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Application of knowledge-driven method for debris-slide susceptibility mapping in regional scale

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Abstract

Debris-slides are a frequent hazard in fragile decomposed metasedimentary rocks in the Anakeesta rock formation in Great Smoky Mountain National Park. The spatial distribution of an existing debris-slide area could be used to prepare susceptibility map for future debris-slide initiation zones. This work aims to create a debris-slide susceptibility map by using a knowledge-driven method in a GIS platform in Anakeesta formation of Great Smoky Mountain National Park. Six geofactors, namely, elevation, annual rainfall, slope curvature, landcover, soil texture and various slope failure modes were used to create the susceptibility map. Debris-slide locations were mapped from the satellite imagery, previous studies, and field visits. A Weighted Overlay Analysis was performed in order to generate the final susceptibility map, where individual classes of geofactors were ranked and were assigned weights based on their influence on debris-slide. The final susceptibility map was classified into five categories: very low, low, moderate, high and very high susceptible zones. Validation of the result shows very high category predicted ~10%, high and moderate categories predicted 75.5% and ~14.5% of the existing debris-slide pixels respectively. This study successfully depicts the advantage and usefulness of the knowledge-driven method, which can save considerable amount of time and reduce complicated data analysis unlike statistical or physical based methods. However, the accuracy of the model highly depends on the researcher's experience of the area and selection of respective geofactors.

Keywords: Debris-slide Susceptibility; Heuristic; Weighted Overlay Analysis; Great Smoky Mountain National Park.

1. Introduction

Debris-slides are fast movements of earth materials, which occur including subarctic regions (Rapp and Stromquist, 1976) and humid tropics (Simonett, 1970). Debris-slides are common in the Appalachian Valley and Ridge, and Blue Ridge physiographic provinces of the United States (Bogucki, 1976). Van Westen (1993) discussed that under the presence of favorable causal and triggering factors, such as earthquakes and extreme rainfall, most of the mountainous terrains are susceptible to slope failure. The same was pointed out by Bogucki (1976), who found that a combination of Appalachian slope and rainfall has eroded the mountains by several thousand noticeable debris-slides. About 2000 slides have formed in Georgia, North Carolina, Tennessee, Kentucky, West Virginia, and Virginia and as many as 200 deaths that may have been caused directly by slide activity from 1940 to recent (Scott 1972, Wooten, et al., 2016). Additionally, these events have caused damage to homes, property and road networks, and have had major impacts on federal lands.

It is important to develop a detailed understanding of the causes and mechanisms of debris-slide events for better prediction and risk assessment. One of the preliminary steps to evaluate events and predict future slide related hazards is to develop debris-slide susceptibility maps (Pradhan, 2011). These maps are used to identify zones that are prone to mass failures depending on the geofactors that have caused the slides in past. Presumably, the same factors would cause the slides in future (Varnes, 1978; Carrara et al., 1995; Guzzetti et al., 1999). Geographic Information Systems (GIS) provides a powerful tool to analyze spatial hazard related data, and hence, it has become indispensable tool for regional slope failure hazard and risk analysis. Several authors have applied different methods to map slope failure susceptibility and hazard (e.g., Nandi and Shakoor, 2010; Pradhan, 2011; Lee and Pradhan, 2007). Regional slope failure mapping is generally grouped into three categories: (i) heuristic or knowledge-driven methods (ii) data-driven methods and (iii) physically based models. The heuristic methods are again divided into direct or indirect methods. A direct heuristic method deals with detailed field investigation of area's geomorphology, geology, and hydrology

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(Brabb, 1984). The accuracy of the method is highly dependent on the experience of the investigator and the precision level of the work (Ghosh et al., 2013). On the other hand, the indirect heuristic methods are based on assigning some weights or rating to the individual geofactors according to their importance, which is solely decided by the investigator, based on similar existing research (Hansen, 1984; Varnes, 1984).

