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LiDAR, GIS, and multivariate statistical analysis to assess landslide risk, Horseshoe Run watershed, West Virginia

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LiDAR, GIS, and Multivariate Statistical Analysis to Assess Landslide Risk, Horseshoe Run Watershed, West Virginia

Kory M. Konsoer

**Thesis Submitted to the Eberly College of
Arts and Sciences at West Virginia
University In Partial Fulfillment of the
Requirements for the Degree of**

Master of Science in Geology

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Abstract:

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Kory M. Konsoer

Current stream restoration practices focus on stabilizing banks, transporting sediment, and creating aquatic habitats. However, only channel morphology data are collected prior to typical restoration project designs. A more thorough approach to assessing restoration projects incorporates the geomorphology of the contributing hillslopes within the watershed. For this project, a landslide risk assessment was conducted for Horseshoe Run watershed in West Virginia using LiDAR data, GIS, and multivariate statistical analysis to provide the restoration projects with information concerning the geomorphology of the hillslopes and identify areas of greater risk for slope failure. A landslide inventory map was created using field observations and remote mapping on a LiDAR-derived shaded relief map within ArcGIS 9.2. Landslides were classified as planar slides, rotational slumps, debris flows, debris fans, debris slides, or active slopes. Seven variables were determined for all landslides: elevation, slope angle, slope aspect, distance from roads, distance from streams, plan curvature, and profile curvature. Similar data on the same seven variables also were collected for a random sample of unfailed slopes, and both data sets were used for discriminant analyses using Minitab 13.30. A first discriminant analysis of all failed and unfailed slopes was 71.8% accurate in predicting failures and non-failed slopes, suggesting a significant difference between the two populations. A second discriminant analysis was 76.3% accurate in determining differences between classifications of slope movements. The discriminant analyses results were used to create a landslide susceptibility map for Horseshoe Run watershed, classifying the hillslopes as low, medium, or high risk for failure. Areas classified as high risk areas were further analyzed to determine whether they were contributing to the channel instability of Horseshoe Run. The landslide susceptibility map also provided a means to evaluate locations of concern for slope stability and also identify potential areas of disturbance for Horseshoe Run.

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Table of Contents

Abstract:.....	ii
Acknowledgements:.....	iii
Table of Contents.....	iv
List of Figures.....	v
List of Plates.....	vi
List of Tables.....	vii
Introduction:.....	1
Purpose:.....	8
Objectives:.....	9
Study Area:.....	10
Bedrock Stratigraphy and Structure.....	14
Previous Studies:.....	21
Methodology:.....	27
Surficial Geology Map:.....	27
Selection of Variables:.....	30
Mapping of the Landslides:.....	34
Statistical Analysis of Landslides:.....	38
Landslide Susceptibility Map:.....	43
Results:.....	45
Surficial Geology Map of Horseshoe Run watershed:.....	45
Landslide Inventory Map and Statistical Analyses:.....	48
Landslide Susceptibility Map:.....	58
Conclusions:.....	62
Discussion of Fluvial Instability on Horseshoe Run:.....	67
Discussion of the Landslide Susceptibility Map:.....	73
References:.....	79
Appendix A:.....	90
Appendix B:.....	107
Appendix C:.....	111
Appendix D:.....	114
Appendix E:.....	119
Appendix F:.....	123

List of Figures

Figure 1: Location map of Horseshoe Run watershed.....	3
Figure 2: Tributary showing evidence of slope movements forcing stream response.....	5
Figure 3: Photograph of Horseshoe Run watershed showing steep terrain and heavy vegetation.....	11
Figure 4: Photograph of Horseshoe Run watershed showing steep topography.	12
Figure 5: Location map of Horseshoe Run watershed in relation to the Cheat River basin.	13
Figure 6: Geologic map of Horseshoe Run watershed.	15
Figure 7: Geologic cross-section of Horseshoe Run watershed..	16
Figure 8: Photograph of a coarse grained alluvial terrace within Horseshoe Run watershed..	19
Figure 9 Coarse, subangular to subrounded cobbles in a debris flow deposit in Horseshoe Run watershed.....	20
Figure 10: Bouldery gelifluction lobes on Backbone Mountain.....	29
Figure 11: LiDAR-derived shaded relief map image showing an example of a debris fan..	35
Figure 12: LiDAR-derived shaded relief map showing an example of a debris flow.	36
Figure 13: LiDAR-derived shaded relief map showing an example of a debris slide.....	37
Figure 14: LiDAR-derived shaded relief map showing an example of a planar slide.....	39
Figure 15: LiDAR-derived shaded relief map showing an example of a rotational slump..	40
Figure 16: LiDAR-derived shaded relief map showing an example of an active slope.. .	41
Figure 17: Large boulder field on Backbone Mountain, Horseshoe Run watershed.....	47
Figure 18: Summary of discriminant analysis of failed versus unfailed slopes within Horseshoe Run watershed.....	52
Figure 19: Summary of discriminant analysis of the classification of slope movements including unfailed slopes.	53
Figure 20: Summary of discriminant analysis of the different classifications of failed slopes within Horseshoe Run watershed.....	54
Figure 21: Rose diagrams showing the preferred aspects for planar slides and rotational slumps within Horseshoe Run watershed.	55
Figure 22: Rose diagram showing the preferred slope aspects for debris flows and debris fans within Horseshoe Run watershed.....	56
Figure 23: Rose diagrams showing the differences in aspect of debris fans and unfailed slopes with slope angles between 28-32°.....	57
Figure 24: Landslide susceptibility map showing the confluence of Wolf Run and Horseshoe Run and the relative sizes of both drainage basins.	77
Figure 25: Landslide susceptibility map showing the location of Maxwell Run and its confluence with Horseshoe Run..	78

List of Plates

Plate 1: Surficial Geology Map of Horseshoe Run watershed, Tucker and Preston Counties, West Virginia.....	87
Plate 2: Landslide Inventory Map for Horseshoe Run watershed	88
Plate 3: Landslide susceptibility map of Horseshoe Run watershed.	89

List of Tables

Table 1: Stratigraphic Units in Horseshoe Run watershed (from Reger, 1923).	17
Table 2: Classifications of surficial geology features and the characteristics used to remotely map them within Horseshoe Run watershed.	31
Table 3: Number of different types of slope movements mapped within Horseshoe Run watershed.	50
Table 4: Mean values of landscape variables used in the landslide analyses for the different types of slope movements.	51
Table 5: Landslide susceptibility risk and the percentage of area within Horseshoe Run.	61

Introduction:

Geologic hazards, such as landslides, are a serious threat to both life and property. In the United States alone, it is estimated that landslide hazards cause between \$1-2 billion in damages and average more than 25 deaths per year (U.S. Geological Survey, Landslide Hazards Program). The state of West Virginia is especially vulnerable to mass-wasting events given its steep topography in the Appalachian Mountains, and the effects of decades of logging and mining. Understanding which factors contribute to slope failures are therefore invaluable in the monitoring, prediction, and mitigation of mass-wasting events.

Mass-wasting events also can have an effect on the natural landscape by modifying the morphology of streams and altering local biologic populations. These two concepts have been linked together by the river continuum concept (Vannote, 1980), which states that the dynamic geomorphologic processes occurring at the reach scale help to define specific habitats in which certain organisms prefer. Therefore, altering the stream morphology can be devastating to local stream ecology. Additionally, numerous studies have shown that an accumulation of fine sediment, often introduced by mass-wasting events or anthropogenic alterations, can have a significant impact on benthic, insect, and fish populations (Kaller and Hartman, 2004; Kreutzweiser *et al.*, 2005; Rabeni *et al.*, 2005; Cordone and Kelley, 1961; Cederholm *et al.*, 1980).

Relationships between hillslope failures and fluvial adjustments have also been intensely studied (Harvey, 2001; Downs and Gregory, 1998; Michaelides and Wainwright, 2002). Many different morphologic responses as a result of landslides have been observed and documented. Debris flows are extremely erosive and have been shown

to scour low order tributaries to bedrock and remove stored sediment from terraces (Cenderelli and Kite, 1998). Debris flows have also been shown to cause damming of stream channels in lower order tributaries in mountain basins (Hoffman and Gabet, 2002). These debris flow dams cause deposition of fine grained sediment upstream and cause braiding downstream due to increases in sediment load. By modifying the channel morphology and sediment transportation, alterations in the stream hydrograph can occur, which may increase the potential risk of flooding for a given segment of the stream.

Through stream restoration, and more specifically natural stream channel design, the negative effects caused by natural and anthropogenic disturbances can be mitigated and often corrected. By diverting flow to the thalweg of the channel, revegetating riparian areas, restoring water quality, and adding habitat structures, biologic communities can proliferate, stream bank erosion can be minimized, and sediment transportation rates can be adjusted. Growing concerns for our national waterways has lead to an increase in the number of stream restoration projects within the past decade. Restoration projects can be seen on large rivers, such as the Mississippi (Theiling, 2006), which affects millions of people, to smaller low-order tributaries that are of great importance to the sustainability of fish and other biologic populations (Muotka *et al.*, 2002).

Horseshoe Run watershed is located in Tucker and Preston counties, West Virginia. The stream is approximately 27.23 km in length and drains an area of about 143.7 km² (55.5 mi²) (Figure 1). Time-series aerial photography has shown that for at least 100 years, Horseshoe Run has migrated widely across its floodplain, transporting large amounts of coarse alluvium. The primary source of the alluvium is believed to be from bank erosion (Greene, 2008) and may also be introduced by local hillslope

Figure 1: Location map of Horseshoe Run watershed. Numbers on map indicate the locations of the examples of surficial features shown in subsequent figures.

processes, mostly landslides and debris flows. This instability has prompted local residents and the Canaan Valley Institute (CVI) to begin implementing natural channel design restoration projects to increase the stability of the channel banks and increase alluvial sediment transportation efficiency in selected reaches.

Exact causes for the excessive sediment supply within Horseshoe Run watershed are unknown; however, one proposed explanation is intense logging around A.D. 1900 (Reger, 1923), which increased runoff and colluvial processes. Whatever the cause of the increased sediment supply, there is a direct relationship between large amounts of colluvial sediments and the instability of stream channels (Korup, 2005; Cenderelli and Kite, 1997). Direct observations within the watershed reveal hillslope sediment is forcing stream response (Figure 2).

Stream restoration techniques have recently focused on increasing channel stability, sediment transport potential, water quality, and habitat rehabilitation. Prior to the implementation of a restoration project, it is common practice to complete an analysis of the current conditions and determine long term goals for each restoration project (Canaan Valley Institute, 2007). In the context of Horseshoe Run, CVI conducted numerous assessments, such as morphological stream assessment, bankfull determination, regional curve validation, and sediment transport assessment and prediction (Canaan Valley Institute, 2007). These assessments were carried out for the lower 6.1 km (3.8 mi) of the stream, and it was determined that heavy sediment loads from upstream, in-channel sources were the primary causes of channel instability (Canaan Valley Institute, 2007).

Figure 2: Tributary showing evidence of slope movements forcing stream response. Location of landslide number 1 shown on Figure 1.

In order to create a fully successful natural channel design restoration project, it is vital to incorporate information for the entire watershed. However, no assessment of the hillslope geomorphology within the watershed was performed before natural channel design techniques were applied. Ignoring, or overlooking, geomorphological hillslope processes within the watershed could leave restoration techniques as futile attempts, or even worse, have a detrimental effect of the watershed as a whole.

Most commonly, slope movements initiate as a result of either brief, high intensity rainfall or prolonged seasonal snowfall and rainfall that provide large amounts of soil moisture. In either case, certain slope conditions prior to rainfall are necessary conditions for slope failure to occur in response to a triggering precipitation event. Variables that describe these conditions include slope angle, slope aspect, vegetation cover, underlying bedrock lithology, geologic structure, soil texture and thickness, soil mineralogy, geohydrology, and proximity to streams and anthropogenic alterations, Slope failures typically result from a combination of these factors; as well as other possible factors.

Many different methods have been used to study and map landslides, such as inventory maps, susceptibility maps, and predictive maps (Van Den Eeckhaut *et al.*, 2007; Wieczorek *et al.*, 2006; Duman *et al.*, 2005; McKean and Roering, 2004). Inventory maps show the location and spatial distribution of previously failed slopes in a given area. Although these types of maps are an important first step in studying landslides, they provide no further information to protect against future landslide events. Susceptibility maps, on the other hand, provide information to assist in landslide prediction. Susceptibility maps are based on general knowledge of how slope failures

occur; for example, designating areas with steeper slopes as higher risk areas. Landslide susceptibility maps show a qualitative likelihood of failure for given areas, and usually categorize slopes as having low, medium, or high risk. While susceptibility maps provide more information than inventory maps, the use of susceptibility maps in preventative management is limited. Predictive landslide maps, however, are more useful for management decisions because they incorporate a probability of slope failure based on dates of previously failed slopes. Information about the frequency of slope failures, along with data collected on specific variables known to increase slope risk, result in an objective landslide predictive map.

Regardless of which type of landslide map is being created, the use of a geographic information system (GIS) is extremely valuable. GIS allows for easy manipulation of digital maps that can be combined to create a final digital output map, presenting those areas at higher risk for landslides, and allows easy updates and corrections that may arise due to new information. The use of GIS is also important when dealing with large study areas that may have limited access, or are difficult to traverse, which is the case for Horseshoe Run watershed. In such cases, the use of remote sensing data, such as Light Detection and Ranging (LiDAR), is invaluable because it optimizes time spent in the field and allows for mapping surficial features that would otherwise be unseen.

Purpose:

The primary working hypothesis for this project is that slope movements are a factor contributing to the channel instability of Horseshoe Run. Consequently, in order to test this hypothesis, a detailed slope analysis is required in order to determine which slope failure factors are the most important within Horseshoe Run watershed and to assess risk at landslide prone sites. Landslide susceptibility was determined by creating a surficial geology map for Horseshoe Run watershed to show the spatial distribution of landforms and deposits. From the surficial map, a landslide inventory map was formed. GIS was used to collect data from each slope movement using seven different LiDAR-derived variables: slope angle, slope aspect, elevation, plan curvature, profile curvature, distance from roads, and distance from streams. The data collected were then tested for correlation between variables and used in a discriminant analysis to determine which factors are most important to slope failure.

Objectives:

An in-depth understanding of the geomorphology of Horseshoe Run watershed is necessary in order to understand sediment transport controls that directly impact restoration efforts. Landslides can affect stream channels not only by direct forcing of channel changes, but also indirectly through legacy sediments stored in the system. Examining the entire watershed, both channels and hillslopes, allows for integrated restoration and management, and will result in the highest level of success.

The objectives of this study are, therefore, to:

1. Create a surficial geology map of the watershed using LiDAR, GIS, and limited field work. This map will show the distribution of landforms and surficial deposits.
2. Determine if statistical thresholds exist between different classifications of slope movements.
3. Determine factors directly influencing slope stability within the watershed using the student's t-test and discriminant analysis.
4. Determine thresholds of failure for each factor, in order to select areas that have a greater risk of slope failure.
5. Create a landslide susceptibility map using advanced multivariate statistical analysis techniques and GIS.
6. Evaluate whether slope failures are a cause of significant channel instability along Horseshoe Run.

Study Area:

Horseshoe Run watershed is located in Tucker and Preston counties, West Virginia. The stream is approximately 27.23 km in length and drains an area of about 143.7 km² (55.5 mi²). The watershed is located in the heavily vegetated, steep terrain of the Appalachian Mountains, and 61 % of the watershed is privately owned (Figure 3 and 4). The run is a tributary to the Cheat River (Figure 5). The watershed's headwaters begin at an elevation of about 1078 m (3,535 ft) and fall nearly 637 m (2,089 ft) before draining into the Cheat River. Land use in the wide valley bottom in the lower part of the watershed is primarily devoted to pasture, whereas hillslopes and ridges are mainly second- or third-growth forest (Reger, 1923).

The lumber industry has a long history in Horseshoe Run watershed and dates back as early as 1825 when the second sawmill in Tucker County was built by Arnold Bonnifield on Horseshoe Run, in the unincorporated town of Pleasant Vale (Fansler, 1962). The Pleasant Vale sawmill was in operation until 1865, and was shortly followed by another sawmill within the watershed; the Leadmine sawmill that was in operation from 1866 to 1880 (Fansler, 1962). In addition to these sawmills, logging and logging railroads also played an important role in the history of the watershed, reaching its peak with the Preston Railroad from 1892 to 1925 (Fansler, 1962). Forests were cleared within the watershed and also the nearby drainage basins. However, unlike most logging operations, the lumber that was harvested within the Cheat River basin was transported uphill to Crellin, Maryland, located just east across the state border, via the South Branch of Wolf Run, gaining roughly 200 m (656 ft) in elevation.

Figure 3: Photograph of Horseshoe Run watershed showing steep terrain and heavy vegetation.

Figure 4: Photograph of Horseshoe Run watershed showing steep topography.

Figure 5: Location map of Horseshoe Run watershed in relation to the Cheat River basin.

Bedrock Stratigraphy and Structure

In the southeastern part of the Horseshoe Run watershed, relatively thin units of resistant lithologies occur, forming Backbone Mountain. The capstone of this ridge is the Pennsylvanian Pottsville Sandstone. Below the Pottsville sandstone are the shaley Mississippian units of the Mauch Chunk Group, the thin Greenbrier Limestone, the resistant Pocono sandstone, and the Devonian Catskill Series, locally called the Hampshire Formation. Below the Hampshire Formation are the thick units of the Chemung Group, a thick Devonian sandy shale with interbedded sandstone units. Horseshoe Run watershed is primarily underlain by the Chemung Group, covering 82% of the area within the watershed (Figure 6). These moderately resistant Chemung rocks exhibit major folding whose fold axes are oriented roughly NE-SW. The overall structure of the watershed can be summarized by a broad, gently folded anticline with limbs dipping at about 14 ° NW and SE on the flanks of the watershed (Figure 7). The contact between the Catskill and Chemung is difficult to identify because it varies spatially and has been interpreted to be inter-tonguing throughout thicknesses of hundreds of feet (Reger, 1923). Within Horseshoe Run watershed, the contact can be recognized by the presence of the Hendricks Sandstone, which marks the top of the Chemung (Reger, 1923). Table 1 summarizes the stratigraphic units' characteristics and thicknesses. The highly resistant Pottsville Sandstone in the Backbone Mountain stratigraphic section is not responsible for the numerous hillslope movements that are observed within the watershed. The vast majority of hillslope movements occur within the sandy shale units of the Chemung Group. There are two main reasons why the hillslope movements are mainly restricted to the Chemung Group: 1) the majority of the watershed is underlain

Figure 6: Geologic map of Horseshoe Run watershed. Chemung and Hampshire formations are Devonian in age; Pocono, Greenbrier, and Mauch Chunk formations are Mississippian in age; Pottsville formation is Pennsylvanian in age; Alluvium is Quaternary in age.

