall MLRA totals because of rounding. Some insignificant digits are shown in percentages so that very small values don't appear as zero. Note ** the extents of water and the Mauch Chunk Group in the area are 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 41.95 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 142,774 non-landslide points in the same locations where landslides were mapped. A geologic unit was not determined for 16 of the non-landslide points. The actual total surface area covered by each geologic unit in the MLRA was calculated independently, but the approximate proportion of each unit in which landslides were mapped was inferred from the proportion of randomly generated points in the unit.

The Conemaugh Group provides an illustrative example of how point data were used. Mapping revealed 8,668 landslides in the group, which the geological map shows as covering 2021.1 mi^2, 22.52 percent of the MLRA. A simple mathematical adjustment of the number of slides based on 41.95 percent MLRA mapping coverage (n = 8,668/0.4195) would give a prediction of 20,663 Conemaugh Group landslides in the whole MLRA and a landslide susceptibility of 1022 failures/100 mi^2. However, the randomly generated point counts shows that 61 percent of the Conemaugh unit was mapped for landslides in the MLRA. The unit was over-sampled because it is dominant in eastern areas of the MLRA, where high-resolution LiDAR allowed landslide mapping, as opposed to other areas lacking high resolution LiDAR. Adjustment to the landslide susceptibility through multiplying by (measured geologic map unit area % / random points located in unit %) yields an approximate susceptibility estimate of 706 failures/100 mi^2 and provides an estimate of only 14,210 Conemaugh Group landslides within the MLRA: a smaller estimate, but still exceptionally high!

All bedrock in the Central Allegheny Plateau is highly susceptible to failure to varying degrees. The overall Central Allegheny Plateau susceptibility of 414 failures/100 mi^2 is more than eight times larger than the 50 failures/100 mi^2 estimate for Appalachian Ridges and Valleys, three times larger than the 138/100 mi^2 estimate for the Northern Alleghenies, and nearly 50 percent more than 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 estimate may be low because a large proportion of Central Allegheny Plateau mapping relied on DEMs based on 2 meter LiDAR, rather than higher resolution 1 meter LiDAR. No significant difference in mappers' ability to identify landslides was perceived during the process, but it is likely more landslides would have been discerned if higher resolution 1 meter DEMs had been uniformly available.

Table 1 shows the Conemaugh Group has both more mapped landslides and the highest susceptibility of any other unit. The estimated 706 failures/100 mi^2 in the Conemaugh Group is 70 percent higher than the area's overall average. No other geologic unit has more than 631 failures/100 mi^2 in any MLRA in West Virginia. Over 58 percent of the LiDAR mapped landslides in the MLRA are in the Conemaugh Group, but this percentage overstates the unit's preponderance in numbers of expected landslides because over 3/5ths of the Conemaugh was mapped at the time of this analysis, in contrast to less than 1/5th of the more extensive Dunkard Group. The Conemaugh is comprised of layers of siltstone and shale, with interbedded sandstone. Shale layers can be incompetent and serve as slip surfaces and can be sources for clay-rich residual and colluvial soils. The unit has long been recognized as landslide prone (Scheffel, 1920).

Monongahela Group landslide susceptibility is almost on par with the whole MLRA. Cardwell and others (1968) list sandstone as the primary rock type in the unit, followed by siltstone, shale, limestone, and coal. The latter includes the intensely mined Pittsburgh Coal, in addition to the Sewickley and Waynesburg seams that which have been surface mined in Monongalia and Marion counties (West Virginia Geological and Economic Survey, 2020a). The Monongahela Group has very limited exposure in other MLRA, where its lower landslide susceptibility may be an artifact of small sample size.

Three other bedrock units, the Dunkard Group, Allegheny Formation, and Kanawha Formation have estimated incidences ranging from 205 to 224 failures/100 mi^2, roughly half of the MLRA average. All three are sandstone dominated, but contain significant interbedded siltstone and shale. All three include coal beds, but are not extensively surface mined in the Central Allegheny Plateau MLRA of West Virginia.

The Dunkard Group is the youngest major bedrock unit in West Virginia, deposited in a span beginning during the late Pennsylvanian and ending early in the Permian period. Although it does not occur elsewhere in the state, the Dunkard Group is the most widespread of the Central Allegheny Plateau units, covering almost 46 percent of MLRA 126 in West Virginia. It is also the least well mapped unit, and the 1489 landslides recorded in less than 1/5th of the unit's area suggest as many as 8000 slope failure might have been mapped had the unit been fully examined.

