International Journal of Design & Nature and Ecodynamics
Vol. 19, No. 5, October, 2024, pp. 1581-1589
Journal homepage: http://iieta.org/journals/ijdne

Mapping Debris Flow Susceptibility Using Frequency Ratio Model in Kundasang, Sabah, Malaysia

Rodeano Roslee[1,2*], Ruth Elisha Alexander[2], Kamilia Sharir[3], Amirah Saidin[1], Dwa Desa Warnana[4], Juan Pandu Gya Nur Rochman[4], Amien Widodo[4]

[1] Faculty of Science and Natural Resources (FSSA), Universiti Malaysia Sabah, Kota Kinabalu 88400, Malaysia
[2] Natural Disaster Research Centre (NDRC), Universiti Malaysia Sabah, Kota Kinabalu 88400, Malaysia
[3] Faculty of Engineering (FKJ), Universiti Malaysia Sabah, Kota Kinabalu 88400, Malaysia
[4] Fakultas Teknik Sipil, Perencanaan & Kebumian, Institut Teknologi Sepuluh Nopember, Gedung Teknik Geofizika, Kampus ITS Sukolilo, Surabaya 60111, Indonesia

Corresponding Author Email: rodeano@ums.edu.my

https://doi.org/10.18280/ijdne.190512

Received: 4 April 2024
Revised: 26 September 2024
Accepted: 8 October 2024
Available online: 29 October 2024

Keywords:
debris flow, frequency ratio, hazard, Kundasang, Sabah, susceptibility map, geographic information system, mitigation strategies

ABSTRACT

Debris flows are significant geological hazards that pose severe risks to human settlements and natural environments. The Crocker Range in Sabah, Malaysia, exemplifies the complex interactions between geological hazards and human activities. This study comprehensively assesses debris flow susceptibility in the Kundasang area of Sabah, utilizing a bivariate Frequency Ratio (FR) model integrated within a Geographic Information System (GIS). Key terrain parameters such as slope aspect, slope curvature, elevation, land use, slope angle, soil association, Stream Power Index (SPI), stream proximity, and Topographic Wetness Index (TWI) are examined to identify the factors influencing debris flow occurrences. The findings indicate that slope aspect, curvature, and elevation play critical roles, with concave and north-facing slopes between 2500 m and 3000 m elevation being highly susceptible due to population density and land use practices. Primary dryland forests and steep slopes, combined with specific soil associations, further increase susceptibility. SPI and proximity to rivers highlight areas of elevated risk, particularly within 100 m of rivers, while TWI reflects increased vulnerability linked to soil water content. By integrating these parameters, the study generates a detailed debris flow susceptibility map, which classifies the southern region, including populated areas, as highly vulnerable. This map provides crucial insights for practical application in land-use planning, forest management, and infrastructure development to mitigate debris flow risks. The study's findings empower policymakers, researchers, and local communities with actionable strategies to safeguard lives and ecosystems against debris flow hazards. Condensed recommendations focus on proactive land-use planning and sustainable forest management to reduce future risk.

1. INTRODUCTION

Debris flows, characterized by their rapid movement and potential for extensive destruction, are among the most severe geological hazards, impacting both human settlements and natural environments [1-3]. Globally documented events have highlighted their capacity to disrupt infrastructure, livelihoods, and lives [4, 5]. The threat is particularly significant in regions prone to seismic activity, where the interaction between debris flows and other geomorphic processes increases the risk and severity of these events [6, 7]. Effective mitigation and land-use planning require a thorough understanding of the factors driving debris flow occurrence, behavior, and runout patterns [8].

In the context of the Crocker Range in Sabah, Malaysia, the interplay between geological hazards and human activities is notably complex [2, 9]. This area has been subject to numerous debris flow incidents, resulting in road closures, economic losses, and distress within affected communities [8, 10]. Inadequate land-use practices, including traditional farming and deforestation, have significantly heightened the susceptibility to debris flows, emphasizing the urgent need for a detailed vulnerability assessment of the region's terrain.

Despite existing research on debris flows in the Crocker Range, there is a noticeable gap in studies that integrate susceptibility mapping with practical implications for community planning and policy-making. Previous studies have largely focused on isolated factors without providing a comprehensive model that could guide land-use and infrastructure development in high-risk areas. Our study addresses this gap by applying the bivariate frequency ratio model to assess debris flow susceptibility in the Kundasang area of Ranau, Sabah. By integrating terrain parameters with Geographic Information System (GIS) tools, this study not only contributes to the academic discourse but also offers actionable insights for local authorities and policymakers. The findings will support the development of targeted strategies to mitigate debris flow impacts, ensuring that infrastructure and community resilience are enhanced. In doing so, this research aims to bridge the divide between theoretical knowledge and practical application, providing a robust foundation for hazard mitigation and adaptation strategies in regions facing similar challenges.

2. STUDY AREA AND GEOLOGICAL BACKGROUND

The study area in Kundasang area, Sabah, is depicted in Figure 1. Nestled in the southeastern region of Mount Kinabalu, its elevation ranges from 570 meters to 4500 meters. The geographical boundaries encompass a longitude spanning approximately 116°30'50"E to 116°37'30"E and a latitude stretching from 6°4'10"N to 5°58'20"N. Kundasang occupies a unique geographical position within the Southeastern part of the Eurasian plate, specifically in the Sundaland block [11]. Renowned for its hilly terrain and recognized as a major hub for highland vegetable production, Kundasang thrives in Sabah's equatorial climate. The region experiences two distinct monsoon seasons: the northeast monsoon (November to March) and the southwest monsoon (May to August). Daytime temperatures in the lowlands typically range between 17℃ and 25℃, while higher elevations exhibit markedly cooler conditions.

Over time, the study area has encountered a series of debris flow incidents, with one particularly devastating event occurring in 2015 after a magnitude 6.0 earthquake [6, 9]. This earthquake and its subsequent aftershocks precipitated extensive rockfalls and landslides around Mount Kinabalu [12]. These geological disturbances led to the destruction of around 15km^2 of soil, rock, and vegetation cover, severely compromising the water catchment's ability to retain and accumulate rainwater.

The 2015 earthquake, a primary hazard event magnitude of 6.0 on June 5, marked a significant seismic occurrence following the 1991 Ranau earthquake [13]. Tragically, this earthquake-induced rock avalanche on Mount Kinabalu's summit claimed the lives of 18 individuals [6]. Subsequently, due to heavy and persistent rainfall, coupled with aftershocks and tremors, a destructive debris flow event transpired on June 15, 2015, in Sungai Mesilou [6]. This secondary hazard destroyed houses and homestays, causing ripple effects across the local community's socio-economic landscape.

