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RESEARCH ARTICLE

GIS-Based analysis of landslide susceptibility in Madi Watershed: Nepal

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ABSTRACT

Landslides are known as the most calamitous natural hazard in Nepal, posing significant threats to human lives, infrastructure, and natural resources. The main objective of this study is to use the Weighted Overlay Method (WOM) in ArcGIS software to generate a map of landslide susceptibility in the study area. Landslide susceptibility assessment is essential to recognize the high-risks areas, which in turn will help solidify land-utilization planning decisions, risk minimization, and disaster prevention measures. The WOM is produced using raster-based Geographic Information System (GIS) employing characteristics such as aspect, curvature, elevation, geology, NDVI (Normalized difference vegetation index), rainfall, distance from rivers, and slope. The analysis of the obtained results shows that slope, geology and rainfall have the greatest influence on landslide occurrence, particularly in the northern region. The study area was classified into four classes of vulnerability zones based on the analytical results. The results showed that increasing elevation, precipitation, non-vegetative land and slope influence the frequency and magnitude of landslides. Consequently, 0.003 percent of total area of watershed were classified as “Low Susceptibility” to landslides, whereas the “Very High Susceptibility” has coverage of 3.447 percent. Similarly, "Moderate Susceptibility" covers 25.703% of the total area and "High Susceptibility" covers 70.847% of the watershed's total area. The areas of high and moderate risk mainly consist of hilly terrain, due to steep slopes and gravity. The region of moderate vulnerability has primarily located in mountainous regions, attributable to hilly vegetation and cloudy weather conditions. In general, aspect with Southeast to Southwest part was more vulnerable to landslides along with increased rainfall and elevation factors with slope degree heightened the area's vulnerability."

Key Words: ***Landslide, Madi watershed, susceptibility, vulnerability, weighted overlay***

INTRODUCTION

The term 'landslide' is typically described as "the descending movement of a mass of rock, debris, or earth under the influence of gravity, with or without water in solid or liquid form." Landslides refer to the gravitational-induced movement of debris, rocks, soil, and earth (Cruden and Varnes, 1996). A landslide can consist of rock, soil, or both, are classified depending on the material and its movement. A slide can be made up of rock or soil or a combination of both. When it is fine it is termed as earth and when it is a little large it is referred to as debris. The manner or mode of motion, such as fall, topple, slide, spread, or flow, describes how the material advances. Such words as “rockfall” and “debris flow” refer to landslides because they incorporate both the material and the movement. A complicated failure involving multiple types of movement, such as a rockslide-debris flow, can also result from a landslide (Highland and Bobrowsky, 2008; Cutter et al., 2013). Landslides occur in a variety of environments, characterized by either steep or gentle slope gradients from mountain ranges to coastal cliffs or even underwater. Even regarding the process of landsliding, knowledge of what controls this process and how these controls are interrelated, remains chiefly unknown as it is therefore evident that geographical location influences those agents that cause natural landslides (Regmi et al., 2010; Ghimire, 2011; Lin et al., 2013; Wang et al., 2015; Petley et al., 2007). Additionally contributing to the occurrence of landslides, one can include such human initiated actions as construction of roads, dams and other similar infrastructural projects. Another significant cause of landslides is also disturbances by mankind through constructing roads or dams and any other man-made project (Erskine, 1973; Hunt et al., 1993; Arbanas and Arbanas, 2015).

Nepal is situated in a seismically very active zone of the earth where the Indian plate is thrusting beneath the Eurasian plate (Chaulagain et al., 2015). This has weakened the slopes, reduced the slope stability threshold, and caused numerous landslides (Dahlquist and West, 2019). The varied geographical features, intricate topography, and geomorphology, as well as the presence of active seismic faults, recent geological formations, and fluctuating climatic patterns attributed to landslide's susceptibility in Nepal (Petley et al., 2007; Bhandary et al., 2013; K. C. et al., 2021). Landslides pose a significant threat to human lives, infrastructure, and natural resources in Nepal, making it one of the most calamitous natural hazards in the country. More than 80% of Nepal's population is prone to natural hazards such as floods, landslides, windstorms, hailstorms, fires, earthquakes, and glacial lake outburst floods (Ministry of Home Affairs [MoHA], 2017). Over the course of the past ten years (2011-2020), a total of 2121 landslide incidents were reported, in addition, resulting the tragic loss of 1206 individuals (K. C. et al., 2023). According to Nepal Disaster Risk Reduction Portal, the landslides exhibit a gradual increase from May to July, reaching their peak, before subsiding in September coinciding with the monsoon season which takes place from June to September.

Landslide susceptibility mapping identifies the probability of landslides in a zone, which in turn will help solidify land-use planning decisions, risk management, and disaster prevention measures. According to landslide susceptibility mapping theory, new landslides will likely occur in areas with geo-environmental conditions similar to those where previous landslides occurred (Guzzetti et al., 2012). The acquired data were analyzed using the Weighted Overlay Method (WOM), which can model potential regions for landslides. These methods play an important role in producing landslide susceptibility maps, as several previous works have demonstrated the potential of WOM.

