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Understanding the Influence of Fractures Along the Swannanoa Lineament During Helene-related Landslide Occurrences

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Abstract

Western North Carolina is prone to landslides under normal rainfall conditions due to the steep topography of the mountains and underlying bedrock structures. However, when a large rain event occurs, it exacerbates this likelihood of landslides. Hurricane Helene impacted the region as one of the deadliest landslide events in recorded history of WNC. At least 2,015 landslides were identified as of March 2025. This study evaluated a section of the Swannanoa Lineament from Asheville to Old Fort, NC to constrain its contribution to landslide occurrences during Helene. This lineament is defined by numerous joints and faults that are part of this brittle fault system. Landslides in this section were identified from the USGS Helene landslide database, from NOAA high resolution imagery collected following the storm, and from field observations. The orientation of the joints, faults, and foliation in the bedrock was then evaluated to see if there was a correlation between their orientations and landslide occurrences. This data was collected in the field and added to existing data provided by the NCGS. The

foliation dominantly strikes NE-SW and dips SE whereas the joints dominantly strike NW-SE with a near vertical dip. Of the 129 landslides identified in the field area, a significant number of them were on south-facing slopes. The orientation of the foliation and joints could create wedge slope failures on south-facing slopes which would explain the preference for that direction. The wedge failures can also occur on E-NE facing slopes, which accounts for the second highest occurrences in these directions. The North Carolina Geological Survey has an existing landslide susceptibility map for Buncombe County. This study shows that bedrock failure planes should be considered in susceptibility evaluation.

1. Introduction

Hurricane Helene was a devastating and deadly tropical storm that impacted much of the Southern United States, one of the most impacted areas being Western North Carolina (WNC). The storm caused unprecedented flooding to take place within a short time frame, especially since the day prior a large rain event occurred. Before Hurricane Helene it is estimated that 6 - 10 inches of rain befell the region as of midnight on September 27th, 2024. By the evening of September 27th, the estimated rainfall tallied for the region as 12 - 20 inches, with some places accumulating more than 20, in a two day period (US, 2024). This storm not only caused extreme flooding, but a huge number of mass movement occurrences (both landslides and debris flows) as well. At least 2,015 landslides were identified as being directly influenced by Hurricane Helene (USGS, 2025). The vast number of landslides were due to the amount of water being present in both the surface and subsurface, which decreased the friction coefficient so much that the soil and rock could no longer hold their static position.

Landslides happen due to several factors, the most prominent being subsurface conditions and friction. The steeper the slope, the higher the gravitational force enacted on the material. With a higher shear force it is easier for the material to slide. Therefore, it is easier for the material to overcome the friction coefficient—the reason the material is stationary to begin with. Landslides can occur more easily if the friction coefficient is reduced, which can be done by adding water. Water follows the path of least resistance, so if there are joints and fractures in the subsurface, water will flow into these spaces. There are two types of landslides focused on within this study: wedge failures and planar failures which involve failure along planes within the bedrock.

Although the east coast of the United States does not lie on or near a plate boundary, there is geologic evidence for tectonic plate movement that can be seen through lineaments on the surface within the Southern Appalichians (Hill, 2013; Langille et al., 2023). The lineaments present in WNC are linear topographic features that cross cut obliquely across the strike of the bedrock foliation (Figure 1). The Swannanoa Lineament, along with the others, are evidence for a result of Cenozoic regional topographic rejuvenation (20 million years ago to present), possibly due to delamination of the lower crust resulting from crustal rebound (Hill, 2013; Langille et al., 2023). The Swannanoa Lineament is an E/W trending feature of faults and joints that are dominantly striking NE/SW.

The goal of this project is to constrain the role that these fractures played in mass movement occurrences. The study area for this project can be seen in Figures 1 and 2. This location was chosen for this project due to it being along a major transportation corridor. Understanding where locations are more susceptible for mass movement occurrences is important to maintain transportation.