Figure 7: Geologic cross-section of Horseshoe Run watershed. . Cpv – Pottsville; Cmc – Mauch Chunk; Cgr – Greenbrier; Cpo – Pocono; Dck – Catskill; Dch – Chemung. Northwestern drainage divide shown by red arrow. Backbone Mountain. is the southeastern drainage divide, and the unnamed ridge under the red arrow is the northwestern drainage divide. Figure taken from Reger, 1923.

Stratigraphic Formation	Age	Thickness (m)	Characteristics
Pottsville Formation Upper Section –Kanawha Group (77 m) Lower Section – New River Group (83 m)	Pennsylvanian	161	The upper section is mostly a continuous conglomeratic sandstone, followed by dark gray shales. The lower section is composed of interbedded shales and pebbly sandstones. Conglomerate units weather into large boulders.
Mauch Chunk	Mississippian	178	Primarily massive red and greenish shales with occasional lenticular, fine-grained, flaggy sandstones.
Greenbrier Limestone	Mississippian	50	Composed on numerous beds of marine limestone separated by thin beds of gray shales. Crinoids and brachiopods prevalent within limestone beds.
Pocono Series	Mississippian	38	At the top of this series is a cliff forming pebbly conglomeratic sandstone, followed by gray and brown medium-grained sandstones.
Catskill Series	Devonian	220	Composed mostly of red shales and red/brown fine-grained micaceous sandstones.
Chemung	Devonian	881	Alternating deposits of olive-green shales and fine-grained sandstones, varying in thickness.

Table 1: Stratigraphic Units in Horseshoe Run watershed (from Reger, 1923).

by the Chemung Group and 2) the Greenbrier Limestone outcrop belt acts as a sink for colluvium originating from Mountain. In addition to these factors, because the Pottsville Formation is so resistant to erosion, the weathered products from this formation are large boulders of coarse sandstone (Hack and Goodlett, 1960). Transportation of these large Pottsville boulders tends to occur as slow creep or local rock fall. In contrast to the weathering products of the Pottsville, since most of the slope movements occur where the underlying lithologies are clastic sandy shales with thin layers of interbedded sandstone, the colluvium and alluvium tend to be composed of coarse, subangular-to-subrounded pebbles and cobbles, including poorly sorted colluvial diamictos (Figures 8 and 9). These diamictos are well exposed where the channel has eroded the toe of the deposit.

Figure 8: Photograph of a coarse grained alluvial terrace within Horseshoe Run watershed. Terrace is composed of coarse, subangular to subrounded pebbles and cobbles exposed by a tributary to Horseshoe Run. Sediment within terrace was most likely introduced into the fluvial system through upstream landslides and debris flows.

Figure 9 Coarse, subangular to subrounded cobbles in a debris flow deposit in Horseshoe Run watershed.

Previous Studies:

Heavy rainfalls often trigger slope movements (Neary and Swift, 1987). In November 1985, heavy rainfalls occurred in eastern West Virginia as a result of complex meteorological events. Hurricane Juan brought moisture into the southern Appalachian Mountains from the Mississippi Valley, which helped to cause a high-pressure anticyclone to become stationary over southeastern Canada while a second low-pressure cyclone moved into the Appalachian region from the Atlantic coast (Colucci *et al.*, 1991). This storm caused many slopes to fail throughout the Germany Valley of Eastern West Virginia and adjacent Virginia (Jacobson *et al.*, 1987). Similarly, in September 2004, the remnants of Hurricane Ivan released heavy rains in Macon County, North Carolina. The heavy rainfall caused a debris flow to occur with an estimated maximum velocity of 14.8 m/s and a discharge of 1275.2 m³/s (Latham *et al.*, 2007). This debris flow caused significant damage to the town below, destroying 15 homes, killing 5 people, and ripping and throwing adjacent trees from its path (Latham *et al.*, 2007).

Since there is no practical way to eliminate episodes of intense infiltration and soil saturation either due to heavy precipitation from intense storms or sudden snow melt, identification of areas prone to slope failure provides the best means to reduce landslide risk. Identification of landslide prone areas must be based on hillslope conditions prior to precipitation. Antecedent geologic conditions can be determined in the field by using standard geological surveying methods and the use of GIS (Carrara *et al.*, 1999).

Slope movements triggered by heavy rainfalls occur as a result of increased pore pressure within the hillslope material (Bakersville and Ohlmacher, 1987). These slope

movements often fail initially along bedding planes where the underlying bedrock is dipping in the down-slope direction (Jacobson *et al.*, 1987). Many studies have been able to link the underlying bedrock and structural geology to increased risk of slope failure, yet other studies have been unable to determine such correlations (Williams and Guy, 1971). These differences in being able to link the underlying geology to slope failures may be explained by the different rock types present in each study area. Jacobson *et al.* (1987) were studying landslides that initiated within sedimentary lithologies and utilized bedding planes, while Williams and Guy (1971) were studying slope failures in the Blue Ridge region of Virginia where the underlying geology is metamorphic and igneous rocks. Although Williams and Guy (1971) did observe jointing within the rocks, they concluded that the joints were not as important as other factors. Still, other studies suggest that slope aspect will have a direct influence on the risk of slope failure (Gryta and Bartholomew, 1987). Kish, 2004, determined slope aspect was a contributing factor to slope failure, however, he recognized that slope aspect was related to another controlling factor; access roads for mining operations.

Underlying lithology and its associated slope material are other well-documented factors contributing to slope failure. Debris flows commonly occur in areas where the underlying bedrock is a non-resistant shale (Jacobson *et al.*, 1987; Lorente *et al.*, 2002; Outerbridge, 1987). These underlying shale units are associated with clayey residuum and if the clays in the residuum are expandable, chances of slope failure are greatly increased (Behling, 1987).

Vegetation can also have a great influence on the slope stability. A slope is considered stable if it is heavily vegetated with trees or plants whose roots extend deep

within the hillslope soil. In contrast, if a slope is covered with only grasses, whose roots extend only into the near surface of the soil, the slope will be less stable (Brooks and Brierley, 1996). The worst case vegetational scenario for slope stability is a barren sloping surface. Without vegetation securing the hillslope, small additions of precipitation, could result in some form of slope movement. Barren slopes most often occur in places influenced by humans or by wildfire. Intense logging, mining, road construction, and many other anthropogenic alterations of hillslopes can cause great increases in risk of slope failure (Behling, 1987).

Researchers in the past created landslide risk maps by hand, identifying only those factors that seemed most important to slope initiation, such as slope angle, vegetation, and lithology. Although these maps were created using the technology at hand, they often relied on qualitative assessments. As studies of landslides and debris flows began to use more of a quantitative approach, they were met with mixed results (Carrara *et al.*, 1999). Factors that determine slope stability have been shown to be both quantitative (slope angle, aspect, tree density) and qualitative (land use, soil type, geology) variables. However, converting qualitative variables into quantitative variables can be rather subjective, and should be approached with as little bias as possible. Therefore, given that the stability of a hillslope can be influenced by so many factors, many recent studies have relied on statistical analysis to try and determine those areas with higher risk for slope failure (Muriuki *et al.*, 2007; Coelho-Netto *et al.*, 2007; Komac, 2006). The increasing versatility of GIS, and the ease at which multiple factors can be integrated, have influenced the current trend of research towards using statistical spatial

analysis and GIS to create these landslide risk assessment maps (Baeza and Corominas, 2001; Dai *et al.*, 2004; He *et al.*, 2003; Ohlmacher *et al.*, 2003; Rickenmann, 1999).

There can be, however, disadvantages in using GIS to create a landslide susceptibility map as noted by Carrara *et al.* (1999). Disadvantages stem from two main areas: 1) any user, experienced or not, can create overlay maps in a GIS, and 2) since the outputs of an overlay analysis are subjective, they can be created by biased users to create inaccurate results. Bias is a major problem with creating overlay maps and it exemplifies how truly subjective these models can be. Statistical analysis should be used prior to any data manipulation within a GIS to avoid such subjectivity. This technique was used by Baeza and Corominas (2001), to properly identify the most influential factors of slope stability within their study area, and then from those results successfully classify 95.6% of failed slopes. In their study, they used a principal component analysis, a *t*-test, and one-way test to select the factors with the most significance. Performing a principal component analysis, allowed them to not only select the factors of most influence, but also determine which factors were conditionally independent from each other. They then used those factors that were independent and most influential as input variables in a discriminant analysis for a final step in their study.

Assessment and prediction of where future landsliding may occur, and the degree of risk associated with a given area, is an underlying objective of most landslide studies. If accurate results are achieved from a landslide susceptibility model, risks to life and property can be minimized. Therefore, transfer of knowledge between researchers, decision makers, and the general public is essential. However, the numerous different

approaches and the varying results associated with those approaches limit the use of a standard method.

The lack of a standard method for landslide susceptibility models has led some of the more current landslide studies to compare the results between differing approaches. Galli *et al.* (2008) compared landslide inventory maps for the Umbria region in central Italy. The three maps Galli *et al.* compared had different scales and were created in different years. The objectives of their study were to ascertain how well the inventory maps 1) described the location, type, and abundance of the landslides, 2) determine the characteristics of the failed areas, and 3) provide reliable information to construct landslide susceptibility models. The results of their study suggest that the scale used to map the landslides, the quality of the aerial photographs or remotely sensed imagery, and the time allotted for the study greatly influence the final landslide inventory map. Due to the importance of inventory maps and the underlying subjectivity associated with them, Galli *et al.* (2008) propose different methods for testing accuracy. Furthermore, they strongly encourage careful and detailed inventory mapping to facilitate accurate landslide susceptibility models, an important step commonly overlooked by researchers performing statistical analyses.

Similar studies have been performed for debris flow susceptibility models. Carrara *et al.* (2008) created five different models to predict locations of debris flow source areas within the Eastern Italian Alps. The models differed in approach: either statistically or physically-based, and the type of terrain unit of reference: slope unit or grid cell. Slope gradient, land use, availability of detrital material, and active erosional processes were shown to have the greatest influence in all their models. Despite the

comparable results, they concluded that the discriminant model using small slope units was the best approach to predicting regional debris flows in their study area.

Although the use of GIS and remote sensing offers a relatively easy and time efficient approach, researchers should be cautious and understanding of the limitations and assumptions associated with landslide modeling. Perhaps one of the biggest complications stems from landslide classification. The classification of landslides forces naturally occurring phenomena, which vary over a continuous spectrum, into discrete categories, and often landslides are complex and have characteristics that fall into different categories simultaneously (Alexander, 2008). Another complication in landslide modeling is the quality of input data, consisting of both landslide inventories and landscape variables (Carrara and Pike, 2008). This quality of data complication reiterates the point made by Galli *et al.* (2008) that inferior observations are commonly gathered quickly in order to apply the data manipulation and multivariate statistical analysis so easily conducted within GIS. However, the sophistication of the technology and methods can not compensate for substandard input data (Carrara and Pike, 2008), and use of such careless models can have devastating consequences to human life and property.

To improve the quality and accuracy of input data for landslide models, remote sensing techniques such as light detection and ranging (LiDAR) can be utilized. LiDAR data are extremely accurate and have the ability to provide invaluable information for relatively large study areas. Yet, regardless of the quality of landscape imagery, careful observations by trained researchers are still required. Along with high resolution imagery, careful selection of landscape variables should be performed in order to maximize the accuracy of the landslide susceptibility model.

Methodology:

Surficial Geology Map:

High-resolution LiDAR data and aerial photos were obtained by CVI via an Optech ALTM 3100 sensor, and an integrated 3 band digital camera (Bennett, 2007). Data acquisition was conducted in 2006 during leaf-off conditions at a flight altitude of 3500 meters above ground level at an air speed of 135 knots (Kinder, 2008). Additionally, the pulse frequency of the sensor was set at 70 kHz with a half scan angle of 20° and a scanning frequency of 35 kHz (Kinder, 2008). Flight plans were designed with 50% overlap in the swaths and a maximum of 4 waveform returns. The LiDAR data allowed creation of a Digital Elevation Model (DEM) with 0.5 m resolution and roughly 15 cm vertical accuracy (Kinder, 2008). These operational parameters and conducting LiDAR data acquisition during leaf-off conditions allowed for a highly accurate, high resolution DEM to be created and provided an invaluable method for remote mapping of surficial features within the watershed.

Post-processing of the LiDAR data to create the 0.5 m DEM was conducted by CVI. From the LiDAR-derived DEM, a shaded relief map was created within ArcGIS 9.2 (ESRI, 2007), using the spatial analyst toolbar, and served as a base map for both field observations and remotely mapped surficial features. Shaded relief maps were created by maintaining a sun altitude of 45° and varying the sun azimuth. Four sun azimuths were used in this study: 45°, 135°, 225°, and 315°. These azimuths all provided useful information by illuminating surficial features on hillslopes within the watershed. The four azimuths were chosen because the main fold axis of the watershed is striking roughly

north – 45° east, and the hillslope aspects within the watershed appear to be, in part, structurally controlled.

The surficial geology map was constructed at a 1:12,000 scale using data gathered in the field and visual inspection of the LiDAR-derived shaded relief maps constructed by Konsoer and Downing at West Virginia University. Field observations were mapped onto LiDAR-derived shaded relief base maps and waypoints were taken using a Garmin handheld 12-channel GPS unit with 10 m accuracy to facilitate the digitization process within ArcGIS 9.2. GPS waypoints correlated well with the LiDAR-derived images (Figure 10), and due to the rugged, steep and heavily vegetated field conditions and extremely high resolution of the LiDAR data, once a firm correlation between field data and GIS data was established, mapping was conducted remotely using the LiDAR-derived shaded relief maps and the high quality aerial photographs, at a scale of 1:3000. More accurate delineations and precise locations of unit boundaries could be made by digitizing at a scale of 1:3000. Surficial features were remotely delineated based upon surface expression and morphology and digitization was conducted using ArcGIS 9.2. During the digitization process, each adjacent surficial unit polygon boundaries were snapped together to ensure no spaces within the mapping area were left unmapped.

Figure 10: Bouldery gelifluction lobes on Backbone Mountain. Red dots indicate GPS waypoints taken in the lobes and show a good correlation between field observations and the high quality LiDAR-derived shaded relief map. General location of these lobes features are shown as number 2 on Figure 1.

Surficial features mapped within Horseshoe Run watershed were as follows, undifferentiated colluvium, bouldery colluvium, bouldery gelifluction lobes, undifferentiated residuum, active floodplain, erosional strath terraces, active stream channels, paved and logging roads, and slope movements. Undifferentiated colluvium was mapped within the Devonian Chemung and Hampshire formations, and was typically composed of cobble and pebble, poorly sorted diamictons. In contrast, the bouldery colluvium was mapped within the areal extent of the Mississippian and Pennsylvanian formations, where large sandstone boulders and cobbles from the Pottsville Formation accumulated along ridge crests and in concave hillslope and local karst depressions. Table (2) shows the different surficial landforms and deposits mapped in Horseshoe Run watershed, and characteristics used to delineate between surficial geology features.

Selection of Variables:

In order to create an objective landslide susceptibility model, data are required for the entire study area, not just areas of slope failure. The importance of having both failure and non-failure sites in analysis makes data acquisition cumbersome and difficult when working in large study areas such as the 144 km² Horseshoe Run watershed. Therefore, the variables that were chosen in this study were variables that could be created within ArcGIS 9.2 quickly and easily, yet still provide high quality data. As a result, variables that have been previously shown to influence slope failure, such as regolith thickness, soil texture, and structural geology, could not

<u>Surficial landform feature</u>	<u>Characteristics used to delineate and map feature</u>
Active Slopes	Slopes actively moving due to oversteepening and undercutting by active channels.
Planar Slides (slides)	Uniform block glides and slides with significant head scarps. Slide material appears uniform and lacks hummocky topography and a clearly defined slide toe.
Rotational Slumps (slumps)	Landslides having lobate and hummocky topography in the toe region of the slide and a visible head scarp.
Debris Flows	Unconsolidated material confined to hillslope hollows with evidence of fluid like flow. Debris material not transported to base of hillslope and still remains confined in hollows.
Debris Fans	Unconsolidated material confined to hillslope hollows. Debris material transported to base of hillslope with a well defined depositional fan present.
Debris Slides	Planar slide of unconsolidated material confined to hillslope hollows. Debris slides lack well defined depositional fans.
Active Channel	Primary channel conveying water at summer base flow
Active Floodplain	Floodplain immediately adjacent to active channel. Multiple secondary channels present with evidence of periodic inundation.
Alluvial Terrace 0	Lowest alluvial terrace above active floodplain. Some secondary channels present with little evidence of periodic inundation.
Terrace Sequences T1-T4	Erosional strath terraces with a thin alluvial veneer. Relative age increases from T1-T4.
Undifferentiated Terraces	Erosional strath terraces with a thicker veneer and undifferentiable by relative age.
Colluvial Boulder Front	Gelifluction fronts composed primarily of Pottsville Formation sandstone boulders.
Bouldery Colluvium	Hillslopes covered in bouldery diamictons.
Undifferentiated Colluvium	Hillslopes covered in undifferentiated diamictons.
Undifferentiated Residuum	Thin veneer of slightly weathered bedrock restricted to ridge crests and slopes too steep to keep material in place. Boulders and cobbles may be present but have not been significantly transported by gravitational forces.

Table 2: Classifications of surficial geology features and the characteristics used to remotely map them within Horseshoe Run watershed.

be used in this model. However, seven variables (slope angle, slope aspect, elevation, plan curvature, profile curvature, distance from roads, and distance from streams) were carefully chosen to characterize the slope conditions and compensate for these “missing” variables, such as soil thickness and texture.

Slope angle and slope aspect were created using the surface analysis tool within the Spatial Analyst extension. Distance from roads and distance from streams were created by using the straight line distance tool within the Spatial Analyst extension. Plan curvature and profile curvature were created using the curvature tool located in the Spatial Analyst Tools. A watershed boundary was delineated by hand from the LiDAR-derived shaded relief maps, and this watershed boundary served as the study area extent for all mapping and calculations within ArcGIS 9.2.