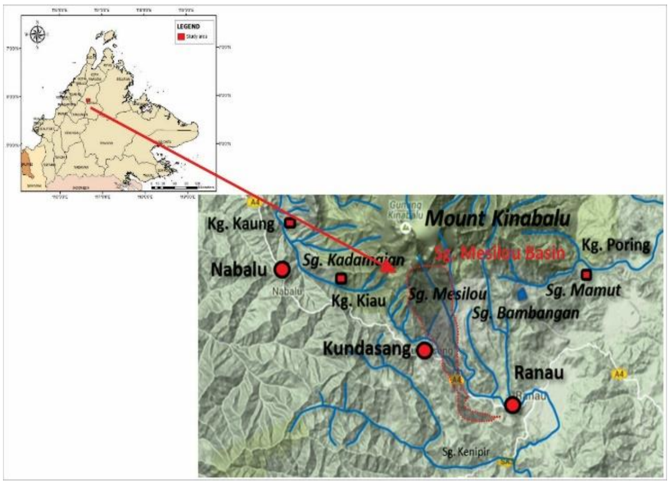

Figure 1. Location of the study area in Kundasang, Sabah

Figure 2. The condition of Mesilou River Basin

The aftermath of the 2015 earthquake was characterized by the stripping of approximately 1500 hectares of vegetation cover, as depicted in Figure 2. This alteration in the landscape reactivated landslides and triggered the accumulation of a substantial volume of earth material within the upstream channels [12]. This accumulation ultimately formed temporary landslide dams [14], which, upon breach, led to the mobilization of debris flows. Notably, the Mesilau watershed in Kundasang (southeast of Mount Kinabalu) and the Kadamaian watershed in Kota Belud (northwest of Mount Kinabalu) were identified as hosts for two debris flow events. The proximity of those residing along the riverbanks made them particularly vulnerable to the impacts of these flows. The accumulation of loose debris resulting from landslides in slopes, gullies, and river valleys served as both sources and transport agents of debris flows during heavy rainfall, substantially altering the course of water flow.

Kundasang, situated within Sabah's west coast region, is a highly susceptible area for mass movement events. A geological and geotechnical assessment underscores that mass movements occur when the structural integrity of slope materials can no longer withstand gravitational forces [15]. In this context, heavy rainfall leads to increased water saturation within slope materials, causing a loss of cohesiveness along rupture planes-a pivotal mechanism triggering mass movements in the study area.

Kundasang's vulnerability is further accentuated by its proximity to the Lobou-Lobou fault line, an integral part of the Crocker fault zone in the northern segment, intersecting with the regional Mensaban fault. This active fault segment, characterized by a sinistral displacement, has significantly influenced geological dynamics. During the Quaternary period, the Lobou-Lobou fault intersected with the Pinousuk Gravel, intensifying mass movements at the junction of the Crocker and Mensaban faults. The region's geological attributes, including high topography, active fault zones, and the unconsolidated Pinousuk Gravel unit, have collectively contributed to landslides in Mesilou. The Pinousuk Gravel, recognized for its loose, porous, and highly weathered nature, emerges as a vulnerable material type directly contributing to landslide occurrences within the study area [16].

3. METHODOLOGY

The assessment of debris flow susceptibility involves utilising the Frequency Ratio (FR) model within a Geographic Information System (GIS) framework (Figure 3). The initiation of this analysis encompasses delineating the debris flow-prone regions using Google Earth Pro. The pivotal dataset for model construction is the Digital Elevation Model (DEM), with a consistent cell size of 30 meters adopted for evaluating all the parameters under consideration. To ensure comprehensive coverage of the primary debris flow region, Kundasang, the DEM is similarly employed to extract the basin.

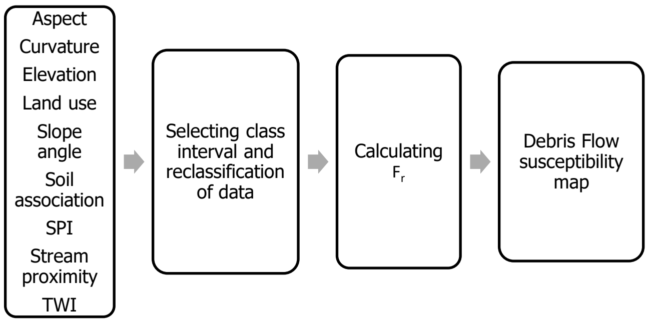

Figure 3. Flowchart of analysing debris flow susceptibility map using frequency ratio model

An extensive review of the pertinent literature underpins the selection of parameters within the FR model. This proactive approach aids in refining the understanding of the contributing factors behind debris flow incidents. Employing ArcGIS version 10.5, diverse parameters are generated and integrated into the FR model. These encompass a spectrum of elements, including slope aspect, slope curvature, elevation, land use, soil association, slope angle (°), Steam Power Index (SPI), stream proximity, and Topography Wetness Index (TWI).

In the classification process, each of the causal factors within the FR model is meticulously treated to ensure an accurate representation of their contributions to debris flow susceptibility. Factors such as slope aspect, slope curvature, elevation, land use, soil association, SPI, and TWI are reclassified employing the Natural Break (Jenks) method. The Jenks method was selected because it optimally partitions data into classes by minimizing the variance within each class and maximizing the variance between classes. This is particularly effective for parameters with non-uniform distributions, such as elevation and slope curvature, where natural groupings or breaks are inherent. By applying this method, the classification reflects the natural structure of the data, ensuring that each class represents a distinct range of values with significant impact on debris flow susceptibility.

In contrast, slope angle (°) and stream proximity are classified through manual interval delineation. This robust methodology ensures the alignment of parameter classifications with the nuances of the landscape and facilitates the accurate interpretation of their roles in the debris flow susceptibility assessment.

3.1 Debris flow conditioning factors

Aspect, often called slope aspect, denotes the direction of the steepest slope on a terrain surface. Some researchers emphasise its significance as a pivotal factor in landslide susceptibility studies [17-19]. Aspect exerts influence over various elements, including the orientation of controlling discontinuities in landslides, precipitation patterns, wind impact, and solar exposure [3, 20]. The reclassification of aspect regions involves partitioning them into distinct classes: flat (-1), north (0°-22.5°), northeast (22.5°-67.5°), east (67.5°-112.5°), southeast (112.5°-157.5°), south (157.5°-202.5°), southwest (202.5°-247.5°), west (247.5°-292.5°), northwest (292.5°-337.5°), and north (337.5°-360°).

Curvature unveils the topographic morphology [21, 22]. Negative curvature signifies concave features, zero curvature corresponds to flat terrain, and positive curvature characterises convex topography [23]. These positive and negative values directly correlate with the range of flow speeds, representing slow to rapid movement. In particular, basin-shaped slopes, commonly observed in landslides, play a significant role [17]. Valleys, characterised by concave slopes, tend to retain groundwater, surface water, sediment, and organic matter, resulting in overhanging soils.