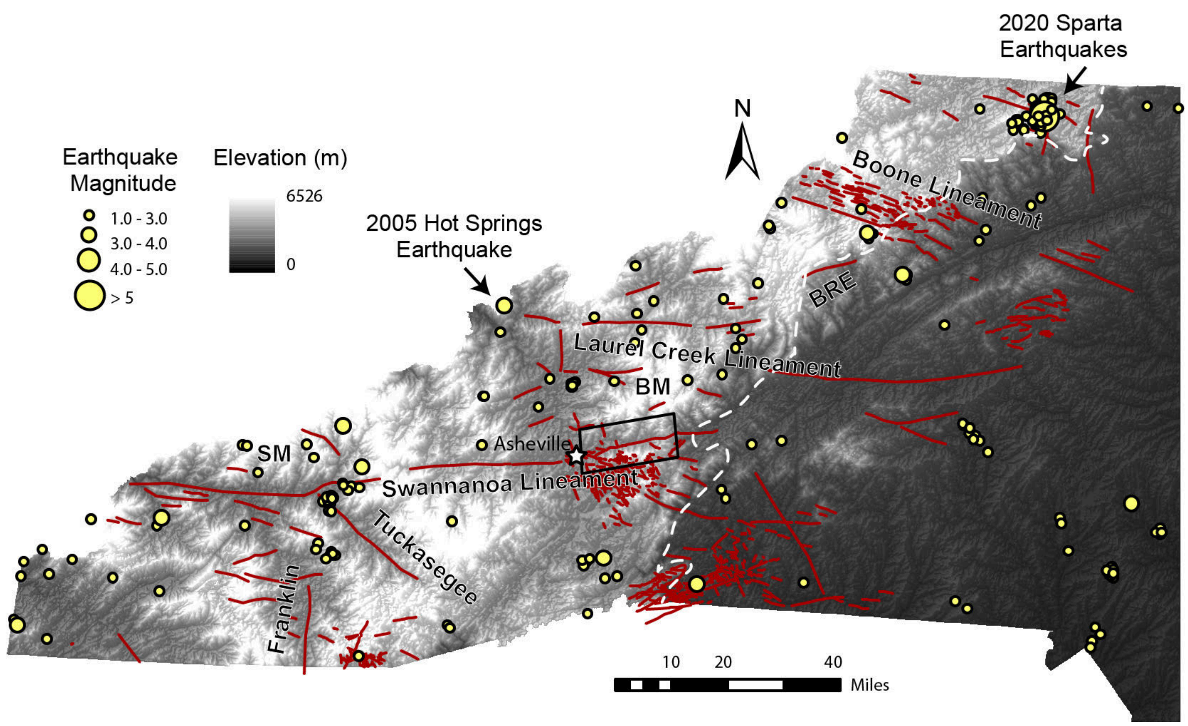

Figure 1. Map showcasing lineament features in Western North Carolina along with earthquakes and their magnitude (modified from Langille et al., 2023). The black box indicates the study area with the white star marking Asheville.

