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Geomorphometric characteristics of landslides in the Tinalah Watershed, Menoreh Mountains, Yogyakarta, Indonesia

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Abstract

A landslide is one of natural hazards that affect humans and their livelihood especially in the mountainous area. The increasing landslide risk due to global climate change and demographic pressure demands integration between disaster risk reduction and sustainability management, for instance, the recently increasing people's awareness of the landslide and its impacts. Landslides occur in particular location regarding both physical and non-physical features of an area, comprising geomorphology, geology, geomorphometry, human activities, earthquake probability, rainfall occurrence, and etc. This research aims to understand the characteristics of the specific land surface that bears susceptibility to landslides using a geomorphometric approach and to analyze the relationship between geomorphometric characteristics and landslide events. The Tinalah watershed is located in Menoreh Mountains, one of mountainous areas in Java where highly frequent landslides occur. Geomorphometric characteristics, derived from DEMs with 2x2-m2 grid resolution, consist of elevation, slope gradient, aspect, profile curvature, plan curvature, and general curvature. The inventory of landslide events, consisting of the location, time, area, perimeter, typology, and activity, is derived from the field maps, local government's report analysis, and interviews with local people. In this research, landslide distribution is mapped using the multi-temporal records of landslide events during 2006-2010. A raster-based spatial analysis reveals the relationship between landslide events and geomorphometric characteristics. Each variable shows the quantitative information of landslide distribution in the Tinalah watershed. As a result, geomorphometric characteristics have the most significant relationship with the landslide distribution in this study area.

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1. Introduction

Geomorphometry was conceptually developed from the 18th until the early 20th century by scientists from the UK, France, and Germany, e.g. Barnabé Brisson (1777–1828), Carl Gauss (1777–1855), and Alexander von Humboldt (1769–1859), respectively[1]. It is a geosciences-based study focusing on the Earth's surface[1] specifically on extracting land surface information from Digital Elevation Models (DEMs). The complex properties of the land surface, formed by different geneses, materials, and processes working on a surface over time[2], are simplified by such extraction into distinctive morphological features, viz. slope, elevation, and curvature[3]. At the same time, DEMs have been used widely not only in geomorphometry but also in other geosciences-based studies, such as geomorphology, hydrology, meteorology, soil sciences, and vegetation studies[1,4]. As the basis of quantitative analysis in geomorphometry, DEMs are derived from field measurement, topographical data (topographical map), and an increasingly wider variety of imagery data (SRTM, ASTER GDEM, SAR, LiDAR, etc.). Therefore, the recently higher availability of DEMs leads to a more frequent use of geomorphometry for terrain analysis.

Land surface is a representation of various interrelated processes in the past (uniformitarianism). Thus, identifying the right processes that form the present characteristics of terrain, as well as their interrelationship, becomes significant in simulating geomorphological dynamics. In order to pinpoint the casual processes with a minimum level of subjectivity, the geomorphometric approach is more preferable than the commonly used heuristic approach. It includes geomorphometric data acquisition[5,6] and geomorphometric data processing[7,8,9,10,11,12]; in which it is also applicable for other geosciences-based studies, such as hillslope studies[13,14,15,16], volcanic studies[17,18], fluvial studies[19,20], tectonic studies[21], and marine geology[22].

A landslide is one of natural hazards that affect humans and their livelihood especially in the mountainous area[23,24]. It is a natural phenomenon that turns into a natural disaster as human intervention starts to occur[25]. For instance, landslides in Java, the most densely populated island in Indonesia, caused 2,095 casualties and 522 injuries in 1981-2007[26]. Furthermore, landslide risk is increasing due to global climate change[27] and demographic pressure[28]. However, such risk has been reduced by increasing people's awareness of the landslide and its impacts[29,30,31].

Disaster risk reduction is part of an effort to maintain the sustainability of human well-being. Resistance and resilience are necessary to adapt to the danger of landslides[32,33,34,35], as well as to survive the devastating impacts of landslides[36,34,35,37]. Integration between disaster risk reduction and sustainable development becomes urgent in order to reduce and eliminate the future damage and loss[38].

The Tinalah watershed is located in Menoreh mountains, one of mountainous areas in Java where highly frequent landslides occur[39]. The probability of such landslide occurrence depends on both physical and non-physical features of the watershed, including geomorphology, geology, geomorphometry, human activities, earthquake event probability, the characteristics of rainfall, etc.[40]. However, geomorphometric characteristics or terrain factors are the base of landslide forecasting[41]. This research aims to analyze the relationship between geomorphometric characteristics and landslide events in order to further comprehend terrain characteristics bearing susceptibility to landslides and to provide basic information on the landslide risk management program.

