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 developed in residuum and colluvium. The Conemaugh Group, a bedrock unit with very few mineable coal resources, has the highest landslide susceptibility, but unconsolidated material produced by mining in other bedrock units 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.

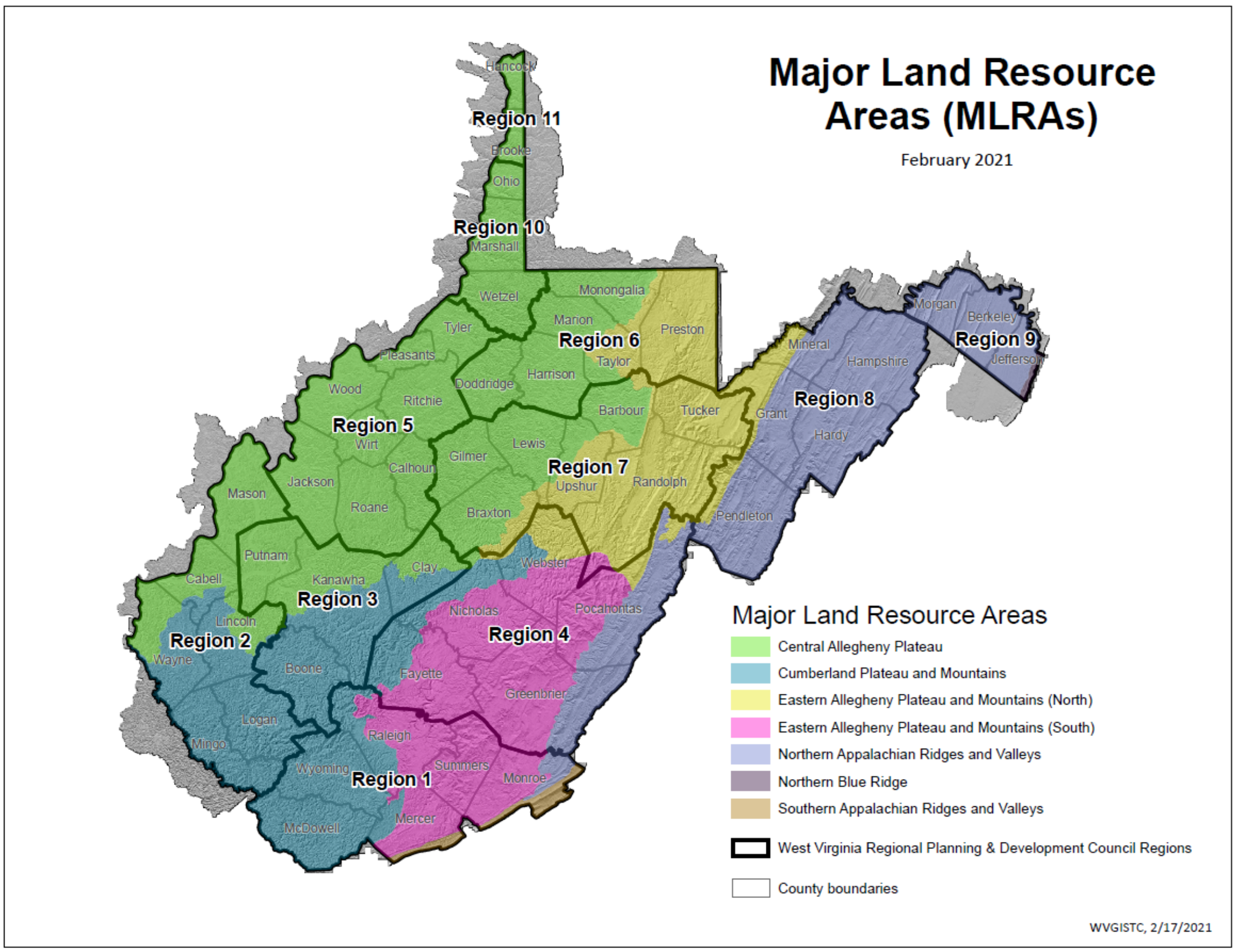

Figure 1: Map of Natural Resources Conservation Service Major Land Resource Areas (MLRAs), Planning and Development Regions, and county boundaries in West Virginia, shown on a shaded relief topographic base map.