Elevation, a pivotal attribute shaped by diverse geologic and geomorphological processes, plays a crucial role [24]. Research has indicated that rainfall and debris flow exhibit heightened occurrence at higher elevations [3]. Utilising DEM data within ArcGIS, the elevation map was created and subsequently categorised into seven classes: <1000m, 1000m -1500m, 1500m-2000m, 2000m-2500m, 2500m-3000m, 3000m-3500m, and >3500m.

Land use significantly influences infiltration rates, evapotranspiration, and the formation of surface runoff, exerting both direct and indirect effects. The regional soil type heterogeneity influences infiltration, which, in turn, shapes overland flows [25]. The land use map, derived from the Sabah Forest Department (1988) and traced as a shapefile in ArcGIS, consists of four primary classes: settlement, scrub, dryland primary forest, and dryland secondary forest.

In landslide susceptibility modelling, slope angle is a pivotal parameter frequently associated with debris flow [26]. The slope angle governs surface runoff [10, 27]. Near the equator, Malaysia experiences a tropical climate with high temperatures and abundant yearly rainfall. Researchers studying slope failure have identified rainfall as one of the prominent triggers for slope failures [17]. Based on the slope classification established by the Department of Mineral and Geoscience Malaysia (JMG, 2006), the slope map is classified into five categories: Flat (<5°), Gentle (5°-15°), Moderate (15°-25°), Steep (25°-35°), and Very Steep (>35°).

Certain soil attributes, including particle size distribution, shape, and pore sizes, play a role in determining debris flow susceptibility. Soil quality impacts water infiltration, interflow and baseflow velocity, and water retention capacity [28]. With their larger surface area, fine-textured soils such as clay and silt tend to retain more water, particularly when unsaturated [29]. The soil association map, created based on the Agriculture Department of Sabah (JPNS, 1976) and traced as a shapefile in ArcGIS, comprises five soil association types: Trusmadi, Crocker, Pinousuk, Bidu-Bidu, and Kinabalu.

The Stream Power Index (SPI) serves to identify potential river erosion and landscape phenomena [17, 23]. As the catchment area and gradient increase, upslope water contribution and flow velocity also rise [17]. The SPI map is classified into five classes: <-8, -8 – -5, -5 – 0, 0 – 3, and 3 – 9.

Proximity to rivers reflects the degree of fluvial erosion and exacerbates slope instability [23]. Streams are crucial in conveying water during and after precipitation, often serving as a basis for debris flow mobility. Areas near rivers with steep slopes experience considerable erosion, amplifying the risk of landslides during intense rainfall and sloping topography [8]. The map incorporates five buffer classes: 100m, 200m, 300m, 400m, and above 500m.

The Topographic Wetness Index (TWI) is widely adopted to characterise the influence of topography on saturated runoff areas' location and size [17]. This index measures soil moisture content dictated by topography. The map categorises TWI into five classes: <5, 5 – 6, 6 – 8, 8 – 11, and 11 – 19.

3.2 Frequency ratio

The methodology employed for debris flow susceptibility mapping in this study relies on the established frequency ratio (Fr) model (Eq. (1)), a widely recognized statistical approach. This model facilitates the integration of various environmental factors as predictors, contributing to the dependent variable. In this context, Fr values above 1 signify a more robust correlation, while values below 1 indicate a weaker correlation [28, 30, 31]. The debris flow susceptibility index is derived by summing the frequency ratio values of individual factors for each pixel, quantifying the likelihood of debris flow occurrence [23].

Consequently, a higher index value corresponds to an elevated susceptibility to debris flow, whereas a lower index value signifies reduced susceptibility [30]. To categorize these indices, the calculated frequency ratio values undergo classification using both Jenks natural breaks and manual classification. This assigns five distinct classes: very low, low, moderate, high, and high susceptibility categories [32]. This refined classification enhances the accuracy of the susceptibility assessment and provides a more actionable basis for mitigation strategies.

$$F_r = \frac{\frac{N_i}{N}}{\frac{S_i}{S}} \quad (1)$$

where,

N_i: No. of pixels in which the debris flow occurred in the i variable

N: No. of pixels with debris flow occurrence

S_i: No. of pixels of the i variable

S: Total number of pixels

The performance of the Frequency Ratio (FR) model was assessed using the Receiver Operating Characteristic (ROC) curve and the corresponding Area Under the Curve (AUC) metric. The ROC curve plots the true positive rate (sensitivity) against the false positive rate (1-specificity), offering a graphical representation of the model's ability to discriminate between different susceptibility classes across various threshold values.

4. RESULTS AND DISCUSSIONS

Several vital insights regarding debris flow susceptibility have been revealed based on analysing various terrain parameters. These findings contribute to a comprehensive understanding of the factors driving debris flow occurrences in the study area.

4.1 Slope aspect

Aspect, which signifies the direction of the steepest slope, plays a noteworthy role in debris flow susceptibility. Southeast-facing slopes encompass the highest distribution (20.16%), while north-facing slopes have the lowest distribution (1.24%) based on Figure 4. However, a closer examination of the Frequency Ratio (FR) values (Table 1) demonstrates that debris flow predominantly transpires on north-facing slopes (1.57), followed by northeast (1.31), southeast (1.29), and east-facing slopes (1.24). These values suggest a higher likelihood of debris flow on slopes with aspects that facilitate moisture accumulation, potentially due to elevated humidity levels in the area. Conversely, northwest-facing slopes exhibited the lowest frequency ratio value (0.09).

Table 1. Relationship between landslide causative factors and landslide distribution