2. Study Area

The Tinalah Watershed covers an area of 44.22 km^2. It is located in the eastern side of Menoreh mountains, Yogyakarta, Indonesia, about 25 km from the center of Yogyakarta City (Fig. 1). The altitude of this watershed ranges from 82-991 meters above the mean sea level, while the relief is dominated by hilly and mountainous areas. The average annual rainfall varies from 2,500-4,000 mm/yr. The lithology of igneous and sedimentary rocks in this area comes from Kebobutak Formation, Jonggrangan Formation, alluvium, and colluvium. Meanwhile, the dominant lithology consists of andesitic breccias, tuff, lapilli tuff, agglomerate, and intercolations of andesitic lava flows (Kebobutak Formation―88.8 % of the area); conglomerate, tuffaceous marl and calcareous sandstone, and limestone and corraline limestone (Jonggrangan Formation―10.2 % of the area); alluvium (0.8 % of the area); and colluvium (0.3 % of the area)[42].

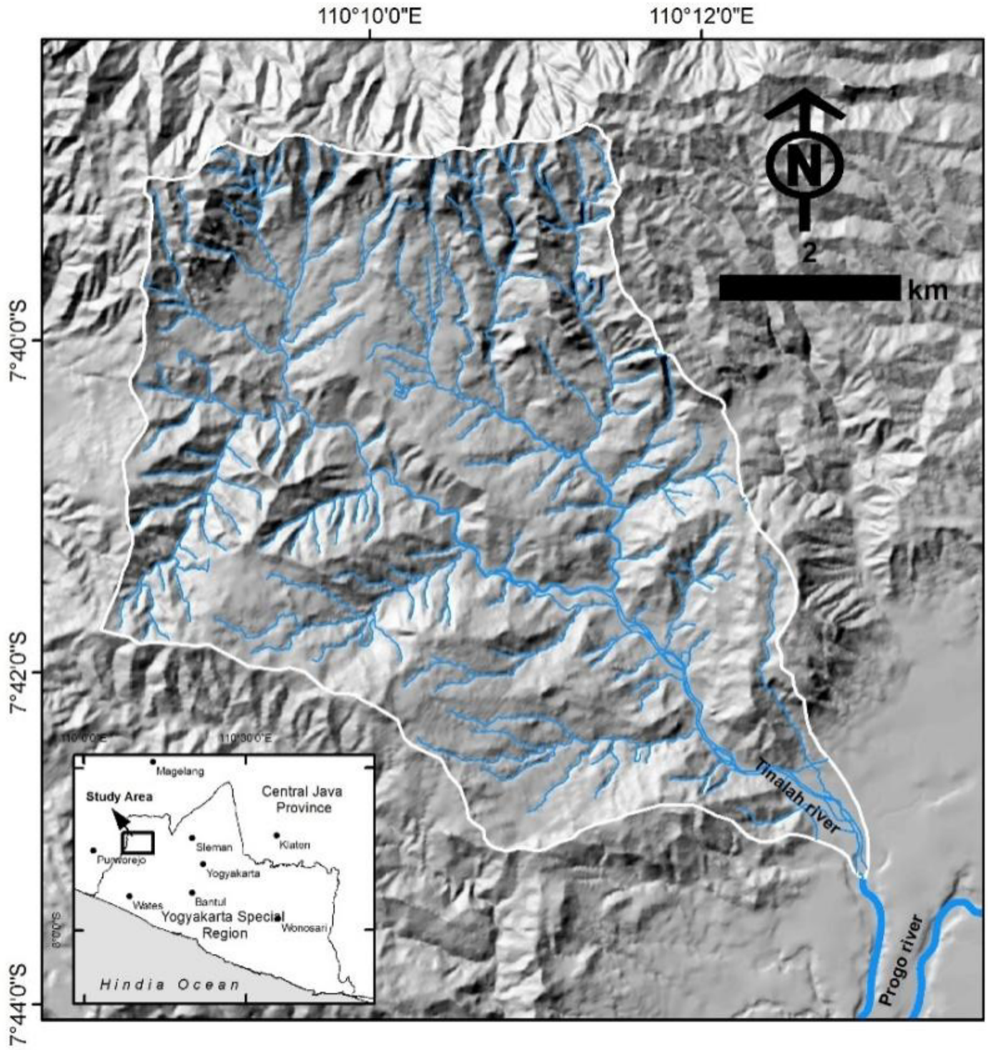

Fig. 1. The Location of the Tinalah Watershed

3. Materials and Methods

The inventory of landslide events, consisting of the location, time, area, perimeter, typology, and activity, is derived from field maps, local government's report analysis, and interviews with local people. As a key parameter to analyze the characteristics of existing landslides, landslide inventory mapping is significant in providing both temporal and spatial distributions of landslide events in the area[43,44,45]. In this research, landslide distribution is mapped using the multi-temporal records of landslide events during 2006-2010.

DEMs with the 2x2 m^2 grid resolution are generated from a digital contour, which is derived from a 1:25,000 digital topographic map using ArcGIS software. This grid resolution is chosen because small scale landslide characteristics are dominant in the area. In landslide inventory mapping, the accuracy and reliability of the analyses rely on the grid size. If the grid resolution is too large, then many landslide events will not be mapped and the number of identified landslides will be less accurate.

