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Landslide Susceptibility Assessment in Nuwakot: An Examination of Methods to Mapping

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Abstract

The highest re-occurring hazard incident in Nepal in 2022 is reported to be fire and landslides. A comprehensive study on understanding and identifying landslide susceptible areas and planning accordingly is perhaps one approach to disaster preparedness. In this context, landslide susceptibility assessment (LSA), plays a key role as a preparedness and mitigation tool at the local level. Landslide susceptibility, theoretically, denotes a geographic location of potential reoccurrence of landslide in an area based on several causative factors. I have conducted this study to explore landslide occurrence in Nepal based on secondary data, and map landslide susceptibility in Nuwakot district by using spatial multi-criteria analysis, SMCA and frequency ratio (FR) method. Then, I have evaluated the results which will support preliminary landslide risk level identification at the local level. Existing secondary data and landslide inventory extracted using satellite imageries were major data sources. Landslides in Nuwakot are concentrated within the range of 1000-1500-meter elevation of 15-25-degree convex slope with gneisses/schists formation. A result using SCMA methodology shows 47% area of Nuwakot under landslide susceptibility, of which 13.6% is highly susceptible whereas FR method resulted 27% area under high susceptible zone. The variation in susceptibility level and area between SCMA and FR methods can be attributed to differential calculated weight factor to geological factors, such as fault, lineament, and lithology. This study concludes that irrespective of methods adopted, landslide susceptibility maps and output data provide useful tools for landslide hazard risk identification and management. The necessity of robust and commonly applicable guidelines at different geographic scales is also obvious.

Keywords: Disaster risk preparedness, frequency ratio, geospatial tools, landslide susceptibility, spatial multi-criteria analysis, triggering factors

Introduction

Landslides are regular geomorphic phenomena and important processes, which alter the earth's landscape. Theoretically, it is gravity acting on a portion of a slope in unstable conditions resulting mass movement causing landslide incident. Landslide occurrence, with

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potentially damaging effect, is referred to as landslide hazard which turns into disaster by causing loss and damage to humans and built environment (UNDRR, 2023). Though hill and mountain areas are characteristic landslide regions, various causative and triggering factors are attributed to landslide occurrence. High-intensity rainfall, continuous heavy rainfall, and geologic instabilities like earthquakes are major causative factors and more recently, landslides in settlement area are attributed to anthropogenic causes like land use mismanagement and haphazard infrastructure construction like roads and buildings (Alexander, 1992; Petley et. al., 2007; Pal et. al., 2016). They have highlighted the human interventions, such as deforestation, demographic change, land use change, and road construction in fragile natural symmetries as important causative factors.

Nepal with its diverse mountainous topography and fragile geology, high altitudinal range, and climate variability within a short distance is exposed to multiple hazards (GoN, 2022). Nepal is ranked as highly vulnerable (score 27.54) and susceptible (score 27.17) to landslides (CFE-DM, 2023). It has high exposure of culturally diverse populations and persistent socio-economic disparities but very low adaptive capacity (score 56.89) to disaster. The highest re-occurring hazard incident in Nepal in 2022 is reported to be a fire (13811 incidents) and landslides (2058 incidents) (GoN, 2022). High-intensity precipitation and earthquake are two main triggering factors in Nepal and rainfall-induced landslides is most prevalent in the hills and mountainous districts (GoN, MoHA, 2019). According to disaster report of 2019, landslide was the major disaster (a total of 483 incidents) during monsoon of 2017-18, which killed 161 persons, affected 1083 families and destroyed 328 houses.

The cost of disaster and benefits of disaster risk reduction are long discussed topics in both academia and policy planning (Merani, 199 1; Upreti & Dhital, 1996; GoN, 2019, Amatya, 2020, UNDRR, 2023;). Increasing landslide incidents in recent years is one of the major challenges to development planning in Nepal as it slowdowns the development process by damaging critical infrastructures and causing human casualties in one hand, and costing more investment for restoring, which otherwise could be used for new development projects (GoN, 2022). Disaster risk reduction, (DRR) through preparedness is hence, regarded as a priority at all levels, by understanding the potential hazard areas and mitigating for risk reduction. The government of Nepal has emphasized the establishment and institutionalization of a GIS-based disaster information management system and actionable risk information as well as an effective dissemination mechanism (GoN, 2018). A comprehensive understanding of disaster risk through a common national framework for risk assessment is hence prioritized. A comprehensive study on understanding and identifying landslide susceptible areas and planning accordingly, is perhaps one approach to disaster preparedness to vulnerability threats, which could support decision-makers in DRR planning and mitigating the potential landslide hazard risk.