The Allegheny and Kanawha formations have very high mapped landslide incidence in other areas in the Mountain State where they are heavily mined for coal. The Allegheny reached 631 failures/100 mi^2 within its limited extent in the Southern Allegheny Mountains, whereas the Kanawha reached 426 failures/100 mi^2 as the most extensive geologic unit in the Cumberland Plateau. Elsewhere, the landslide incidences in the two units are comparable to, or somewhat lower than, in the Central Allegheny Plateau.

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 methods and age of mining activity may account for significant variation, but these factors have not been addressed in this project. Generally, the role of mining on slope stability is not apparent from geologic data alone, and the relationships between mined lands and landslide susceptibility is more precisely addressed through discussion of soil parent materials.

The Mauch Chunk Group is limited to such a tiny area in the Central Allegheny Plateau (0.2 mi^2) that no landslides were mapped within its boundaries, although the geologic unit has exceptionally high susceptibility in other MLRA. Red laser light used to collect LiDAR data cannot significantly penetrate water, obscuring any underwater landslides, so it is unsurprising that no landslide initiation points were mapped in water polygons, which total only 5.6 mi^2 within the MLRA. The mapped extents of these two units are so limited that inferences on susceptibility should not be drawn concerning either unit in the Central Allegheny Plateau.

Landslide susceptibility in Central Allegheny Plateau alluvium is significantly lower than in bedrock units in the MLRA, but the 71 landslides/100 mi^2 identified in this unit is much higher than the 0 to 11 landslides/100 mi^2 documented for alluvium in other MLRA. As will be discussed in a later section, disparities in the abundance of landslides in the alluvium geological unit and comparable soil parent materials suggest as yet unidentified issues with the geologic data. The only geologic map unit composed of unconsolidated sediments, alluvium typically shows low landslide susceptibility despite its low inherent strength; its apparent stability is a result of the low-relief bottomland topography where alluvium occurs throughout most of West Virginia. The relatively high incidence of alluvial landslides the Central Allegheny Plateau may reflect the widespread existence of alluvial terraces in this MLRA compared to other areas. These terraces, which may include ancient lake deposits, were created by major rerouting and incision of the Ohio, Kanawha, and Monongahela river systems during the last two to three million years (Bonnett and others, 1991; Jacobson and others, 1988; White, 1896). More broadly, this geologically recent river erosion in the Central Allegheny Plateau has led to an instability of valleys and adjacent slopes that contributes to the MLRA's overall high landslide incidence.

Debris Flows: Although debris flows make up a tiny fraction of landslides in the Central Allegheny Plateau inventory, the sudden nature, extent, and other characteristics of debris flows and the consequent risks to safety and civil infrastructure warrant brief examination of how they relate to geology (Table 2). Debris susceptibility varies between geologic units, and the geology of the small sample of 45 debris flows looks dissimilar from overall landslides in the area.

WVGES Geologic Map Unit	Geologic Period	Mapped Debris Flows Count	% Debris Flows Mapped in Unit	% Random Points in Unit	Meas. Unit Area Mi^2	Meas. Unit Area %	Approx % of Unit Mapped	Estimate Debris Flows /100 Mi^2
Water	Quat.	0	0.0	0.00	5.6	0.07	**	**
Alluvium	Quat.	0	0.0	5.86	435.0	5.06	48	0
Dunkard Group	Perm./Penn.	13	28.9	20.12	3930.8	45.73	18	1.8
Monongahela Group	Penn.	12	26.7	31.21	1842.6	21.44	61	1.1
Conemaugh Group	Penn.	20	44.4	34.04	2021.1	23.52	61	1.7
Allegheny Formation	Penn.	0	0.0	6.88	299.4	3.48	83	0
Kanawha Formation	Penn.	0	0.0	1.87	60.0	0.70	100	0
Mauch Chunk Group	Miss.	0	0.0	0.01	0.2	0.003	100	**
Overall MLRA		45	100.0	100.00	8594.7	100.00	42	1.3

*Table 2. Frequency of debris flows in Central Allegheny Plateau geologic map units, show in stratigraphic order. Sum of percentages may not equal overall MLRA totals because of rounding. Some insignificant digits are shown in percentages so that very small values don't appear as zero. Note ** the extents of the water geologic unit and the Mauch Chunk Group in the area are too small for meaningful estimation of failures/100 mi^2.*

Debris flows were mapped in the three most extensive geologic units, but none were identified in units covering less than 1800 mi^2. The overall MLRA average of 1.3 debris flows/100 mi^2 is less than documented in the Northern Alleghenies (1.9), Ridges and Valleys (4.0), Cumberland Plateau (4.0), and Southern Alleghenies (6.9). The scarcity of mappable debris flows in the Central Allegheny Plateau and the adjacent Northern Allegheny Mountains may reflect their greater distance from the Gulf of Mexico and Atlantic moisture sources that provide the levels of atmospheric moisture required for the intense rainfall that triggers most Appalachian debris-flow events.