Landslides has threatened the communities and ecosystems in the regions of Madi watershed, influenced by unstable geology, steep terrain, and erratic rainfall, as exemplified by the event of 3rd August 2010, which had blocked the river in Naune village, Kaski, endangering the people (Khanal et al., 2013). The existing susceptibility map lacks continuation and updates, further, addressing these gaps by applying Weighted Overlay Method (WOM) in ArcGIS, the study aims to generate a landslide susceptibility map of Madi watershed.

The primary objective of this study is to use (Weighted Overlay Method) WOM in ArcGIS software to create a map of the susceptibility of landslides in the study area. The Weighted Overlay Method (WOM), which is produced using raster-based GIS (Goodchild, 2011) employing characteristics such as aspect, curvature, elevation, NDVI, rainfall, distance from river and slope, will be utilized in developing the landslide susceptibility map.

Study area

The figure illustrated as Fig. 1 depicts the watershed of the Madi River, which is the study area, covering an estimated area of 1123 sq.km. This region falls under the jurisdiction of three districts, viz., Kaski, Lamjung, and Tanahun, located in the Gandaki Province. Eventually, this stream converges with other tributaries to form the Gandaki River basin, which is the second-largest river basin in Nepal. The coordinates for the study area are 84°0'0" E to 84°20'0" E longitude and 28°0'0" N to 28°30'0" N latitude, with the elevation ranging from 303 meters to 7943 meters above sea level. The area encompasses three main geological formations: Lesser Himalayan meta-sediments, Higher Himalayan crystalline rocks, and Tibetan sedimentary Tethys sediments.). The Madi Watershed of south western part of Nepal has high vulnerability to environment degradation due to complication in geology, increased slope of the area and excessive monsoon precipitation (Khanal and Watanabe, 2008,). Likewise, upper part of the area has slope gradient which is highly steep and amount of rainfall is higher comparatively (Gurung, 2013). The name "Madi" is a portmanteau of the words “Ma,” which means 'mother,' and “di,” which means 'water' in the Magar language. Kapuche Lake, recognized as Nepal's lowest elevated glacier lake, is located at an altitude of 2546 meters above sea level. This lake serves as the origin of the Madi River.