Landslide susceptibility assessment (LSA), plays a key role as a preparedness and mitigation tool at the local level. LSA maps, a visual easy to understand tool, illustrate the spatial distribution of potential landslide occurrence areas and associated risk. Landslide susceptibility refers to potential landslide incident areas based on locational characteristics (USGS, 2008). With the advancement in geospatial technology and increasingly open access to data, LSA research is flourishing, and different approaches, methods and techniques have been adopted (Bishop et. al., 2011; van Westen et. al., 2013; Lee, 2019; Malik, & Kumar, 2022; Chowdhury, 2023). However, each method and techniques have its advantages and limitations and very few studies, to date have been carried out to compare different methods and their validity in Nepal (Ghimire & Timalsina, 2020). Similarly, a combination of different topographic climatic and geologic characteristics, play a significant role in triggering and conditioning landslide occurrence (Dai, et. al., 2002;) In this context, the present study is carried out to explore landslide occurrence in Nepal based on secondary data, map landslide susceptibility in Nuwakot district of central Middle Mountain region by using two different LSA methods (semi-quantitative and quantitative) and evaluate the results which will support for preliminary landslide risk level identification at the local level. Furthermore, the resulting susceptibility area map was verified based on previous studies (Joshi et.al, 2017) and the landslide database from the DRR portal of MoHA.

Conceptual Frame and Past Studies

Landslide susceptibility, theoretically, denotes a geographic location of potential reoccurrence of landslide in an area based on a number of causative factors (NDMA, 2019). The susceptible areas are determined by associating primary factors that contribute to the sliding process (USGS, 2008). These primary factors include natural triggering factors like excessive and heavy rainfall than normal, geological fluxes, and mechanism like earthquakes and volcanoes, fault lines and lineaments. Human activities like haphazard construction, mining, and excavation, and grading of the slope also trigger landslides. Conditioning factors like slope steepness and curvature, terrain morphology, geology and rock structure, soil types, and texture as well as underlying hydrology (Joshi et. al., 2017; NDMA, 2019). A combination of both triggering and conditioning factors results in different types of landslides.

An abundant knowledge base exists on landslide hazard and risk mapping. Landslide hazard assessment (LSA) is one of the widely embraced research themes due to the advancement in geospatial data, methods, and tools since the early 90s (Dai, 2002; Van Westen, et. al., 2008; Lee, 2019). It is commonly denoted using different terms like landslide mapping, landslide hazard zonation, and landslide susceptibility mapping to note a few. Landslide susceptibility assessments are based on different methods mostly quantitative statistical/deterministic to probabilistic/predictive approaches ranging from ground-based engineering geological, geomorphological, to computer-based geophysical methods (USGS, 2008; Lee, 2019; Kumar et. al., 2023). There are also semi-quantitative and qualitative most common among those are heuristic and expert knowledge-based approaches (Prakash, 2012, Ghimire & Timalsina, 2020). One of the notable early quantitative susceptibility assessments is factor analysis with the weighted hazard zonation method published by the Department of Regional Development and Environment, USA in 1991 (Highland, 2008) and a case study in Indian mountains by Pachauri & Pant (1992). Similarly, a notable early study using qualitative and semi-quantitative methods is of the Bureau of Indian Standards, BIS (1998). BIS method is based on ranking of six causative factors of slope instability which comprises: lithology, structure, slope morphometry, relative-relief, land cover and land use and hydrological condition.

In Nepal, GIS-based landslide hazard assessment has been one of the most widely studies research domains since 1990s, before which very few studies existed mostly based on field investigation and aerial photo interpretation (Ives & Messerli, 1981; Khanal, 1996; Dhakal et. al., 2000; Dhital, 2000; Tianchi & Gurung, 2001). These studies discuss data and technology applied for landslide susceptibility (Chaudhary et. al., 2017; Dahal, 2017), other discuss several triggering and conditional factors, spatial and temporal variation, and causes and consequences of landslide hazards Paudel et. al., 2003; Aryal, 2012; Shrestha, et. al., 2016; Joshi, et. al., 2017; Acharya & Lee, 2019; Lamichhane & Bhattarai, 2019; KC, et al., 2020) while many other discuss the comparative analysis of methods, tools, and techniques (Regmi, et. al., 2010; Regmi. et al., 2014; Ghimire, & Timalsina,2020) using semi-quantitative and quantitative approaches and few studies tested methodology to examine calculated susceptibility and ground reality (Dangi et. al., 2019).The later study, focused on earthquake-induced landslides to test the landslide hazard assessment methodology. The slope aspect, slope angle, distance from geological thrust and earthquake epicenter were taken as causative and triggering factors and output hazard maps were verified in the field.