The small sample of debris flows in the MLRA allows few geologic inferences. Twenty of the 45 debris flows were mapped in the Conemaugh Group, the unit with the second highest debris flow susceptibility. The incompletely mapped Dunkard Group appears to have the most debris flows /100 mi^2, although the sample size and limited mapping coverage may not permit significant differentiation between the Dunkard and the Conemaugh or Monongahela groups. Identification of just a handful of unmapped debris flows could change the appearance of Table 2 without necessarily conveying any meaningful trend. Debris flows may have long run outs, so some locations in geologic units with low susceptibility may be at risk due to conditions far upslope.

Soils

Analysis of mapped landslides and the digital NRCS Soil Survey Geographic database (SSURGO) indicate soil parent material and drainage class correlate with landslide susceptibility in the Central Allegheny Plateau. The SSURGO 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 task. Soil series are the basis of soil mapping, and most soil series develop from a dominant parent material and have a dominant drainage classification. Nevertheless, very few sizeable landforms contain only one soil series. Most soil map polygons in mountainous landscapes are designated by the one or two most dominant soil series, though other series exist as inclusions in the polygons. In typical MLRA 126 soil survey map units, parent material and drainage class are apt to differ significantly throughout individual polygons. The inexactness of soil maps and the dominance of only three parent materials and two drainage classes in the MLRA limit analyses to very general interpretations about soils and where landslides initiate in the Central Allegheny Plateau.

Soil Parent Material: SSURGO data provide the basis for 11 different soil parent materials in the Central Allegheny Plateau (Table 3). Water is not true soil parent material, but is included in SSURGO data and Table 3. Parent material and drainage class were not determined for three of the 14,927 mapped slides and 23 of the 142,774 non-landslide points modelling by Maxwell and others (2020); these points are not incorporated into soil attribute tables that follow.

NRCS Soil Parent Material	Landslide Count	% of All Failures	% Non-Landslide Points	Approx. Mapped Area Mi^2	Approx. Failures /100 Mi^2
Residuum, Acid Clastic	12,193	81.70	61.78	2227.5	547
Residuum, Calcareous Clastic	1425	9.55	11.86	427.5	333
Colluvium	997	6.68	13.26	478.0	209
Mining Regolith	171	1.15	0.76	27.4	625
Disturbed Areas	90	0.60	1.74	62.9	143
Recent Alluvium	39	0.26	5.67	204.3	19
Old Terrace Alluvium	6	0.04	3.21	115.8	5
Lake Deposits	3	0.02	0.47	17.0	18
Water	0	0.00	1.23	44.2	0
Eolian Sands	0	0.00	0.02	0.8	**
Residuum, Limestone	0	0.00	0.004	0.2	**
Overall Central Allegheny Plateau	14,924	100.00	100.00	3605.5	414

*Table 3. Dominant soil parent materials for slides (including slumps) in the Central Allegheny Plateau, listed in decreasing order of landslide counts. Sum of columns may not equal overall MLRA totals because of rounding. An added insignificant digit is shown for limestone residuum percentage so its small value doesn't appear to be zero. Note ** the extents of the eolian sands and limestone residuum in the area are too small for meaningful estimation of failures/100 mi^2.*

Almost 98 percent of slides were mapped in residuum developed from clastic sedimentary bedrock or in colluvium, parent materials that occur at almost 87 percent of points randomly selected across the Central Allegheny Plateau (Table 3). Over four-fifths of mapped slides occur in acid clastic residuum; the parent material's estimated 547 landslides/100 mi^2 indicate it is significantly more susceptible to failure than the MLRA as a whole. The 333 landslides/100 mi^2 in calcareous clastic residuum is high, but below the MLRA average; this material yields the second highest total number of slides, even though it covers the third largest area. Colluvium, which covers the second largest extent, shows about half of the slide susceptibility of the whole MLRA.

Mining regolith is the most slide-prone parent material (Table 3). Most of the mining regolith slides mapped in this MLRA lie within the Conemaugh and Monongahela group bedrock units, most likely associated with materials produced by extensive mining of the Pittsburgh Coal, which lies immediately above the contact boundary between the two groups. Landslide mapping in the Southern Alleghenies have identified many landslides associated with old unreclaimed coal mine benches, haul roads, and spoil accumulated downslope from mines (Remo, 1999; Yates and others, 2016), but landslides also occur 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 if the exceptional landslide susceptibility in mining regolith is relic from old practices or an issue common to mined lands of all generations.