Slope Angle –Slope angle is measured as the rate of change in elevation in the direction of steepest descent. Slope angle is a first order derivative calculated from the DEM. Slope angle is a dominant factor through which gravity induces movement of water and slope materials (Wilson and Gallant, 2000). Slope, therefore, has implications for the potential energy of the slope material and surface and subsurface flow of water.

Slope Aspect – measured in degrees clockwise from true north, it is the orientation of a slope in the direction of steepest descent (Wilson and Gallant, 2000). In other words, it is the direction a person would be looking while standing on the slope with their back facing upslope. Slope aspect has many implications, such as soil moisture content and vegetation as determined by solar radiation.

Elevation –Elevation is measured as the vertical distance above mean sea level, measured in meters. Elevation is used to calculate numerous other variables, which can

be either first or second derivatives, and has implications for potential energy, temperature, and vegetation (Wilson and Gallant, 2000).

Plan Curvature – Plan curvature is the curvature in the horizontal plane of a contour line, or the rate of change in aspect along a contour (Wilson and Gallant, 2000). Plan curvature is a second derivative of the DEM, and is a measure of the rate of change of a first derivative, slope aspect. Plan curvature values that are negative represent diverging flows and values that are positive represent converging flow. This variable allows determination of noses and hollows, and serves as a surrogate for convergence and divergence of flow across the landscape.

Profile Curvature – Profile curvature is the curvature in the vertical plane, or the rate of change of slope of a contour-orthogonal line. Profile curvature is a second derivative of the DEM, and is a measure of the rate of change of the first derivative, slope angle. Profile curvature values that are negative represent increasing slope downhill (convex flow profile) and values that are positive represent decreasing slope downhill (concave flow profile). Profile curvature measures the rate of change of potential gradient and has implications for changes in flow velocity and sediment transport (Wilson and Gallant, 2000).

Distance from Roads – Distance from roads was measured as a linear distance from mapped out roads. Although paved roads reduce the rate and capacity of infiltration, diversion of surface water into ditches may increase infiltration and decrease slope stability. Cuts and fills associated with roads commonly create local instabilities and promote slope failure.

Distances from Streams –Distance from streams was measured as a linear distance from mapped active channels. Streams may be erosional agents, removing slope material from the base of a slope, causing over-steepening and eventual failure of the slope. Slopes that are in close proximity to active channels are at higher risk of slope failure than those slopes at distance.

Mapping of the Landslides:

Mapped landslides were categorized as planar slides, rotational slumps, debris fans, debris flow, debris slides, or active slopes. Assignment of individual slope movements into a category was performed by visual inspection of the LiDAR-derived shaded relief map, focusing at surface morphology, head scarps, and displacement of slope material (Table 2). Numerous remotely mapped slope movements were field checked in order to insure proper classification. The classification of landslides was based upon classification schemes proposed by Varnes (1978), Campbell et al. (1985), and Hungr et al. (2001).

Debris fans were classified as unconsolidated material confined to hillslope hollows. The debris material has been transported to the base of the hillslope with a well defined depositional fan spreading out on the floodplain and evidence of a fluid-like debris tail (Figure 11). Debris flows were mapped separately from the debris fans because the debris flows were still confined within the hillslope hollow. These unconsolidated slope failures display fluid-like flow and lack a depositional fan (Figure 12). Debris slides were mapped as planar slides of unconsolidated material confined within hillslope hollows, having hummocky topography, and lacking evidence of fluid-like flow (Figure 13).

Figure 11: LiDAR-derived shaded relief map image showing an example of a debris fan. Location of this debris fan is shown as number 3 on Figure 1.

Figure 12: LiDAR-derived shaded relief map showing an example of a debris flow. Location of debris flow is shown as number 4 on Figure 1.

Figure 13: LiDAR-derived shaded relief map showing an example of a debris slide. Location of debris slide is shown as number 5 on Figure 1.

Planar slides were mapped as being a relatively uniform block displaying translational glides and slides with significant head scarps. These planar slides lack hummocky topography and display no signs of a slide toe (Figure 14). Rotational slumps display hummocky topography, secondary scarps within the failure, and have a well defined slide toe at the base of the failure. These slumps also lack a well defined head scarp, suggesting more of a vertical head scarp failure and not a lateral displacement as seen with the planar slides (Figure 15). Lastly, the active slopes were classified as slopes actively moving due to oversteepening and undercutting by the active channels (Figure 16).

Statistical Analysis of Landslides:

The landslide inventory map shows the spatial distribution of displaced slope material. The purpose of this project, however, was to determine the conditions under which slope failure occurs. To determine the conditions, initiation points were identified for each landslide through visual inspection of head scarps, erosional surfaces, and slope breaks on hillslope profiles. These initiation points were then buffered, using a 4 meter buffer tool within ArcGIS 9.2, to create polygons for data generation. Buffering of the initiation points allowed for an average of roughly 14 raster cell attributes to be calculated, instead of a single cell that could bias results because of microscale variability or errors in LiDAR data.

The LiDAR-derived DEM was resampled to create a 2 m DEM from the original 0.5 m DEM. This transformation to lower resolution data allowed for a smaller data set and faster calculations within ArcGIS 9.2, without sacrificing resolution required to map

Figure 14: LiDAR-derived shaded relief map showing an example of a planar slide. Location of planar slide is shown as number 6 on Figure 1.

Figure 15: LiDAR-derived shaded relief map showing an example of a rotational slump. Location of rotational slump is shown as number 7 on Figure 1.

Figure 16: LiDAR-derived shaded relief map showing an example of an active slope. Location of active slope is shown as number 8 on Figure 1.

at 1:12,000 scale. Seven different data layers were created from the LiDAR-derived DEM to serve as the variables for this study: slope angle, slope aspect, elevation, plan curvature, profile curvature, distance from roads, and distance from streams. Data collection was conducted using the zonal statistics function within the Spatial Analyst extension of ArcGIS 9.2. Output tables were combined to create a full landslide data table (Appendix A).

Unfailed slope data also were collected to compare with the failed slope data and determine any differences between the two populations. Unfailed slopes were randomly selected within the watershed using the Hawth's Tools extension within ArcGIS 9.2. The random selection created a shapefile of 150 points that were then buffered to 4 m to allow for an average of raster attributes to be calculated. Unfailed slope data were then gathered on the same seven variables using the same approach used for the failed slope initiation points. Output tables were combined to create an unfailed data table to use in the statistical analysis process (Appendix A).

Statistical analyses of the failed and unfailed data tables were conducted using Microsoft Excel 2007, Minitab 13.30, and Oriana 2.02e (Microsoft, 2007; Minitab Inc., 2000; Kovach Computing Services, 2007). Minitab 13.30 was used to determine mean, standard deviation, and variance for each variable on each type of slope movement (i.e. debris flow, slide, slump, unfailed). All variables were then tested for normality, and Box-Cox Transformations were performed within Minitab 13.30 to transform non-normally distributed variables into normally distributed variables. These transformations were performed using the option of optimum lambda (λ), which chooses the method of transformation that will produce the most normal distribution.

The transformed data were then split into subgroups based upon the type of slope failure and tests of equal variance were performed for each pair. The tests for equal variances were performed in order to conduct two sample student's t-tests between each set of data. Student's t-tests are used to determine if there is significance between the means of two populations. The variables were then tested for any correlation and the data were entered into a discriminant analysis function to determine differences between landslide classifications. Oriana 2.02e software, specifically designed to work with circular data, was used to analyze the slope aspect data and create rose diagrams for each different type of slope movement for comparison between groups. Circular data, such as azimuth data, often have trends in two directions, for example NW-SE, and therefore require specific statistical analyses to be performed.

Landslide Susceptibility Map:

A landslide susceptibility map was created for Horseshoe Run watershed within ArcGIS 9.2 using the results from the multivariate statistical analysis comparing all failed slopes to all unfailed slopes. The discriminant analysis function, derived by Minitab 13.30, was entered into the Raster Calculator within the Spatial Analyst toolbar of ArcGIS 9.2. The output produced by the Raster Calculator assigns risk of failure values to each cell within the watershed. Higher risk values indicate a higher susceptibility for failure and lower risk values indicate relatively stable slopes. The values calculated by the raster calculator within ArcGIS 9.2 were then reclassified based on one standard deviation of the risk population distribution, and five categories were defined: low risk, low-medium risk, medium risk, medium-high risk, and high risk. These classification breaks were chosen because of the statistical background and resulted in the least user

biased distribution. The landslide susceptibility map was then used to (1) identify those areas within the watershed that are at higher risk for slope failure, and (2) as an interpretative tool for assessing the overall hillslope stability of the watershed.

Results:

Surficial Geology Map of Horseshoe Run watershed:

The 1:12,000 scale surficial map of the watershed shows the spatial distribution of surficial deposits and landforms (Plate 1). Alluvium, colluvium, and residuum surficial deposits were mapped in the watershed. Mapped landforms consisted of slope movements, active channels, terraces, and active floodplains. Roads, both paved and logging, were also mapped from the high resolution LiDAR-derived shaded relief map.

The resistant quartzose lithologies that hold up Backbone Mountain result in interesting surficial geology landforms. Boulder fields and boulder streams, composed of the Pottsville sandstones and conglomerates, were concentrated in local hollows on the slopes of Backbone Mountain (Figure 17). Despite the high resolution of the LiDAR-derived shaded relief maps, boulder fields and boulder streams were unidentifiable on the image and, therefore, were not mapped. Long lobate landforms on the slopes of Backbone Mountain had surface morphology similar to gelifluction, or solifluction, lobes (Ritter, Kochel, and Miller, 2002). In either case, these identified features exhibit signs that they were slow moving surficial deposits of regolith. These lobate features (Figure 10) were identified from the LiDAR-derived shaded relief maps by a break in slope and in the field by the coarse grained boulders and cobbles located along the leading edge of the landform.

The Greenbrier Limestone on Backbone Mountain also created interesting surficial geology. Although obvious karst features, such as sinkholes and caves, were not observed at the surface during the field season, their presence is acknowledged by accumulation of large colluvial boulders and cobbles derived from the formations above.

Numerous springs originating from the Greenbrier Limestone outcrop belt were identified in the field. These springs were often very diffuse, yet in many locations, where discharge of ground water was sufficient, localized channels formed. However, similar to the boulder fields and boulder streams, remote identification of the springs and the spring-fed channels using the LiDAR-derived shaded relief map was not possible and these features were not mapped.

Figure 17: Large boulder field on Backbone Mountain, Horseshoe Run watershed.

Landslide Inventory Map and Statistical Analyses:

The landslide inventory map (Plate 2) shows the spatial distribution of slope movements within Horseshoe Run watershed. The slope movements shown in the inventory map are classified according to the characteristics outlined in Table 2. Of the 152 different slope movements, rotational slumps are most abundant, followed by planar slides and active slopes (Table 3).

Each type of slope movement was analyzed over each of the variables, except for slope aspect, to determine mean, standard deviation, and variance (Table 4). Slope aspect data were analyzed separately from the other variables because these data are circular. The results of the remaining variables were used to compare between the different types of slope movements to determine if there was a statistical difference between populations. Significance between the variables was tested by using the two sample student's t-test, which tests whether two independent sample means are equal (Appendix B). The student's t-test was used for these data sets because there were less than 40 observed failures for each type of slope movement. Appendix C summarizes the means, standard deviations, variances, and normality for each type of landslide.

The landslide summary data were then tested for correlation between variables using Minitab 13.30. The output correlation matrix shows that the seven variables are weakly correlated, as shown by the correlation coefficients, and therefore could be used in a discriminant analysis. Multiple discriminant analyses were implemented to determine which model had the highest level of accuracy. One of the most accurate models compared all failed slopes to all unfailed slopes (Figure 18). This model accurately identified 71.8% of the slopes. A Discriminant analysis using the different types of failed

slopes, along with the unfailed slopes, was 59.2% accurate at classifying slope movements to a specific type of failure (Figure 19). However, a discriminant analysis using only failed slope data resulted in accurate specific landslide type classification for 76.3% of failed slopes (Figure 20). These results indicate that there is a statistical difference between unfailed slopes and, failed slopes, and also between the different types of slope movements.

Slope aspect data were analyzed within Oriana 2.02e, software designed to work with circular data such as azimuths. Rose diagrams were created for each type of slope movement. Results from these graphs show that there is a difference in preferred orientation between the different types of slope movements. Planar slides and rotational slumps occur most often on northwest and southeast facing slopes, whereas debris flows and debris fans occur most often on northeast facing slopes (Figures 21 and 22). Appendix D shows orientation data for each type of slope movement.

The results from the rose diagrams were compared to the unfailed slopes to determine if there was any correlation between slope aspect and slope angle. For example, debris flows occurred on slope angles averaging 30.3 °. The unfailed slope angle data were subdivided into equal interval classes and each subdivision was plotted on a rose diagram (Appendix E). Comparing the rose diagram for the debris flows to the rose diagram for unfailed slope angles 28-32 ° shows that these two populations are different (Figure 23). These results from the subdivided unfailed slope angle data suggest that there is no correlation between slope aspect and slope angle. Therefore, the results from comparisons of slope aspect between failed slope types are valid.

Type of Landslide	Number of Individual Landslides Identified
Active Slopes	28
Debris Fans	17
Debris Flows	17
Debris Slides	13
Planar Slides	38
Rotational Slumps	39

Table 3: Number of different types of slope movements mapped within Horseshoe Run watershed.

Type of Slope Movement	Slope Angle (°)	Elevation (m)	Plan Curvature (radians per meter)	Profile Curvature (radians per meter)	Distance to Roads (m)	Distance to Streams (m)
Active Slopes	35.95	563.75	-1.04	-1.70	219.22	61.30
Planar Slides	21.77	670.39	-0.94	1.86	139.69	210.78
Rotational Slumps	21.03	680.53	-0.40	0.67	118.06	234.95
Debris Fans	26.12	662.44	-3.25	0.49	90.68	230.51
Debris Flows	30.30	717.16	-1.52	0.07	115.78	440.88
Debris Slides	32.28	625.49	0.11	-0.61	217.79	220.73
Unfailed Slopes	19.25	702.73	0.10	0.17	142.24	347.57

Table 4: Mean values of landscape variables used in the landslide analyses for the different types of slope movements.

Discriminant Analysis: Status versus Trans Slope, Trans Aspect, ...

Linear Method for Response: Status

Predictors: Trans Sl Trans As Trans El Trans Cu Trans Ro Trans St Trans Pr

Group fail unfail

Count 152 451

Summary of Classification

Put into True Group....

Group fail unfail

fail 102 120

unfail 50 331

Total N 152 451

N Correct 102 331

Proportion 0.671 0.734

N = 603 N Correct = 433 Proportion Correct = 0.718

Figure 18: Summary of discriminant analysis of failed versus unfailed slopes within Horseshoe Run watershed.

Discriminant Analysis: Type versus Trans Slope, Trans Aspect, ...

Quadratic Method for Response: Type

Predictors: Trans Sl Trans As Trans El Trans Cu Trans Ro Trans St Trans Pr

Group	active s	debris f	debris f	debris s	landslid	slump	unfail
Count	28	17	17	13	38	39	451

Summary of Classification

Put intoTrue Group....

Group	active s	debris f	debris f	debris s	landslid	slump	unfail
active s	27	0	0	0	3	1	19
debris f	0	13	2	1	1	2	25
debris f	0	2	15	1	1	0	10
debris s	1	1	0	10	4	4	24
landslid	0	0	0	0	20	4	43
slump	0	1	0	1	6	25	83
unfail	0	0	0	0	3	3	247
Total N	28	17	17	13	38	39	451
N Correct	27	13	15	10	20	25	247
Proportion	0.964	0.765	0.882	0.769	0.526	0.641	0.548

N = 603 N Correct = 357 Proportion Correct = 0.592

Figure 19: Summary of discriminant analysis of the classification of slope movements including unfailed slopes.

Discriminant Analysis: Type versus Trans Slope, Trans Aspect, ...

Quadratic Method for Response: Type

Predictors: Trans Sl Trans As Trans El Trans Cu Trans Ro Trans St Trans Pr

Group active s debris f debris f debris s landslid slump

Count 28 17 17 13 38 39

Summary of Classification

Put intoTrue Group....

Group	active s	debris f	debris f	debris s	landslid	slump
active s	27	0	0	0	3	1
debris f	0	13	2	1	1	2
debris f	0	2	15	1	1	0
debris s	1	1	0	10	4	4
landslid	0	0	0	0	23	4
slump	0	1	0	1	6	28
Total N	28	17	17	13	38	39
N Correct	27	13	15	10	23	28
Proportion	0.964	0.765	0.882	0.769	0.605	0.718

N = 152 N Correct = 116 Proportion Correct = 0.763

Figure 20: Summary of discriminant analysis of the different classifications of failed slopes within Horseshoe Run watershed. Only failed data was used in this analysis.

Planar Slides and Rotational Slumps

Figure 21: Rose diagrams showing the preferred aspects for planar slides and rotational slumps within Horseshoe Run watershed.

Debris Flows and Debris Fans

Figure 22: Rose diagram showing the preferred slope aspects for debris flows and debris fans within Horseshoe Run watershed.

Figure 23: Rose diagrams showing the differences in aspect of debris fans and unfailed slopes with slope angles between 28-32°.

Landslide Susceptibility Map:

The results from the discriminant analysis comparing all failed and unfailed slopes were used to create a landslide susceptibility map for Horseshoe Run watershed. The variables used in this analysis were: slope angle, slope aspect, elevation, plan curvature, profile curvature, distance from roads, and distance from streams. The linear discriminant analysis function that was calculated by Minitab 13.30 was entered into the Raster Calculator within the Spatial Analysis Toolbar of ArcGIS 9.2. The following equation is the linear discriminant function that was calculated by Minitab 13.30 and entered into ArcGIS 9.2:

$$F = 0.492(sl) + 0.014(as) + 0.107(el) - 0.275(pl) + 0.031(dr) - 0.02(ds) + 0.163(pr)$$

where, *sl* is the slope angle,

as is the slope aspect,

el is the elevation,

pl is the plan curvature,

dr is the distance from roads,

ds is the distance from streams,

pr is the profile curvature.