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 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 as shown in a U.S. Geological Survey (USGS) map by Fenneman and Johnson (1946) and the Allegheny Plateau province as 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, 2003) 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.

The NRCS 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 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 limestone units 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 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 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 highwalls. 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 than those from other MLRAs in the state.

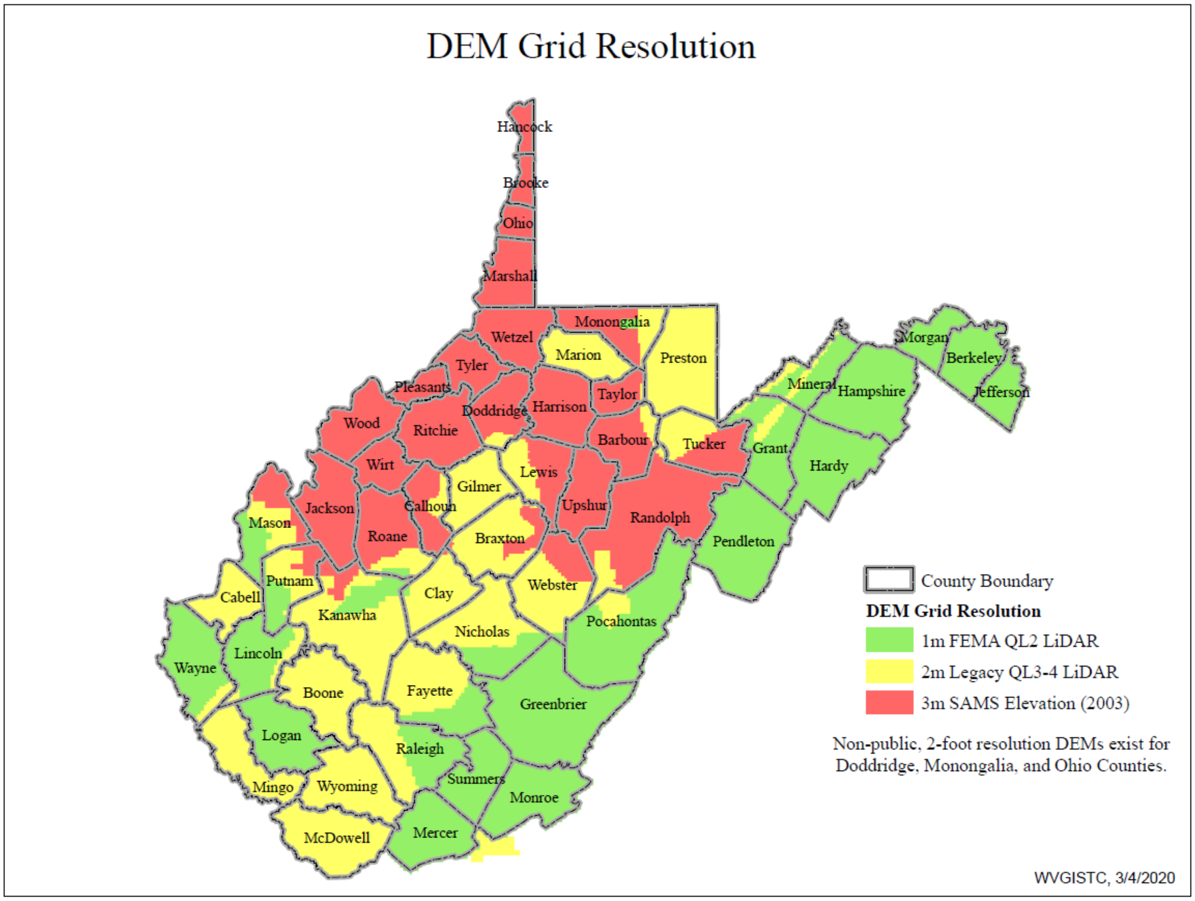

Figure 2: Map of Digital Elevation Models (DEM) availability for West Virginia at the onset of landslide analysis in March 2020. Analysis focused on areas with 1 or 2 meter DEMs.

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.