Parameter	Class	% Class Pixels	% Debris Flow Pixels	F_r
Aspect	Flat	3.87	2.71	0.70
	North	8.43	13.20	1.57
	Northeast	10.81	14.18	1.32
	East	15.81	19.57	1.24
	Southeast	20.16	25.95	1.29
	South	18.15	14.96	0.82
	Southwest	13.46	7.71	0.57
	West	5.85	1.25	0.21
	Northwest	2.21	0.21	0.09
	North	1.24	0.26	0.21
Curvature	Concave	4.14	8.27	2.00
	Flat	44.50	43.76	0.98
	Convex	51.36	47.97	0.93
Elevation	<1000m	2.49	1.74	0.70
	1000m-1500m	35.60	11.50	0.32
	1500m-2000m	34.51	12.85	0.37
	2000m-2500m	14.60	28.57	1.96
	2500m-3000m	6.27	29.88	4.77
	3000 m-3500m	4.14	15.03	3.63
	>3500m	2.39	0.41	0.17
Land Use	Secondary Forest	4.28	0.00	0.00
	Primary Forest	46.13	80.48	1.74
	Scrub	9.03	4.13	0.46
	Settlement	40.55	15.39	0.38
Slope (°)	<5°	2.54	0.48	0.19
	5°-15°	26.09	8.61	0.33
	15°-25°	30.97	13.98	0.45
	25°-35°	25.08	22.09	0.88
	>35°	15.32	54.85	3.58
Soil Association	Bidu-bidu	7.01	8.30	1.18
	Kinabalu	16.57	68.88	4.16
	Trusmadi	27.87	4.01	0.14
	Crocker	8.04	2.82	0.35
	Pinousuk	40.51	15.99	0.40
Stream Power Index (SPI)	<-8	7.58	1.73	0.23
	-8- -5	14.85	12.26	0.83
	-5-0	36.47	20.10	0.55
	0-3	33.69	48.14	1.43
	3-9	7.42	17.76	2.40
Stream Proximity	<100m	21.82	39.71	1.82
	200m	20.99	19.02	0.91
	300m	19.26	11.63	0.60
	400m	16.52	8.92	0.54
	>500m	21.41	20.71	0.97
Topographic Wetness Index (TWI)	<5	32.99	35.40	1.07
	5-6	41.80	36.97	0.88
	6-8	17.07	19.23	1.13
	8-11	5.77	5.67	0.98
	11-19	2.36	2.74	1.16

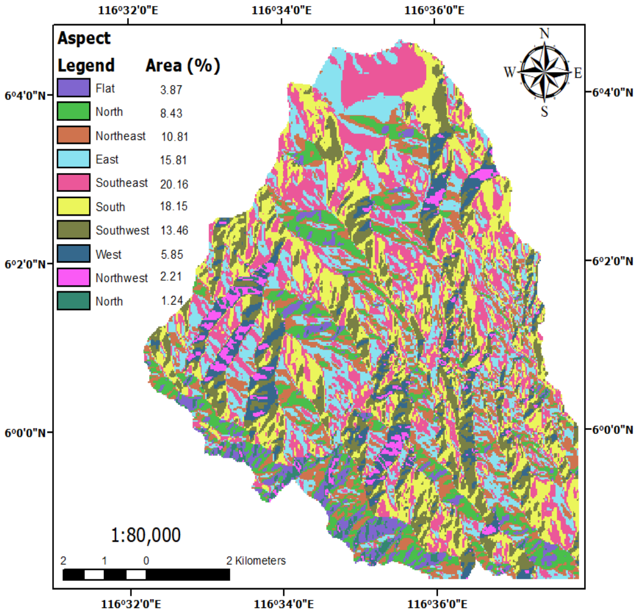

Figure 4. Aspect map

4.2 Slope curvature

The curvature of the terrain, as depicted in Figure 5, indicates that convex shapes are predominant (51.36%). In concave regions, however, the frequency ratio value is notably higher (2.00), indicating a greater susceptibility to debris flows. This concurrence could be attributed to the hydrostatic pressure build-up resulting from water accumulation at the base of concave terrain forms [32].

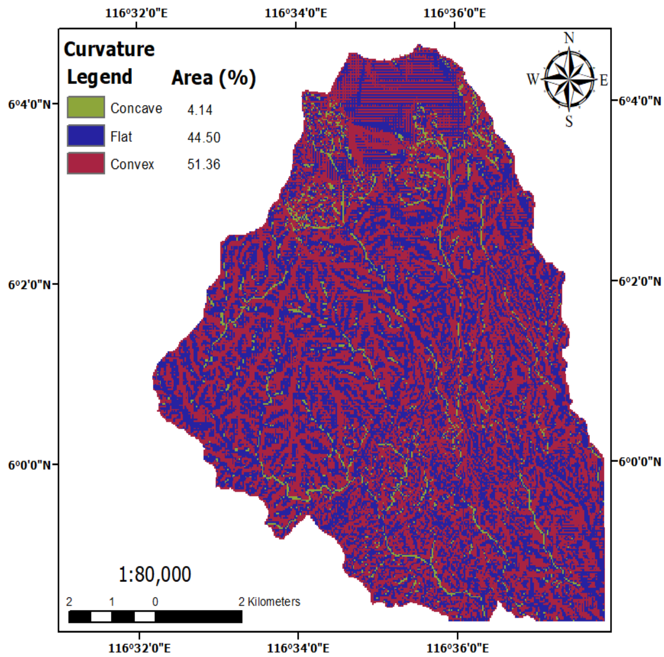

Figure 5. Curvature map

4.3 Elevation

Elevation, a crucial attribute, is distributed across different ranges (Figure 6). Table 1 reveals that the 2500m-3000m elevation class exhibits the highest frequency ratio value (4.77), indicating a substantial likelihood of debris flow occurrence. This elevation range is noteworthy due to its high population density, which includes settlements and small businesses, making it particularly vulnerable.

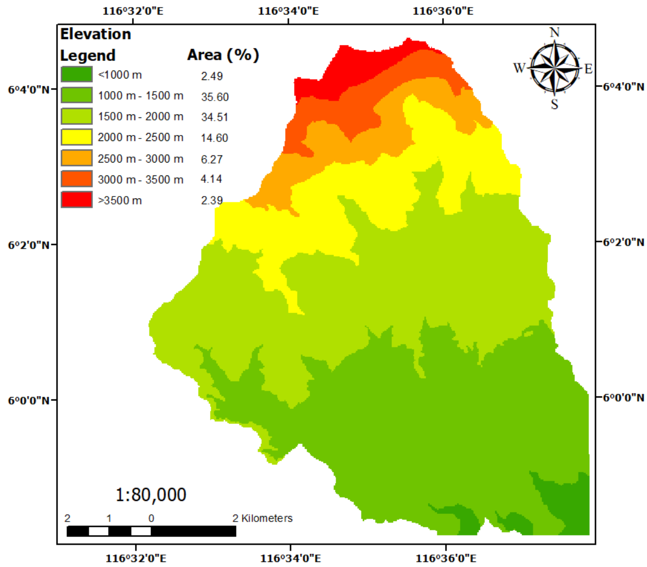

Figure 6. Elevation map

4.4 Land use

As depicted in Figure 7, land use illustrates that 46.13% of the area is covered by dryland primary forest, while settlements cover 40.55%. Regarding frequency ratio values (Table 1), dryland primary forest displays the highest value (1.74), indicating an elevated susceptibility to debris flows. Scrub and settlement areas, however, exhibit lower values of 0.46 and 0.38, respectively. Notably, dryland secondary forest areas have a frequency ratio of 0, implying reduced susceptibility.