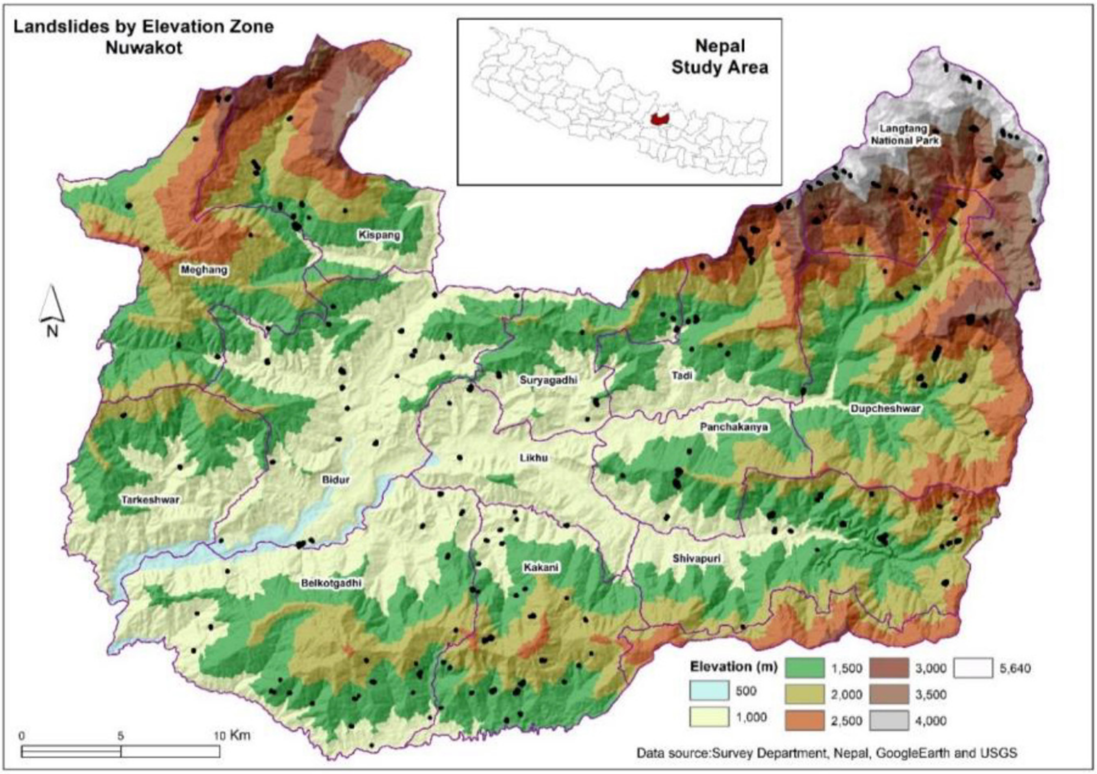

Fig. 1: Study area map
(Source: GIS map prepared by researcher (data source: USGS, GoogleEarth, 2024, and Survey Department, Nepal)

3.2 General Approach, Data, and Method

There are various approaches and methods to landslide susceptibility mapping and assessment. Most widely used are landslide inventory mapping, bi-variate, and multivariate index-based landslide susceptibility mapping. The basis of the assessment method ranges from existing secondary sources and desk study to advanced statistical modeling based on fuzzy logic, machine learning, and artificial intelligence, and AI has been practiced widely in recent years (Shano, 2020).

Two different methods for landslide susceptibility mapping were carried out in this study. The first method is a landslide inventory and process-based semi-quantitative mapping approach with the assumption of continuous landslide density in space. The second method adopted is bivariate index-based landslide susceptibility mapping using frequency ratio. The assumption of this method is that a probability of landslide occurrence is higher where frequency ratio of past landslide is high as opposed to non-occurrence for a given factor in a specific area (Abinet, 2023). Application of this method demonstrated that the success rate is slightly higher (76%) than the prediction rate (75%) and it is a simple, reliable and effective model for landslide susceptibility mapping.

Landslide inventory was prepared for this study using historical landslide occurrence and damages caused by MoHA, DRR portal (*http://www.drrportal.gov.np/*). The record of 110 landslides captured the period from 1978 (the first reported event) to September 2023. Landslide polygons data was extracted from Sentinel-2 imagery of 2017 and GoogleEarth platform 2023, OSM, and USGS. DRR portal data was verified with landslide polygons and a total of 202 matching landslide polygons were finalized for spatial characteristics analysis.

Baseline spatial data and sources included 30x30 meter SRTM digital elevation model, DEM and Landsat 8 image for land cover and normalized difference vegetation index, NDVI from USGS. Slope, aspect, curvature, and relative relief were derived using SRTM DEM. Similarly, river network from digital topographical sheets of the Survey Department, DoS (1997), Soil data from SOTER, 2009 database, geological features: fault and lineament, lithology and rock type from the Department of Mines and Geology, DoMG (2009), and rainfall data 2009-2020 from Department of Hydrology and Meteorology, DHM. Fault lines and lineaments and earthquake epicenters available from USGS is used as a proxy to earthquake data as no detailed data on earthquake Peak ground acceleration is available. Due to the unavailability of earthquake factor data, integrated susceptibility mapping was carried out by combining both earthquake-triggered and precipitation triggered as opposed to the methodology adopted by GoN, 2010.