This linear discriminant function shows that slope angle, plan curvature, and profile curvature are the three most important factors controlling the stability of the hillslopes. The Raster Calculator then produced an output which assigned each raster cell

within the watershed a risk of failure value. These values were then reclassified as low risk, low-medium risk, medium risk, medium-high risk, and high risk.

The landslide susceptibility map identifies those areas within the watershed that have a higher risk for slope failure (Plate 3). Results from the susceptibility map indicate that only 6.09% of the watershed is at high risk for slope failure and that the majority of the watershed (41.62%) is only at a medium risk for slope failure (Table 5). Visual inspection of the susceptibility map shows that the high risk areas are concentrated into a few areas within the watershed. One of the locations of concentrated high risk is located on the southern end of Backbone Mountain within the Carboniferous formations, despite most of the slope movements occurring in other locations within the Devonian formations. This false high risk area on Backbone Mountain suggests that the other variables used in this study, such as slope angle and elevation, are also very important in predicting where slope movements might occur. Additionally, variables that were not used in this study, such as lithology, are also important contributing factors in predicting locations of slope stability. The high resistivity of the Pottsville sandstone, and the fact that the Pottsville formation weathers into large boulders helps to minimize the potential risk for slope failure within this formation of Backbone Mountain. The presence of a false high landslide susceptibility on Backbone Mountain warrants further field and remote sensing analysis to determine which factors are significantly contributing to slope failure in this area.

Comparing the locations of high risk within the watershed to those locations of mapped slope movements shows a correlation between these two groups in areas underlain by Devonian rock. Although not every slope movement was initiated within a

high risk area, no slope movement was initiated in an area less than medium risk, suggesting that the 71.3% accuracy of the discriminant analysis between failed and unfailed slopes is affecting the landslide susceptibility map. However, because the landslide susceptibility map was created objectively by using the landscape variables and multivariate statistical analyses, it can be used to make general statements about the slope stability within Horseshoe Run watershed and bring attention to certain areas that have a higher risk for slope failure.

Landslide susceptibility risk	Proportion of area in Horseshoe Run watershed (%)
low risk	7.43
low-medium risk	24.46
medium risk	41.62
medium-high risk	20.48
high risk	6.09

Table 5: Landslide susceptibility risk and the percentage of area within Horseshoe Run.

Conclusions:

The statistical analyses described above show that certain types of slope movements have similar characteristics and can be classified based on those observations. Active slopes, which were accurately classified in 96.4% of cases by the discriminant function, are an obvious example. The data show that active slopes occur at sites with an average slope angle is 35.9° and the average distance from streams is only 61 m. However, having data for one type of slope movement explains only half of the story; when these means are compared to the means for the other types of slope movements; it becomes apparent that active slopes are a distinctive group from the other classifications.

Comparisons of the rose diagrams indicate that different types of slope movements have different preferred orientations. Debris flows and debris fans occurred on slopes with a northeast orientation, whereas planar slides and rotational slumps occurred on slopes with a northwest and southeast aspect. Two possible explanations for this preferred orientation may be (1) the orientation of the breached northeast-southwest anticlinal structure across the watershed, and (2) differences in microclimate between northeast and northwest facing slopes. Planar slides and rotational slumps may be utilizing the bedding planes on the limbs of the anticline as failure surfaces. Additionally, since the south facing slopes receive more solar radiation than the north facing slopes, temperatures are warmer and evapotranspiration rates are higher (Hack and Goodlett, 1960). Greater evapotranspiration rates on the south facing slopes may be another factor explaining why planar slides and rotational slumps are occurring on these slopes in lieu of other types of failures.

Similarly, the northeast facing slopes within Horseshoe Run watershed receive the lowest amount of heating from solar radiation because they receive solar rays during morning hours when temperatures are cool, as opposed to the northwest facing slopes, which receive solar rays during afternoon when temperatures are warmer. This difference in temperature also results in lower rates of evapotranspiration, more soil moisture, and differences in vegetation, and these factors may favor debris flow initiation on northeast facing slopes.

These results suggest that there are significant differences between failed slopes and unfailed slopes, and between the different classifications of slope movements; however, the results may provide only limited information regarding the current geomorphic processes operating within Horseshoe Run watershed. Field observations, along with intensive and detailed study of the LiDAR-derived shaded relief maps, suggest that most slope movements within the watershed are not a result of recent failures. Although there are a few planar slides that exhibit a well defined head scarp, the majority of slope movements show evidence of substantial reworking by erosional or colluvial processes. Hillslope cross-sections through slope movements lack any clear significant scars or abrupt breaks in slope that would imply recent failure. In addition, most failed slopes have been revegetated and now appear stable. The relict nature of the landslides could explain the relatively moderate level of accuracy in the discriminant analyses between types of slope movements and failed and unfailed slopes.

As a result, a susceptibility model or predictive model of where future landsliding may occur based on the location of past failures may be inappropriate for Horseshoe Run watershed. Without understanding the full conditions under which these slopes failed, it

is difficult to predict, with some accuracy, where slopes may fail in the future. Conditions such as climate, vegetation, and the corresponding geomorphic processes influencing the watershed, could have been quite different 10,000 or more years ago.

Historic records from local residents also indicate that landslides and debris flows have not been a common geologic hazard in the past 100 years. Fansler (1962) reported that a large precipitation event in 1888 produced the second most damaging flood event in Tucker County history and reported large slope failures occurring on Backbone Mountain near the town of Hendricks, but the heavy precipitation event that created the 1985 flood on the Cheat River left no large documented landslides within Horseshoe Run watershed despite the fact that landslides and debris flows were well documented in several areas of West Virginia and Virginia (Jacobson, 1991; Colucci *et al.*, 1991; Jacobson *et al.*, 1991).

Without radiocarbon dates or other Quaternary dating methods on the slope movements within Horseshoe Run watershed, nothing can be said with certainty about when the failures occurred. One of the possibilities is that the slope failures occurred under a different climate, dominated by a different set of geomorphic processes. During the Wisconsin glacial event, climate in the Appalachian Highlands and Interior Highlands, south of the glacial limit, was significantly different than it is today (Clark and Ciolkosz, 1988). Temperatures in July may have been 5 to 15 C° lower, and large areas in the Appalachian would have been above the forest limit; these cooler climatic conditions resulted in periglacial processes and landforms (Clark and Ciolkosz, 1988). Periglacial processes produce heavy amounts of colluvium through frost action, and create features such as boulder streams and boulder fields (Clark and Ciolkosz, 1988).

Under these conditions, thick amounts of coarse colluvium would have been created and stored in hillslope hollows. As the climate warmed and greater precipitation intensity was introduced, those thick colluvial deposits would have been flushed downslope as either debris flows or landslides (Kochel, 1987).

Similar observations and models have been created for the central Blue Ridge of Virginia (Kochel and Johnson, 1984; Kochel, 1987; Eaton *et al.*, 2003). In June 1995, more than 1000 slope failures occurred as a result of a heavy precipitation event in the Blue Ridge Mountains. The slope movements, mostly debris flows, incised into previously deposited debris flows and stream channels, exposing the Quaternary stratigraphy (Eaton *et al.*, 2003). Pollen collected from the stratigraphy, along with radiometric dating, was used to determine the frequency of debris flows in the region. Eaton *et al.* (2003) calculated from the measured dates that debris flow activity recurred on average every 2500 years, and has been intermittently active since 25,000 YBP. The 2500 year recurrence interval suggests that once a debris flow occurs, a period of colluviation must occur in order to reload the hillslope hollows (Hack and Goodlett, 1960).

Combining these models of colluviation rates and frequency of debris flows can help to explain a possible scenario for Horseshoe Run watershed. The climate near the end of the Pleistocene most likely resulted in higher colluviation rates which loaded hillslope hollows with an abundant supply of sediment, and as the climate began to warm during the early Holocene, greater amounts of precipitation resulted in debris flow activity that flushed out the hollows. The warmer climatic regime during the Holocene

also resulted in lower colluviation rates and variations in the style of precipitation within this region of the Appalachian Mountains (Hirshboeck, 1991).

Based upon field observations and study of LiDAR-derived shaded relief maps, combined with the evidence of paleoperiglacial landforms (boulder fields and boulder streams), slope movements within Horseshoe Run watershed appear to be relict from a different, cooler climate regime that would have been operating near the end of the Pleistocene or early Holocene. A late Pleistocene or early Holocene age precludes logging within the watershed as a cause of the slope movements. In addition, the logging roads within the watershed cross-cut the slope movements, further suggesting that the logging operations did not cause the slope failures to occur. Considering the vast amount of logging roads, and the fact that logging operations had been occurring since the late 1800's, it is possible that many of the roads visible on the LiDAR-shaded relief maps are over 100 years old. If these logging roads are cross-cutting the landslides, then this implies that the landslides are at least older than the logging roads.

Further evidence that the landslides are relict comes from field observations of the slope movements. The fact that many of the slope movements appear to have been heavily reworked and revegetated with large trees suggests that failure may have occurred under conditions that are different from today. Since frequency and time are important factors in predictive models, without knowing when the landslides occurred precludes the creation of a predictive landslide initiation model. However, the data collected for the different classifications of slope movements do provide evidence that the characteristics of the landscape contribute to the type of failure that is likely to occur.

Discussion of Fluvial Instability on Horseshoe Run:

A good approach to assess the dynamic condition of fluvial systems is landscape sensitivity analysis (Downs and Gregory, 1994). This type of analysis, in combination with other geomorphic assessments conducted for the entire watershed, may provide information pertaining to the equilibrium state of the system. This method is far superior to the Rosgen approach for stream restoration as currently practiced because without a comprehensive geomorphic assessment of the watershed, restoration practices could have limited success, or worse has a detrimental effect. To assess the fluvial condition of Horseshoe Run, the concepts of landscape sensitivity and hillslope-channel coupling can be utilized to provide a watershed scale assessment.

Landscape sensitivity was first introduced by Brunsden and Thornes (1979), and gave a definition as “the likelihood that a given change in the controls of a system will produce a sensible, recognizable, and persistent response”. Brunsden and Thornes address many issues concerning geomorphic stability, including transient behavior caused by perturbations, either internal or external, and the proximity of the system to geomorphic thresholds. Since its introduction, many interpretations of sensitivity have been given. A few of these interpretations are outlined by Downs and Gregory (1993):

- ratio of disturbing forces to resisting forces
- propensity for change shown as proximity to threshold conditions
- ability to recover from change
- a complex combination of all of the above.

Based on the results of the landscape sensitivity analysis, landscapes can be classified as either insensitive, also referred to as robust, or sensitive (Brunsden and

Thornes, 1979). Robust landscapes are stable in that they dampen the effects of perturbations, because of controlling resistances with the ability to minimize disturbance and easily restore the system to its original state through feedback mechanisms (Brunsden, 1993). Sensitive landscapes differ in that they are more vulnerable to disturbances, operate near major threshold boundaries, and exhibit internal instability. In delicate landscapes, recovery to perturbations may be extremely slow or incomplete.

Sensitivity analysis requires a rather large data set, typically gathered over decades. Necessary data include longitudinal and cross-sectional stream profiles, sediment transport rates, hillslope sediment delivery rates, precipitation and temperature values, and vegetation. Data sets of this size are often not available for fluvial systems and can make watershed analysis and management extremely difficult. However, sensitivity analyses for fluvial systems can be conducted by studying the degree of coupling of the system.

Harvey (2001) provides a good definition of coupling, and delineates three states of coupling and the scales at which they may operate. *Coupled* systems display free transmission of energy and materials between components, *not coupled* systems show no linkages and are therefore considered buffered, and *decoupled* systems were once coupled but through geomorphic change are no longer coupled. These three degrees of coupling can operate at the zonal, reach, and hillslope-channel scales.

Harvey (2001) used the concepts of coupling to assess the sensitivity of the Howgill Fells in northwest England. Using data from a 30 year monitoring program, Harvey was able to show that the sensitivity of the study area depended on the frequency and magnitude of perturbations, specifically large floods and punctuated sediment events,

and the ability of the system to modify those disturbances through internal coupling characteristics. Results showed that channel morphology adjusted to basally induced gullies that introduced large volumes of sediment. However, as gully development progressed, revegetation occurred, which stabilized slopes. Based on the results, Harvey concluded that the Howgill Fells is in dynamic equilibrium, yet may be operating near threshold conditions. If an event of sufficient magnitude occurred within the watershed, it may cause the system to cross that geomorphic barrier.

Important to Horseshoe Run Watershed is the degree of coupling of the system at the hillslope-channel scale. Although no long term data have been collected, certain qualitative conclusions and predictions can be made by examining channel response to sediment supply from the hillslopes, the magnitude and frequency characteristics of slope movements, and the dynamics of the coupling relationship.

Results and observations from mapping slope movements in Horseshoe Run watershed show that there is a preferential slope aspect for debris flows, which differs from the preferential slope aspect of the landslides and may be due to variations in the structural geology, vegetation, and microclimate. In many hollows, debris flows are not delivered to the tributary below, but are retained on the slope. Other debris flows in the watershed are delivered to main tributaries or Horseshoe Run directly, and show signs of heavy reworking and erosion at the distal end of the debris flow. Similarly, the landslides show situations of relatively short head scarp displacements or reworking of the landslide toe by the streams. Aggradation in this watershed is limited to low-order tributaries; however, bedrock controlled reaches occur in all orders of tributaries and Horseshoe Run, suggesting fairly competent transportation capabilities.

Taylor and Kite (2006) studied three watersheds in the Appalachians, all underlain by the Acadian clastic wedge, which are predominately sandstones and shales. Horseshoe Run watershed is in close proximity to these three watersheds and shares similar lithologic characteristics. The three watersheds in the study were the Little River basin, the Fernow Experimental Forest, and the North Fork basin. Geomorphic analyses were carried out in all three watersheds and estimates of the percentage of valley bottom storage were calculated using a GIS.

Detailed mapping of the three watersheds showed that the Little River basin has a much wider valley bottom, produced by aggrading sediment supply, allowing for sediment storage, and the stream was mostly alluvial with very little bedrock exposed, whereas, Fernow and North Fork watersheds have v-shaped valleys with little room for sediment storage and numerous bedrock controlled reaches. Taylor and Kite (2006) attributed the unique character of the Little River basin to frequent, large sediment inputs that the fluvial system can not handle, as opposed to the diffuse style of sediment delivery that takes place in Fernow and North Fork. As a result, the Little River system is aggrading and the valley bottom is widening. This, in turn, is causing more deposition of debris fans due to the decrease in slope and stream power, and is creating a positive feedback environment.

By studying the geomorphic influence of sediment input rates and styles on valley bottoms and sediment storage capabilities, Taylor and Kite (2006) were able to assess the equilibrium of the three watersheds in their study. Using percentage of bedrock controlled reaches and aggradation as indicators, they concluded that the Little River Basin is in disequilibrium. The wide valley bottom allows for stream power to be

distributed over a larger area, resulting in an overall decrease in the stream's transporting ability. Another result of the wide valley bottom is the decoupling of the hillslopes from the channel, which allows debris flows to be preserved as depositional fans on top of the valley terraces and adds to the aggrading system. This positive feedback is driving the system further and further away from equilibrium.

Applying these same principles to Horseshoe Run, a qualitative assessment of the state of equilibrium of the system can be made. Since Horseshoe Run has many reaches that are bedrock controlled, and the valley does not appear to be aggrading, the system can be interpreted as in equilibrium. However, aggrading reaches in some of the low-order tributaries of the watershed also suggest that Horseshoe Run watershed is still attempting to flush out large sediment inputs and move towards a more stable equilibrium. In other words, Horseshoe Run may be operating near a geomorphic threshold, and, given a large enough disturbance, the watershed may cross a geomorphic barrier, resulting in disequilibrium. Evidence of fluvial disequilibrium may include pool-riffle spacings that do not follow the average 5-7 channel widths or occurrence of riffles within meander bend reaches (Leopold, Wolman, and Miller, 1964).

Although preliminary, qualitative assessments can be made based on the methods described above, the exact condition of equilibrium cannot be determined until further quantitative analyses are conducted. If ages of stratigraphically distinct debris flow events can be determined at locations in Horseshoe Run watershed, then frequency and magnitude characteristics can be calculated and the equilibrium state may be resolved. Given the limited data for the watershed, initial assessments can be carried out by looking

at the degree of coupling between the hillslopes and channel, and the implications it may have on the sensitivity of the watershed.

Considering the data collected, the discriminant analyses performed, the field and remote sensing observations that suggest the slope movements are Late Pleistocene or early Holocene, and the concepts of landscape sensitivity and hillslope coupling mentioned above, I believe that the channel instability on Horseshoe Run is not a direct result of the slope failures. However, I believe that the slope movements are indirectly contributing to the channel instability, along with logging and deforestation of the floodplain. As settlement within the watershed occurred, the forested valley bottom would have been cleared, either by burning or clear-cutting, and converted to grazing and farmland. This change of land use would have resulted in the liberation of the legacy sediments introduced by the pre-Holocene slope movements. As a result of this increased sediment supply, the channel morphology would have changed to more of a braided system in order to increase its transporting capabilities.

Discussion of the Landslide Susceptibility Map:

Despite evidence that the slope movements within Horseshoe Run watershed may be prehistoric, a landslide susceptibility map can still be used to understand and assess certain landscape characteristics that might be conducive for slope failures. These characteristics, which were obtained objectively using multivariate statistical analyses, provide information concerning possible locations for future concern based upon the relative level of risk determined by the linear discriminant function.

Detailed visual inspection of the landslide susceptibility map reveals that a significant percentage of higher landslide risk areas are concentrated within the upper watershed and all along Backbone Mountain. As mentioned earlier, the modeled high risk areas associated with Backbone Mountain are misleading considering the vast majority of slope movements occurred within the Devonian strata. Future landslide susceptibility models should attempt to incorporate information regarding the bedrock geology in order to de-emphasize the risk for failure on Backbone Mountain. For this study, because bedrock geology was not chosen as a landscape variable, focus for areas of concern within the watershed is limited to areas underlain by Devonian bedrock.

The areas of concern within Horseshoe Run watershed, underlain by the Devonian strata, can be used to estimate possible locations for disturbance within the watershed. These areas of concern have the potential to provide large amounts of sediment to lower reaches of the watershed. However, these sediment supply areas need to have the size potential to create a disturbance in the lower reaches of the watershed and also on the main stem of Horseshoe Run. Studies have shown that fluvial geomorphic disturbances caused by increased sediment loads from tributaries to main stems often scale with the

ratio of the tributary to the main stem (Benda *et al.*, 2004). In other words, larger tributaries have greater potential for morphological change in the main stem by introduction of punctuated sediments and large woody debris.