Data-driven methods are mostly statistical, which include bivariate and multivariate analysis and are primarily based on the observed data of landslides and relevant spatial geofactors (Nandi and Shakoor, 2010; Ghosh et al., 2013). In these methods, several causative factors for debris-slides are integrated with the slide inventory to statistically model the relationship between the geofactors and slope failure. (Van Westen, 1993). Nandi and Shakoor (2017) used the same approach to study debris-slide susceptibility in Little Pigeon River (WPLPR) watershed in the southern Appalachian Mountains, where debris-slide locations were identified from aerial photographs, and satellite images. Topographical, bedrock geology, and hydrological data were collected, processed, and constructed into a spatial database using GIS. Logistic regression model was used to evaluate the role of these factors in controlling debris-slide susceptibility. While the method was rigorous and powerful, the limitations of the method were (i) time consuming and not recommended for urgent projects, and (ii) rock discontinuity data were not used as input variable. Therefore, the objective of this research is to include bedrock discontinuity data that play crucial role in controlling the debris-slide events in the form of rock kinematical index, and create a knowledge-driven susceptibility model for predicting the spatial probability of debris-slide initiation zones.

2. Study area

The study was conducted in the Anakeesta rock formation in the Upper West Prong Little Pigeon River watershed (WPLPR), Great Smoky Mountain National Park, TN. The elevation of the study area ranges from 1105 m to 2010 m. Temperature in Great Smoky Mountains varies from -2.22˚C (28 ˚F) to 31.11˚C (88˚F) at the base and -7.2˚C (19 ˚F) to 18.33˚C (65˚F) at the ridges. The area receives annual rainfall of 1397mm (55 inches) at the base and 2159 mm (85 inches) at the highest point of the park. The rainfall increases with increase in the elevation and is highest at the Anakeesta formation. Torrential rainfall associated with severe thunderstorms and hurricanes are the main triggering factors for debris-slide in the study area (Bogucki, 1976; Clark, 1987).

Geologically Anakeesta formation is characterized by fine grained dark colored sedimentary and metasedimentary rock having craggy pinnacle structure i.e., needle-shaped rock faces and steep slopes. The dark color of the rocks is mainly due to presence of graphite and some part of the formation exhibits rusty orange color due to presence of iron sulfide minerals mainly pyrite. The main rock types include phyllite, chloritoid slate, graphitic and sulfidic slate, feldspathic sandstone, laminated metasiltstone and coarse grained metagraywacke (Southworth et al., 2012). Different sets of discontinuities exist in form of joints, fractures and to some extent as cleavage, which enhance the weathering along these discontinuity planes.

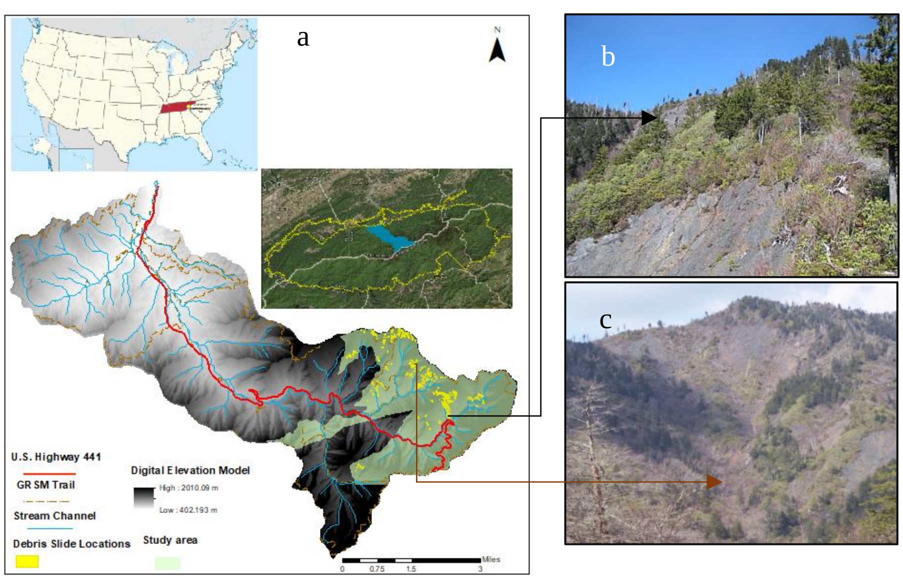

Fig. 1. Study area (a), Debris-slide initiation zones photos in Anakeesta Formation (b, c). [Photo courtesy: Greg Hoover (b) gosmokies.knoxnews.com (c)]

3. Methodology

The present study used both digital data and field investigation. A flow chart in Fig. 2, provids a step by step process of the methodology.