It is a summative weighted spatial multi-criteria analysis, SCMA (*Equation i*) which is modified after Nepal hazard assessment methodology (GoN, 2010 modified after NGI, 2004 & Nadim et. al., 2006) where weights for triggering and conditioning factors were assigned as specified in landslide hazard zonation mapping in mountainous terrain guideline of Bureau of Indian standards, BIS, 1998. The analysis was carried out by combining triggering factors (precipitation and earthquake) and susceptibility factors (Topography, geology, and soil and land cover/use) slope, lithology, and soil moisture).

Landslide Susceptibility Ranking (LSR):

$$\mathbf{LSR} = \Sigma\,(Pc_{rn} + Eq_{rn}) + (Ge_{rn} + Dd_{rn} + Lu_{rn} + Slp_{rn} + So_{rn} + RR_{m} + SA_{m\ldots\ldots}) \qquad \text{(i)}$$

Where, rn = Rank,

Factors: *Pc*= Precipitation, Eq = Fault and Lineaments, Ge = Lithology/Geology, Dd = Drainage density, Lu = Land use/Land cover, *Slp*=Slope, So = Soil texture *RR*=Relative Relief, SA=Slope Aspect

Individual class of each layer was assigned 0 to 1 class weight value based on the AHP method and for all eleven layers accordingly (Table 1). Based on landslide inventory, geology, topography and geomorphology, soil and land cover/ land use, and using equation i, weighted values are calculated and summed. Ranks 1 to 3 were assigned for each susceptibility factor and high to low susceptibility ranks were summed and the final rank grouped as High, Moderate and Low through Jenk's natural break method.so the higher the rank (i.e. value 1) higher the landslide susceptibility (High) and vice-versa.

The second method was landslide susceptibility index calculation based on the frequency ratio(FR) method (Nohani et al., 2019), as well as with a modification as cross-overlay of landslide area over each factor class is used for factor density weight calculation. The landslide susceptibility map (LSIM) was computed from the FR values of parameters classes with influencing landslides as predicted ratio (PR) weight together (*Equation ii*). The factor ratio in terms of weight computed for the landslide causative factor is shown in Table 2.

$$LST = \sum_{j=1}^{n}(W_j \; x \; F_i) \quad \text{(ii)}$$

where, W.j = weight of causative factor based on ratio, Fi = the causative factor map product from FR value of I classes of causative factors j, and n = the number of causative factors.

Table 1: Calculated weight factor for susceptibility mapping

S.N.	SCMA		LSI (FR)	
	Factor	Factor	Factor	Weight (PR)*
1	Aspect	0.6	Aspect	0.14
2	Relative relief	0.7	Curvature	0.06
3	Distance to Fault	0.6	Distance to Fault line	0.08
4	Distance to Stream	0.4	Distance to Stream	0.09
5	Landuse	0.7	Land Use	0.12
6	Lithology	1.5	Lithology	0.08
7	Slope	1.9	Slope	0.1
8	Soil erosion	0.8	Soil Erosion	0.08
9	Vegetation cover	0.5	NDVI	0.1
10	Drainage Density	0.4	Distance to Road	0.08
11	Precipitation	2.3	Elevation	0.1

Source: Calculated using AHP and GIS
Note: * Detail is presented in Annex 1: Calculated frequency ratio

The FR technique was used to establish the relationships between the distribution of landslide occurrence locations and each causative factor by establishing a correlation between these factors. The weight for each causative factor of the landslide is firstly determined, then landslide susceptibility indexes map has generated by a weighted summation of causative factors in the GIS environment. The weight of each causative factor is defined as the natural logarithm of the landslide density in the class over the landslide density in the factor map as follows (Van Westen et al., 1997; Dou et al., 2015).

$$Wi = \ln\left(\frac{density\ class}{density\ map}\right) = \ln\left(\frac{N_{pix}(S_i)/N_{pix}(N_i)}{\sum N_{pix}(S_i)/\sum N_{pix}(N_i)}\right) \qquad \text{(iii)}$$

where Wi = the weight given to a certain causative class of factor parameter. Density class is the landslide density within the parameter class, Density Map is the landslide density of the entire factor map for all classes, Npix(Si) = the number of landslide pixels in a certain class, and Npix(Ni) = the total number of pixels in all classes.

The entropy index has been used to estimate the difference between the average shares of a single causative factor with proportion from the total causative factors used in the whole system. The predicted ratio (PR) of each causative factor parameter has been computed based on the information coefficient of the parameter with the parameter value to total value ratio (Bednarik et al., 2010).

$$PRj = \frac{FR}{\sum_{j=1}^{n} FR} \qquad \text{(iv)}$$

4. Results

4.1 Landslide Inventory

Landslide inventory mapping is a simplest yet effective tool in landslide susceptibility assessment. A total of 110 landslide incidents were recorded in Nuwakot district since 1978 to September 2023. Spatial and temporal variation in past landslide incidents is visible in Table 2. The least number of landslide incidents (only five) was recorded between the 10-year period of 1987-1997 followed by the 1078-1988 period. The increasing number of landslide incidents was noted since 1998 and the highest number of incidents (45) between the six years of 2018-2023 can be attributed to the 2015 Gorkha earthquake. Regarding spatial distribution, the highest number was reported in Kakani rural municipality followed by Belkotgadhi and Bidur municipalities, which are the most populated local units of the district. Tarakeshwor rural municipality which is located in the south-western part has the lowest number of reported landslide incidents (Only one). The economic loss caused by this landslide was estimated to be twenty-one million and five-hundred and forty-eight thousand Nepalese rupees (NRS. 21,548,500) and human fatalities of sixty-two persons destroying 752 houses.