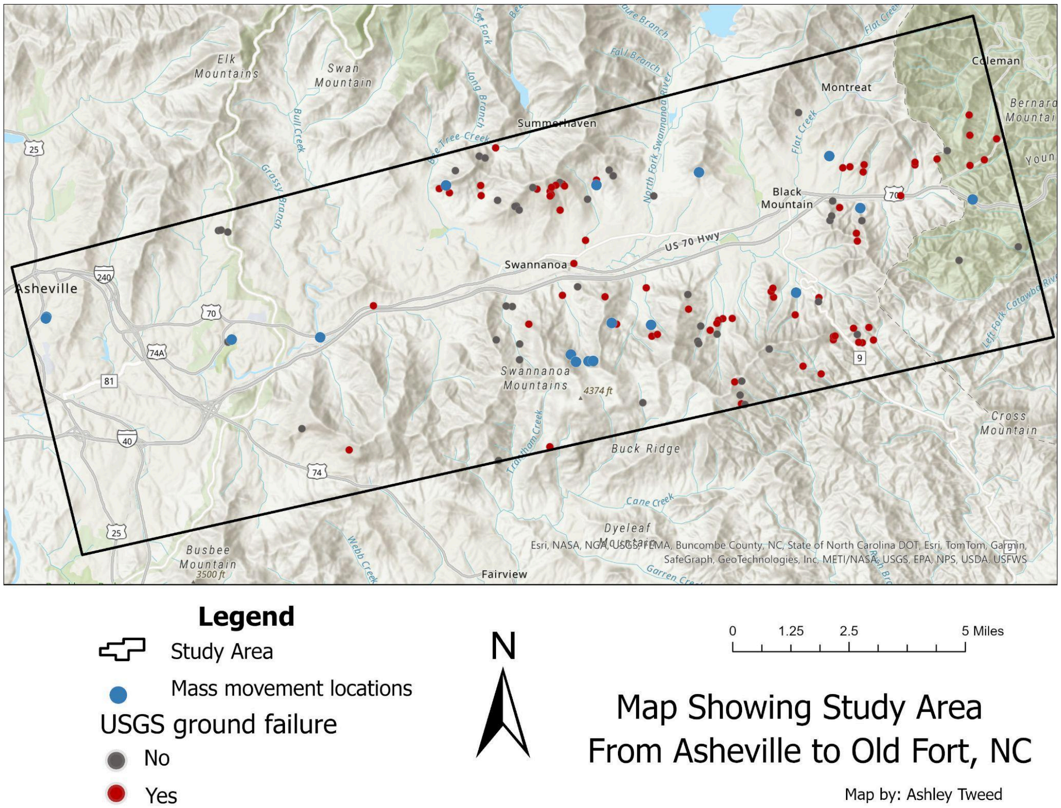

Figure 2. Map showing the study area along with locations of mass movement occurrences identified from the USGS database (grey and red) along with locations identified for this project (blue). The USGS discerned whether infrastructure was impacted (red dot) or not (grey dots).

2. Methods

To assess the role of bedrock fractures in the occurrence of landslides, GIS and field work were used to identify landslides, bedrock structures obtained in the field and from the NCGS were constrained, and their relationship to slope failures were evaluated.

2.1 Geographic Information Systems

Aerial imagery was used to compare pre- and post- Helene damage within the Swannanoa Lineament, predominantly around I-40 and I-70, from Asheville to Old Fort North Carolina. Landslides in this section were identified from the USGS Helene landslide database in ArcGIS PRO, from NOAA high resolution imagery collected following the storm, and from field observations. An aspect (slope direction) map was derived to constrain mass movement occurrences to determine likelihood of bedrock involvement. When the slope direction is favorable with subsurface joints, fractures, and foliation a mass movement event is likely to occur.

Secondary analytical analysis was performed using R script in Posit Cloud. The resulting histograms were then produced to determine bedrock involvement in landslide occurrences from Hurricane Helene. To achieve the histograms derived for this study the “ggplot2” package was used with restraining factors to isolate mass movement types (landslides and debris flows) along with no restraints to obtain an overall relationship between aspect and frequency.

2.2 Field Work

Field work was performed to both confirm landslide locations and to determine if bedrock was involved. Strike and dip measurements were collected, as well as joint and foliation measurements. These measurements were then used along with pre-existing data to perform analysis.

2.3 Slope Stability Analysis

Stereonets for landslides are used to visualize three dimensional relationships between joints and faults, foliation of the rock, and slope along with an angle of repose which is the steepest angle that a material can be sloped without sliding down. A generalized schematic of the two landslide types can be seen in Figure 3 to allow the reader to understand the stereonets that were produced through the freeware program Stereonet. For slope stability analysis the general angle of repose that is used for the steep topography found in Western North Carolina is 30 degrees, which dictates where the friction angle is drawn on a stereonet. The friction angle is then used to determine if an area is susceptible to a landslide when compared to the slope. The landslide type is determined by the angles of fractures and joints or foliation planes. A planer failure occurs when the dip of the foliation is below the failure angle resulting in it sliding. When visualized on a stereonet, this is when the foliation is within twenty degrees of the slope within the friction angle. A wedge failure occurs when two features within the bedrock intersect with one another and are within the failure angle. When visualized on a stereonet, this is when the two bedrock features intersect within the friction angle.

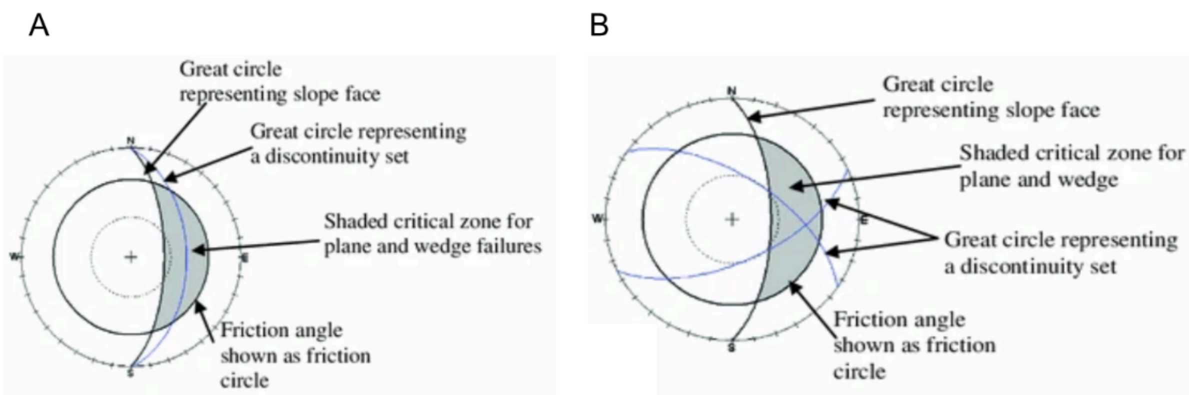

Figure 3. Stereonet representations of planar failure (A) and wedge failure (B). The shaded area is formed by the great circle that represents the slope face and the angle of repose, 30°. Planar failure occurs when the strike of the discontinuity set is within 20° of the slope strike and the great circle of the discontinuity set plots in the critical zone. Wedge failure occurs when two discontinuity sets cross in the critical zone.