DEMs provide geomorphometric characteristics, i.e. elevation, slope gradient, aspect, profile curvature, plan curvature, and general curvature, in raster-based GIS environment using Spatial Analyst. Elevation is considered to be determinant because of the assumption that landslides are represented in a particular elevation, while slope gradient—a rate of elevation change—is highly related to the occurrence of landsliding[46,] and aspect—the direction of the slope, viewed from the north—is the key to identify significant features of landslide events[48]. A spesific curvature is, then, characterized as having specific attribute contributing to landslide events. These variables are overlayed to each other in a raster-based GIS environment. Furthermore, the attributes of geomorphic data are crossed with landslide data, thus, the number of landslide events in each variable is identified to reveal the relationship between landslide events and geomorphometric characteristics.

4. Results and Discussion

4.1. Spatial Distribution of Landslides

A spatial analysis is conducted to comprehend the landslide distribution in the study area (Fig 2). A total of 138 landslide events, varying up to the largest size, i.e. 1,207.2 m^2, with an average of 129.5 m^2 are found in the Tinalah watershed. These landslides are unevenly distributed from the lower to the upper area especially in the hilly and mountainous region. Each of them falls under the typlogy of translational slides (62.3%), rotational slides (15.9%), debris slides (8.7%), creep (8%), earth flows (2.9%), and rockfalls (2.2%).

4.2. Geomorphometric Characteristics

There are six variables used to calculate the geomorphometric characteristics of the Tinalah watershed, as shown in Fig 3. The elevation ranges from 82-991 m with an average of 536 m, while the slope varies from $0\text{-}71^0$ with a high slope inclination dominating the upper part of the watershed and the curvature varies from concave to convex with flat curvature dominating the watershed.