Table 2: Recorded landslides and losses 1978-2023

SN	Period	Reported Landslide	Reported Losses	Total	Local units	Reported Landslide
1	1978-1987	5	Fatalities	62	Belkotgadhi	24
2	1988-1997	4	Missing People	6	Bidur	18
3	1998-2007	21	Injured	24	Dupcheshwor	4
4	2008-2017	35	Affected Family	752	Kakani	27
5	2018-2023	45	Govt. House Partially Damaged	1	Kispang	2
6	**Total**	**110**	Private House Fully Damaged	151	Likhu	3

7			Private House Partially Damaged	35	Myagang	2
8			Cattles Loss	72	Panchakanya	4
9			Displaced Shed	12	Shivapuri	11
10					Suryagadhi	6
					Tadi	8
					Tarakeshwor	1
					Total	110

Source: *http://www.drrportal.gov.np,* MoHA, 2023.

4.2 Spatial Characteristics of Landslide Distribution

The spatial distribution of the landslide demonstrates many clusters and three major clusters are apparent, namely, northeastern, central south, and northwestern (refer to Fig. 1). Proximity analysis carried out in GIS found that are eight settlements within a 50-meter distance of landslide, and are relatively vulnerable to landslide disaster, 151 settlements are within a 500-meter distance of landslide. Spatial distribution characteristics, as depicted in Figure 2. It shows that most of the landslides are attributed to 15 to 25-degree slopes indicating location near a densely populated area whereas fewer (less than 10%) are to be higher than 45 degrees (Fig 2a). Likewise, most of the landslide occurred at the convex slope followed bb linear slope. Few were found at the concave slopes (Fig. 2b). Distribution regarding elevation range demonstrates higher frequencies in 1000 to 1500-meter elevation followed by 500 to 1000meters (Fig. 2c). Lithologically, distribution is dominant in schists/gneisses rock formation (Fig 2d). Similarly, more than 50% of landslides were found along fault and lineament areas.

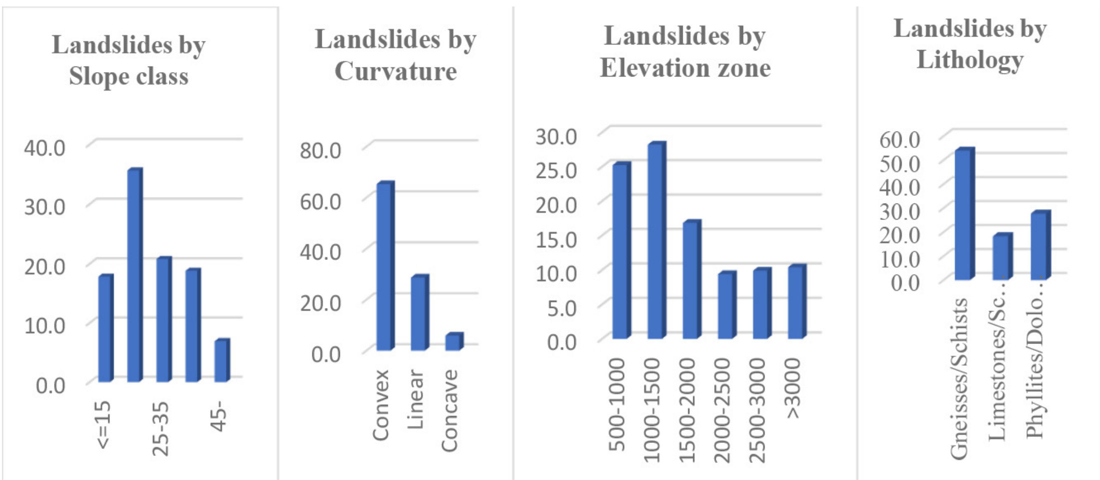

Fig. 2: Spatial characteristics of landslides
Source: Calculated using GIS

4.3 Landslide Susceptibility

SMCA method: Calculated landslide susceptibility map based on semi-quantitative SCMA methodology show that 47% area of Nuwakot is susceptible to landslide, of which 152.4 km2 (13.6%) is highly susceptible, 216.8 Km2 (19.6%) is moderately susceptible and 154.5 km2 (13%) lies in low susceptibility zone (Fig.3). However, more than 50% area is not susceptible to landslide hazard those are mostly lowland and river floodplains and may be potential to another type of hazard i.e. flood and soil erosion.