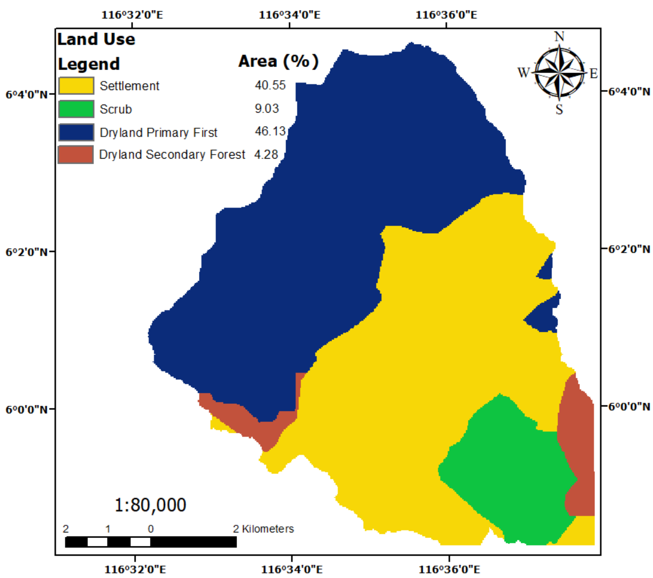

Figure 7. Land use map

4.5 Slope angle

Slope angles are another crucial determinant of debris flow susceptibility (Figure 8). Based on Table 1, slopes greater than 35° have the highest frequency ratio value (3.58), indicating a significant correlation between steep slopes and debris flow occurrences. This aligns with the intuitive understanding that steeper slopes provide the impetus for debris flow.

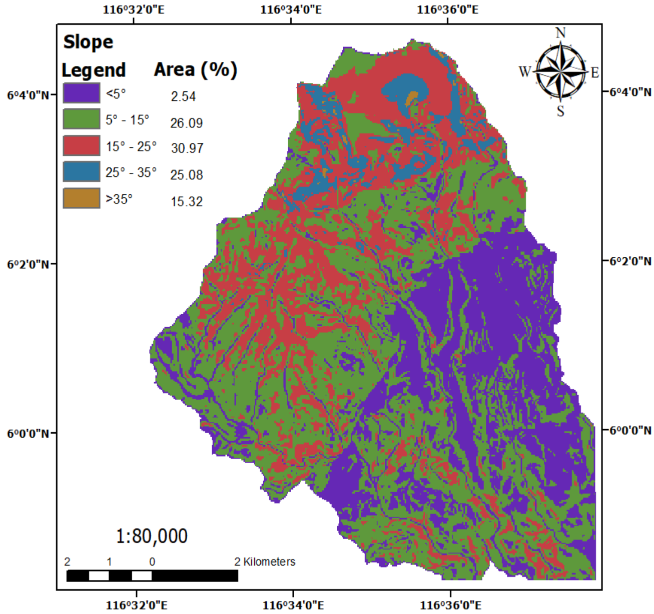

Figure 8. Slope map

4.6 Soil association

The type of soil association significantly influences susceptibility (Figure 9). Kinabalu exhibits the highest frequency ratio value (4.16), followed by Bidu-Bidu (1.18), as depicted in Table 2. Kinabalu and Bidu-Bidu are situated at higher elevations, which might contribute to their increased susceptibility to initiating debris flows in the upper north side of the study area.

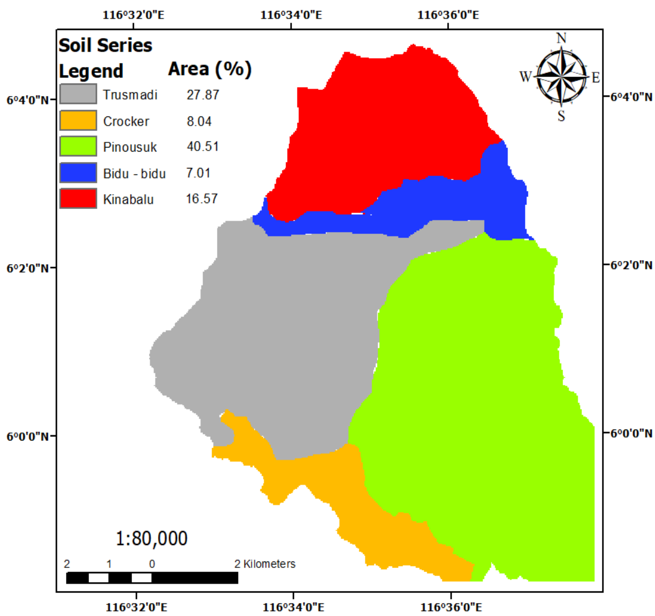

Figure 9. Soil association map

4.7 Stream power index

Stream Power Index (SPI) values, as shown in Figure 10, provide insights into erosion potential. Based on Table 2, debris flows are notably more likely to occur in areas with SPI values of 3-9 (frequency ratio value of 2.39), followed by SPI values of 0-3 (frequency ratio value of 1.43). These findings suggest higher SPI values correlate with increased erosional capacity and debris flow susceptibility.

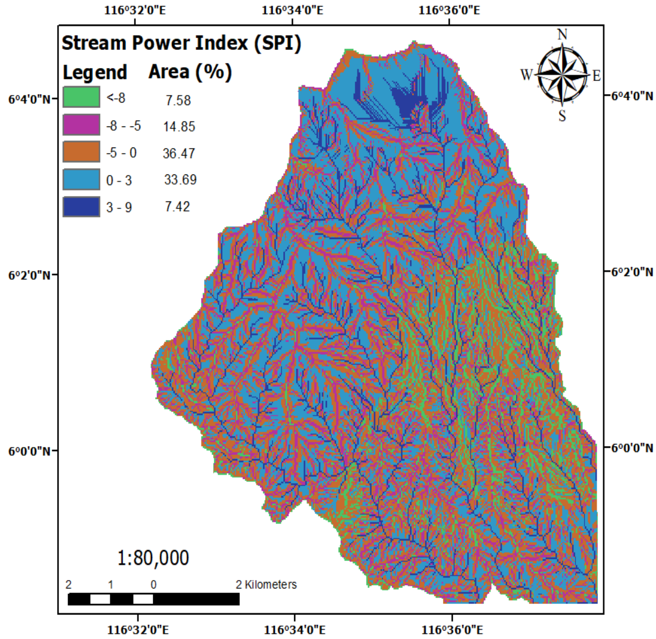

Figure 10. Stream Power Index (SPI) map

4.8 River proximity

Proximity to rivers significantly affects susceptibility (Figure 11). Debris flows within 100m of rivers are notably more likely to occur (frequency ratio value of 1.82), as highlighted in Table 2. The erosive processes associated with river proximity contribute to increased instability in these areas.