3.1. Digital Data

In order to create the debris-slide susceptibility map, six geofactors, namely, elevation, rainfall accumulation, soil texture, landcover, slope curvature, and various bedrock discontinuity layers responsible for slope failures were used. Elevation and slope curvature maps were derived from LiDAR Digital Elevation Model (DEM) of 0.76m spatial resolution. The LiDAR DEM for Tennessee is available at TNGIS website (http://www.tngis.org/). Soil texture, landcover and rainfall accumulation maps were collected from the National Park Service's database (https://irma.nps.gov/DataStore/Search/Quick) (Fig.3.a-e). Debris-slide initiation locations were digitized from historical to recent aerial photos and satellite imageries, and about 30% of the locations were confirmed during field studies. The debris-slide initiation locations were used to evaluate the suitability of susceptibility analysis.

3.2. Field investigation and Kinematical index

Geometrical relationship between orientations of the topographic slope and geological discontinuities play important role in controlling the slope instability in an area, which is known as rock kinematics. Slope instability analysis based on this mutual relationship is known as rock kinematic analysis. Factors like topographic slope angle and aspect, internal friction angle of the rock and orientation of geological discontinuities combined with each other control slope stability within a rock mass. Depending upon the number of geological discontinuities and their orientations with the topography, three different modes of rock failure can occur (i) Planar (ii) Wedge (iii) Topple (Eq. 1 and 2) (Ghosh et al., 2010). The kinematical index layer was prepared using the geometric relationship between geological discontinuities and the topographic slope angle and direction (Fig. 3f). From field mapping and previous work, structural orientations (dip angle and dip direction) of a total of 313 discontinuities were used in the study. The internal friction angle (ϕ) of the bedrock was estimated from Rock Mass Rating system data collected in the field (Bieniawski, 1989). Topographic slope angle (θ) was obtained from the LiDAR DEM, dip/plunge angle (β) and direction of discontinuities were obtained by plotting the structural data in Stereonet 10 software (Allmendinger et al., 2012). Subsequently, the following equations were used in ArcGIS to spatially detect the areas where slope failures were kinematically possible (Ghosh et al. 2010):

$$\phi \leq \beta \leq \theta \text{ (for Plane and Wedge Failure)} \tag{1}$$

$$\theta \geq [\, \phi + (90° - \beta)] \text{ (for Topple Failure)} \tag{2}$$

Eleven combinations of planer, wedge and topple failures were possible in the study area that produced 11 different kinematic layers susceptible to failure. The wedge type of failures were dominant in the study area, and were more prevalent in bedding (52°⟶151°) and Joint1 (50°⟶255°) governed discontinuities. All layers were ranked based on presence of actual debris-slide initiation location, and the ranked layers were combined into one kinematic index layer. A detailed description of the preparation of composite kinematic index layer is presented in a forthcoming paper (Das, et al., in preparation).

A Weighted Overlay Analysis was performed to generate the debris-slide susceptibility map, using a heuristic approach. Weighted Overlay Analysis tool is available in the Spatial Analyst extension in ArcGIS 10.5. All geofactor layers were converted into raster format and rescaled to 0.76-m grid size before the susceptibility analysis. Based on the field studies and prior knowledge of the study area, the individual classes of the geofactors were ranked and the relative weights were assigned to each individual geofactor. The weights represented the degree of influence of individual geofactors in producing debris-slides in the region on a scale of 0 to 100 that added up to 100%. Table 1 summarizes the different geofactors and their corresponding weighting that were used in the susceptibility analysis.

Table 1. Summary table of the geofactors.