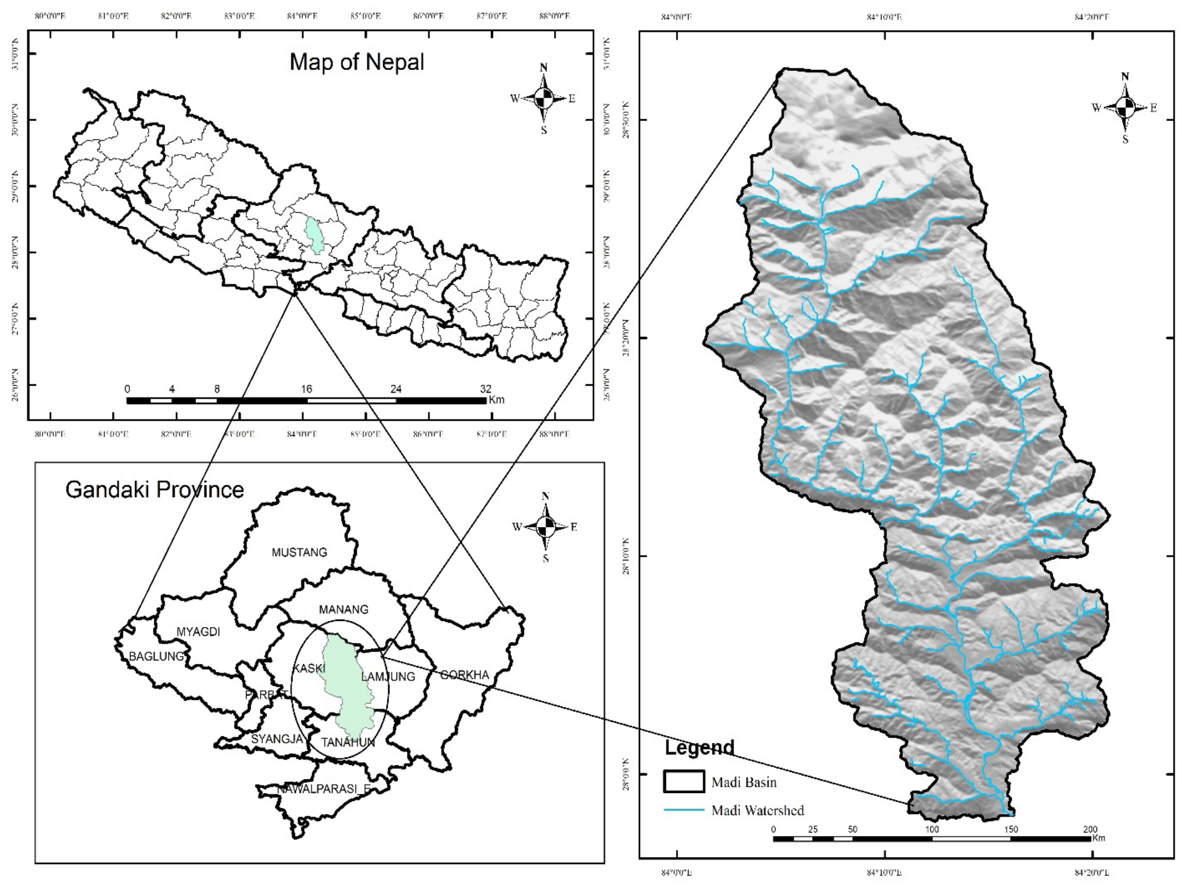

Fig. 1: Location map of the study area

METHODOLOGY

The Weighted Overlay Method (WOM) is a widely used method for combining different layers into a single output layer, where the method involves assigning a weight to each layer according to its relative significance in determining landslide susceptibility (Jamil et al., 2022). This study follows following research design:

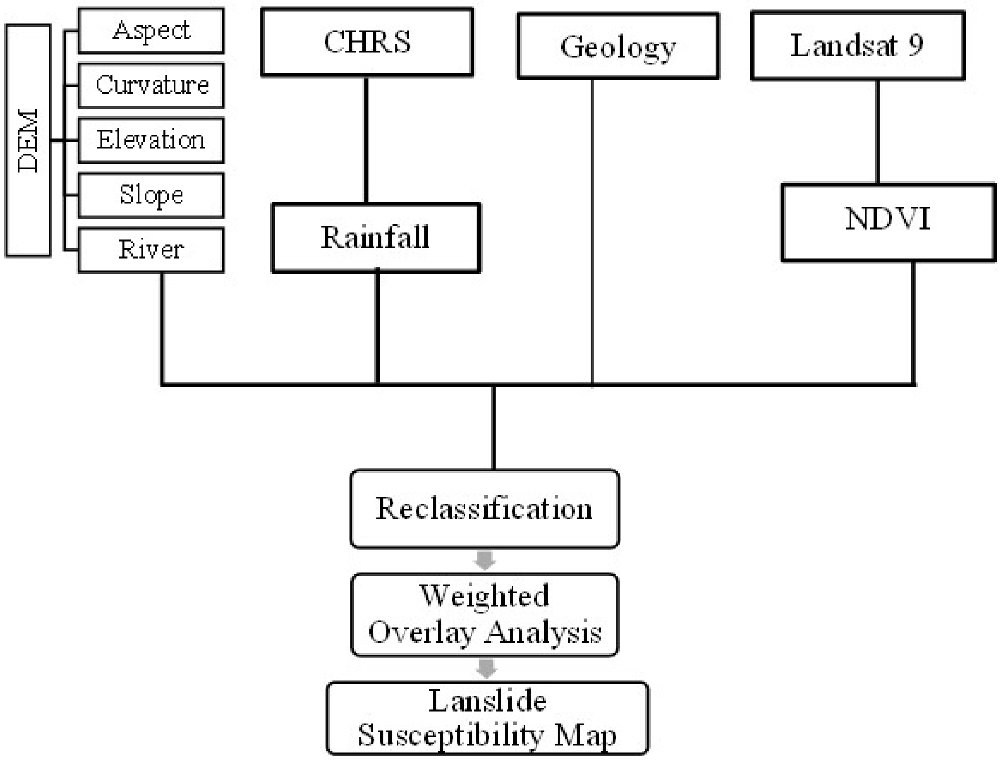

Fig. 2: Research design

WOM combines various environmental factors for the landslide susceptibility analysis as each factor is allocated an appropriate weight so as to detect vulnerable areas (Shit et al., 2016). It was combined with utilization of remote sensing and geographic information system (GIS) techniques to create the map of the Madi watershed's landslide susceptibility. A Digital Elevation Data (DEM) and Landsat 9 of resolution 30m were extracted from Earth Explorer (earthexplorer.usgs.gov). Additional data on rainfall was sourced from CHRS Data Portal. To determine the likelihood of landslides in each area, the information with data on aspect, curvature, elevation, geology, NDVI, rainfall, distance from rivers, and slope were overlaid. When integrating each of these different types of data in the ArcGIS Spatial Analyst tool, it was able to build up a holistic perspective of the area's likelihood of landslide occurrence.