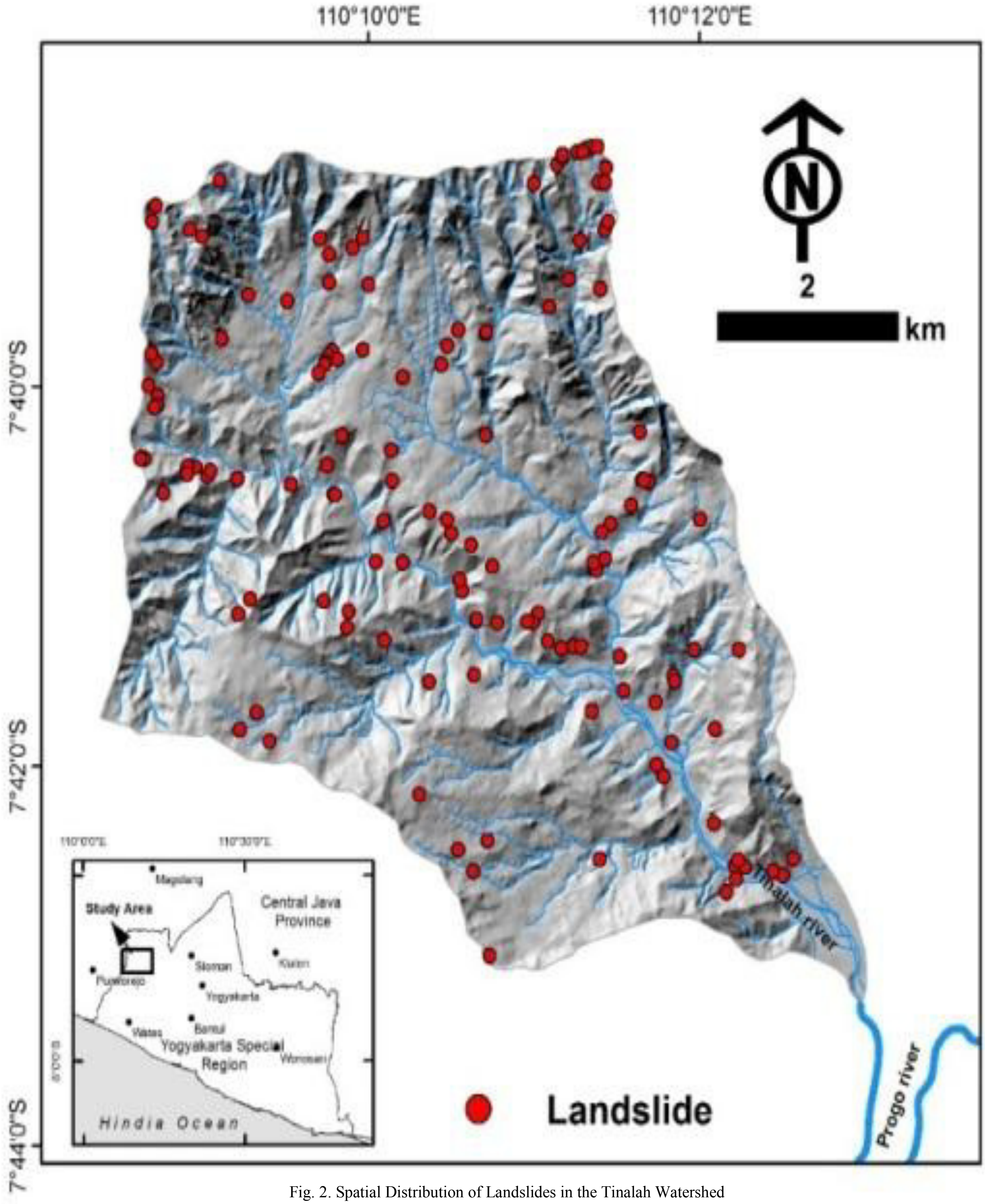

Fig. 2. Spatial Distribution of Landslides in the Tinalah Watershed

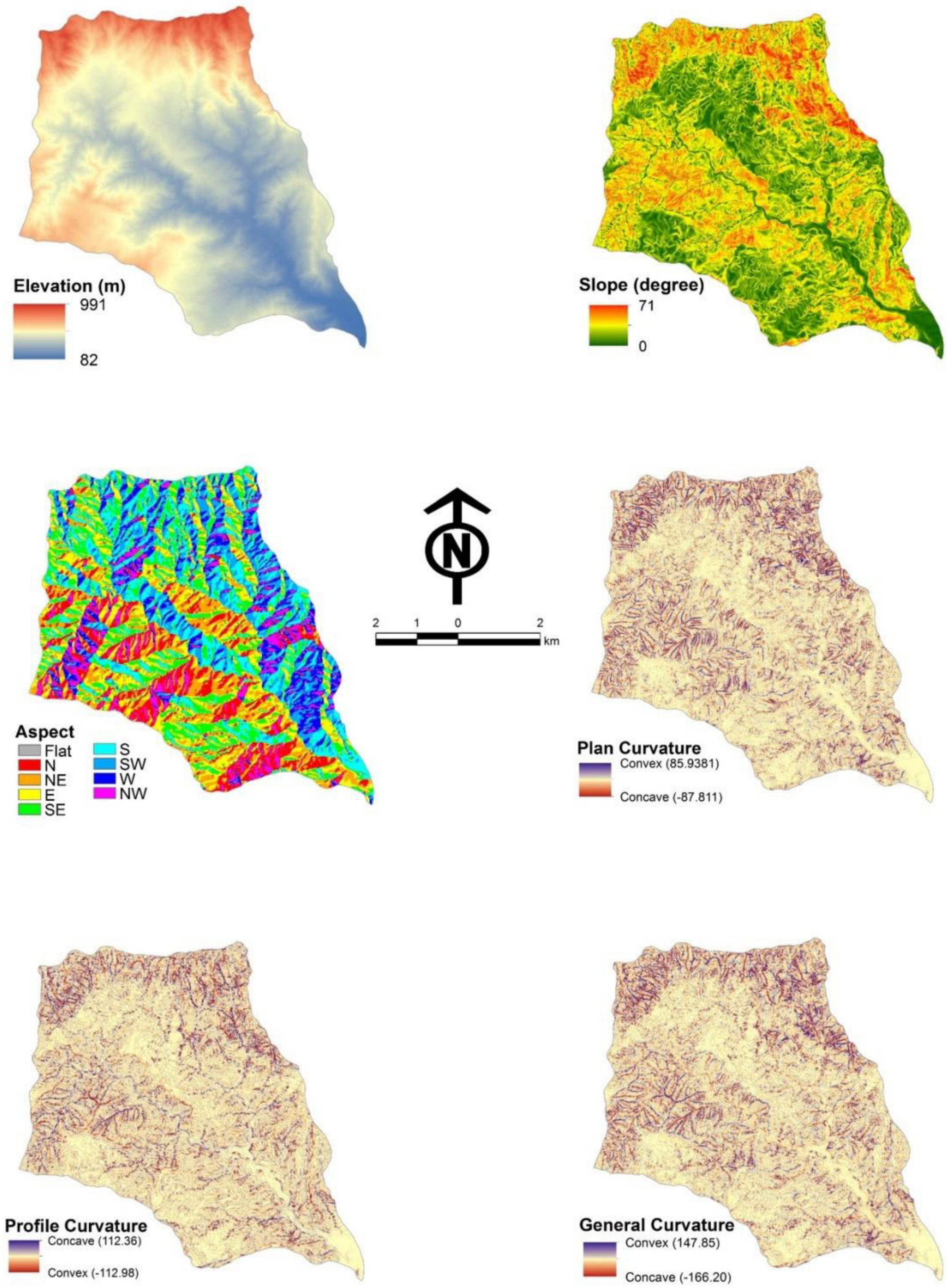

Fig. 3. Geomorphometric characteristics of the Tinalah watershed: (a) slope, (b) aspect, (c) altitude, (d) profile curvature,(e) plan curvature and (f) general curvature

4.3. Geomorphometric Characteristics and Landslide Events

Landslide events are unevenly distributed from an elevation of 120-944 meters above the sea level, meanwhile the indications of event possibility are also found in some elevations. A landslide dominantly occurs at 512 m.a.s.l. followed by 275, 465, 475, 601, and 626 m.a.s.l. (Fig 5a). This result is similar to [49] the result which finds that the landslide occurs in an elevation of higher than 400 m.a.s.l. In conclusion, the occurrence of lanslides in a higher elevation is more frequent than the one in a lower elevation, regarding the association of higher slope inclination in a higher elevation. In addition, the presence of unstable materials and weathered rocks or soil also contributes to the possibility of landslide occurrence. At the same time, the dominant east-to-west direction of a slope (aspect) provides more proneness to landslide occurrence due to the existence of more exposed weathered material as the basic reason of landslide formation in this direction, as confirmed[50].

Landslides are found at a slope of 1-56^0 with a dominant occurrence at 20^0, as revealed [50] that landslides occur at

