Geomorphic Features Explain Spatial Patterns of Landslides in Northern Vietnam

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Abstract: The key triggering factor of landslide formation is excessive rainfall. However, other predisposing factors influence landslide formation intensity, clustering, and features. Topography belongs to the most important yet understudied factors controlling landslide activity and characteristics. We selected two regions in northern Vietnam and used extensive landslide datasets to explore potential terrain features and geomorphometric characteristics that might have been interpreted as predisposing agents of landslides. In Ho Bon and Xuan Minh regions, elevation, hillslope steepness, potential soil wetness, and slope height were the most important factors, differentiating regions and indicating the high occurrence of landslide forms. The results could aid different spatial prediction models and help to construct more robust landslide susceptibility maps.

Keywords: ***Landslide, Geomorphometry, Hillslope, Mass movement, Geohazard.***

Introduction

Landslide spatial prediction models require precise information on landslide positions and factors that bring valid information on features triggering or influencing landslide formation. As the information on rainfall, the most important landslide trigger in Vietnam, is limited and usually on a low-resolution spatial scale, other types of spatial data are used to build models and construct landslide susceptibility maps. Due to a growing volume of digital elevation models in middle and high resolutions, topography and terrain features are frequently used as indirect and supportive information on landslide predisposing factors. The present study explores how topography differentiates landslide features and clustering between northern Vietnam regions. We also explore which factors may be crucial in building the most robust spatial prediction models.

Methodology

Landslides were identified manually from high-resolution post-event satellite imagery using the Planet Basemap (5 m/px: https://www.planet.com/basemaps/) and Google Earth software. We mapped 992 landslides formed in Ho Bon and 509 in Xuan Minh. For each region, a digital elevation model (DEM) was acquired from the Amazon Web Service Terrain Tiles using the *elevatr* R package (Hollister et al., 2023). Based on the 4-m DEM, the following raster layers were calculated: surface slope and angle, topographic wetness index (TWI), slope height, and geomorphons (Jasiewicz and Stepinski, 2013). These variables were calculated using the *terra* (Hijmans, 2023) or *Rsagacmd* (Pawley, 2024) package. DEM was also used to derive specific information on landslides: maximum and minimum elevation of landslide forms, the elevation difference between the highest and lowest edges of landslides, and landslide length, defined as the distance between the highest and lowest landslide point. Landslide length and area were computed using the *sf* package (Pebesma, 2018).

Results

Both regions feature high potential for landslide activity due to steep slopes, soil moisture conditions, and significant height differences between river bottoms and mountain ridges (expressed as slope height) that can reach even 2000 m within a 2.5 km distance. The slope height (SH) and elevation were higher for Ho Bon, and this difference between the study sites was statistically significant. Soil moisture conditions of the study sites were controlled by rainfall and its spatiotemporal characteristics, and potential soil wetness was measured by TWI, which follows topography configurations such as elevation, surface slope, and length. The dendritic pattern of both TWI and SH metrics suggests a highly diffused concentration of soil moisture under favorable rainfall conditions. Similarly, geomorphons show hillslopes as a predominance landform element of both landscapes. In Ho Bon, landslides formed predominantly in higher positions (over 750 m a.s.l.) and slopes exposed to NE and S, which slightly higher TWI characterized. Landslide features such as area, length, and elevation difference were higher in the Xuan Minh area, but in Ho Bon, values of the maximum elevation of landslide scars were higher (up to 1191 m a.s.l.) and statistically different from Xuan Minh.

Discussion

In Vietnam, landslide clusters are formed during typhoons and tropical storms (Das et al., 2024). Both areas investigated in the present study experienced the formation of regional landslide clusters, which can be linked to specific geomorphic patterns differentiating the landscape dynamics of these regions. Terrain elevation is the most fundamental landscape characteristic, adding to the high variability in landslide formation instances. Ho Bon landslides reached higher elevations but were shorter and smaller. Increasing elevation increases surface slope, TWI, and slope height, which potentially play a role in landslide formation in both regions. However, their effects were stronger in Ho Bon, where landslide quantity reached almost 1000. Landslide spatiotemporal clusters were also observed in other parts of northern and central Vietnam (Das et al. 2024) and world regions with various climates and under different soil cover properties controlling landsliding (Crozier, 2005; Pawlik et al., 2023). In central Vietnam, Typhoon Ketsana (2009), Tropical Storm Padul (2013), and Typhoon Molave (2020) resulted in a total number of almost 20,000 triggered landslides (Das et al. 2024). For all three landslide events, elevation and rainfall were the most important variables that added to increased landslide probability.

The terrain aspect is another frequently considered topography feature because the ground surface exposition to precipitation and sun rays can impact hillslope hydrology and plant dynamics. Several studies have shown that landslide formation within southerly exposed terrains was associated with sun exposure, drought, and lack of vegetation, and those occurring in the north were related to heavy rainfall, humidity, and the water-holding capacity of the soil. Regarding the present study regions, there is no clear conclusion and regularity. Ho Bon landslides featured bimodal distribution, with most landslides formed within N-NE slopes. Xuan Minh landslides feature unimodal distribution, with most forms facing S. This discrepancy cannot be related to the vegetation cover, which is similar among sites.

Conclusions

Although there were apparent differences in triggering factors, the landscape response on the regional level was similar – many landslides formed during monsoon season. In such analyses, it is hard to consider the effect of landscape maturation and preparedness, which takes years before landslide formation. Landslide pulses are essentially stochastic following the rainfall intensity and sums, which are not necessarily a direct outcome of atmosphere dynamics. Vegetation cover, human impact, topography, the stage of soil development, and the depth of weathering profiles are all key factors of landslide formation; however, their relative influence may diminish under extreme rainfall conditions, as rainfall intensity becomes the dominant triggering mechanism.

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