Benda *et al.* (2004) analyzed results from 14 published field studies that documented morphologic alterations of stream confluences caused by punctuated sediment supplies and introduced woody debris within North America. The results of Benda *et al.* (2004) suggest that there is a threshold ratio of tributary drainage area to main stem drainage area, below which the effects of the tributary will not be significant. This threshold indicates that debris flows originating from small tributary basins (less than 1 km²) will only affect main stem river basins that drain up to 50 km² (Benda *et al.*, 2004); these authors state that in humid environments, tributary to main stem ratios between 0.04 and 0.8 correspond to probability values of 0.6 to 0.9 that an effect will be significant.

Applying these tributary to main stem ratios, and the corresponding probability values, to Horseshoe Run watershed will help to identify areas of concern within the watershed that have the size and sediment supply potential to create disturbances within the watershed. For example, at the confluence between Wolf Run (20.1 km²) and Horseshoe Run (48.6 km²), the ratio is 0.414 (Figure 24). This tributary to main stem ratio indicates that Wolf Run has the potential to influence the stream sediment transport balance below its confluence with Horseshoe Run. Additionally, the landslide susceptibility map within the Wolf Run basin shows that a majority of the slopes are classified as medium to high risk for slope failure. Combining the high tributary to main stem ratio of 0.414 with the potential risk for many slopes within the Wolf Run basin,

suggest that the confluence between Wolf Run and Horseshoe Run has the potential to cause significant disturbance on the main stem of Horseshoe Run.

Similarly, these concepts can be applied to the entire watershed in order to determine those locations of concern. Another location of concern is in the headwaters of Horseshoe Run. The landslide susceptibility map for this area shows high risk of slope failure and ratios of tributary to main stem are rather large. At some locations, the high risk areas are located on slopes adjacent to Horseshoe Run, indicating some level of coupling between the hillslopes and the channel, and would be a location of direct sediment supply to the stream. Another location deserving of attention is Maxwell Run (Figure 25). Although Maxwell Run is located roughly 4.5 km upstream from the mouth of Horseshoe Run, the drainage area of Maxwell Run is still relatively large (9.4 km^2) and gives a tributary to main stem ratio of about 0.08. Maxwell Run drainage basin also has many slopes classified as medium to high risk for slope failure, and the concentrated area of high risk on Backbone Mountain drains into Maxwell Run. These high risk areas indicate large sources of sediment and therefore could have significant alterations of channel morphology downstream and at the confluence with Horseshoe Run.

These locations of concern for disturbance within Horseshoe Run watershed provide only an initial investigation into the landslide susceptibility of the watershed. Further analyses should be conducted in order to determine whether the mapped landslides within the watershed are still unstable and whether they are truly prehistoric. However, current areas of concern for slope stability within the watershed are those areas that are mapped as active slopes. These active slopes are currently failing as a result of undercutting and oversteepening by the active channels and provide a current source of coarse sediment to

the fluvial system.

Figure 24: Landslide susceptibility map showing the confluence of Wolf Run and Horseshoe Run and the relative sizes of both drainage basins. White star shows approximate location of the confluence. Wolf Run is the tributary flowing from the east and Horseshoe Run is flowing from the north.

Figure 25: Landslide susceptibility map showing the location of Maxwell Run and its confluence with Horseshoe Run. White star shows approximate location of confluence. Maxwell Run is the tributary valley coming in from the southeast.

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Slope Movements within Horseshoe Run watershed,
Tucker and Preston Counties, West Virginia

Plate 2: Landslide Inventory Map for Horseshoe Run watershed showing spatial distribution of landslides and the different types of slope movements mapped within the watershed.

Landslide Susceptibility Map for Horseshoe Run Watershed

Plate 3: Landslide susceptibility map of Horseshoe Run watershed. The black line shows the approximate boundary between the Devonian and Carboniferous formations. Observations suggest that the associated risk for failure values along Backbone Mountain are heavily overestimated.

Appendix A: Data from failed and unfailed slopes used for landslide analyses within Horseshoe Run watershed.

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
1	fail	debris slide	24.80	243.94	710.77	-0.94	15.89	285.70	-0.11
2	fail	debris slide	38.40	240.43	597.70	-2.39	45.23	226.72	-0.02
3	fail	slump	29.07	284.96	646.30	-0.25	5.12	355.32	-0.39
4	fail	landslide	18.48	110.48	547.48	-0.48	84.64	181.97	2.08
5	fail	slump	17.86	134.82	616.43	-1.43	261.69	256.06	2.20
6	fail	slump	22.24	93.18	681.51	0.78	69.31	315.38	0.37
7	fail	slump	16.68	114.60	598.56	-0.34	96.77	145.14	2.61
8	fail	landslide	33.35	107.59	547.36	-1.68	121.30	105.77	1.99
9	fail	debris fan	12.14	38.50	614.26	-2.63	209.62	290.37	0.04
10	fail	debris flow	32.37	295.24	759.37	0.90	62.91	582.70	-1.59
11	fail	debris flow	30.41	333.18	744.33	-1.00	73.65	654.67	-1.27
12	fail	active slope	27.05	210.78	610.19	-3.37	1.45	75.41	-0.38
13	fail	landslide	29.35	142.65	735.99	1.31	37.26	326.25	-2.32
14	fail	landslide	17.49	158.24	751.20	0.23	86.77	330.40	-0.24
15	fail	landslide	36.17	89.96	832.98	1.13	23.00	281.41	-0.41
16	fail	slump	7.12	105.71	883.22	-0.55	35.25	459.36	0.83
17	fail	active slope	36.13	285.13	591.38	3.61	246.54	46.77	-5.20
18	fail	slump	19.05	157.94	670.84	-2.89	38.93	187.66	-0.04
19	fail	slump	14.32	114.90	621.30	0.79	61.90	135.64	3.70
20	fail	debris slide	30.00	35.37	568.85	-0.56	283.00	93.88	-1.65
21	fail	debris slide	34.87	219.54	692.49	-0.98	93.37	371.95	-1.89
22	fail	debris fan	27.07	46.20	702.25	-0.50	78.92	529.25	0.08
23	fail	debris flow	25.62	47.48	726.86	0.22	238.49	480.69	-0.39
24	fail	active slope	23.39	15.23	548.41	-0.42	282.64	69.59	-3.20
25	fail	debris flow	28.08	307.88	778.36	0.16	1.78	602.65	-0.44
26	fail	debris flow	28.82	338.70	780.99	0.58	14.91	799.24	-1.06
27	fail	debris flow	27.81	309.22	761.48	-2.17	27.52	586.89	0.27
28	fail	slump	16.51	70.08	675.41	-0.17	64.97	253.12	-0.15
29	fail	landslide	30.39	269.60	714.83	-3.06	211.20	474.86	-0.43
30	fail	slump	6.69	53.95	671.88	2.02	121.63	356.39	-1.62
31	fail	slump	16.64	239.47	646.07	-0.84	190.12	339.52	0.37
32	fail	slump	8.33	207.11	594.06	-2.12	254.57	224.22	-0.10
33	fail	active slope	40.41	141.06	473.72	-1.41	477.36	66.81	4.42
34	fail	active slope	26.84	159.86	475.08	-1.13	471.62	54.83	5.74
35	fail	debris slide	34.63	173.57	501.27	8.21	433.93	113.66	-6.43
36	fail	debris flow	35.04	40.00	635.38	-0.78	322.63	394.32	0.81
37	fail	debris fan	30.30	49.52	655.66	-1.26	150.63	374.16	0.35

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
38	fail	debris slide	33.00	221.94	529.14	-0.02	695.79	183.31	-0.42
39	fail	active slope	34.49	245.02	503.46	-8.67	395.79	79.99	2.98
40	fail	active slope	44.25	169.33	483.61	-1.13	153.08	41.99	-1.51
41	fail	debris fan	22.37	190.87	573.66	-3.94	199.87	218.44	-0.25
42	fail	debris fan	33.62	155.78	565.32	0.50	590.01	151.43	-0.01
43	fail	debris slide	32.69	56.47	644.24	-0.70	75.07	261.63	0.91
44	fail	debris slide	34.47	33.31	633.34	-1.06	138.55	251.43	-1.26
45	fail	landslide	33.65	254.69	537.11	-2.92	153.93	64.36	8.26
46	fail	slump	16.00	294.24	647.83	1.17	20.61	362.43	0.05
47	fail	debris flow	35.02	125.86	680.14	-4.22	263.01	350.93	0.09
48	fail	debris flow	32.38	111.11	699.75	-1.20	183.13	398.24	-0.46
49	fail	landslide	33.39	238.69	656.21	-0.64	140.62	324.61	1.35
50	fail	landslide	24.21	306.18	573.48	-0.97	563.77	167.55	1.52
51	fail	active slope	35.77	207.88	581.53	-0.38	107.40	56.01	-3.18
52	fail	active slope	37.17	227.53	593.25	-2.94	99.25	47.08	1.13
53	fail	slump	30.82	302.38	665.88	0.00	323.36	240.00	-0.79
54	fail	landslide	15.30	273.51	595.96	2.32	309.51	107.47	-2.58
55	fail	landslide	21.25	293.90	690.57	0.34	288.44	287.76	-0.47
56	fail	landslide	23.07	292.60	609.55	-1.88	238.43	86.79	3.04
57	fail	landslide	22.12	289.93	613.45	0.28	136.87	74.20	1.40
58	fail	slump	25.17	270.96	651.49	-3.55	30.36	137.08	2.33
59	fail	slump	6.18	150.31	732.68	-0.63	3.21	298.25	1.66
60	fail	slump	16.96	276.77	685.64	0.44	1.71	125.27	1.92
61	fail	slump	17.51	78.84	693.88	-0.90	231.26	225.31	-0.71
62	fail	slump	36.07	271.80	680.71	-0.67	177.34	258.95	0.29
63	fail	active slope	27.41	250.25	569.47	-1.14	216.29	58.79	-1.19
64	fail	debris slide	38.21	256.92	560.44	2.00	193.65	168.30	-1.44
65	fail	debris flow	29.81	20.15	672.17	-0.18	12.54	191.25	-0.39
66	fail	debris fan	26.69	69.51	633.18	-1.89	44.72	129.72	-0.20
67	fail	active slope	32.28	129.00	557.97	0.77	113.47	78.94	-1.74
68	fail	active slope	26.88	179.28	543.39	3.11	166.51	57.07	-2.05
69	fail	landslide	22.44	109.79	620.22	-1.03	277.96	219.96	0.39
70	fail	debris flow	34.59	35.51	773.34	-6.67	43.32	477.30	3.86
71	fail	debris flow	26.96	139.92	743.84	-1.75	15.50	539.64	0.90
72	fail	debris fan	25.72	37.80	667.58	-1.65	8.42	344.79	-0.61
73	fail	debris flow	31.56	215.97	700.21	-1.08	15.04	256.49	0.47
74	fail	slump	24.63	107.10	679.03	0.50	25.26	233.66	0.16
75	fail	slump	25.86	150.93	643.05	-1.01	10.52	211.54	0.68
76	fail	landslide	25.55	90.24	753.69	-0.07	19.00	340.83	-2.91

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
77	fail	landslide	21.49	119.90	668.74	-2.51	59.60	114.11	4.03
78	fail	landslide	10.24	126.56	660.11	0.26	39.23	173.16	2.13
79	fail	active slope	46.09	230.99	587.26	0.68	20.70	33.65	-1.62
80	fail	slump	17.06	129.36	856.93	0.24	89.41	254.47	0.28
81	fail	landslide	31.01	128.04	745.25	2.15	72.78	268.90	-2.04
82	fail	landslide	6.32	164.35	788.46	-1.52	269.94	387.55	2.11
83	fail	landslide	12.60	186.08	688.12	-2.41	31.88	140.19	3.61
84	fail	slump	17.25	160.62	744.11	-0.14	150.28	165.40	1.12
85	fail	slump	23.56	147.31	731.76	0.21	104.68	152.38	-0.54
86	fail	slump	22.15	106.07	712.33	-0.90	35.00	255.20	2.29
87	fail	slump	19.36	129.44	711.38	0.27	15.64	265.64	0.24
88	fail	landslide	17.79	146.98	671.59	0.02	39.87	152.32	2.35
89	fail	landslide	35.66	194.89	666.21	-0.70	22.38	207.35	3.33
90	fail	landslide	18.59	131.42	695.63	-2.09	2.25	234.24	2.78
91	fail	landslide	36.45	116.61	681.51	-0.44	335.35	324.71	2.12
92	fail	landslide	14.73	158.98	615.60	-3.51	417.83	115.40	4.62
93	fail	slump	5.99	254.10	723.54	-2.50	435.42	505.62	4.28
94	fail	slump	12.90	125.59	615.20	0.17	358.02	161.55	0.41
95	fail	landslide	27.61	136.88	672.70	-3.02	36.70	75.91	9.26
96	fail	slump	30.59	273.62	649.30	0.20	204.85	196.29	0.46
97	fail	landslide	12.73	141.69	687.40	-0.54	38.60	103.42	0.34
98	fail	active slope	42.02	284.02	618.57	-1.96	196.43	82.88	4.31
99	fail	slump	23.63	131.19	748.71	-0.85	66.59	357.99	0.29
100	fail	active slope	36.85	178.88	632.41	-3.15	305.81	78.07	2.44
101	fail	active slope	22.16	164.85	624.38	-0.27	374.08	80.77	-0.66
102	fail	debris flow	32.80	260.52	741.16	-1.16	266.92	321.03	0.17
103	fail	landslide	24.05	288.96	640.53	1.63	430.27	143.24	0.30
104	fail	active slope	27.28	282.32	616.26	-0.87	234.23	69.85	-3.10
105	fail	active slope	29.85	246.49	600.11	0.12	97.14	48.50	-3.82
106	fail	slump	36.84	77.53	667.89	1.93	36.59	219.64	-1.39
107	fail	active slope	43.30	88.27	564.25	1.18	161.98	35.00	-16.07
108	fail	active slope	29.09	30.25	560.49	4.22	24.89	47.56	-0.88
109	fail	slump	28.87	40.38	575.54	1.26	34.55	137.83	-0.99
110	fail	active slope	33.33	249.08	560.16	-2.87	181.74	40.07	-3.70
111	fail	debris flow	31.12	258.29	706.70	-0.97	226.62	317.10	0.07
112	fail	active slope	42.26	255.49	581.45	-1.38	189.01	74.15	-1.03
113	fail	debris slide	32.74	268.68	714.40	-0.53	267.52	350.41	-0.17
114	fail	debris slide	35.69	246.80	632.27	-1.92	262.46	188.41	0.89
115	fail	debris fan	29.04	99.07	682.10	-12.84	18.53	232.51	7.58

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
116	fail	debris fan	31.93	22.83	669.24	-0.10	19.55	138.52	-3.30
117	fail	landslide	31.58	238.25	686.79	-1.95	203.50	242.25	1.08
118	fail	debris fan	31.78	34.53	672.79	-8.40	9.97	218.16	4.13
119	fail	debris fan	30.84	219.34	694.32	-11.95	17.09	248.58	1.20
120	fail	debris fan	24.52	44.94	682.40	-0.57	1.51	205.21	2.13
121	fail	landslide	15.56	242.69	660.93	-3.15	75.36	187.66	4.77
122	fail	landslide	17.79	169.17	688.67	-4.47	23.09	255.20	6.85
123	fail	landslide	16.61	303.12	709.34	-2.25	20.20	157.82	0.87
124	fail	debris fan	26.64	76.88	681.49	-5.71	7.02	233.62	1.70
125	fail	debris fan	22.53	34.51	675.42	-0.27	3.66	169.66	-5.57
126	fail	debris fan	25.75	39.01	694.14	-3.48	30.25	197.58	0.22
127	fail	debris flow	26.06	77.93	673.93	-1.65	31.49	268.20	0.16
128	fail	landslide	15.15	244.49	647.30	-1.54	41.47	93.25	4.61
129	fail	active slope	42.74	236.98	623.77	-4.05	4.58	37.85	1.48
130	fail	slump	37.09	273.11	656.82	-2.35	30.77	98.77	1.97
131	fail	landslide	13.18	315.81	758.24	-0.09	72.60	319.63	1.63
132	fail	slump	15.84	263.72	758.69	-0.34	53.95	273.01	0.20
133	fail	landslide	7.08	257.23	698.42	-0.32	155.55	196.44	0.60
134	fail	slump	17.98	315.30	764.54	-0.93	15.26	138.29	1.36
135	fail	debris fan	17.00	207.25	747.80	-2.73	144.21	158.38	0.46
136	fail	landslide	1.97	304.84	775.45	0.06	109.92	247.41	-0.35
137	fail	slump	31.34	297.42	680.83	-0.16	19.07	89.26	-1.45
138	fail	debris slide	24.40	285.09	714.50	0.29	125.97	253.70	2.81
139	fail	debris slide	25.74	287.42	631.93	0.02	200.78	120.44	0.88
140	fail	slump	25.06	249.85	740.21	-0.54	49.39	285.06	-0.23
141	fail	debris flow	26.67	80.32	613.73	-4.91	168.81	273.69	0.02
142	fail	slump	37.15	117.00	554.18	1.49	320.99	114.52	-1.21
143	fail	active slope	53.96	100.05	519.30	-2.64	242.32	40.09	-2.79
144	fail	active slope	43.53	112.94	513.14	-3.45	248.84	59.01	2.02
145	fail	active slope	23.93	92.75	538.20	2.90	276.69	63.35	-7.13
146	fail	active slope	63.06	108.12	513.45	-1.04	227.27	24.75	-10.34
147	fail	landslide	17.15	181.39	610.76	1.99	84.33	230.04	4.55
148	fail	landslide	35.97	180.08	576.98	-4.31	32.93	265.09	0.61
149	fail	debris fan	26.12	82.32	649.90	2.18	7.66	78.36	0.29
150	fail	active slope	34.94	50.12	600.23	-3.33	621.06	167.47	-2.43
151	fail	slump	33.26	325.45	593.44	0.47	405.10	81.55	4.96
152	fail	slump	10.42	208.72	669.33	-3.52	154.84	290.15	0.74
153	unfail	unfail	30.88	39.21	595.72	-2.40	190.31	195.79	0.77
154	unfail	unfail	8.04	233.80	717.94	-1.23	128.13	554.38	0.31