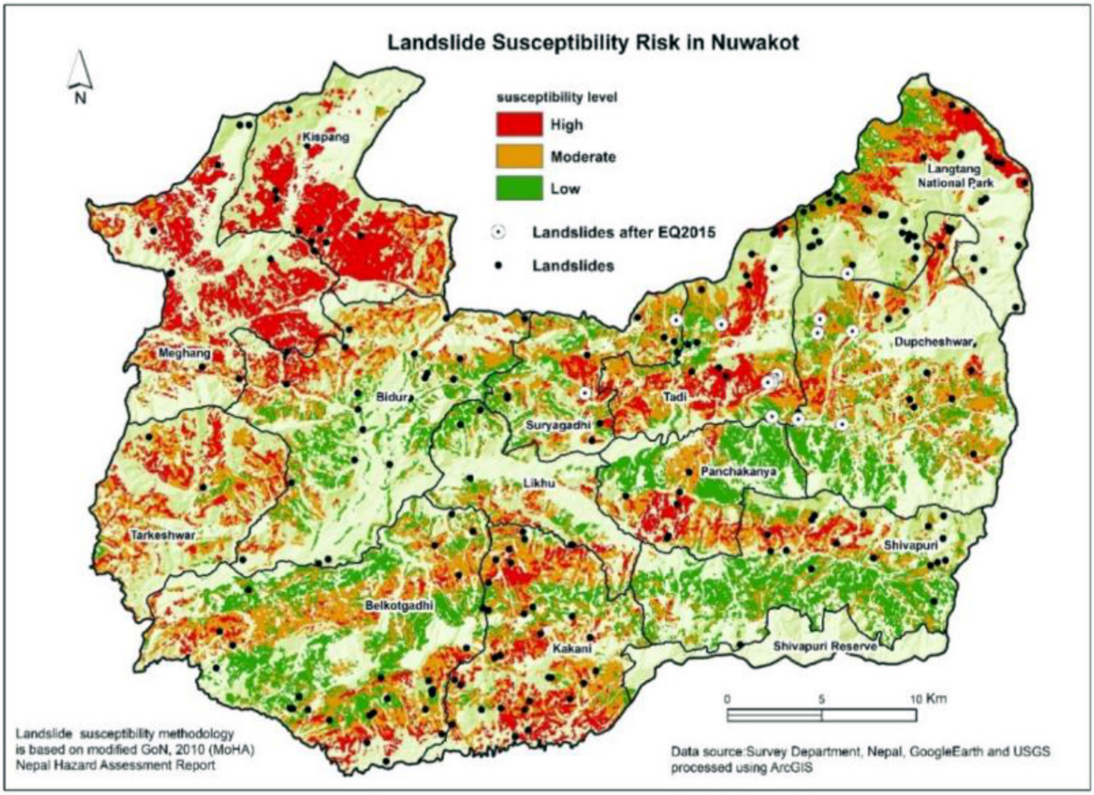

Fig. 3: Spatial distribution of landslide susceptible area map (calculated using SMCA) (Source: GIS map prepared by researcher (data source: USGS, GoogleEarth, 2024, and Survey Department, Nepal)

Spatial variation in landslide susceptibility is visible at the local municipal level. The highly susceptible area is concentrated in two rural municipalities namely Kispang and Meghang both located in the northwestern part of the district. Kakani, Tadi, and Tarakeshwor rural municipalities also comprise relatively large high susceptible area coverage whereas Shivapuri, Likhu, and Dupcheshwor are relatively low in landslide susceptibility and it is largely due to higher lowland coverage in these municipalities (Fig. 4).

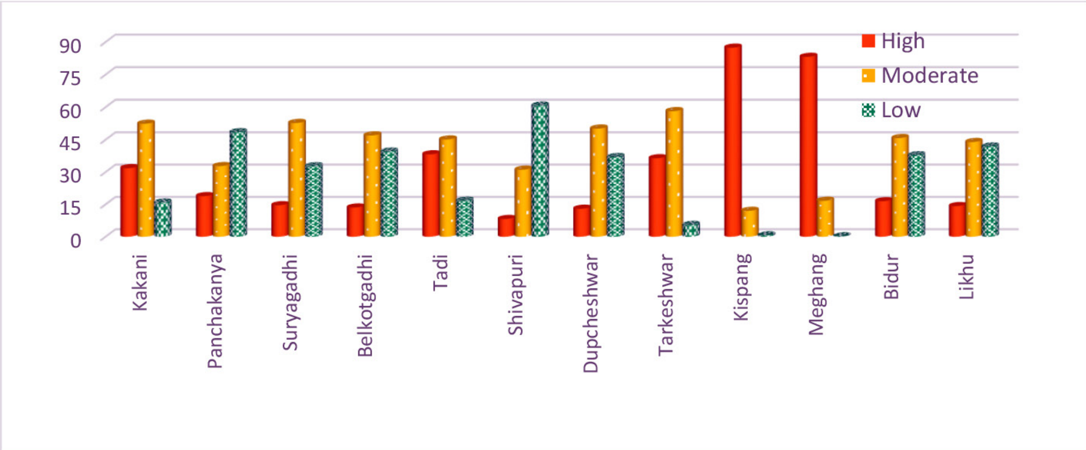

Fig. 4: Spatial distribution of landslide susceptible area at the municipal level (SMCA method)