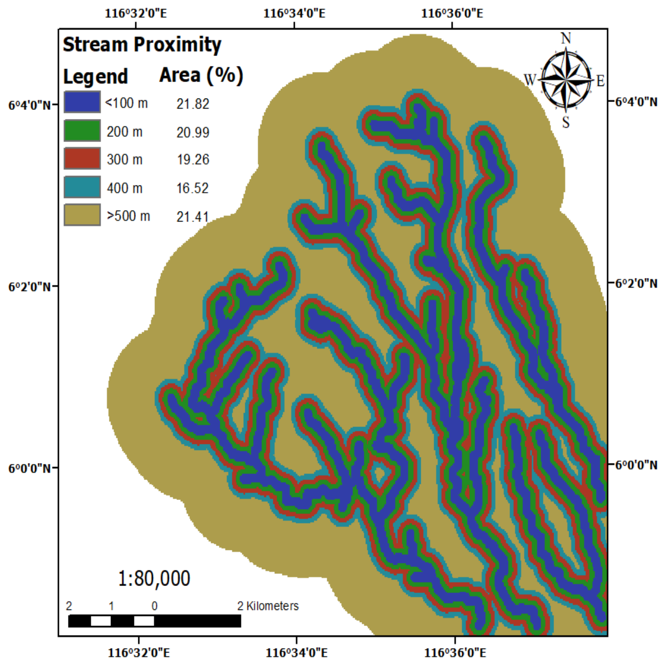

Figure 11. Stream proximity map

4.9 Topographic wetness index

Topographic Wetness Index (TWI), as indicated in Figure 12, showcases a pattern of increasing susceptibility as TWI values rise. Table 2 substantiates this trend, with higher TWI values associated with greater frequency ratio values. This underscores the link between elevated soil water content and increased susceptibility.

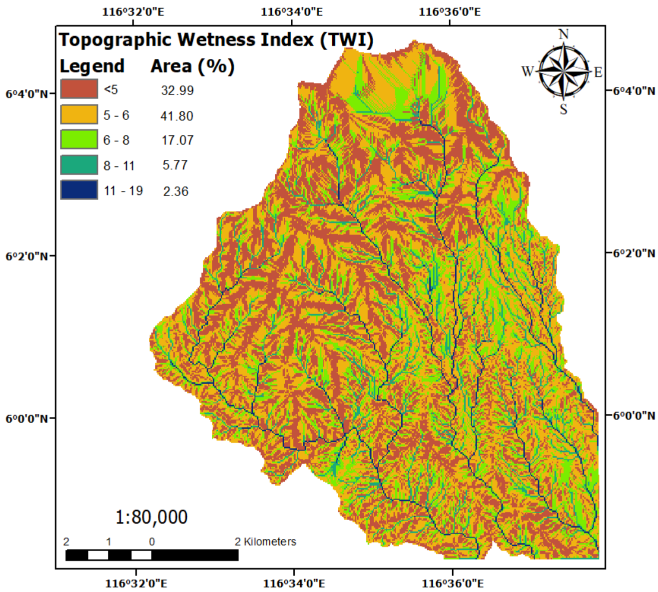

Figure 12. Topographic Wetness Index (TWI) map

Table 2. Summary of the debris flow susceptibility class

Class of Debris Flow Susceptibility	Area (km^2)	Area (%)
Very Low	13.44	16.87
Low	23.40	29.36
Moderate	9.84	12.34
High	30.22	37.92
Very High	2.80	3.51
	79.7	100

4.10 Debris flow susceptibility analysis

The debris flow susceptibility map developed in this study reveals significant variations in susceptibility across the Kundasang area, with high susceptibility concentrated in the southern region, encompassing communities such as Mesilou, Kg. Lembah Permai, Kg. Cinta Mata, Kg. Kauluan, and Kg. Lipasu Lama. These findings align with previous studies in similar regions, such as the work of Chen et al. [26] in Subao River Valley, China, and Lee and Pradhan [28] in Selangor, Malaysia, where steep slopes and specific land use patterns were identified as critical factors influencing debris flow susceptibility (Figure 13). However, our study's incorporation of the Topographic Wetness Index (TWI) and Stream Power Index (SPI) provides a more nuanced understanding of hydrological influences, which are less emphasized in prior studies. This approach highlights the novelty of our research and its potential to refine susceptibility models for regions with complex terrain and climatic conditions.

It is evident that the northern part of the study area, including Mount Kinabalu, serves as a potential initiation zone for sediments, which, upon downstream movement, may transition to a transportation or even a deposition zone. The geomorphological and climatological factors, including steep slopes, elevation differences, and heavy precipitation, contribute to the heightened debris flow susceptibility in the area. Furthermore, upstream damming locations, stripped vegetation cover, and anthropogenic factors such as road construction further exacerbate the susceptibility.

The ROC curve plots the true positive rate against the false positive rate, providing a visual representation of the model's diagnostic ability across different threshold values. The AUC value obtained for the model was 0.839 (Figure 14), indicating a strong predictive performance. This value suggests that the model has a high ability to distinguish between debris flow-prone and non-prone areas, with performance significantly better than random guessing. The model's predictive accuracy was validated by dividing the dataset into training and validation sets, where the training set was used to construct the model, and the validation set assessed its performance. The results confirm the FR model's reliability for identifying areas susceptible to debris flows in the study region, providing a valuable tool for hazard assessment and mitigation planning. Future work could further enhance the model's accuracy by incorporating additional factors such as rainfall intensity and land cover changes, and by testing its applicability in different geographical settings.