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
155	unfail	unfail	28.82	334.94	660.13	0.48	115.11	14.15	-2.32
156	unfail	unfail	23.82	64.33	711.08	-1.27	103.43	30.42	0.64
157	unfail	unfail	21.31	188.41	747.55	1.00	26.27	412.41	-1.40
158	unfail	unfail	37.52	295.05	601.79	-3.78	91.90	128.84	3.49
159	unfail	unfail	9.64	97.89	717.91	0.21	26.51	233.60	0.13
160	unfail	unfail	16.99	130.95	694.83	0.80	41.92	481.35	0.25
161	unfail	unfail	26.88	342.93	802.90	0.58	28.77	122.78	-0.37
162	unfail	unfail	35.79	64.25	562.74	-0.58	563.77	80.73	-0.69
163	unfail	unfail	28.98	30.87	730.55	2.13	21.12	254.66	-2.34
164	unfail	unfail	27.38	199.24	650.31	0.38	495.68	238.83	0.15
165	unfail	unfail	22.11	239.97	627.37	1.09	80.17	101.24	0.34
166	unfail	unfail	29.86	322.76	842.80	-0.09	13.40	327.54	-0.49
167	unfail	unfail	20.71	17.32	696.64	-2.14	115.67	33.91	-0.98
168	unfail	unfail	15.96	11.35	480.01	1.07	160.99	296.11	1.15
169	unfail	unfail	19.02	298.17	559.54	0.27	167.43	350.63	1.45
170	unfail	unfail	18.32	178.38	729.69	3.24	273.52	261.91	-3.44
171	unfail	unfail	21.32	141.78	649.86	-1.13	20.36	122.09	-0.66
172	unfail	unfail	25.73	200.06	687.70	-0.46	49.37	569.96	-0.68
173	unfail	unfail	29.45	322.95	570.98	0.77	143.56	65.49	-0.28
174	unfail	unfail	10.03	115.35	666.03	-2.16	33.07	4.12	5.93
175	unfail	unfail	53.52	236.52	529.62	3.55	6.08	130.33	2.03
176	unfail	unfail	26.30	4.89	752.26	0.12	12.79	210.77	2.03
177	unfail	unfail	2.77	254.05	745.77	-0.47	8.39	188.34	-0.48
178	unfail	unfail	9.29	231.57	475.03	1.03	123.83	259.21	-0.77
179	unfail	unfail	16.77	89.34	767.43	-1.02	29.10	280.76	-1.65
180	unfail	unfail	0.59	81.09	504.61	-0.07	16.36	25.25	0.49
181	unfail	unfail	3.87	209.26	705.78	1.07	141.37	31.77	1.54
182	unfail	unfail	8.56	207.96	813.33	-0.14	8.36	253.75	0.18
183	unfail	unfail	20.77	215.02	573.00	-0.04	155.89	123.62	0.50
184	unfail	unfail	28.82	170.19	684.95	0.45	12.77	507.90	2.28
185	unfail	unfail	26.72	107.90	600.91	-1.06	102.30	60.65	1.26
186	unfail	unfail	32.93	345.54	737.68	-0.60	14.37	362.01	-3.40
187	unfail	unfail	23.82	157.39	676.24	0.25	20.69	115.84	0.74
188	unfail	unfail	33.35	299.08	623.16	3.57	86.43	157.54	-1.14
189	unfail	unfail	15.01	311.14	867.40	1.95	30.80	449.75	-0.74
190	unfail	unfail	16.23	311.18	888.04	0.44	15.26	628.53	-0.49
191	unfail	unfail	29.38	255.10	621.08	0.61	93.00	88.67	-0.26
192	unfail	unfail	16.12	258.00	754.88	0.12	181.97	170.41	-0.80
193	unfail	unfail	24.83	50.59	611.90	-1.03	33.95	23.83	0.91

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
194	unfail	unfail	30.39	350.87	692.98	0.09	193.83	151.29	0.03
195	unfail	unfail	25.89	91.72	682.30	0.67	356.56	177.54	0.03
196	unfail	unfail	21.95	86.42	578.61	-0.26	62.08	189.06	1.55
197	unfail	unfail	21.43	310.72	942.00	-0.08	26.22	818.58	0.56
198	unfail	unfail	8.33	223.45	754.13	-1.70	4.30	223.67	1.58
199	unfail	unfail	19.78	269.20	840.83	0.47	32.06	485.97	-1.26
200	unfail	unfail	7.66	313.29	582.39	0.44	139.96	15.36	2.97
201	unfail	unfail	21.95	48.68	701.44	1.21	46.69	108.74	-0.59
202	unfail	unfail	52.88	126.71	614.19	4.20	448.04	234.94	0.91
203	unfail	unfail	34.83	70.56	619.54	-2.10	23.15	47.42	0.16
204	unfail	unfail	29.98	312.76	642.32	0.11	57.74	322.56	2.53
205	unfail	unfail	18.37	318.64	765.64	0.29	84.08	228.26	-0.71
206	unfail	unfail	36.62	197.09	522.29	-4.19	14.71	157.59	4.64
207	unfail	unfail	28.85	87.59	718.81	-0.65	95.00	293.32	-0.13
208	unfail	unfail	15.55	95.04	733.31	-2.99	90.61	433.08	0.41
209	unfail	unfail	18.54	187.98	732.40	0.77	39.67	189.71	-0.19
210	unfail	unfail	31.81	108.50	581.02	-0.03	408.19	159.81	-0.26
211	unfail	unfail	2.83	237.94	849.06	0.23	4.86	643.61	0.13
212	unfail	unfail	19.24	91.23	556.36	-2.32	204.88	41.88	4.52
213	unfail	unfail	30.09	291.30	619.56	0.66	81.64	155.66	-0.08
214	unfail	unfail	20.56	353.88	760.80	0.41	45.00	364.57	1.41
215	unfail	unfail	16.11	227.78	740.84	-0.27	119.54	268.77	0.07
216	unfail	unfail	2.42	57.88	471.42	0.09	469.37	96.90	0.32
217	unfail	unfail	23.27	313.78	577.88	0.34	195.11	375.44	-0.63
218	unfail	unfail	14.97	70.60	766.78	0.79	7.54	452.02	-1.25
219	unfail	unfail	17.89	319.98	618.20	2.03	15.17	310.55	0.20
220	unfail	unfail	11.30	315.57	845.90	0.43	70.54	641.25	-0.18
221	unfail	unfail	13.13	322.29	738.38	0.63	166.80	204.90	-1.44
222	unfail	unfail	5.14	249.92	613.09	-1.98	330.70	2.95	4.75
223	unfail	unfail	20.09	9.54	726.77	2.17	112.10	62.34	-3.50
224	unfail	unfail	12.58	323.25	973.89	-0.58	10.27	687.89	0.03
225	unfail	unfail	27.17	255.91	649.72	1.36	228.11	89.03	0.14
226	unfail	unfail	11.68	289.43	829.13	0.39	43.27	318.19	0.04
227	unfail	unfail	16.95	42.08	656.14	-0.13	21.66	46.17	1.20
228	unfail	unfail	14.93	338.13	743.70	0.16	148.80	165.52	-0.69
229	unfail	unfail	1.30	307.11	823.71	0.08	99.96	474.81	-0.20
230	unfail	unfail	22.41	71.38	662.79	-0.54	280.30	711.47	0.85
231	unfail	unfail	34.22	23.42	652.38	0.23	3.66	585.74	2.77
232	unfail	unfail	28.73	158.22	778.73	0.19	39.67	204.13	-0.83

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
233	unfail	unfail	11.83	177.20	750.15	0.92	9.94	292.32	1.80
234	unfail	unfail	29.23	244.46	514.86	-0.14	290.60	49.35	-0.42
235	unfail	unfail	26.50	325.78	607.31	0.46	5.85	453.38	0.50
236	unfail	unfail	26.12	252.73	679.59	0.67	8.52	97.34	-0.22
237	unfail	unfail	21.77	253.92	635.43	0.71	65.59	73.52	1.26
238	unfail	unfail	4.62	296.68	480.12	0.58	67.26	10.98	-2.92
239	unfail	unfail	31.25	78.52	809.87	-0.02	91.08	29.18	0.72
240	unfail	unfail	21.91	220.62	691.85	1.65	5.03	167.23	-0.27
241	unfail	unfail	13.65	164.58	746.22	0.26	179.21	261.60	0.15
242	unfail	unfail	1.96	42.68	467.63	0.19	52.32	31.16	-0.41
243	unfail	unfail	29.98	325.86	625.34	1.54	55.08	57.66	-2.08
244	unfail	unfail	11.85	285.07	849.12	-3.03	1.45	115.27	-1.11
245	unfail	unfail	11.33	298.67	794.08	0.41	95.23	927.91	-0.37
246	unfail	unfail	13.62	289.74	720.20	0.22	69.00	257.12	0.59
247	unfail	unfail	24.63	44.91	688.06	0.12	69.40	282.90	0.59
248	unfail	unfail	13.67	350.92	811.30	0.98	7.22	354.68	-2.02
249	unfail	unfail	12.63	87.94	711.60	1.02	116.27	105.81	-3.31
250	unfail	unfail	26.68	221.92	694.51	0.44	10.82	302.66	1.59
251	unfail	unfail	31.37	228.10	642.79	0.10	9.60	129.73	-0.02
252	unfail	unfail	6.73	286.65	743.99	0.10	92.57	117.66	-0.38
253	unfail	unfail	20.66	90.30	771.80	0.14	128.71	393.66	-5.35
254	unfail	unfail	18.29	234.16	752.45	0.66	34.72	303.73	-0.46
255	unfail	unfail	11.80	216.49	819.57	-0.45	194.54	97.37	-0.13
256	unfail	unfail	10.47	148.08	764.25	0.26	112.17	289.33	-0.24
257	unfail	unfail	27.41	283.96	594.43	-0.54	53.00	54.67	0.53
258	unfail	unfail	29.85	27.19	658.31	-0.46	5.08	217.05	-9.76
259	unfail	unfail	29.36	94.30	625.86	-0.80	255.30	192.37	0.48
260	unfail	unfail	18.73	118.84	574.25	2.30	371.34	162.58	-3.24
261	unfail	unfail	11.43	98.75	857.57	-0.04	30.27	323.96	-0.11
262	unfail	unfail	14.84	46.20	786.74	0.74	5.06	16.74	-0.04
263	unfail	unfail	27.18	146.34	717.59	-1.15	46.14	359.95	0.22
264	unfail	unfail	27.77	209.07	546.06	-0.18	130.24	95.55	-0.45
265	unfail	unfail	19.80	175.06	684.32	-3.19	148.16	243.00	15.62
266	unfail	unfail	21.80	123.61	814.34	-1.04	2.57	546.58	1.80
267	unfail	unfail	10.14	273.35	723.51	-0.28	41.26	188.38	-2.59
268	unfail	unfail	5.42	296.38	814.48	0.52	25.52	130.27	-0.22
269	unfail	unfail	21.05	233.94	600.23	0.53	88.41	402.49	-0.73
270	unfail	unfail	11.93	319.65	540.81	1.36	429.01	141.04	-1.11
271	unfail	unfail	10.67	134.65	708.92	0.33	54.13	556.02	-0.05

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272	unfail	unfail	32.44	44.18	721.58	1.98	175.11	115.94	-0.67
273	unfail	unfail	38.33	274.57	619.88	2.91	326.47	101.14	11.51
274	unfail	unfail	7.14	322.45	453.93	0.03	206.25	100.06	-3.13
275	unfail	unfail	21.23	292.70	727.57	0.32	31.76	111.01	-0.25
276	unfail	unfail	4.07	266.35	471.52	0.65	52.44	29.03	-4.40
277	unfail	unfail	34.79	271.90	745.46	-0.89	125.15	93.66	1.43
278	unfail	unfail	29.32	243.41	587.40	-0.43	241.33	27.98	-0.02
279	unfail	unfail	20.79	263.56	715.43	0.09	242.68	424.10	-0.84
280	unfail	unfail	6.31	283.98	754.90	-0.32	121.66	226.81	-0.83
281	unfail	unfail	8.84	312.89	820.90	1.36	33.42	216.96	-0.20
282	unfail	unfail	31.52	198.19	588.03	-1.90	285.30	128.14	-1.45
283	unfail	unfail	13.49	69.64	584.15	-0.42	6.60	3.63	3.76
284	unfail	unfail	13.82	100.13	705.41	0.25	10.32	254.16	0.36
285	unfail	unfail	20.79	122.08	644.90	-1.11	252.96	25.68	4.43
286	unfail	unfail	7.36	219.42	588.78	3.67	79.45	5.08	-1.03
287	unfail	unfail	16.40	150.68	802.79	0.03	59.46	605.18	-0.08
288	unfail	unfail	26.30	237.43	720.02	0.11	34.80	331.33	2.04
289	unfail	unfail	14.32	243.32	863.83	2.11	105.14	424.81	-3.26
290	unfail	unfail	10.12	240.96	569.11	-0.25	64.08	140.85	1.49
291	unfail	unfail	32.67	35.39	541.11	-0.04	129.03	56.90	-0.93
292	unfail	unfail	33.88	110.04	748.41	-0.76	83.34	408.38	0.15
293	unfail	unfail	13.98	79.02	748.37	0.50	1.83	32.77	0.71
294	unfail	unfail	23.93	250.72	731.42	1.03	2.25	416.91	1.31
295	unfail	unfail	22.33	256.16	707.45	0.24	27.23	64.35	0.23
296	unfail	unfail	27.40	151.09	665.98	-1.04	221.56	543.01	0.36
297	unfail	unfail	20.64	152.40	739.51	-0.16	235.80	255.17	0.16
298	unfail	unfail	15.67	299.67	962.35	-0.16	48.95	719.80	0.56
299	unfail	unfail	18.10	280.52	803.69	0.18	67.64	821.65	0.17
300	unfail	unfail	11.21	149.92	766.26	-0.92	34.58	412.28	0.27
301	unfail	unfail	19.11	112.58	714.06	2.71	3.33	401.80	0.31
302	unfail	unfail	31.97	223.00	607.89	0.11	87.79	66.36	-0.58
303	unfail	unfail	15.54	285.76	751.39	-0.04	61.22	274.46	-0.01
304	unfail	unfail	17.25	150.45	807.95	0.67	573.31	1274.88	-0.21
305	unfail	unfail	12.13	223.98	734.02	-2.28	7.47	574.16	6.11
306	unfail	unfail	19.69	273.22	758.27	0.30	420.50	411.51	-0.92
307	unfail	unfail	21.32	289.77	707.76	3.09	169.62	819.24	-1.20
308	unfail	unfail	8.12	259.65	974.32	0.77	2.81	948.36	-1.08
309	unfail	unfail	5.51	95.27	1004.00	1.87	47.61	1109.50	-0.43
310	unfail	unfail	13.91	296.80	838.67	0.01	151.86	296.14	-0.27

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311	unfail	unfail	30.36	312.22	740.68	-0.60	40.50	540.23	0.21
312	unfail	unfail	27.10	355.03	739.63	-1.08	65.46	344.72	0.57
313	unfail	unfail	10.78	250.71	802.02	0.50	45.93	396.00	-0.46
314	unfail	unfail	8.62	215.49	684.22	2.26	370.18	1784.50	-5.82
315	unfail	unfail	7.97	58.48	499.08	-0.79	400.74	12.77	5.65
316	unfail	unfail	11.97	212.33	772.20	0.68	5.08	565.99	-2.51
317	unfail	unfail	31.86	71.67	684.57	-0.94	198.38	185.22	-0.61
318	unfail	unfail	27.66	331.74	736.90	0.47	15.63	123.19	0.91
319	unfail	unfail	13.30	12.04	800.13	-0.31	87.15	307.70	0.40
320	unfail	unfail	1.93	188.90	840.42	0.77	1.46	404.48	-0.35
321	unfail	unfail	14.92	17.72	663.74	-0.75	1.58	374.74	1.23
322	unfail	unfail	29.31	56.54	618.55	-0.42	122.58	115.32	-0.31
323	unfail	unfail	2.63	151.88	993.19	0.19	80.98	1351.35	0.40
324	unfail	unfail	1.88	154.22	784.31	0.37	47.33	148.71	-0.86
325	unfail	unfail	21.45	210.07	693.07	0.59	53.99	160.93	-0.28
326	unfail	unfail	22.25	276.25	639.40	-0.70	7.13	328.79	-0.72
327	unfail	unfail	22.23	267.65	747.68	0.05	602.04	842.35	0.89
328	unfail	unfail	15.25	328.65	907.54	-0.87	23.96	579.68	0.02
329	unfail	unfail	24.11	79.77	692.46	-2.46	53.65	4.95	12.23
330	unfail	unfail	9.07	179.26	731.74	1.80	139.13	324.45	-0.98
331	unfail	unfail	16.18	91.61	649.81	0.62	4.01	101.63	-2.19
332	unfail	unfail	31.43	270.11	672.22	-0.02	193.88	122.90	-0.18
333	unfail	unfail	25.91	61.45	689.71	-0.12	1.17	112.56	4.94
334	unfail	unfail	12.36	90.64	784.14	-1.18	1153.62	1733.02	8.30
335	unfail	unfail	25.93	63.23	658.96	-1.60	24.45	498.14	1.84
336	unfail	unfail	32.64	78.76	640.88	0.32	54.60	52.77	-1.34
337	unfail	unfail	19.51	256.64	747.33	-0.15	31.46	271.69	0.83
338	unfail	unfail	12.37	51.27	789.38	-0.86	75.23	413.25	-0.39
339	unfail	unfail	23.58	246.85	738.66	0.41	137.54	456.94	0.49
340	unfail	unfail	2.71	193.96	448.19	0.17	772.72	642.02	0.14
341	unfail	unfail	2.77	170.38	1012.35	0.47	235.81	1444.20	0.07
342	unfail	unfail	8.80	334.75	873.97	0.54	51.23	835.88	0.60
343	unfail	unfail	31.59	88.46	713.60	1.12	22.35	140.31	0.03
344	unfail	unfail	25.57	170.13	657.91	-0.48	315.32	252.00	0.18
345	unfail	unfail	22.22	97.42	705.93	0.69	16.36	14.24	-4.59
346	unfail	unfail	10.97	311.17	574.54	0.48	205.24	271.83	-0.13
347	unfail	unfail	17.38	131.99	596.34	-0.28	166.55	26.89	1.50
348	unfail	unfail	24.02	243.58	717.73	1.05	341.56	211.02	-0.91
349	unfail	unfail	30.15	202.15	674.17	2.17	82.46	19.84	-5.64