FR method: Calculated landslide susceptibility map based on FR methodology shows that 27% area (317 Km^2) of Nuwakot is highly susceptible to landslide, 63.1 % is moderately susceptible and 9.3 % lies in the low susceptibility zone (Fig.5). However, less than around 10 % area is not susceptible to landslide hazard those are mostly lowland and river floodplains and may be potential to another type of hazard i.e. flood and soil erosion.

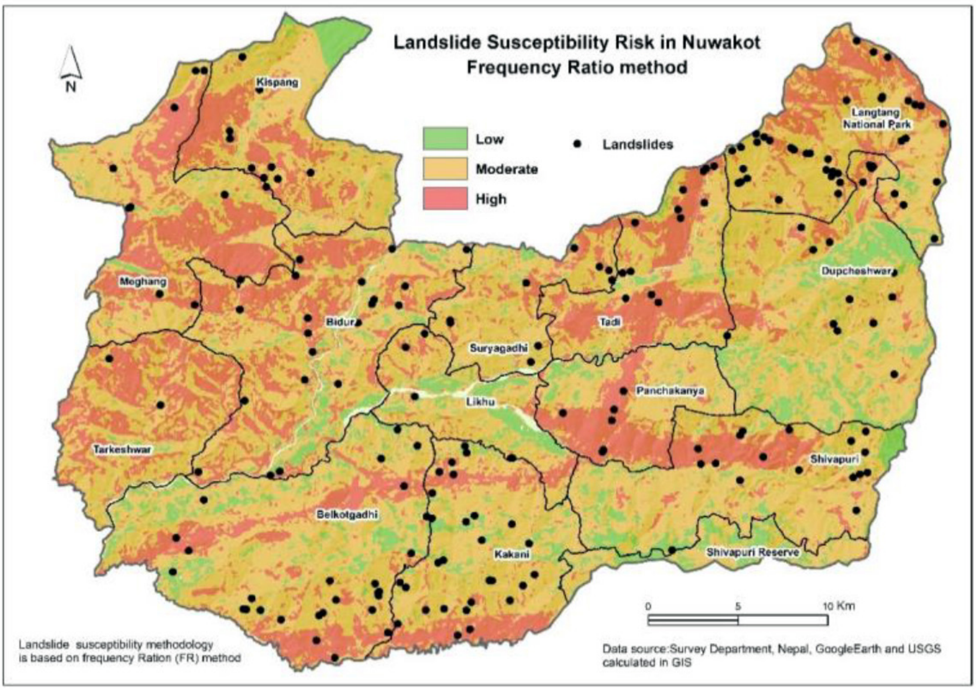

Fig. 5: Spatial distribution of landslide susceptible area map (calculated using FR method) (Source: GIS map prepared by researcher (data source: USGS, Google Earth, 2024, and Survey Department, Nepal)

Likewise, as spatial variation in landslide susceptibility found using the SMCA method, the FR method also exhibits similar variation (Fig. 6). The highly susceptible area concentration is found in four rural municipalities namely Meghang, Tadi, and Tarakeshwor followed by Panchakanya and Kispang. both located in the northwestern part of the district. Kakani, Tadi, and Tarakeshwor rural municipalities also comprise relatively large high susceptible area coverage whereas Shivapuri, Likhu, and Dupcheshwor are relatively low in landslide susceptibility and it is largely due to higher lowland coverage in these municipalities.

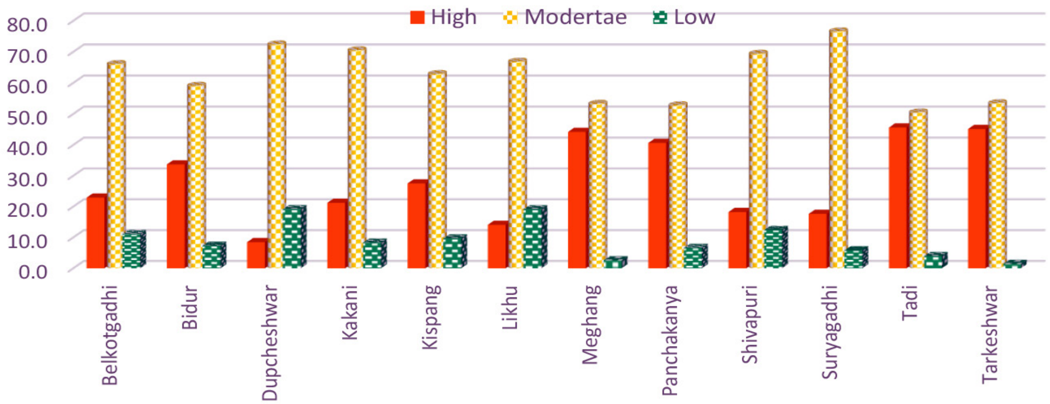

Fig. 6: Spatial distribution of landslide susceptible area at the municipal level (FR method)
(Source: Calculated using GIS by researcher)