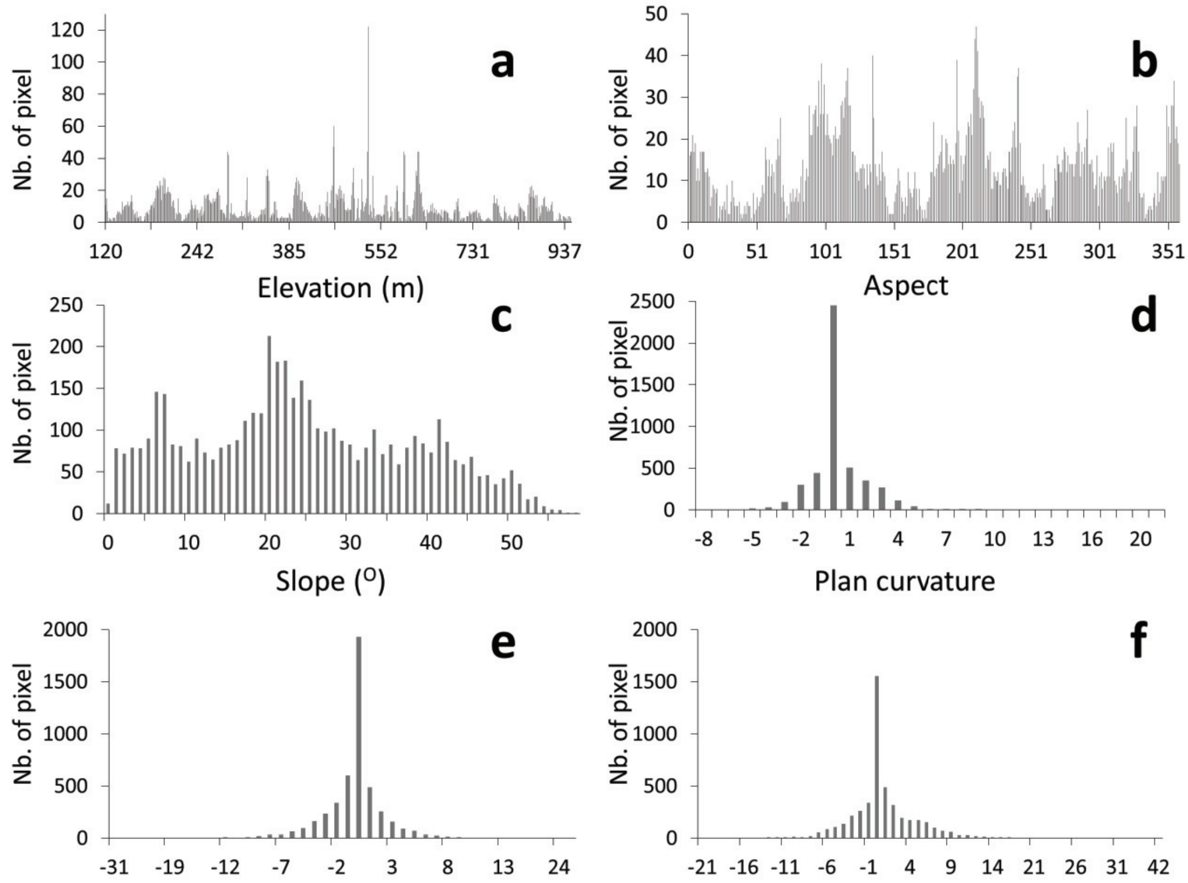

Fig. 4. Geomorphometric Characteristics of Landslides in the Tinalah Watershed

30-40^0,[51] landslides occur at 16-30^0, and [49] landslides occur at 20-30^0. The probability of landslide occurrence on this range shows that a stepper slope is likely to contribute to landslide events; however, landslides are rarely found in a slope inclination of more than 56^0 due to the small number of weather materials, which imply the absence of materials for landslide generation. Moreover, a slope with flat curvature (0) is more prone to landslide occurrence than the ones with concave and convex curvatures. The variety of curvature itself depends on the presence of landslide events. The plan curvature ranges from -8 to +22, while the profile curvature ranges from -31 to +25 and the general curvature ranges from -21 to +42 (Fig 5.d-f).

5. Conclusion

Land surface characteristics, known as geomorphometric characteristics, have a significant relationship with the landslide distribution in the Tinalah Watershed, for instance, the landslide occurrence coincides mostly with an elevation of higher than 400 m.a.s.l., a slope of 20^0, an east-to-west slope direction, and a flat curvature. The GIS- and event-based analyses on the spatial and temporal distribution of landslides provide valuable information with less effort and time consumption in landslide studies. Therefore, this approach should be more developed in the future especially regarding the importance of understanding geomorphometric characteristics of a watershed in creating a disaster risk reduction plan. Combining such characteristics with the level of existing human intervention in the area as well as public awareness of the determinant parameter of landslide occurrence, for instance, by avoiding or relocating activities and by buillding the preventive infrastructure located in a landslide-prone elevation or slope inclination, will decrease the likelihood of hazardous impacts of landslides on local people and the surrounding ecosystem. Furthermore, applying a disaster management plan on a landslide-prone watershed is part of the integrated watershed management with a focus on the sustainable development. For instance, providing comprehensive tools, such as a landslide inventory map, a parameter distribution map, etc., in understanding the scope of the devastating impacts of landslide is useful for stakeholders and interested parties in the decision making process. In conclusion, such easily understandable tools are also very useful devices for increasing people's awareness of landslides which likely result in the sustainable disaster management.

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