Geofactor	Source	Average (Range)	Weight
Elevation	Digital Elevation Model	1526 m (1105m – 2010m)	30
Rainfall	National Park Services	2051mm (1854mm– 2159mm)	25
Soil	National Park Services	Channery loam, Channery silt loam, Loam, Slide area, Peat, Very Channery loam	15
Kinematical Index	Digital elevation model and Lithological map (National Park Service)	5.68 (0 - 57.95)	15
Landcover	National Park Services	Barren land, Deciduous forest, Developed Open space, Developed low intensity, Developed medium intensity, Evergreen Forest, Mixed Forest, Shrub	10
Curvature	Digital Elevation Model	-6.62 (-6839 to + 11380)	5

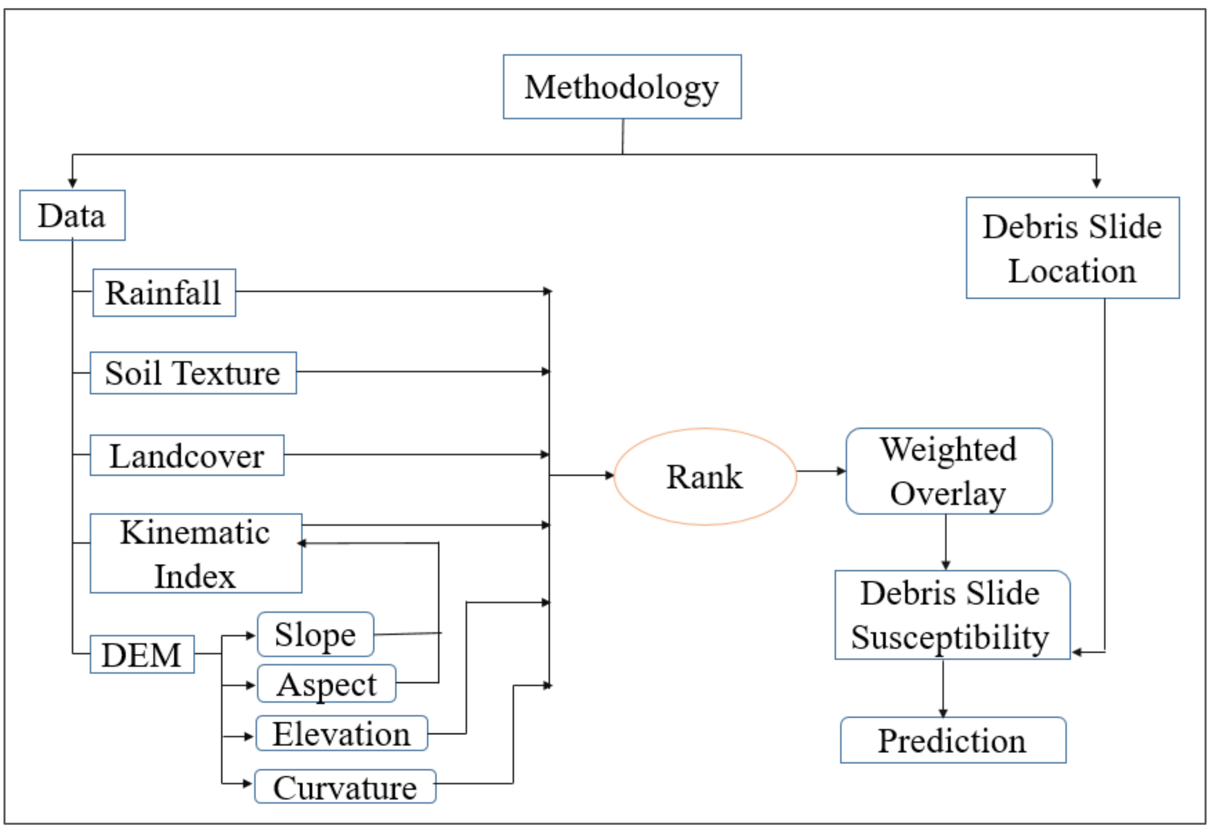

Fig. 2. Flow chart of the methodology.