Table 1: Open-source spatial dataset used in study

S.N.	Data	Resolution	Source
1	DEM and Landsat 9	30m	Earth Explorer (earthexplorer.usgs.gov)
2	Rainfall	0.25°*0.25°	CHRS Data Portal (uci.edu)
	Geology		U.S. Geological Survey (Wandrey & Law, 1998)
3	Geology		U.S. Geological Survey (Wandrey and Law, 1998)

The Weightage were assigned manually in terms of influencing factors under the expert opinion and literature's related to landslide susceptibility. In addition, the entries for scale value were done in terms of suitability; 1 being not suitable followed by 2 less suitable, 3 being moderate, 4 for suitable and 5 highly suitable and more. Rainfall is a key trigger for likelihood of a landslides by decreasing shear strength and increasing pore, especially in regions with steeper slope (Crozier, 2010b). That's why, rain and slope were identified as significant factors for landslide susceptibility with the weighted of 15 and 30 percent, respectively. Geology is the second most crucial factor assigned 20 percent as sedimentary rocks are comparatively softer and vulnerable to weathering and can contain clay or shale and will slide over each other when wet (What Are Sedimentary Rocks?) (U.S. Geological Survey, 2016). Also, it is necessary to note that some metamorphic rocks may contain weak plane that causes them to slide in the given circumstances. Aspect is the also most crucial factor assigned 10 percent. It is important to note that NDVI and elevation are assigned a weight of 5 percent each and curvature 10 percent. In the case of curvature, concave curvature (negative values) indicates areas of concentration where water flows across the surface of the earth to increase water accumulation. This can lead to a situation where the volume of water in the soil becomes higher, which serves as a catalyst for landslides (Zhou et al., 2002). Generally, some factor like aspect (10%) which is direction of slope face; where Southeast to Southwest part is more vulnerable to landslides as conditions like exposure of the sun that causes drying and subsequent cracking of the soil hence releases a lot of strength and cohesion (Pareta and Pareta, 2012). Therefore, the scale value of five has been assigned to the aspect for category of 144.78376 to 209.89107 degree. The weightage for river was given five percent.

Table 2: Weightage distribution for parameters (Weightage of each sub-class of landslide conditioning factor using expert opinion)

Parameters	Class	Field Value	Scale Value (weightage)
Aspect (10 %)	-1 to 74.014945 (N- E to NE)	1	2
	74.014945 to 144.78376 (E – NE to SE)	2	4
	144.78376 to 209.89107 (SE to SW)	3	5
	209.89107 to 280.659886 (SW to W- NW)	4	3
	280.659886 to 359.920959 (W-NW to N)	5	1

Parameters	**Class**	**Field Value**	**Scale Value (weightage)**
Curvature (10%)	-6.224893 to -0.957676 (Highly Concave)	1	5
	-0.957676 to -0.25202 (Concave)	2	4
	-0.25202 to 0.264621 (Flat)	3	3
	0.264621 to 0.982878 (Convex)	4	2
	0.982878 to 6.552519 (Highly Convex)	5	1
Elevation (m) (5%)	304	1	1
	2196	2	2
	4089	3	3
	5981	4	4
	7873	5	5
Geology (20%)	Tertiary Igneous Rock	1	3
	Jurassic Metamorphic & Sedimentary Rock	2	4
	Others	3	1
	Undivided Precambrian Rock	4	2
NDVI (5%)	-0.133167 to 0.013554 (non-vegetation)	1	5
	0.013554 to 0.090907 (Low Vegetation)	2	4
	0.090907 to 0.153757 (Moderate Vegetation)	3	3
	0.153757 to 0.20452 (High Vegetation)	4	2
	0.20452 to 0.419659 (Very High Vegetation)	5	1
Rainfall (mm) (15%)	829 – 923	1	1
	924 – 1021	2	2
	1022 – 1124	3	3
	1125 – 1218	4	4
	1219 – 1413	5	5
River (5%)	500	1	5
	900	2	4
	1700	3	3
	5500	4	2
	7000+	5	1
Slope(degree) (30%)	0 – 13	1	1
	14 – 22	2	2
	23 – 30	3	3
	31 – 40	4	4
	41 – 60	5	5