SSURGO data suggest disturbed land has below average slide 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 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.

Soil polygons linked to the other six parent materials have slides/100 mi^2 values that are underrepresented by a factor of 20 or more. No slides were mapped within water, eolian sands, or limestone residuum parent material polygons. The absence of slides in water may arise from the fact that red laser light used in LiDAR will not significantly penetrate below water surfaces, whereas the low numbers in the other two materials may lack statistical significance because of the tiny areas they cover.

Recent alluvium, old terrace alluvium, and lake deposits are all unconsolidated deposits analogous to the broad WVGES alluvium geologic unit. Collectively, the three NRCS parent materials exhibit 14 slides/100 mi^2 (Table 3), just one-fifth of the susceptibility indicated by the alluvium geologic map unit (Table 1). NRCS and WVGES data both show relatively low susceptibility compared to the whole Central Allegheny Plateau, but the reasons for the five-fold disparity between by polygons from geologic maps versus polygons from soil maps is unclear. Particularly problematic, though not shown in table 3, is the fact that only four mapped landslides occurring in the alluvium geologic unit polygons were also found to be located within alluvial or lake sediment soil parent materials. Inexplicably, 133 mapped landslides located in the alluvium geologic unit appear to be located in residual soil parent materials. It may be revealing that randomly selected points indicate the WVGES geologic map alluvium polygons covers less than 158 mi^2 of the LiDAR-mapped area, whereas NRCS soil parent material polygons indicate the alluvial and lake deposits, when combined, cover more than 337 mi^2 in the very same area. The WVGES state geologic map is very conservative in its portrayal of non-bedrock geologic units, so the larger extent of alluvium and associated deposits indicated by NRCS soil parent material is presumably more accurate.

Tabulation of debris flows within the Central Allegheny Plateau shows these long-runout failures initiate in only two soil parent materials (Table 4). Two-thirds of the debris flows were mapped in acid clastic residuum while one-third were identified in calcareous clastic residuum. The small total number of debris flows and limited extent of some soils parent materials prevent meaningful statistical analysis, but calcareous clastic residuum appears over-represented with debris flows.

NRCS Soil Parent Material	Debris Flow Count	% of Debris Flows	% Non-Landslide Points	Approx. Mapped Area Mi^2	Approx. Debris Flows /100 Mi^2
Residuum, Acid Clastic	30	66.7	61.78	2227.5	1.3
Residuum, Calcareous Clastic	15	33.3	11.86	427.5	3.5
Colluvium	0	0.0	13.26	478.0	0.0
Mining Regolith	0	0.0	0.76	27.4	0.0
Disturbed Areas	0	0.0	1.74	62.9	0.0
Recent Alluvium	0	0.0	5.67	204.3	0.0
Old Terrace Alluvium	0	0.0	3.21	115.8	0.0
Lake Deposits	0	0.0	0.47	17.0	0.0
Water	0	0.0	1.23	44.2	0.0
Eolian Sands	0	0.0	0.02	0.8	**
Residuum, Limestone	0	0.0	0.004	0.2	**
Overall Central Allegheny Plateau	45	100.00	100.00	3605.5	1.2

Table 4. Dominant soil parent materials for debris flow initiation sites mapped in the Central Allegheny Plateau. Materials are listed in decreasing order of the number of all slides shown in Table 3.

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 drainage class of "water" is assigned to some MLRA 126 soil layer polygons and shown in Table 5.

NRCS Soil Drainage Classification	Mapped Slide Count	% of Mapped Slides	% Non-Landslide Points	Approx. Mapped Area Mi^2	Approx. Failures /100 Mi^2
Excessively Drained	5	0.03	0.52	18.6	27
Somewhat Excessively Drained	10	0.07	0.16	5.9	171
Well Drained	14,448	96.75	90.68	3269.4	442
Moderately Well Drained	415	2.78	5.53	199.5	208
Somewhat Poorly Drained	45	0.30	1.14	41.2	109
Poorly Drained	1	0.01	0.74	26.7	4
Very Poorly Drained	0	0.00	0.00	0.0	**
Water	10	0.07	1.23	44.2	23
Central Allegheny Plateau Total	14,934	100.00	100.00	3605.5	414

Table 5. Drainage classes for soils and relative abundance of LiDAR mapped slides (including slumps) in the Central Allegheny Plateau. Classes are listed from most drained to least drained. Sum of columns may not equal totals because of rounding.