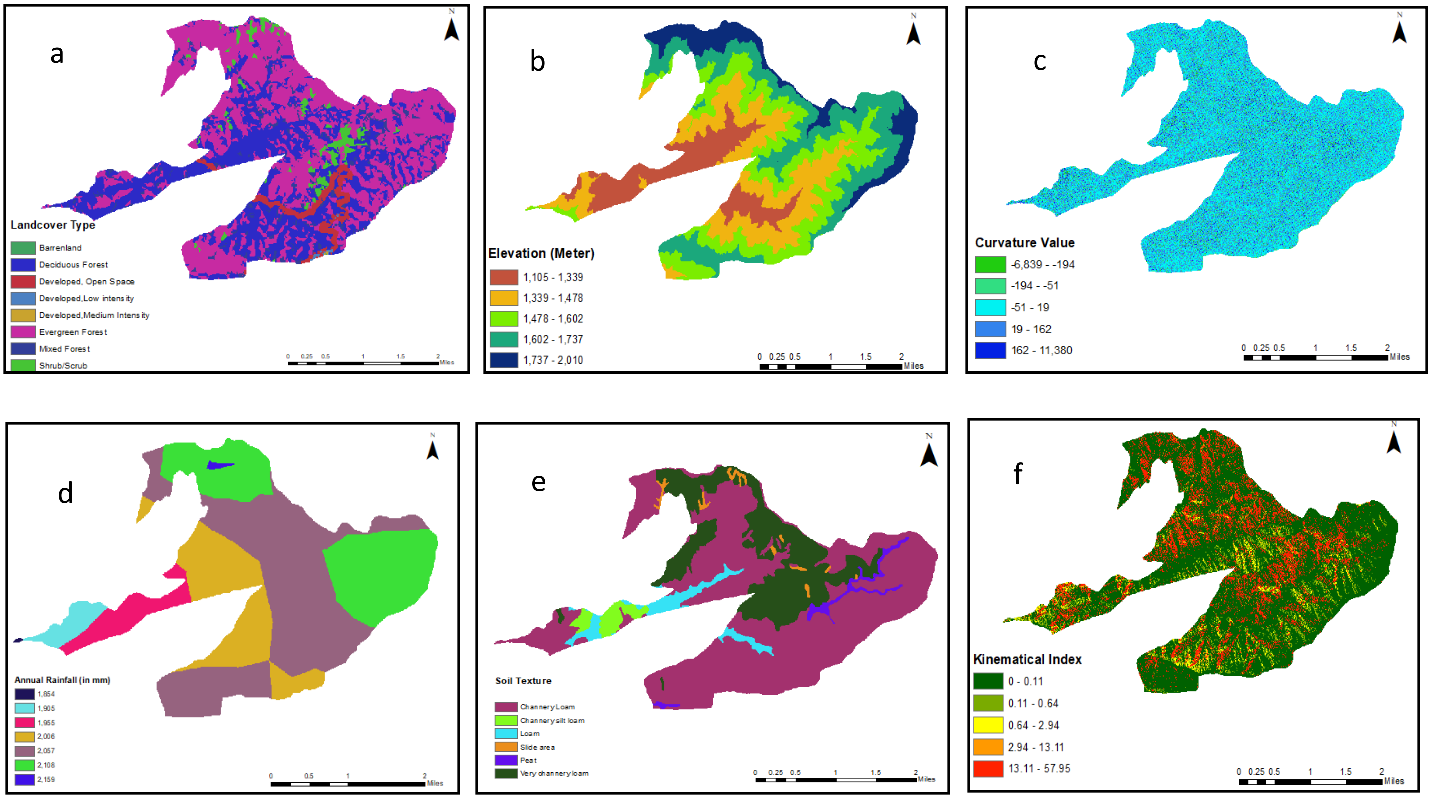

Fig. 3. (a) Landcover Map; (b) Elevation Map; (c) Curvature Map; (d) Annual Rainfall Map; (e) Soil Texture Map; (f) Kinematical Index Map.

4. Result

In the study area, there were 256 debris-slide initiation zones (Fig. 1a). Majority of debris-slides were present in the Newfound Gap and Mt. LeConte areas in the northeastern corner. The elevation of the area ranged from 1105 m to 2010 m with a mean of 1526.64 m (Fig. 3b), rainfall varies from 1854.2 mm to 2159 mm (Fig. 3d) and curvature ranged from -6839.87 to +11380 having mean of -6.62 (Fig. 3c) (Table 1). The negative curvature value stands for upwardly convex surface and positive value indicates concave surface at that cell.