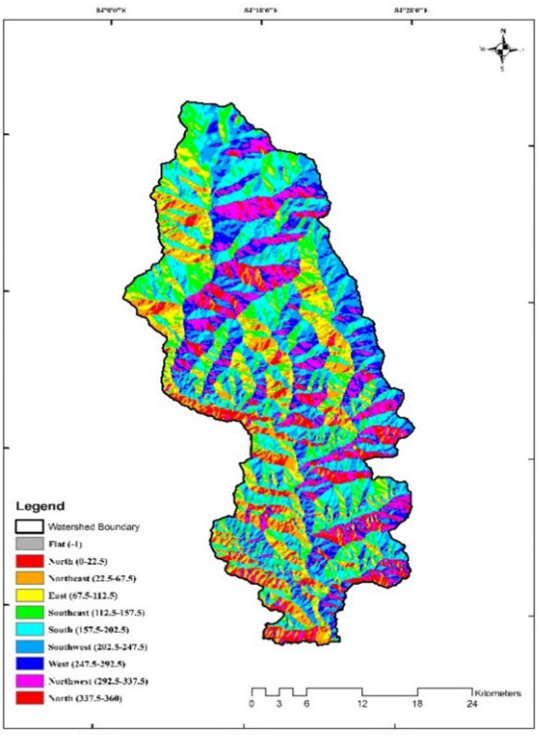

Fig. 3: Aspect map of Madi watershed

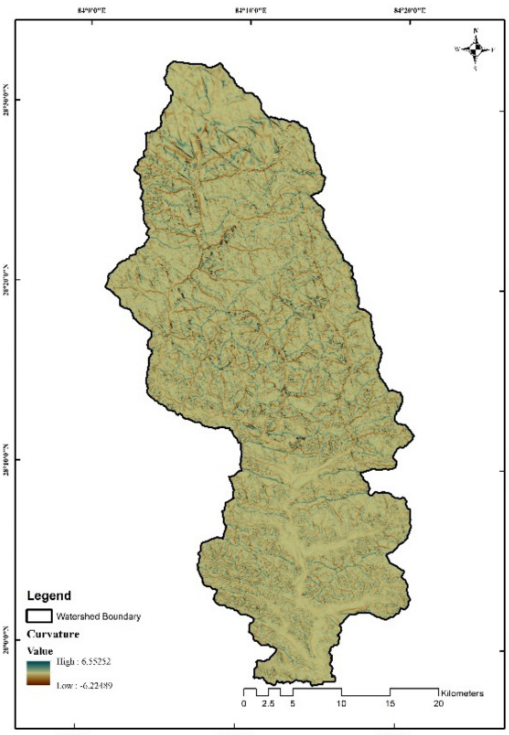

Fig. 4: Curvature Map of Madi watershed

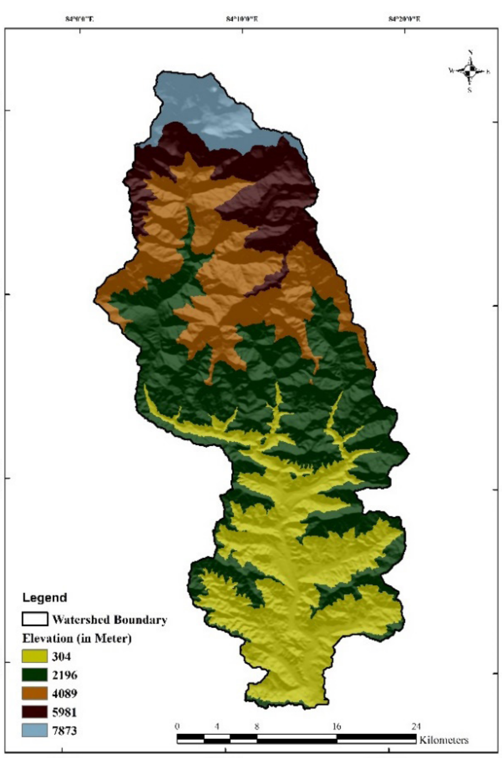

Fig. 5: Elevation Map of Madi watershed.

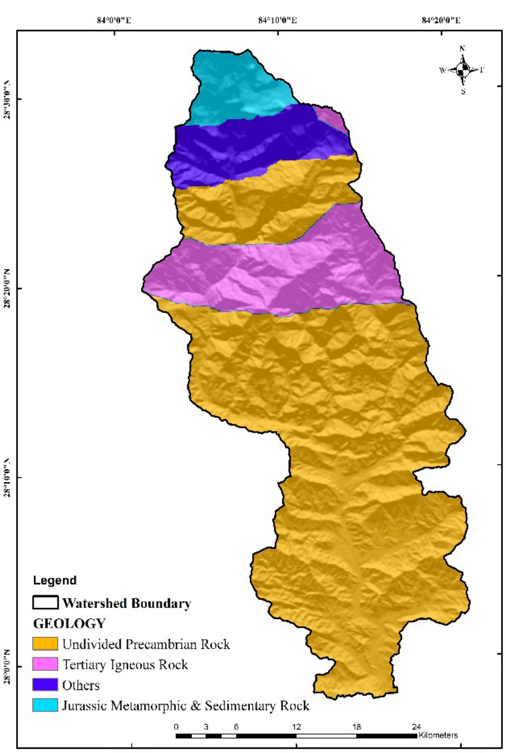

Fig. 6: Geology Map of Madi watershed.