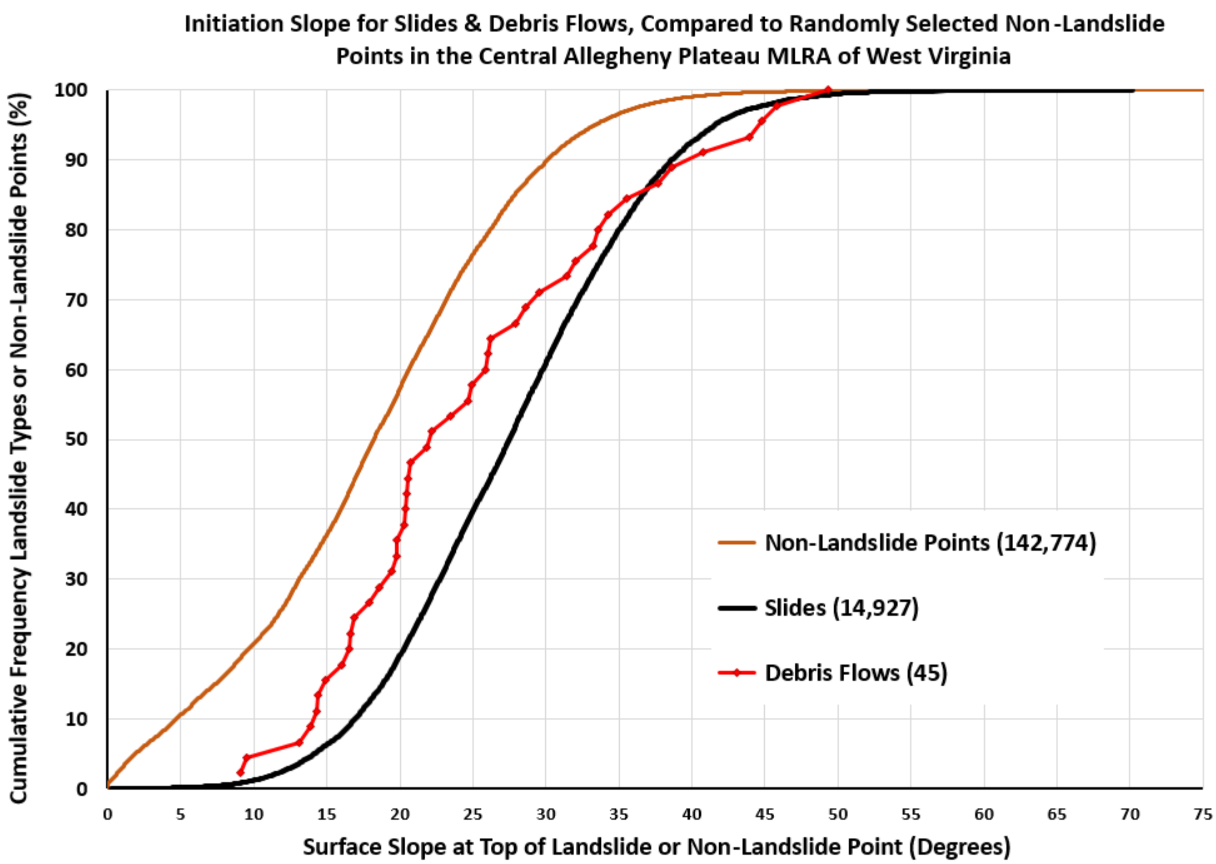

Figure 3. Comparison of initiation slopes for slides (including slumps) and debris flows with randomly selected points in the Central Allegheny Plateau of West Virginia. Initiation slope was measured at the uppermost point on a landslide as mapped from LiDAR-based DEMs.

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 MLRAs 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.