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350	unfail	unfail	21.00	228.37	640.41	-0.68	135.07	58.77	-0.79
351	unfail	unfail	26.93	102.72	693.87	-2.81	63.12	48.36	1.49
352	unfail	unfail	4.59	157.24	592.61	0.59	90.96	16.27	-3.73
353	unfail	unfail	28.34	114.24	625.91	-1.52	61.37	43.09	-0.43
354	unfail	unfail	24.67	20.59	634.14	-0.93	744.72	1023.22	0.42
355	unfail	unfail	2.64	227.69	646.88	0.04	20.38	22.54	-0.09
356	unfail	unfail	18.40	297.42	551.90	0.59	160.97	313.15	0.24
357	unfail	unfail	14.03	295.11	862.53	-0.56	599.77	1621.50	0.12
358	unfail	unfail	24.04	273.44	784.71	0.68	120.23	608.62	-0.29
359	unfail	unfail	4.32	228.83	550.15	-0.30	28.24	42.73	1.61
360	unfail	unfail	0.69	205.99	442.99	0.46	324.74	339.08	0.29
361	unfail	unfail	20.95	167.40	693.73	-4.79	29.81	169.29	1.11
362	unfail	unfail	17.23	313.07	785.59	0.84	314.95	1095.89	-0.80
363	unfail	unfail	12.23	269.98	795.29	-0.78	18.86	440.48	0.82
364	unfail	unfail	6.96	180.72	740.25	-0.76	57.79	180.11	0.09
365	unfail	unfail	30.75	348.63	639.53	-0.50	104.12	163.25	0.78
366	unfail	unfail	22.08	140.42	774.99	1.02	14.73	72.18	-1.18
367	unfail	unfail	27.36	146.74	707.05	-0.49	155.15	141.74	-0.15
368	unfail	unfail	14.38	189.63	685.46	-0.41	80.16	693.16	0.40
369	unfail	unfail	21.73	90.13	743.10	-0.72	11.00	50.50	1.48
370	unfail	unfail	10.67	128.28	933.68	0.88	380.74	1040.70	-0.64
371	unfail	unfail	34.31	180.67	528.83	1.91	140.04	74.36	0.38
372	unfail	unfail	13.53	292.18	989.21	0.13	50.35	755.72	-0.22
373	unfail	unfail	4.42	247.30	486.15	0.47	76.10	117.59	0.16
374	unfail	unfail	19.73	321.93	941.64	1.77	125.99	1171.49	-1.38
375	unfail	unfail	21.19	299.88	670.37	-0.41	13.62	49.83	0.74
376	unfail	unfail	32.74	101.92	705.94	1.16	151.35	278.48	0.31
377	unfail	unfail	24.05	295.32	828.32	-0.65	17.36	590.18	0.88
378	unfail	unfail	34.61	43.28	666.55	0.17	39.29	132.71	-0.09
379	unfail	unfail	32.40	57.88	702.58	2.10	17.35	208.79	-1.23
380	unfail	unfail	12.73	229.71	589.98	3.29	8.30	220.88	-1.69
381	unfail	unfail	33.62	254.66	568.03	2.03	221.59	66.58	-0.43
382	unfail	unfail	13.54	303.03	883.81	0.56	74.36	559.91	-0.24
383	unfail	unfail	8.27	265.14	1042.98	-0.63	334.26	940.99	-0.24
384	unfail	unfail	26.67	129.54	709.24	-0.40	15.69	968.65	-4.05
385	unfail	unfail	14.27	301.20	908.21	0.61	16.33	441.45	0.49
386	unfail	unfail	12.89	299.14	712.74	0.18	35.31	415.26	0.85
387	unfail	unfail	22.34	120.13	654.90	-1.93	235.53	3.79	8.48
388	unfail	unfail	31.26	288.47	630.78	0.59	259.65	126.73	0.15

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
389	unfail	unfail	19.89	143.80	777.40	-0.05	24.84	419.95	-0.04
390	unfail	unfail	47.21	328.40	512.99	0.29	49.70	92.19	-1.41
391	unfail	unfail	0.73	140.62	730.57	0.08	45.17	649.90	-0.10
392	unfail	unfail	17.36	268.82	640.41	0.12	21.52	68.31	1.43
393	unfail	unfail	15.17	127.24	639.68	-6.39	56.38	78.30	8.14
394	unfail	unfail	8.57	206.77	612.56	2.47	772.46	115.66	-1.72
395	unfail	unfail	4.06	235.79	577.96	2.77	338.65	7.49	-3.49
396	unfail	unfail	26.82	316.32	509.80	0.65	35.41	134.75	0.77
397	unfail	unfail	7.23	103.06	1015.91	-0.14	111.26	1140.10	0.59
398	unfail	unfail	23.95	32.35	769.72	-0.16	15.60	192.44	-0.88
399	unfail	unfail	19.19	211.91	748.66	1.86	9.22	204.97	-0.73
400	unfail	unfail	17.85	165.50	752.42	0.99	726.73	1553.01	-0.35
401	unfail	unfail	36.30	163.24	647.85	-0.16	112.39	371.53	-1.48
402	unfail	unfail	32.71	39.06	665.32	1.09	454.51	1163.18	-1.16
403	unfail	unfail	7.80	308.41	500.26	1.05	941.58	1211.75	-1.32
404	unfail	unfail	17.30	124.19	592.55	0.00	61.64	111.46	-0.49
405	unfail	unfail	14.21	174.93	775.67	-4.13	12.08	530.78	1.43
406	unfail	unfail	13.94	113.58	697.27	-0.43	14.55	599.79	-0.13
407	unfail	unfail	26.87	336.98	616.50	-0.31	2.30	227.60	-0.13
408	unfail	unfail	7.48	181.05	785.72	2.39	64.54	305.69	-1.07
409	unfail	unfail	26.09	246.27	606.63	0.87	1056.02	1334.09	0.24
410	unfail	unfail	6.12	323.41	500.96	-0.13	416.20	95.99	0.33
411	unfail	unfail	28.20	148.08	742.84	0.97	3.52	227.74	-1.57
412	unfail	unfail	21.21	276.28	681.96	-0.35	9.43	221.81	0.00
413	unfail	unfail	19.10	187.72	639.39	0.22	50.24	225.26	-0.07
414	unfail	unfail	24.31	340.29	777.37	-0.04	176.58	113.02	0.60
415	unfail	unfail	9.33	209.01	819.90	-0.14	18.90	76.90	-0.02
416	unfail	unfail	16.63	312.96	639.01	0.13	119.05	367.31	-1.49
417	unfail	unfail	16.01	117.43	663.60	-0.25	22.40	73.38	-0.36
418	unfail	unfail	26.16	99.82	617.65	0.61	11.24	450.47	0.53
419	unfail	unfail	8.37	339.64	516.94	0.71	268.01	179.12	-0.20
420	unfail	unfail	30.95	209.28	642.58	0.17	112.09	450.55	-0.07
421	unfail	unfail	3.03	245.62	562.93	1.04	305.14	37.82	0.72
422	unfail	unfail	21.78	319.88	714.79	-0.27	61.28	961.07	-0.07
423	unfail	unfail	5.17	318.54	873.29	0.26	258.95	247.06	-1.02
424	unfail	unfail	10.40	143.80	798.11	0.41	191.32	54.59	-0.15
425	unfail	unfail	10.50	9.53	777.30	0.24	13.46	225.19	-0.59
426	unfail	unfail	32.12	22.47	711.46	-0.03	404.81	109.31	2.17
427	unfail	unfail	25.94	267.68	700.83	-0.34	157.11	44.98	0.94

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
428	unfail	unfail	29.29	137.53	622.31	0.29	18.09	74.81	1.43
429	unfail	unfail	26.64	42.60	608.28	-0.10	11.84	71.02	0.72
430	unfail	unfail	28.69	303.78	838.15	-0.27	45.73	527.35	-0.91
431	unfail	unfail	31.47	142.99	454.35	3.02	22.50	170.80	-1.23
432	unfail	unfail	10.51	348.59	811.48	0.89	61.88	448.91	-0.51
433	unfail	unfail	17.58	67.33	605.13	0.07	26.04	133.66	-0.98
434	unfail	unfail	8.72	158.09	761.05	0.17	24.65	346.01	-0.45
435	unfail	unfail	2.37	115.98	575.44	0.20	271.93	6.92	-2.07
436	unfail	unfail	21.78	173.14	666.23	0.25	505.01	188.61	0.03
437	unfail	unfail	43.93	298.69	588.05	3.97	115.13	271.63	-7.93
438	unfail	unfail	5.88	123.32	1032.67	0.29	73.79	1072.81	-0.31
439	unfail	unfail	29.81	131.94	570.73	-0.35	140.43	104.88	2.16
440	unfail	unfail	19.54	27.37	800.22	-1.86	39.17	620.41	0.51
441	unfail	unfail	1.63	230.54	443.81	-0.11	522.78	430.90	-0.10
442	unfail	unfail	2.54	138.62	984.98	0.74	188.76	1217.65	1.22
443	unfail	unfail	13.89	330.57	520.90	0.13	71.11	272.51	0.44
444	unfail	unfail	9.63	319.11	848.47	0.05	108.49	321.94	-0.18
445	unfail	unfail	22.26	232.72	772.78	0.29	10.24	188.30	0.21
446	unfail	unfail	16.85	299.64	759.35	0.43	46.85	524.51	-0.10
447	unfail	unfail	25.32	97.84	675.29	1.68	45.50	69.08	-0.53
448	unfail	unfail	22.25	246.68	604.24	-1.55	413.50	138.99	1.33
449	unfail	unfail	6.68	170.77	757.67	0.88	104.31	416.74	-0.36
450	unfail	unfail	33.70	226.48	565.05	-0.11	34.93	53.36	-0.81
451	unfail	unfail	23.10	22.23	783.50	0.84	91.59	158.79	-0.90
452	unfail	unfail	20.63	140.38	762.27	-0.24	520.56	1360.29	0.32
453	unfail	unfail	21.54	183.08	724.58	-0.50	47.23	254.96	-0.17
454	unfail	unfail	27.17	315.39	712.97	0.61	40.32	264.64	-0.44
455	unfail	unfail	30.94	133.78	619.82	-1.77	119.56	22.84	-2.10
456	unfail	unfail	26.25	321.61	647.86	0.97	2.31	152.67	0.18
457	unfail	unfail	20.23	333.10	689.13	-1.89	44.23	650.13	-0.22
458	unfail	unfail	10.88	74.48	724.86	1.75	210.16	230.68	-4.96
459	unfail	unfail	31.18	76.60	717.42	-1.15	32.12	201.23	1.03
460	unfail	unfail	14.97	303.14	784.76	3.13	4.25	441.71	-1.89
461	unfail	unfail	22.29	113.31	712.67	0.32	98.36	2.36	6.30
462	unfail	unfail	0.76	119.88	445.24	0.24	258.37	157.84	0.09
463	unfail	unfail	22.16	37.06	773.38	-0.50	190.60	732.20	1.02
464	unfail	unfail	27.03	301.24	762.42	0.23	162.36	352.80	-0.81
465	unfail	unfail	29.21	33.96	620.39	0.12	93.35	124.84	0.23
466	unfail	unfail	29.46	250.10	651.20	0.02	264.95	155.69	0.22

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
467	unfail	unfail	11.30	290.30	847.65	3.76	4.06	557.94	-2.04
468	unfail	unfail	25.76	326.24	672.49	-1.20	75.78	255.28	-0.31
469	unfail	unfail	28.96	335.53	738.11	-1.48	57.59	248.16	2.46
470	unfail	unfail	26.56	244.67	675.56	-0.05	22.88	76.15	-0.27
471	unfail	unfail	11.35	106.07	641.67	0.10	23.40	244.25	0.48
472	unfail	unfail	27.52	174.62	583.98	0.73	117.88	55.06	0.29
473	unfail	unfail	4.20	160.57	488.18	-0.51	156.39	10.67	2.80
474	unfail	unfail	35.91	22.14	691.93	1.12	17.00	113.00	0.85
475	unfail	unfail	28.11	199.15	476.63	1.48	22.57	43.54	0.56
476	unfail	unfail	33.81	59.80	659.27	0.71	38.65	144.21	0.34
477	unfail	unfail	7.17	152.49	796.81	0.65	84.67	254.10	-1.39
478	unfail	unfail	14.74	280.57	846.99	0.64	7.00	275.53	0.97
479	unfail	unfail	22.83	51.41	620.04	-2.08	171.57	25.09	2.90
480	unfail	unfail	9.94	110.75	757.63	-0.18	616.16	1419.42	0.43
481	unfail	unfail	2.83	158.61	766.87	0.80	144.59	120.95	-0.24
482	unfail	unfail	6.26	140.99	793.86	-0.23	52.80	154.14	0.60
483	unfail	unfail	6.55	199.20	722.18	-0.36	3.12	119.82	0.69
484	unfail	unfail	35.46	196.34	500.68	0.13	142.57	27.90	2.07
485	unfail	unfail	18.65	184.64	665.51	-0.63	51.82	320.52	0.11
486	unfail	unfail	33.38	279.08	535.59	-1.79	131.66	137.78	0.13
487	unfail	unfail	19.06	291.21	891.83	0.86	12.52	267.39	0.22
488	unfail	unfail	24.84	291.64	753.45	-0.79	126.21	506.28	3.16
489	unfail	unfail	29.53	248.17	609.70	-0.57	237.96	133.17	0.95
490	unfail	unfail	13.60	70.54	525.35	-0.23	47.78	78.66	3.12
491	unfail	unfail	18.53	158.01	674.96	-0.88	24.28	265.51	0.26
492	unfail	unfail	30.71	190.44	1006.28	2.22	695.55	1793.78	-3.44
493	unfail	unfail	24.25	245.70	731.43	0.29	100.30	81.67	-0.32
494	unfail	unfail	6.34	237.43	997.54	-1.71	48.20	823.93	-0.27
495	unfail	unfail	15.14	101.55	787.26	0.05	1361.78	2085.13	0.27
496	unfail	unfail	17.77	317.72	909.74	1.62	7.94	912.40	-1.69
497	unfail	unfail	28.12	186.68	830.77	-0.40	6.73	575.96	0.45
498	unfail	unfail	13.92	262.84	676.57	-0.19	103.28	87.11	-0.35
499	unfail	unfail	29.55	350.24	732.72	-0.01	23.15	202.90	0.31
500	unfail	unfail	19.62	314.23	801.09	0.47	327.69	778.87	-0.11
501	unfail	unfail	17.80	352.93	872.21	0.53	46.36	852.30	-1.28
502	unfail	unfail	7.56	183.29	713.38	-0.52	17.77	21.62	3.93
503	unfail	unfail	10.60	315.24	838.59	-0.31	40.28	626.26	0.06
504	unfail	unfail	18.86	264.83	814.62	1.22	23.31	11.65	-5.02
505	unfail	unfail	11.40	234.21	742.50	-0.29	518.44	1471.18	0.72

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
506	unfail	unfail	22.81	215.59	639.28	-1.17	17.40	261.18	1.06
507	unfail	unfail	27.24	231.77	622.46	-3.73	357.81	28.99	13.19
508	unfail	unfail	9.61	46.86	542.08	-0.92	661.43	178.56	-0.28
509	unfail	unfail	15.65	338.65	583.99	-1.16	56.63	190.47	1.68
510	unfail	unfail	19.53	287.49	731.53	-0.32	111.07	376.66	-0.39
511	unfail	unfail	24.90	126.84	650.08	-0.06	332.32	511.44	0.73
512	unfail	unfail	10.97	267.77	1034.00	-0.50	302.98	870.35	0.36
513	unfail	unfail	17.00	332.63	961.48	-0.06	69.00	859.84	0.02
514	unfail	unfail	13.87	57.41	602.38	-1.37	1.48	22.92	11.64
515	unfail	unfail	15.90	287.46	754.37	0.47	55.98	370.18	-0.40
516	unfail	unfail	7.38	279.72	776.47	0.95	34.77	419.57	-0.54
517	unfail	unfail	14.05	304.15	749.17	-0.30	16.24	269.76	0.32
518	unfail	unfail	16.16	289.49	887.67	-0.17	27.27	387.24	0.52
519	unfail	unfail	4.88	104.74	773.73	0.55	1181.03	1158.48	-0.87
520	unfail	unfail	1.33	126.85	449.03	0.28	1376.23	1286.52	0.50
521	unfail	unfail	5.65	53.91	814.16	-1.92	38.86	205.33	0.49
522	unfail	unfail	31.44	94.67	697.02	-1.30	187.39	264.69	3.58
523	unfail	unfail	23.09	89.85	795.32	1.05	16.69	64.52	-1.90
524	unfail	unfail	12.49	200.25	769.54	-0.20	103.79	721.95	0.28
525	unfail	unfail	25.11	70.37	748.23	0.40	3.66	350.98	2.94
526	unfail	unfail	23.99	297.88	734.24	-0.87	24.41	331.35	-1.82
527	unfail	unfail	21.90	350.77	687.85	-0.25	5.33	293.99	1.95
528	unfail	unfail	25.81	73.51	702.95	0.05	295.91	236.96	0.63
529	unfail	unfail	15.31	176.11	730.69	-0.17	54.69	227.84	0.14
530	unfail	unfail	7.54	169.41	837.84	0.03	1175.64	1586.73	-0.16
531	unfail	unfail	19.38	280.81	731.97	-1.35	52.12	235.82	0.26
532	unfail	unfail	5.01	198.55	605.54	0.78	51.08	14.87	0.05
533	unfail	unfail	6.21	251.19	725.07	-3.31	264.75	1518.11	3.44
534	unfail	unfail	15.09	274.87	715.08	-0.15	8.78	358.38	-0.54
535	unfail	unfail	21.40	107.22	771.49	-0.47	22.28	372.41	-1.70
536	unfail	unfail	17.60	221.95	810.71	0.44	126.26	458.00	0.19
537	unfail	unfail	40.80	50.77	609.43	-0.53	284.92	300.82	-0.25
538	unfail	unfail	22.45	317.54	719.34	-0.06	12.51	39.37	-0.61
539	unfail	unfail	1.76	131.84	773.48	0.98	142.85	349.58	-0.82
540	unfail	unfail	35.51	45.62	611.49	-0.45	165.09	108.69	1.12
541	unfail	unfail	3.75	294.93	835.98	-0.18	109.68	948.76	-0.22
542	unfail	unfail	19.77	107.41	712.31	4.69	76.17	871.59	-0.14
543	unfail	unfail	22.94	8.19	735.35	0.22	54.53	210.03	0.47
544	unfail	unfail	20.03	254.70	674.89	-0.41	817.67	1113.10	-0.46