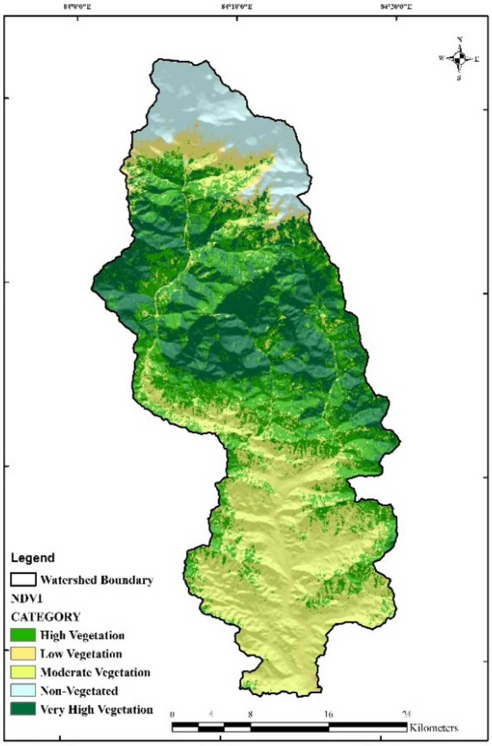

Fig. 7: NDVI Map of Madi watershed.

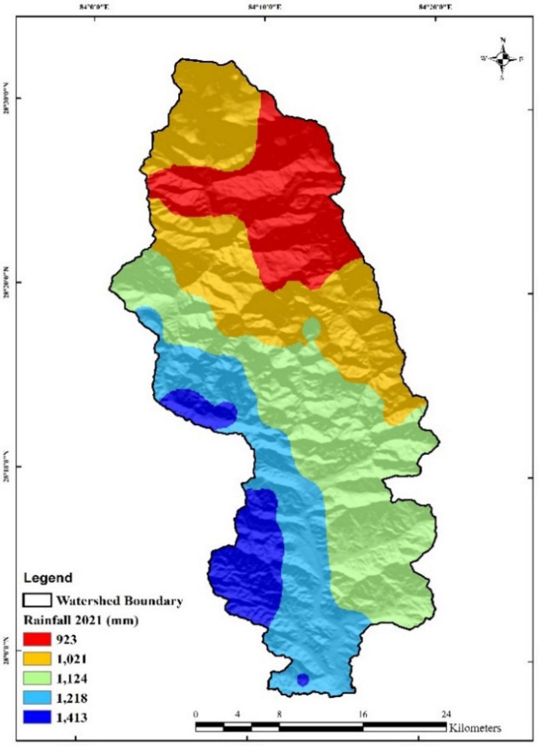

Fig. 8: Rainfall Map of Madi watershed.

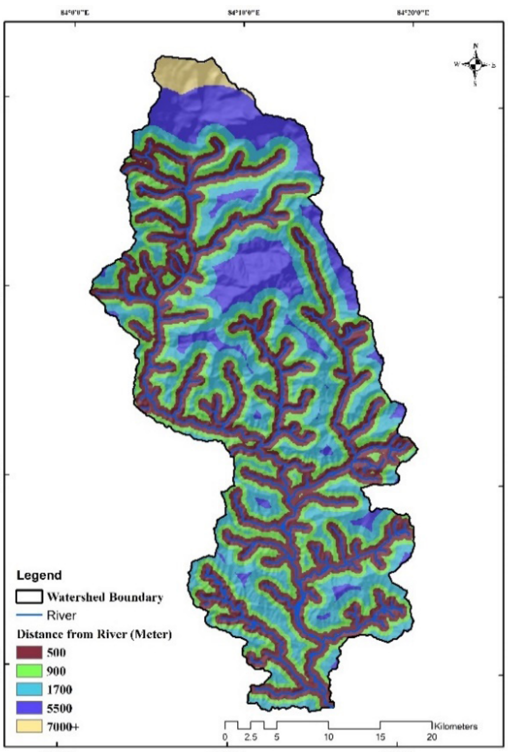

Fig. 9: River Map of Madi watershed.

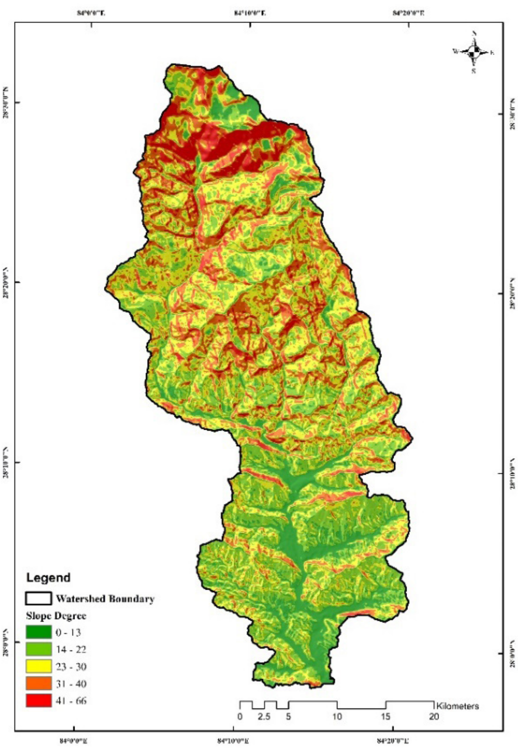

Fig. 10: Slope Map of Madi watershed.