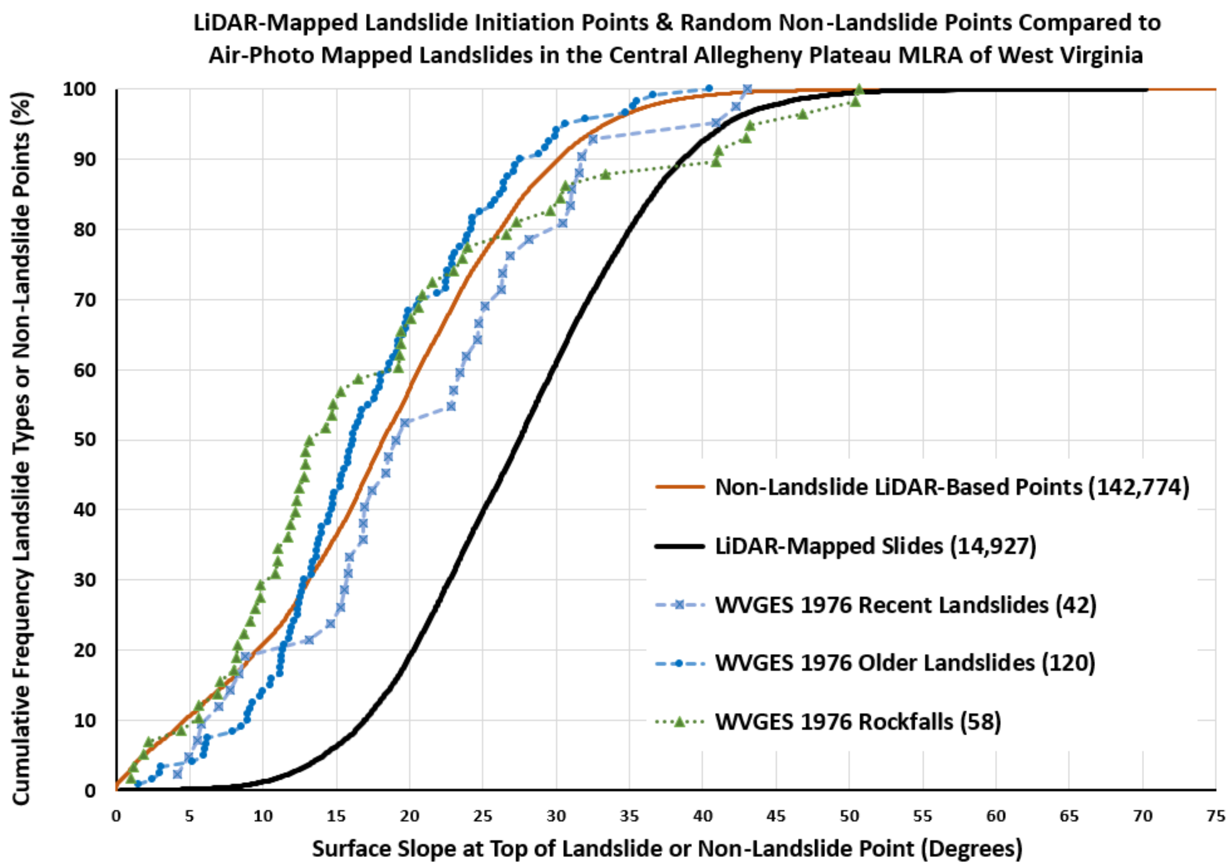

Figure 4. Comparison of initiation slopes for LiDAR-mapped landslides (including debris flows) identified in this project and air-photo-mapped landslides identified by the West Virginia Geological & Economic Survey (1976) with randomly selected points in the Central Allegheny Plateau. Initiation slope 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, 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 may 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 MLRAs. Accordingly, time constraints and uncertainties put these maps at a low priority resource that was 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, 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.

Geologic Map Units and Landslide Susceptibility: 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 142,774 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. 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 the Conemaugh unit comprised 61 percent of the area 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 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 3/5^{ths} 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 exceptionally 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 and the Sewickley and Waynesburg seams, 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 MLRAs, 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 the Allegheny has been more heavily mined within the Central Allegheny Plateau MLRA.

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 $1/5^{th}$ 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 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 the 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 MLRAs. 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 MLRAs. The only 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 reflects the widespread existence of high alluvial terraces in this MLRA compared to other areas. These high terraces 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, the geologically recent 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.

Urban and rural development enhances landslide susceptibility in many areas of West Virginia (Fonner, 1987). Recent geologic history, geology, and development may work together to produce the exceptionally high landslide susceptibility in the MLRA. 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 in Central Allegheny Plateau that have deeply incised in the last few million years.

Debris Flows: Although debris flows make up a very small fraction of all 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 water 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 mean 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 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.

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