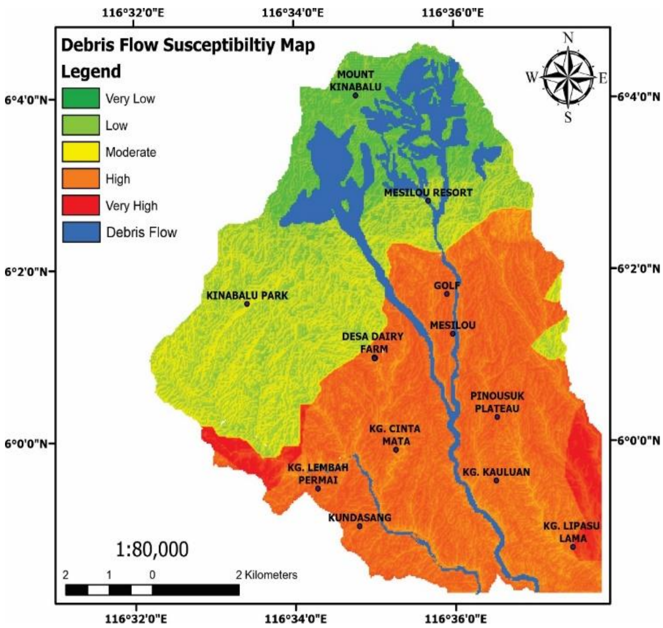

Figure 13. Debris flow susceptibility map

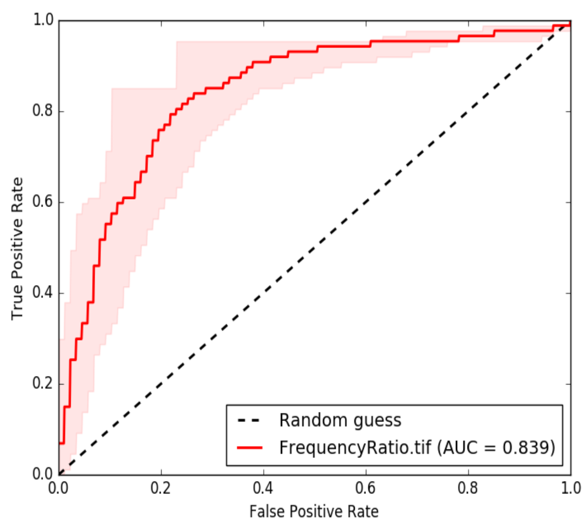

Figure 14. Validation result

5. CONCLUSIONS

Debris flows pose significant threats to human settlements and the natural environment, particularly in regions prone to seismic activity and geomorphic processes. This study focused on the Kundasang area in Sabah, Malaysia, to comprehensively assess debris flow susceptibility and provide insights for effective hazard mitigation strategies. By integrating a bivariate Frequency Ratio (FR) model with Geographic Information System (GIS) techniques, we analyzed various terrain parameters, including slope aspect, curvature, elevation, land use, slope angle, soil association, Stream Power Index (SPI), stream proximity, and Topographic Wetness Index (TWI), to understand the factors influencing debris flow occurrences.

Our analysis revealed that parameters such as slope aspect, curvature, elevation, and land use significantly influence debris flow susceptibility. Specifically, concave terrains and north-facing slopes, elevations between 2500m and 3000m, and areas dominated by dryland primary forest exhibit higher susceptibility. Additionally, steep slope angles and specific soil associations, like the Kinabalu soil type, further increase susceptibility. The SPI and proximity to rivers highlighted areas at greater risk, particularly those within 100 meters of rivers, while higher TWI values indicated increased susceptibility due to elevated soil water content.

The comprehensive debris flow susceptibility map generated for the study area identifies varying levels of risk, with the southern region, including populated communities, particularly vulnerable to debris flow hazards. These findings highlight the complex interplay of geomorphic, climatic, and anthropogenic factors contributing to the heightened susceptibility observed in the Kundasang area.

The methodology and findings from this study can be applied to other regions with similar topographical and environmental conditions, such as areas with steep terrain and active seismic activity, to develop effective mitigation and land-use strategies tailored to local conditions. Based on these findings, we recommend that land-use planning in high-susceptibility areas incorporate zoning regulations that limit development on steep slopes and near riverbanks. Establishing buffer zones around high-risk areas and enforcing construction restrictions can reduce the risk of property damage and loss of life. Sustainable forest management practices, including reforestation and controlled land clearing, should be prioritized to stabilize slopes and reduce soil erosion. Infrastructure development should be carefully planned, considering the terrain's vulnerabilities, to avoid exacerbating debris flow susceptibility. These insights will empower decision-makers, researchers, and local communities to implement proactive measures that safeguard lives, infrastructure, and ecosystems against the persistent threat of debris flows.

ACKNOWLEDGMENT

Sincere gratitude to Natural Disaster Research Centre (NDRC) and Faculty of Science and Natural Resources (FSSA), Universiti Malaysia Sabah (UMS) for providing easy access to laboratories and research equipment. Highest appreciations also to the research grant award (SDK-0120, SBK0335-2017, SDK0130-2020, GUG0534-2/2020 and GKP0036-2021) to finance all the costs of this research.

REFERENCES

[1] Sharir, K., Lai, G.T., Simon, N., Ern, L.K., Madran, E., Roslee, R. (2022). Debris flow susceptibility analysis using a bivariate statistical analysis in the Panataran River, Kg Melangkap, Sabah, Malaysia. IOP Conference Series: Earth and Environmental Science, 1103(1): 012038. https://doi.org/10.1088/1755-1315/1103/1/012038

[2] Joe, E.J., Tongkul, F., Roslee, R. (2019). Behaviour of channelised debris flow in the crocker range of Sabah, Malaysia: A case study at Ulu Moyog, Penampang. Geological Behavior, 3(1): 28-32.

[3] Chang, M., Tang, C., Zhang, D.D., Ma, G.C. (2014). Debris flow susceptibility assessment using a probabilistic approach: A case study in the Longchi area, Sichuan province, China. Journal of Mountain Science, 11: 1001-1014. https://doi.org/10.1007/s11629-013-2747-9

[4] Menier, D., Mathew, M., Pubellier, M., Sapin, F., Delcaillau, B., Siddiqui, N., Ramkumar, M., Santosh, M. (2017). Landscape response to progressive tectonic and climatic forcing in NW Borneo: Implications for geological and geomorphic controls on flood hazard. Scientific Reports, 7(1): 457. https://doi.org/10.1038/s41598-017-00620-y

[5] Kritikos, T., Davies, T. (2015). Assessment of rainfall-generated shallow landslide/debris-flow susceptibility and runout using a GIS-based approach: Application to western Southern Alps of New Zealand. Landslides, 12: 1051-1075. https://doi.org/10.1007/s10346-014-0533-6

[6] Yusoff, H.H.M., Razak, K.A., Yuen, F., Harun, A., Talib, J., Mohamad, Z., Ramli, Z., Abd Razab, R. (2016). Mapping of post-event earthquake induced landslides in Sg. Mesilou using LiDAR. IOP Conference Series: Earth and Environmental Science, 37(1): 012068. https://doi.org/10.1088/1755-1315/37/1/012068

[7] Liu, M., Chen, N., Zhang, Y., Deng, M. (2020). Glacial lake inventory and lake outburst flood/debris flow hazard assessment after the Gorkha earthquake in the Bhote Koshi Basin. Water (Switzerland), 12(2): 464. https://doi.org/10.3390/w12020464

[8] Sharir, K., Simon, N., Roslee, R. (2018). The influence of landslides parameters contributing to runout zones using GIS-based empirical model in Kundasang, Sabah. ASM Science Journal, 11(3): 254-266.