RESULT AND DISCUSSION

For this study, all the thematic maps of the study area were classified with respect to seven criteria using the Weighted Overlay Method (WOM) in ArcGIS 10. 4 assigning weights for each parameter manually. The Table 3 and Fig. 9, represents the landslide susceptibility of Madi watershed.

Table 3: Classes of Landslide Susceptibility

S.N.	Susceptibility Classes	Area (sq.km)	Landslide %
1	Low Susceptibility	0.037	0.003
2	Moderate Susceptibility	288.645	25.703
3	High Susceptibility	795.617	70.847
4	Very High Susceptibility	38.701	3.447
	Total	1123	100

The classes range from "Low Susceptibility" to "Very High Susceptibility". The largest region of watershed comes under 'High Susceptibility' class with 795.617 square kilometers coverage, which accounts for 70.847% of the total area. From the distribution, it indicates that almost three-quarters of the watershed area represents the high susceptibility to landslides. Followed by "Moderate Susceptibility" class that comprises 288.645 square kilometers (25.703% of total area), depicting a substantial portion of watershed moderately risk of experiencing landslides. At the same time, "Very High Susceptibility" category covers 38.701 square kilometers, accounts for 3.447% of overall area of the watershed, indicating areas with a decreased landslide risk when compared to first two categories, but higher risk of landslide among all susceptibility class. On the other hand, "Low Susceptibility" class are relatively smaller in coverage as shown in the map (Fig. 11) below, occupying just 0.037 square kilometers (0.003%). The Fig. 11 highlight that a minimal portion of the region falls under extreme prone in susceptibility spectrum. Distribution of this risk reveals that the majority of the region is with moderate to high risks while there is very little area with either very low or very high risk of landslides.

While very highly susceptibility zones comprise a smaller percentage, they require intensive approaches to eliminate tendencies towards landslides and reduce the impacts of the phenomenon. However, the low susceptibility areas are relatively static but should be kept this way to maintain their motionless nature as the potential damages they could cause can be enormous and could potentially turn into devastating zones in the future. Overall, the area's general landslide risk varies from low to high; therefore, implementation of proper planning of land use and monitoring is crucial. The susceptibility map can be an essential instrument for local officials and urban planners to pinpoint high-risk zones and determine which mitigation strategies should take precedence. Additionally, it aids in the development of land use regulations and emergency response plans aimed at minimizing the threat of landslides.