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545	unfail	unfail	23.23	118.47	674.56	0.49	8.12	105.78	1.57
546	unfail	unfail	12.54	282.99	760.47	1.03	132.74	377.68	-0.23
547	unfail	unfail	31.23	182.54	636.39	0.32	110.59	721.55	-0.40
548	unfail	unfail	25.15	77.93	800.63	0.67	504.63	646.81	-0.16
549	unfail	unfail	15.40	134.67	813.63	0.85	35.80	466.57	-0.90
550	unfail	unfail	21.58	299.82	715.53	0.69	50.58	181.91	0.32
551	unfail	unfail	14.38	216.13	799.68	0.13	18.58	345.48	-1.73
552	unfail	unfail	32.59	137.03	634.82	-0.08	52.45	87.71	-5.79
553	unfail	unfail	12.94	37.25	596.16	0.22	23.08	224.42	-0.68
554	unfail	unfail	24.84	271.94	693.83	1.09	14.42	148.38	-0.56
555	unfail	unfail	17.12	316.82	910.07	0.09	47.26	607.69	-0.91
556	unfail	unfail	5.38	269.36	560.87	-0.51	117.38	3.00	2.45
557	unfail	unfail	32.82	319.66	642.13	0.31	29.70	240.39	0.89
558	unfail	unfail	20.68	190.22	653.62	-1.23	513.85	919.49	-0.72
559	unfail	unfail	12.42	182.55	803.98	-3.45	64.00	629.95	4.24
560	unfail	unfail	31.42	76.38	707.42	-0.25	176.97	230.98	0.27
561	unfail	unfail	28.67	160.63	555.31	0.73	191.26	17.37	-0.84
562	unfail	unfail	11.95	205.56	699.82	-0.54	203.12	145.23	0.31
563	unfail	unfail	18.54	207.46	735.21	0.10	23.14	857.34	0.01
564	unfail	unfail	14.96	328.37	607.56	-0.84	44.17	372.66	0.62
565	unfail	unfail	8.84	256.98	754.86	-0.05	47.77	124.36	0.21
566	unfail	unfail	34.63	45.72	604.83	-1.54	18.01	87.65	2.52
567	unfail	unfail	24.86	64.34	599.67	1.22	2.05	46.68	2.05
568	unfail	unfail	39.43	284.21	658.38	-0.46	27.23	16.77	-10.02
569	unfail	unfail	4.74	173.48	792.33	0.67	111.36	256.92	-0.62
570	unfail	unfail	25.29	63.53	730.89	-0.10	285.93	1296.41	-0.14
571	unfail	unfail	16.66	324.19	846.30	-0.46	391.77	1290.63	0.14
572	unfail	unfail	9.03	205.92	560.80	-1.00	51.76	44.66	4.93
573	unfail	unfail	25.55	345.49	675.92	0.81	165.26	111.36	-0.24
574	unfail	unfail	17.21	310.21	917.55	-0.02	5.60	823.93	-0.09
575	unfail	unfail	17.74	321.45	927.45	-1.30	2.01	725.51	1.77
576	unfail	unfail	32.37	135.95	632.31	4.14	210.04	235.25	0.38
577	unfail	unfail	30.19	87.91	622.69	0.11	381.44	116.92	0.22
578	unfail	unfail	6.71	188.83	596.01	-1.91	158.06	9.60	5.69
579	unfail	unfail	20.21	277.56	652.57	-0.34	13.88	352.78	-0.04
580	unfail	unfail	3.95	125.57	492.96	0.60	109.44	35.32	-0.95
581	unfail	unfail	9.02	54.48	727.35	3.09	132.41	1195.87	-0.48
582	unfail	unfail	23.40	223.12	703.43	-0.43	123.85	435.91	0.64
583	unfail	unfail	10.35	158.28	737.35	1.28	27.87	152.22	-0.41

Value	Status	Type	Slope (°)	Aspect (°)	Elevation (m)	Curvature (radians per meter)	Dist. to Roads (m)	Dist. to Streams (m)	Profile curvature (radians per meter)
584	unfail	unfail	16.32	288.37	726.17	0.66	20.11	14.84	-0.83
585	unfail	unfail	5.28	174.15	814.69	1.23	64.92	663.78	-1.14
586	unfail	unfail	25.17	116.45	588.76	-0.34	216.60	33.04	0.43
587	unfail	unfail	38.67	47.32	497.75	-1.36	39.11	5.33	5.11
588	unfail	unfail	24.57	152.89	740.48	0.51	638.96	304.31	-0.93
589	unfail	unfail	10.84	356.76	840.22	0.09	142.61	434.73	-0.33
590	unfail	unfail	34.56	286.01	575.77	-0.79	164.11	24.39	1.77
591	unfail	unfail	8.84	212.68	772.28	0.55	59.86	223.10	0.40
592	unfail	unfail	9.59	268.32	746.72	0.25	78.86	203.56	-0.54
593	unfail	unfail	21.42	295.17	695.60	-0.40	22.89	444.76	-0.10
594	unfail	unfail	18.74	165.91	737.91	-0.15	57.22	467.00	-0.03
595	unfail	unfail	23.91	41.71	598.45	1.35	30.08	111.97	-2.29
596	unfail	unfail	20.03	187.24	687.06	-0.27	487.51	303.06	-0.06
597	unfail	unfail	16.74	213.49	622.50	-0.31	11.55	21.06	-0.36
598	unfail	unfail	26.33	33.47	701.14	-1.47	10.78	218.12	1.42
599	unfail	unfail	13.60	253.34	720.45	-4.19	120.12	41.76	3.85
600	unfail	unfail	14.67	121.62	765.90	0.61	644.85	1539.21	-0.41
601	unfail	unfail	12.29	103.83	741.95	-0.05	2.92	129.53	-2.38
602	unfail	unfail	28.72	47.83	540.97	0.68	224.77	37.72	10.14
603	unfail	unfail	25.74	90.65	449.15	3.10	773.89	656.19	-15.10

Appendix B: Two sample student's t-tests for each variable and type of slope movement. Results show significant difference at the 95% confidence limit.

Slope Angle	Active Slopes	Planar Slides	Rotational Slumps	Debris Fans	Debris Flows	Debris Slides
Active Slopes	EQUAL					
Planar Slides	Different	EQUAL				
Rotational Slumps	Different	Similar	EQUAL			
Debris Fans	Different	Different	Different	EQUAL		
Debris Flows	Different	Different	Different	Different	EQUAL	
Debris Slides	Similar	Different	Different	Different	Similar	EQUAL
Unfailed	Different	Similar	Similar	Different	Different	Different

Elevation	Active Slopes	Planar Slides	Rotational Slumps	Debris Fans	Debris Flows	Debris Slides
Active Slopes	EQUAL					
Planar Slides	Different	EQUAL				
Rotational Slumps	Different	Similar	EQUAL			
Debris Fans	Different	Similar	Similar	EQUAL		
Debris Flows	Different	Different	Different	Different	EQUAL	
Debris Slides	Different	Different	Different	Similar	Different	EQUAL
Unfailed	Different	Different	Similar	Different	Similar	Different

Plan Curvature	Active Slopes	Planar Slides	Rotational Slumps	Debris Fans	Debris Flows	Debris Slides
Active Slopes	EQUAL					
Planar Slides	Similar	EQUAL				
Rotational Slumps	Similar	Similar	EQUAL			
Debris Fans	Different	Different	Different	EQUAL		
Debris Flows	Similar	Similar	Different	Similar	EQUAL	
Debris Slides	Similar	Similar	Similar	Different	Similar	EQUAL
Unfailed	Different	Different	Different	Different	Different	Similar

Profile Curvature	Active Slopes	Planar Slides	Rotational Slumps	Debris Fans	Debris Flows	Debris Slides
Active Slopes	EQUAL					
Planar Slides	Different	EQUAL				
Rotational Slumps	Different	Different	EQUAL			
Debris Fans	Similar	Similar	Similar	EQUAL		
Debris Flows	Similar	Different	Similar	Similar	EQUAL	
Debris Slides	Similar	Different	Different	Similar	Similar	EQUAL
Unfailed	Different	Different	Similar	Similar	Similar	Similar

Distance from Roads	Active Slopes	Planar Slides	Rotational Slumps	Debris Fans	Debris Flows	Debris Slides
Active Slopes	EQUAL					
Planar Slides	Similar	EQUAL				
Rotational Slumps	Different	Similar	EQUAL			
Debris Fans	Different	Different	Similar	EQUAL		
Debris Flows	Different	Similar	Similar	Similar	EQUAL	
Debris Slides	Similar	Similar	Different	Different	Different	EQUAL
Unfailed	Different	Similar	Similar	Different	Similar	Different

Distance from Streams	Active Slopes	Planar Slides	Rotational Slumps	Debris Fans	Debris Flows	Debris Slides
Active Slopes	EQUAL					
Planar Slides	Different	EQUAL				
Rotational Slumps	Different	Similar	EQUAL			
Debris Fans	Different	Similar	Similar	EQUAL		
Debris Flows	Different	Different	Different	Different	EQUAL	
Debris Slides	Different	Similar	Similar	Similar	Different	EQUAL
Unfailed	Different	Similar	Similar	Similar	Different	Similar

Appendix C: Mean, standard deviation, and variance for each of seven landscape variables for the different types of slope movements mapped within Horseshoe Run watershed.

Variables for Active Slopes	Mean	Standard Deviation	Variance
Slope Angle (°)	35.95	9.59	91.88
Elevation (m)	563.75	47.09	2217.26
Plan Curvature	-1.04	2.69	7.22
Profile Curvature	-1.70	4.49	20.14
Distance to Roads (m)	219.22	149.22	22265.65
Distance to Streams (m)	61.30	26.58	706.72

Variables for Debris Fans	Mean	Standard Deviation	Variance
Slope Angle (°)	26.12	5.48	30.01
Elevation (m)	662.44	45.47	2067.72
Plan Curvature	-3.25	4.23	17.93
Profile Curvature	0.49	2.76	7.64
Distance to Roads (m)	90.68	147.08	21633.41
Distance to Streams (m)	230.51	107.77	11613.54

Variables for Debris Flows	Mean	Standard Deviation	Variance
Slope Angle (°)	30.30	3.14	9.88
Elevation (m)	717.16	50.12	2511.85
Plan Curvature	-1.52	2.02	4.07
Profile Curvature	0.07	1.19	1.41
Distance to Roads (m)	115.78	112.01	12546.86
Distance to Streams (m)	440.88	167.75	28140.04

Variables for Rotational Slumps	Mean	Standard Deviation	Variance
Slope Angle (°)	21.03	9.00	80.92
Elevation (m)	680.53	67.97	4619.57
Plan Curvature	-0.40	1.33	1.77
Profile Curvature	0.67	1.52	2.32
Distance to Roads (m)	118.06	121.93	14867.36
Distance to Streams (m)	234.95	99.16	9833.14

Variables for Debris Slides	Mean	Standard Deviation	Variance
Slope Angle (°)	32.28	4.73	22.34
Elevation (m)	625.49	71.31	5084.86
Plan Curvature	0.11	2.66	7.07
Profile Curvature	-0.61	2.18	4.75
Distance to Roads (m)	217.79	183.92	33824.78
Distance to Streams (m)	220.73	86.82	7537.62

Variables for Planar Slides	Mean	Standard Deviation	Variance
Slope Angle (°)	21.77	9.18	84.19
Elevation (m)	670.39	69.49	4829.41
Plan Curvature	-0.94	1.76	3.08
Profile Curvature	1.86	2.74	7.48
Distance to Roads (m)	139.69	136.44	18615.72
Distance to Streams (m)	210.78	99.41	9882.51

Variables for Unfailed Slopes	Mean	Standard Deviation	Variance
Slope Angle (°)	19.25	9.67	93.49
Elevation (m)	702.73	115.32	13297.90
Plan Curvature	0.10	1.29	1.66
Profile Curvature	0.17	2.50	6.26
Distance to Roads (m)	142.24	202.20	40885.80
Distance to Streams (m)	347.57	362.12	131156.00

Appendix D: Aspect data for each type of slope movement

Planar Slides

Rotational Slumps

Debris Fans

Debris Flows

Debris Slides

Active Slopes

Unfailed Slopes

A wind rose plot for 'Unfailed Slopes'. The plot shows wind frequency by direction and speed. The directions are labeled N, E, S, and W. The wind speed ranges are 0-10, 10-20, 20-30, 30-40, and 40-50. The highest frequency is in the NW direction, with speeds between 10 and 30. Other significant frequencies are in the N, NE, and S directions.

Direction	0-10	10-20	20-30	30-40	40-50
N	10	20	30	10	0
NE	10	20	30	10	0
E	10	20	30	10	0
SE	10	20	30	10	0
S	10	20	30	10	0
SW	10	20	30	10	0
W	10	20	30	10	0
NW	10	20	30	10	0

Appendix E: Aspect data for unfailed slopes categorized by slope angle

Unfailed Slopes (0-12 degrees)

Unfailed Slopes (12-20 degrees)

Unfailed Slopes (20-24 degrees)

Unfailed Slopes (24-28 degrees)

Unfailed Slopes (28-32 degrees)

Unfailed Slopes (32+ degrees)

Appendix F: Primer on LiDAR data acquisition

LiDAR (LIght Detection And Ranging) is a remote sensing technique similar to radar only instead of using radio waves, LiDAR involves the use of pulses of light (Lillesand, Kiefer, and Chipman, 2004). The pulses of light that are directed towards the Earth's surface are reflected off various features on the ground, either vegetation or ground surface, and the time required to return back to the sensor can be used to calculate elevation data (Lillesand, Kiefer, and Chipman, 2004). LiDAR data acquisition is performed using a photogrammetric aircraft with a high-resolution airborne GPS, an inertial measuring unit (IMU), a rapidly pulsing laser, a highly accurate clock, and substantial and robust computer capabilities (Lillesand, Kiefer, and Chipman, 2004). The GPS unit records the x, y, z , data for the sensor location and the IMU is required to measure the angular orientation of the sensor with respect to the ground. In most modern LiDAR sensors, 20,000 to 50,000 pulses of light can be emitted per second, or 20 to 50 kHz (Lillesand, Kiefer, and Chipman, 2004).

The accuracy of the LiDAR data and the associated cost of acquisition are a function of the operational parameters of the instrument and flight plan (Lovell *et al.*, 2005). The main parameters that affect the LiDAR survey are aircraft height, flight speed, half scan angle, pulse frequency, and scan frequency (Lovell *et al.*, 2005) (Figure 1). The zig-zag ground pattern of most LiDAR sensors is produced by a scanning mirror within the sensor, and half of the zig-zag pattern is considered the scan half angle. One method to increase the accuracy of the LiDAR data is to increase the density of the ground points, or footprint. This can be accomplished by decreasing the aircraft height, slowing the flight speed, or reducing the scan half angle (Hodgson and Bresnahan, 2004). An

Figure 1: Diagram showing a generalized flight path for LiDAR data acquisition. Diagram taken from Lovell *et al.*, 2005.

additional parameter that can also have an affect on the accuracy of the LiDAR data is the scanning angle of the sensor, which is measured as the angle between a vertical line from the aircraft and the angle at which the light is being emitted (Holmgren, Nilsson, and Olsson, 2003) (Figure 2).

For most ground surface digital elevation models (DEM), LiDAR data acquisition is performed using a small scanning angle to ensure minimal interference with vegetation, and 30% to 50% of swath overlap to minimize gaps in the reflected LiDAR data (Lillesand, Kiefer, and Chipman, 2004). In addition to a small scanning angle, LiDAR acquisition is often performed during leaf-off and at low flight elevations in order to achieve small laser footprints under minimum interference conditions (Hodgson and Bresnahan, 2004).

A common wavelength of light used in LiDAR acquisition is 1064 nm, which is in the near infrared spectrum (Holgren, Nilsson, and Olsson, 2003; Goodwin *et al.*, 2006). A benefit of LiDAR is the number of reflections, or returns, that recorded by the sensor. As the thousand of light pulses are emitted from the laser, some of the light waves will reflect off the canopy leaves or braches of trees while others will penetrate through the leaf cover and reflect off understory vegetation and the ground surface. The multiple reflections can then be interpreted and correlated and multiple elevation surfaces can be derived (Lillesand, Kiefer, and Chipman, 2004) (Figure 3). Additionally, the magnitude of the reflected pulse can be recorded and is referred to as intensity (Hodgson and Bresnahan, 2004). These intensities can also be used to filter-out the less intense vegetation returns and provide the last returns which are reflected from the ground surface and are higher in magnitude (Hodgson and Bresnahan, 2004).

Figure 2: Diagram showing the scanning angle used during LiDAR data acquisition. Diagram taken from Holmgren, Nilsson, and Olsson, 2003.

Figure 8.62 Lidar pulse recording multiple returns as various surfaces of a forest canopy are "hit." (Courtesy Earth-Data International.)

Figure 3: Diagram showing the multiple returns and the various intensities of the reflected waveforms from the emitted pulses of light during LiDAR data acquisition. Diagram taken from Lillesand, Kiefer, and Chipman, 2004.

The errors associated with LiDAR data are inherent errors of the equipment and human error resulting from interpretation. The positional errors in LiDAR data collection are associated with the GPS equipped on the aircraft, the inertial navigation unit, used for estimating points between GPS corrections, and the IMU used for measuring the direction of the laser (Hodgson and Bresnahan, 2004). Human error is introduced if an automated intensity filter is not used and interpretation of the waveform returns is required. However, even despite the inherent errors associated with the data acquisition, LiDAR data can be extremely accurate, both horizontally and vertically. Many LiDAR-derived DEM's have been recorded as having vertical accuracies of 26 cm to 153 cm (Hodgson and Bresnahan, 2004). These highly accurate results provide an invaluable tool for research in numerous fields such as geology, geomorphology, forestry, ecology, and geography.