3. Results

A poles to planes stereonet that depicts average foliation direction along the Swannanoa lineament (Figure 4). Figure 5 is a poles to planes stereonet that depicts average fracture orientation along the Swannanoa lineament. The generalized slope stability stereonet (Figure 6) was derived using Figures 4 and 5 as they show the generalized trends seen for the Swannanoa lineament. These generalized point to pole stereonets depict planer features of bedrock in an efficient non cluttering way making it easier to interpret. Figure 4 shows that landslides are most likely to move perpendicular to the foliation. Figure 5 shows that landslides are most likely occurring either perpendicular or parallel to the fractures.

A field image of a wedge failure (Figure 7) is interpreted in the slope stability stereonet seen in Figure 8. This landslide is an east facing wedge failure off of I-240 along the lineament. The color was superimposed on this figure in Adobe Illustrator to provide clarifying information for the reader.

South facing slopes are the most abundant within this study area (Figure 9). As can be seen in Figures 10-12, there is a spike in frequency for south facing slopes. However, when the mass movement occurrences are separated from one another there is no longer a strong definite preference for the south. There is a strong preference for south facing slopes that indicates bedrock played a big role in why so many landslides occurred in the presence and wake of Hurricane Helene.

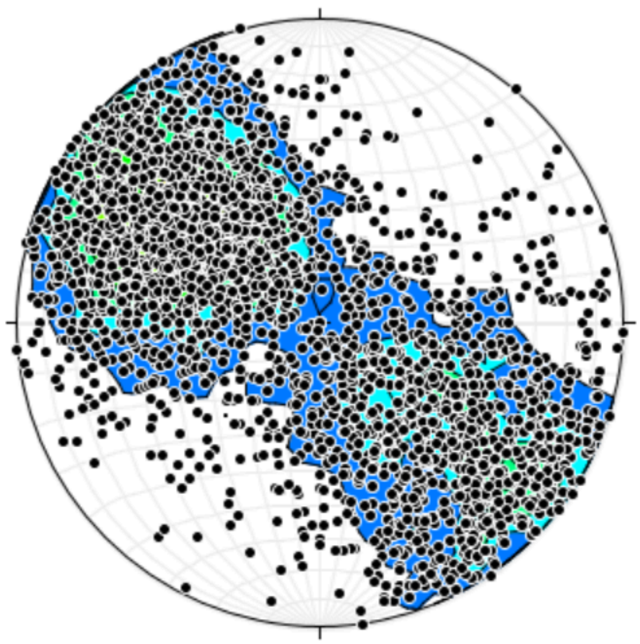

Figure 4. Stereonet showing foliation (poles), plotted perpendicular to actual orientation, depicting the average strike of the foliation as NE-SW. If there were planar failures along these planes then the slides would go NW-SE.

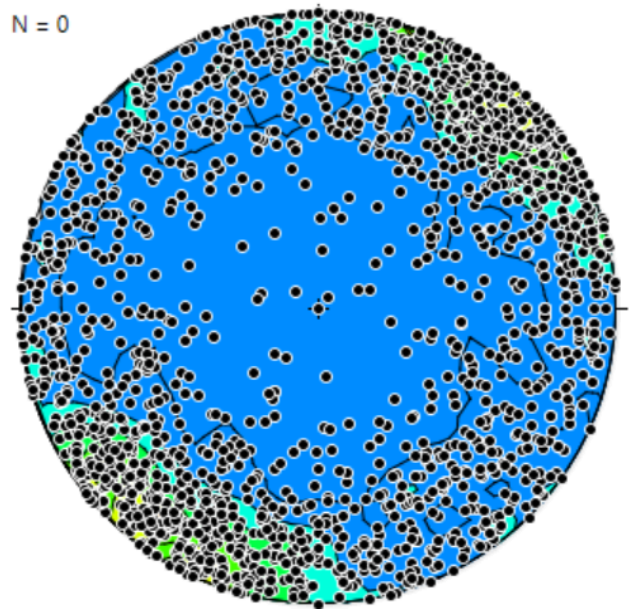

Figure 5. Stereonet showing fractures (poles-joints and faults), plotted perpendicular to actual orientation. Joints are dominantly striking 130 and 310, so if there are landslides along the Swannanoa Lineament joints, they would slide perpendicular to or parallel to these fractures.