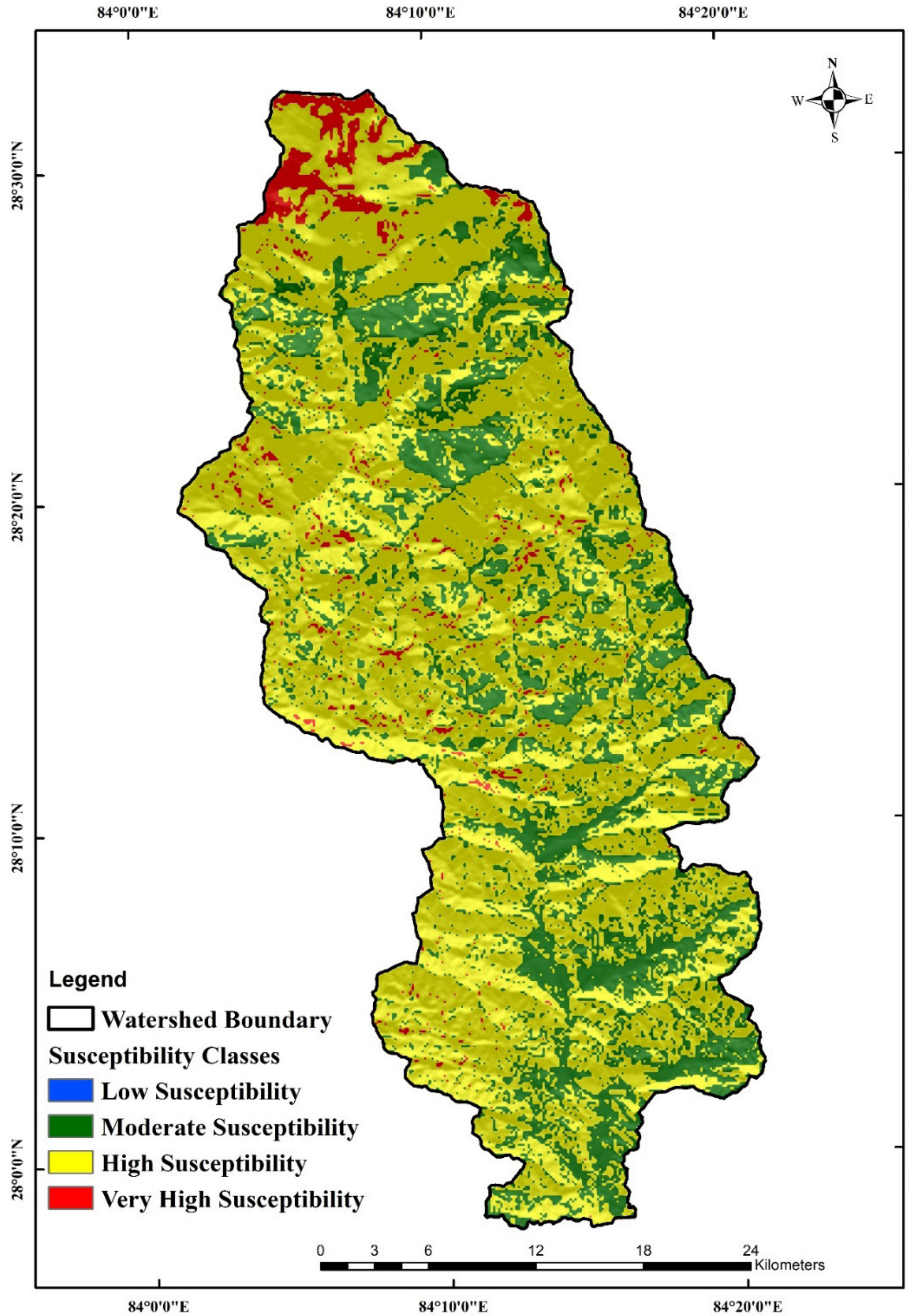

Fig. 11: Landslide susceptibility map derived from weighted overlay method

CONCLUSION

In conclusion, this study demonstrates the effectiveness of the Weighted Overlay Method in creating a map of the Madi watershed's landslide susceptibility. The analysis of landslide susceptibility in the study area indicates a significant prevalence of high-risk zones; it can be stated that most of the area belongs to high and moderate susceptible regions and combinedly make up more than 95% of the total area of the Madi watershed. That is why, it is possible to conclude that the quantity of the territory which contains a high risk of landslides constitutes important portion of the territory need to be undertaken the measures that will help in preventing the risk of landslide. Furthermore, the" Very High Susceptibility" areas are constrained to a small percentage of the total geographic area, which is approximate 3.447%, it requires intensive and strong preventive measures due to its highest sensitivity to landslide hazards. Although the "Low Susceptibility" areas has received little coverage in this paper, it also requires high concern because of their sensitivity and influence on surrounding areas. The level of detail thus enables the planners in the fields of land-use planning, development of infrastructure and planning of disaster preparedness measures.

Based on the study findings, we conclude that the landslide susceptibility map needs to be frequently revised with the existing environment as well as the climatic conditions undergoes constant change. The integration of this data provides a comprehensive assessment of landslide risk by integrating various conditioning factors, which helps with urban planning and disaster preparedness efforts, for the reason that has revealed several areas that are highly susceptible to landslides, which could have disastrous repercussions for those residing there. The areas of high and moderate landslide risk mainly consist of hilly terrain, where steep slopes and gravity can cause landslides. Mapping landslide susceptibility in mountainous regions is usually difficult due to poor access, dense vegetation, and cloudy weather conditions. Based on the obtained results, it is evident that slope, higher elevated region, precipitation and non-vegetative zone greatly influence landslide occurrence. Mostly, regions with high precipitation, slope instability and non-vegetative region, especially in the northern region land having exposure to sun are in the vulnerable zone. Close proximity to rivers in these zones could lead to landslides that might block rivers and create debris dams, which could burst and produce floods affecting anthropogenic activities. More importantly, the zones that are identified as high landslide susceptibility doesn't mean that landslide will occur any soon, it is indication of more favorable to landslides. Furthermore, in mitigating risk of landslides, it becomes necessary to have modern forms of monitoring and warning system in zones that are moderately to highly vulnerable. Moreover, the land-use policies should encourage the proper use of the land and restrict approval of risky activities. Landslide awareness, sustainable construction, and civil engineering procedures including help using retaining walls and effective drainage techniques need to be taught to the people of the community. Additionally, new research aimed at refining existing susceptibility maps, coordinated actions of scientific institutions and governmental bodies, and cooperation with the inhabitants will improve the efficiency of disaster management and actions.

As this study is based on secondary data and it hasn't been verified with the historical landslide inventory so, there need to be conducting additional investigations for more accuracy. There are also need of exploring different approaches to weighting the various variables used in the analysis. While the Weighted Overlay Method is useful, other techniques such as the Analytical Hierarchy Process (AHP) might be more appropriate depending on the data or terrain characteristics. Future projects can enhance the precision and reliability of their findings by considering alternative approaches.

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