Soil polygons assigned as "well drained" contain over 90 percent of randomly selected points in mapped potions of the Central Allegheny Plateau MLRA, account for almost 97 percent of slide initiation points, and have the highest slide susceptibility (Table 5). Although not shown in table 5, well drained soils also account for 44 of 45 debris flows mapped in the MLRA. Clearly this drainage class presents slope stability issues, but their near ubiquity in the Plateau make well drained soils very difficult to avoid. This drainage class commonly occurs on steep slopes, so its over-representation in number of slides may reflect a key role of slope as a control of both soil drainage and landslide initiation.

Moderately well drained soils cover 5.5 percent of the area and contain the second highest number of slides and second highest landslide susceptibility of any class. Small slide counts and limited extents suggest interpretations from other drainage classes may not be robust. Collectively, somewhat poorly drained and somewhat excessively drained soils make up 1.3 percent of randomly selected points in the MLRA and both have moderately high susceptibilities well below the MLRA average. Poorly drained and excessively drained soils comprise under 1.3 percent of random points but have very low susceptibilities. As expected because of the refection of LiDAR by water surfaces, very few slides were mapped in water drainage class polygons. Very poorly drained soils are not located in any soil polygons, thus they are not associated with any landslides.

Soil moisture is a transient characteristic. Drainage classes are assigned under normal moisture conditions, but most landslides fail under unusual 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 table, improper surface drainage alteration, or failure of waterlines.

Compared to geologic maps, soil maps are potentially more precise proxies for the distribution of unconsolidated earthy materials and their associated drainage classes. However, the scale and extent of soil map polygons in West Virginia commonly are orders of magnitude larger than the dimensions of landslide initiation scars, while drainage over the entire polygon is typically assigned based only on the map units primary soil series, which commonly has different parent material or drainage class than 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 may be dominated by 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 colluvium. According to this model, landslides would tend to initiate in local inclusions of soils more poorly drained than in the better drained adjacent soils that dominate map polygons. Soil scientists are working to address polygon scale issues in mapping mountain soils, so future landslide research may have precise soil-landscape model data for susceptibility analysis.

Other Landslide Factors

Although many factors influencing slope stability are universal, some aspects of slope stability in the Central Allegheny Plateau differ from other areas in West Virginia. Anthropogenic disturbance is significant in the Plateau, especially in urban areas and landscapes underlain by or adjacent to coal-bearing bedrock. Urban and rural development has long been known to enhance landslide susceptibility in West Virginia (Scheffel, 1920; Fonner, 1987). Although not easily documented using LiDAR-based DEMs, unreclaimed mine high walls have high local rock-fall susceptibility, while rock falls elsewhere in the area commonly occur on over-steepened road and railroad cuts or construction and excavation sites.

Hillslopes underlain by weak bedrock or soil may obtain a significant fraction of their shear strength from tree roots, so intensive clearing for timber harvesting or real estate development may lessen slope strength. Ill-designed or poorly constructed roadways, commercial sites, and housing developments may lead to surface drainage disruptions that cause unprecedented soil saturation and abnormal slope destabilization. The importance of good engineering design, based on slope-stability site analysis by professional geologists and certified civil engineers, cannot be over-emphasized. Neither can the importance of long-term monitoring and maintenance of constructed drainage and retaining structures.

Bedrock geology, anthropogenic development, and drainage history may work together to contribute to the exceptionally high landslide susceptibility in the Central Allegheny Plateau. The two most susceptible geologic units, the Conemaugh and Monongahela groups, crop out in six of the top seven West Virginia cities ranked by 2020 population: Charleston, Huntington, Morgantown, Wheeling, Fairmont, and Weirton (U.S. Census Bureau, 2021). Parkersburg, the fourth most populous city, lies in a landscape dominated by the Dunkard Group and alluvium. All seven of these cities lie along river systems that have deeply incised in the last few million years.

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. One of the most remarkable rainfall events in United States history occurred within the Central Allegheny Plateau, when 19.5 inches of rainfall fell during 2 hours and 10 minutes on 18 July 1889 in the Wood County community of Rockville (Smith and others, 2011). Newspaper accounts of the event describe “torrents” (The Daily State Journal, 1889), a term that occasionally in the past was applied to landslides now known as debris flows. USGS landslide mapping by Hackman and Thomas (1978) did not specifically address the impact of the 1889 event, but their Rockport topographic quadrangle map does show an unusually high concentration of landslides in the area where extraordinary rainfall was recorded.

Outside of MLRA 126, 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, 1993). 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. 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 Central Allegheny Plateau and elsewhere in the state may become more frequent with ongoing changes in climate.

This assessment targeted the geographic distribution of landslide susceptibility as a step in assessing landslide risks. 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.

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