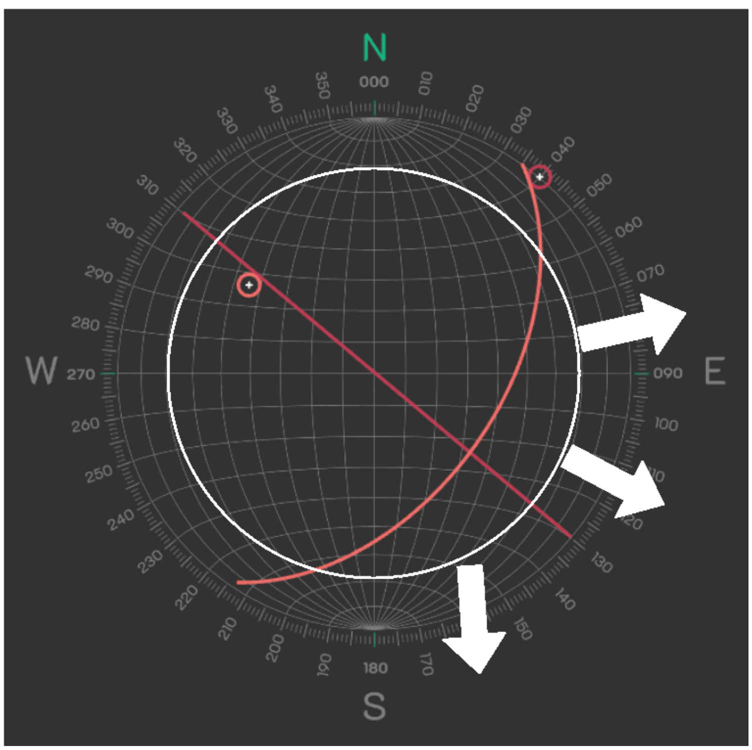

Figure 6. Stereonet showing the generalized slope stability found in association with the Swannanoa lineament. The white arrows dictate the directions in which wedge failures will occur, using the foliation and joints (red lines) and the failure angle (white circle).

Figure 7. Field photo of the landslide indicated in figure 9. East facing wedge failure landslide that is located off of I-240 towards Knoxville, TN with a person for scale.

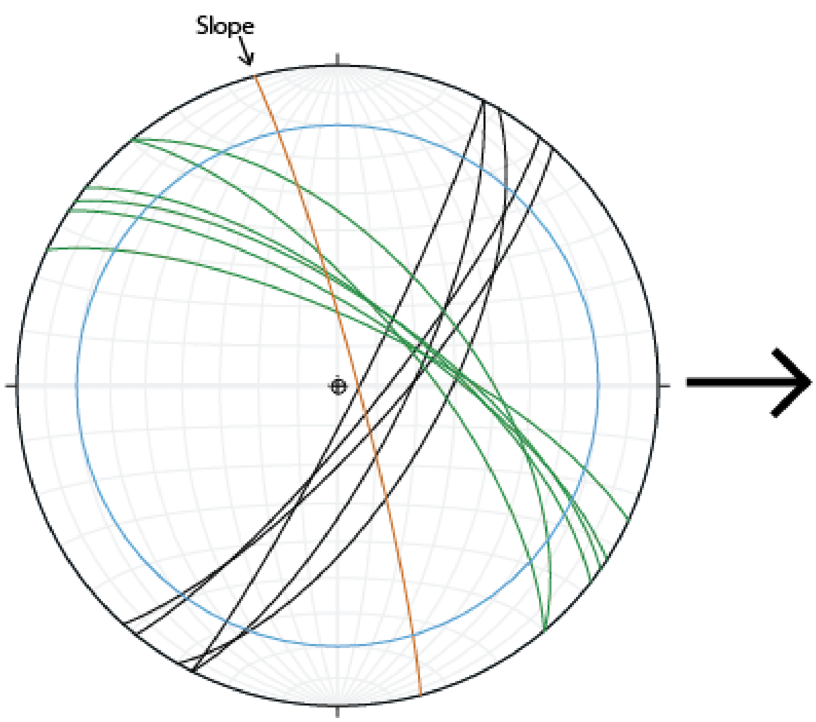

Figure 8. Stereonet showing the slope stability in association with a landslide along the Swannanoa lineament. The orientation of the joints present are indicated by the green

set of lines and the foliation of the bedrock is indicated by the black set of lines. The large black arrow dictates the direction where wedge failure occurred, using the failure angle (blue circle). The slope is dictated by the orange line and labeled as such.