[9] Wang, Y., Wei, S., Wang, X., Lindsey, E.O., Tongkul, F., Tapponnier, P., Bradley, K., Chan, C.H., Hill, E.M., Sieh, K. (2017). The 2015 M w 6.0 Mt. Kinabalu earthquake: An infrequent fault rupture within the Crocker fault system of East Malaysia. Geoscience Letters, 4(1): 1-12. https://doi.org/10.1186/s40562-017-0072-9

[10] Sharir, K., Roslee, R., Ern, L.K., Simon, N. (2017). Landslide factors and susceptibility mapping on natural and artificial slopes in Kundasang, Sabah. Sains Malaysiana, 46(9): 1531-1540. https://doi.org/10.17576/jsm-2017-4609-23

[11] Sharir, K., Simon, N., Roslee, R. (2016). Regional assessment on the influence of land use related factor on landslide occurrences in Kundasang, Sabah. In AIP Conference Proceedings. AIP Publishing, 1784(1): 1-6. https://doi.org/10.1063/1.4966853

[12] Tongkul, F. (2017). The 2015 ranau earthquake: Cause and impact. Sabah Society Journal, 32: 1-28.

[13] Roslee, R., Termizi, A.K., Indan, E., Tongkul, F. (2018). Earthquake vulnerability assessment (EVAs): A study of physical vulnerability assessment in Ranau area, Sabah, Malaysia. ASM Science Journal, 11(2): 66-74.

[14] Rosli, M.I., Kamal, N.A.M., Razak, K.A. (2021). Assessing earthquake-induced debris flow risk in the first UNESCO world heritage in Malaysia. Remote Sensing Applications: Society and Environment, 23: 100550. https://doi.org/10.1016/j.rsase.2021.100550

[15] Taharin, M., Roslee, R., Amaludin, A. (2018). Geotechnical characterization in hilly area of Kundasang, Sabah, Malaysia. ASM Science Journal, 11: 124-131.

[16] Simon, N., Azlan, N.N.N., Roslee, R., Hussein, A., Ern, L.K., Sharir, K. (2017). Physical soil characterization on stable and failed slopes of the Ranau-Tambunan road, Sabah, Malaysia. Nature Environment and Pollution Technology, 16(2): 659.

[17] Achour, Y., Garçia, S., Cavaleiro, V. (2018). GIS-based spatial prediction of debris flows using logistic regression and frequency ratio models for Zêzere River basin and its surrounding area, Northwest Covilhã, Portugal. Arabian Journal of Geosciences, 11(18): 550. https://doi.org/10.1007/s12517-018-3920-9

[18] Mojaddadi, H., Pradhan, B., Nampak, H., Ahmad, N., Ghazali, A.H.B. (2017). Ensemble machine-learning-based geospatial approach for flood risk assessment using multi-sensor remote-sensing data and GIS. Geomatics, Natural Hazards and Risk, 8(2): 1080-1102. https://doi.org/10.1080/19475705.2017.1294113

[19] Simon, N., Crozier, M., de Roiste, M., Rafek, A.G., Roslee., R. (2015). Time series assessment on landslide occurrences in an area undergoing development. Singapore Journal of Tropical Geography, 36(1): 98-111. https://doi.org/10.1111/sjtg.12096

[20] Deng, X., Li, L., Tan, Y. (2017). Validation of spatial prediction models for landslide susceptibility mapping by considering structural similarity. ISPRS International Journal of Geo-Information, 6(4): 103. https://doi.org/10.3390/ijgi6040103

[21] Rahmati, O., Pourghasemi, H.R., Zeinivand, H. (2016). Flood susceptibility mapping using frequency ratio and weights-of-evidence models in the Golastan Province, Iran. Geocarto International, 31(1): 42-70. https://doi.org/10.1080/10106049.2015.1041559

[22] Pourghasemi, H.R., Pradhan, B., Gokceoglu, C. (2012). Application of fuzzy logic and analytical hierarchy process (AHP) to landslide susceptibility mapping at Haraz watershed, Iran. Natural Hazards, 63: 965-996. https://doi.org/10.1007/s11069-012-0217-2

[23] Angillieri, M.Y.E. (2020). Debris flow susceptibility mapping using frequency ratio and seed cells, in a portion of a mountain international route, Dry Central Andes of Argentina. Catena, 189: 104504. https://doi.org/10.1016/j.catena.2020.104504

[24] Ayalew, L., Yamagishi, H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. Geomorphology, 65(1-2): 15-31. http://doi.org/10.1016/j.geomorph.2004.06.010

[25] Samanta, S., Pal, D.K., Palsamanta, B. (2018). Flood susceptibility analysis through remote sensing, GIS and frequency ratio model. Applied Water Science, 8(2): 66. https://doi.org/10.1007/s13201-018-0710-1

[26] Chen, X., Chen, H., You, Y., Liu, J. (2015). Susceptibility assessment of debris flows using the analytic hierarchy process method-A case study in Subao river valley, China. Journal of Rock Mechanics and Geotechnical Engineering, 7(4): 404-410. https://doi.org/10.1016/j.jrmge.2015.04.003

[27] Roslee, R., Simon, N., Tongkul, F., Norhisham, M.N., Taharin, M.R. (2017). Landslide susceptibility analysis (LSA) using deterministic model (infinite slope)(DESSISM) in the Kota Kinabalu area, Sabah, Malaysia. Geological Behavior, 1(1): 06-09. https://doi.org/10.26480/gbr.01.2017.06.09

[28] Lee, S., Pradhan, B. (2007). Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models. Landslides, 4(1): 33-41. https://doi.org/10.1007/s10346-006-0047-y

[29] Roslee, R., Sharir, K. (2019). Soil erosion analysis using RUSLE model at the Minitod area, Penampang, Sabah, Malaysia. Journal of Physics: Conference Series, 1358(1): 012066. https://doi.org/10.1088/1742-6596/1358/1/012066

[30] Wubalem, A. (2021). Landslide susceptibility mapping using statistical methods in Uatzau catchment area, northwestern Ethiopia. Geoenvironmental Disasters, 8(1): 1. https://doi.org/10.1186/s40677-020-00170-y

[31] Meena, S.R., Mishra, B.K., Tavakkoli Piralilou, S. (2019). A hybrid spatial multi-criteria evaluation method for mapping landslide susceptible areas in kullu valley, himalayas. Geosciences, 9(4): 156. https://doi.org/10.3390/geosciences9040156

[32] Cao, C., Xu, P., Wang, Y., Chen, J., Zheng, L., Niu, C. (2016). Flash flood hazard susceptibility mapping using frequency ratio and statistical index methods in coalmine subsidence areas. Sustainability, 8(9): 948. https://doi.org/10.3390/su8090948