The debris-slide initiation zone susceptibility map from the Weighted Overlay Analysis were classified into: very low, low, medium, high, and very high susceptibility categories (Fig. 4). Only 0.03 % and 9% of the total map area were located under very low and low susceptibility zone, respectively. When the area was compared with the actual debris-slide initiation zones, these areas exhibited no trace of past or recent slide activities. Medium susceptibility zone occupies 43.43% of the study area and predicted 14.44 % of actual debris-slide occurrence zones. High susceptibility zone represented the largest area in the map (45.43%) and accounted for 75.53 % slides in the study area. Very high susceptibility covered only 2% of the total study area; however, it predicted nearly 10% of the known slide locations (Fig. 5).

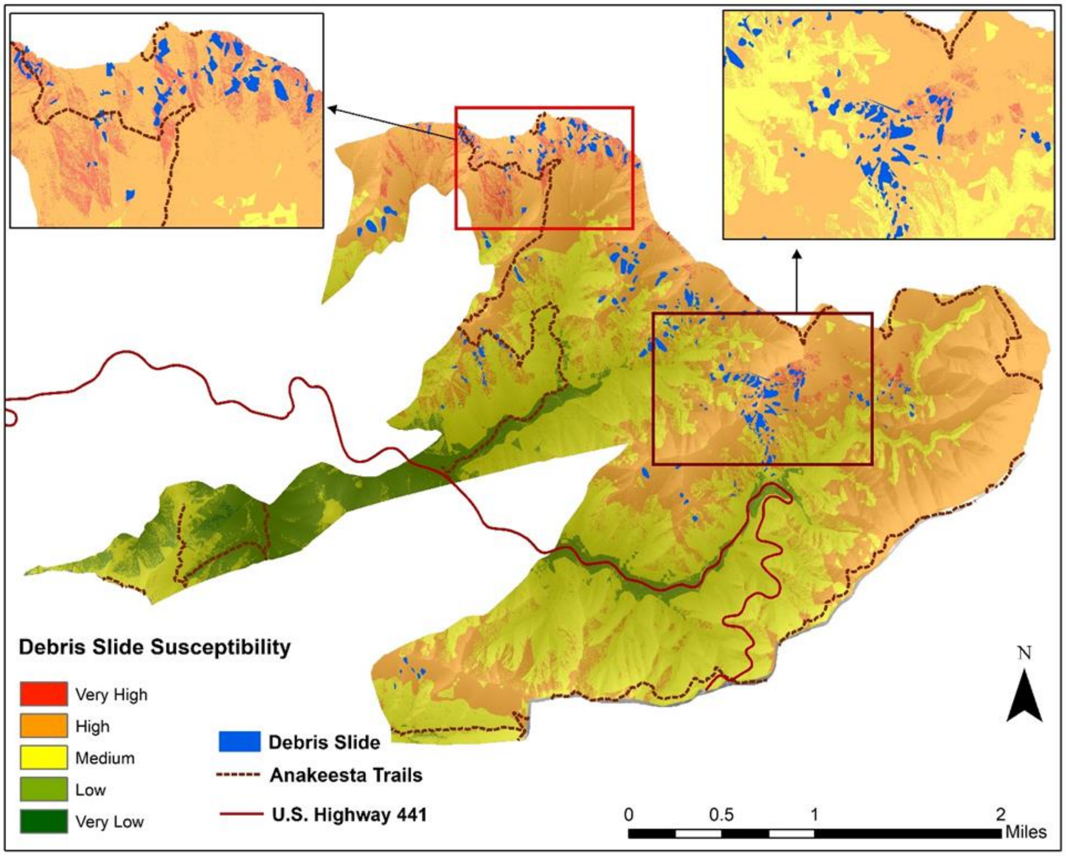

Fig. 4. Debris-slide susceptibility map.