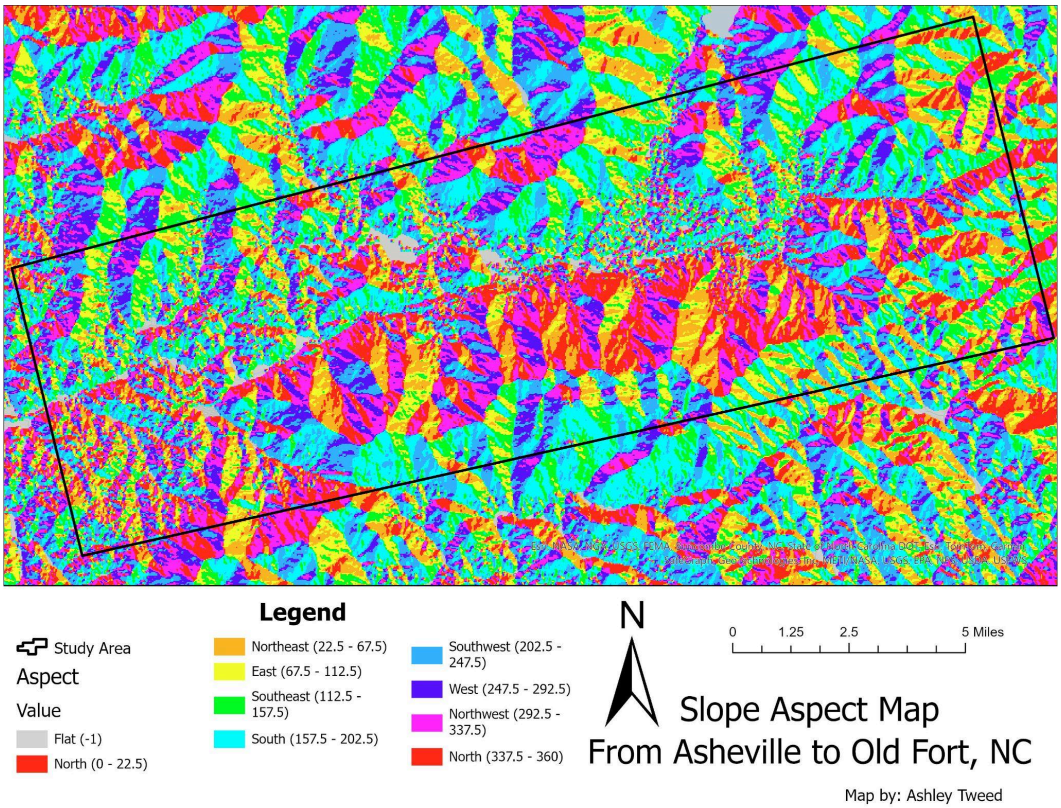

Figure 9. Map showing slope aspect both within and surrounding this study area. The legend indicates what colors correspond to what directions.

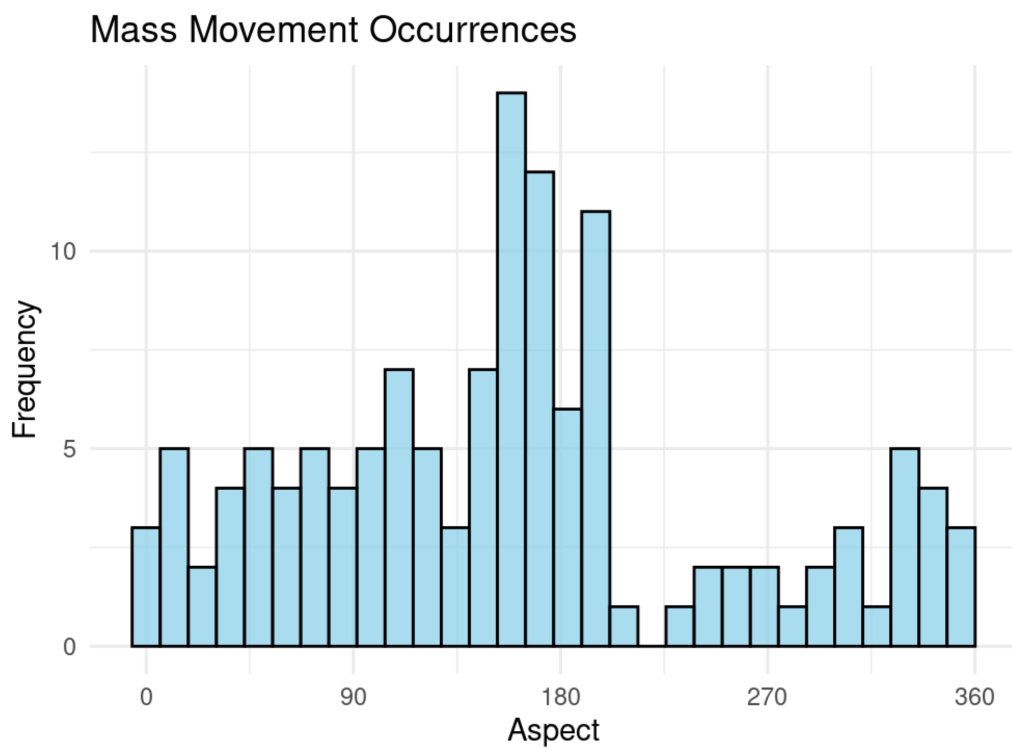

Figure 10. Histogram showing the number of mass movement occurrences in relation to which direction the slope is facing within the study area.

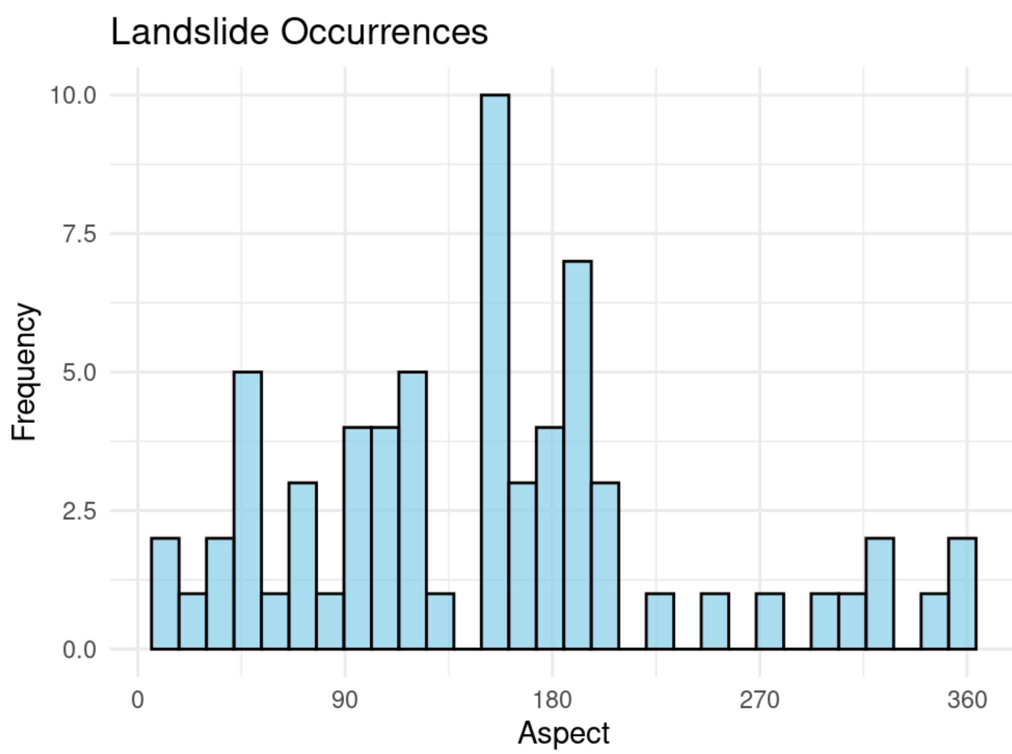

Figure 11. Histogram showing the number of landslide occurrences in relation to which direction the slope is facing within the study area.