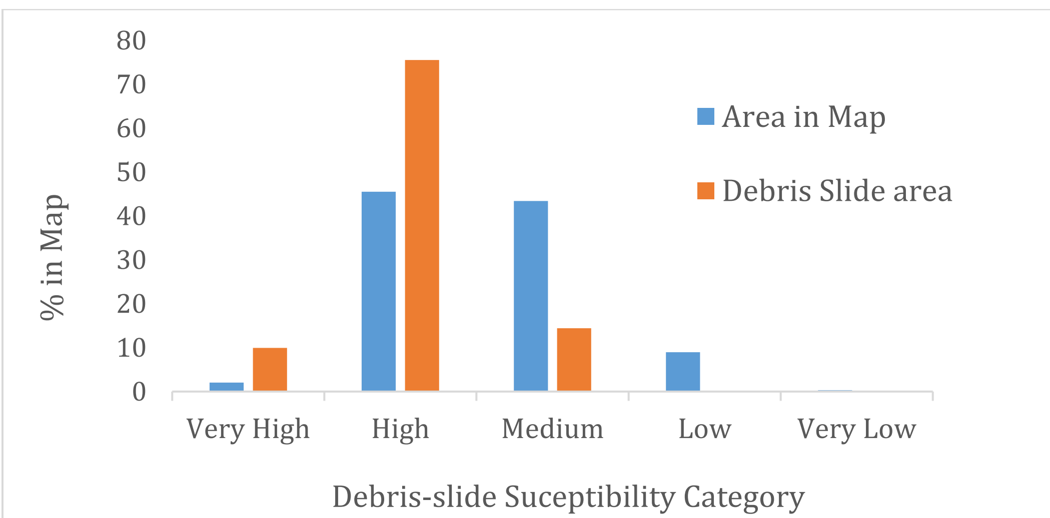

Fig. 5. Debris-slide susceptibility zones compared to the known slide initiation areas.

5. Discussion

Anakeesta ridge in the northeastern part of the study area has experienced failures in the past and is expected to experience failures under the present climatic, geological, and hydrological conditions. Failures in high elevation, and high rainfalls area support the finding. On the other hand, the very channery loam soil texture seems to have a positive correlation with debris-slide initiation zones, which are subangular, blocky, and friable earth materials derived from weathering of phyllitic Anakeesta formation. Evergreen forest and shrub are the dominant vegetation in the area and show strong spatial relation with debris-slides. Curvature does not reveal any trend with the initiation of slides. Debris-slides could be found in both concave and convex surfaces. The field study and spatial analysis suggested the presence of kinematically triggered failures due to movement of geological discontinuities within bedrock. The investigation also suggested that initial wedge failures dominated the slides on steeper slopes and these slides were eventually converted into debris flows with increasing water content, and soil/decomposed plant/broken rock debris as they moved along existing drainage channels. The present drainage channels were probably paleo debris flow channels, but they were not studied during this research.

The model predicted the existing debris-slides with high accuracy, where 86% of the known slides were situated in high and very high susceptibility categories. However, this study focused on rapid analysis using a heuristic approach. Success of a heuristic model relies on the expert's opinion and selection of incorrect geofactors and assigning inappropriate weighting can lead to erroneous results. Future work will apply data-driven statistical-based approaches like logistic regression or artificial neural networks to model the debris-slide susceptibility and compare the results with the heuristic approach used in the existing study. The study used 256 debris-slide initiation zones; however the dates of failure were unknown, therefore, several thunderstorms and hurricanes induced debris-slides could not be studied. That hindered the spatio-temporal probability analysis of debris-slides in the area. In the future, a time-stamped debris-slide inventory should be generated in order to provide a complete spatio-temporal hazard analysis of the area.

6. Conclusion

This paper successfully demonstrated the usefulness of the heuristic model or knowledge-driven method in order to rapidly generate debris-slide susceptibility map. This study also introduced a kinematical index layer, which is a new addition, and could be included as one of the structural geology based geofactors for debris-slide susceptibility modelling. A satisfactory result was achieved by using this new variable. Validation of the model shows most of the debris-slides (86%) were located in the very high and high susceptible zones. Therefore, it can be concluded that the geofactors used in this study were appropriate with the region's conditions and most likely to be important for predicting debris-slides in the study area.

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