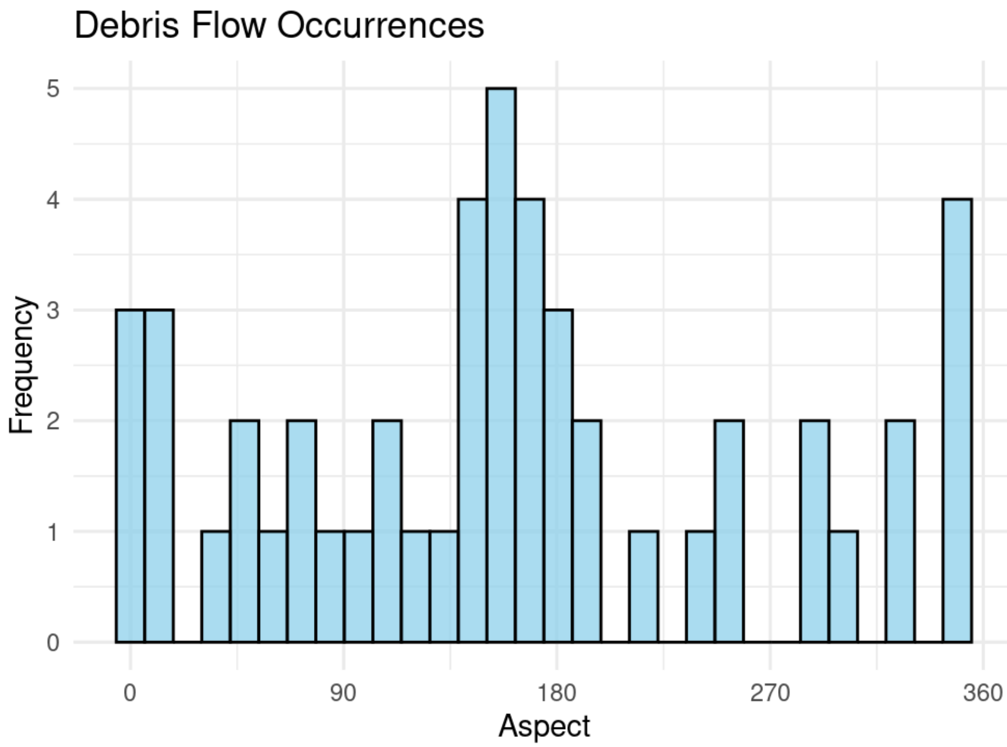

Figure 12. Histogram showing the number of debris flow occurrences in relation to which direction the slope is facing within the study area.

4. Discussion

By deriving an aspect map in ArcGIS (figure 9), it can be seen that there is a disproportionate abundance of north and south facing slopes when compared to those of east and west. Figure 10 shows mass movement occurrences (landslides and debris flows) in correspondence to slope aspect within the study area: the x-axis though numerical depict cardinal direction as zero is north, 90 is east, 180 is south, 270 is west, and 360 is north again. This figure depicts an even distribution with an exception for south facing slopes. The dominance of mass movement occurrences on south facing slopes could be due to the disproportionate amount of land in the field area facing south compared to the other cardinal directions (Figure 9). However, when the mass movement types are separated, the distribution changes, which means that even though there is a higher percentage of south facing slopes than the other cardinal directions, this is not the reason for the spike toward the south.This change can be seen when looking at debris flow distribution; rather than the one spike there are three (Figure 12). This is due to there not being a strong preference for south facing slopes, but rather roughly an equal concentration for north and south facing slopes as a result of the topography and aspect of the study area. This is because there is little to no bedrock involvement and influence for frequency debris flows. An important note about debris flows is that they occur without a strong influence of bedrock structures. While they can be triggered by a landslide, this is not the primary cause, since intense rainfall is the main trigger.

Whereas when looking at Figure 11 the distribution for landslides shows a strong preference toward the south with a slight peak in the east, with no corresponding peaks for a north preference, as the strong south preference is due to the orientation of the fractures and joints along with foliation. This matches with what the generalized slope stability stereonet indicates, wedge failures occur predominantly facing south and east, meaning that there is a strong influence of bedrock that made landslides occur within the corridor when the storm took place. Alternatively, planer failure, as determined solely by foliation, will occur NW-SE (Figure 4), explaining the slight rises in frequency in these directions. When comparing Figures 11 and 12 together, the correspondence of north and south for debris flows and the absence of such for landslides means that there is a statistical confidence for bedrock involvement in a large number of the landslides present in the study area. If the slope direction was the primary factor for both debris flows and landslides, then the histograms would all show the north and south bias that the debris flows show since they are the most abundant in the study area.

5. Conclusion

Hurricane Helene was disastrous for Western North Carolina in many ways, one of which being mass movement occurrences. These occurred, in part, due to topography, slope direction, and bedrock involvement. The existing landslide susceptibility map from the NCGS currently does not take into account bedrock features contributing to landslide susceptibility. As determined by this study, there is substantial evidence that bedrock has a strong influence on landslides in this area due to the Swannanoa lineament. Considering this fact, the landslide susceptibility map should take into account the orientation of bedrock fractures, joints, and foliation in regards to slope aspect. By utilizing bedrock fractures to help determine landslide susceptibility it would help understand where infrastructure should be rebuilt in wake of the storm as well as where new infrastructure is proposed.

6. Acknowledgments

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7. References

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