The susceptibility mapping carried out using two different methods discloses slight variations in the spatial distribution of susceptibility levels at district and municipal levels. This variation is largely due to the differential weight assignment factor of the method being used in case of geological factors like fault, lineament, and lithology by system as well as differences in causative and conditioning factors adopted for example in SCMA method, NDVI and distance to road is not included whereas in FR method, drainage density and precipitation is excluded.

Discussion

Spatial and temporal variation in landslide occurrence was found in the study district. A study carried out in Nepal, using the 2011-2020 landslide database, accords with the current study which also found variations of landslide distribution in space and time, together with the increased number of landslides in recent years (Chaudhary et. al., 2017; KC et. al., 2020). The landslide density increased from 0.85 events/1000 Km^2 (2011) to 3.34 events/1000 Km$^{2.}$ This scenario can be indicative of how earthquakes as primary triggering factor causing natural shifting of landslide occurrence. It is creating uncertainty which urges for better assessment and regular monitoring for potential disaster risk management. Studies also show that there is significant spatial variation in disaster history in Nepal and localized small-scale disasters collectively have a greater impact on society in terms of casualties than national large-scale disasters (Nadim et. al., 2006; Aryal, 2012; Chaudhary et. al., 2017). However, a study showed that heavy rainfall of 300mm rainfall in a day, triggered a landslide of 9 Km2, at the head valley with a 39-degree slope in 2002 in Kathmandu Valley (Paudel et. al., 2003).

Distribution characteristics of landslides in Nuwakot show that concentration is on 1000-1500-meter range elevation of 15-25-degree convex slope with gneisses/schists formation. This finding varies with the spatial distribution characteristics demonstrated by previous studies in Nuwakot in terms (Joshi et. al., 2017). The previous study shows a high concentration of landslides in a 25-30-degree slope (43%) with a dominant concave face (51%) which is slightly different from the current finding of 21% in 25-35 degrees and in contrast to only six percent in concave face. The different findings may be attributed to a number of landslides being studied –202 in this study and 542 in the previous one. Another study carried out in the Nuwakot district revealed that m of the landslides is concentrated in a convex slope greater than 35 degrees (Dangi et. al, 2019).

The variation is found among several landslide incidents between the reported case of the DRR database of GoN, 2023) and spatial landslide inventory. The highest number of reported cases in DRR database was in Kakani (27) whereas spatial inventory show Langtang National Park has the highest number (39). This variation shows the neighborhood relation of hazard incidents with nearby settlements. The landslides in the national park are relatively farther to settlement and hence may not have been reported. However, the landslide incidence in the upstream area may have a major downstream effect (Amatya, 2020). This shows the importance of spatial inventory of landslides which is an effective tool for landslide-related disaster management.

Landslide susceptibility mapping of the current study identified high susceptible area concentrated near and along fault lines and lineament suggesting earthquakes as primary triggering factor and study carried out by the Government of Nepal and ADPC (2010) also indicated that 56.17% area of Nuwakot is highly susceptible to earthquake related risk whereas rainfall related susceptibility risk covers only 3.48% area. Another study has also similar findings showing an increased number of landslides from 38 covering an 11.8-hectare area pre-earthquake to 66 covering a 124.2-hectare area after the earthquake of 2015 (Shrestha et. al., 2016). Similarly, coinciding with the current study, it also found that north eastern area has a high potential risk of landslide occurrence which may cause 30 household causalities with an estimated economic loss of USD 556,175.

The difference in area coverage of landslide susceptibility is notable in previous studies using qualitative,23 % high-hazard area, vis-à-vis quantitative methods, and 10% high-hazard area (Regmi e. al., 2010). However, another study shows similar area coverage for different levels of susceptibility but higher performance of the FR method over the statistical index and weight of evidence method. A study carried out by Joshi et. al. (2017) also revealed slightly different results from the current study due to variations in a number of indicators, variables classification, and weightage factor.

The landslide inventory and potential hazard mapping and zonation is an aid to local disaster risk management, where technical institutional capacity is deficient or absent and financial resources are limited (Amatya, 2020). Landslide management practices in other countries also include various measures such as land-use planning and construction and development control regulations (Prakash, 2012). The most important role of local authorities in mitigating landslide hazard risk is outlined through a systematic institutional mechanism. Such mechanism incorporates short-term and long-term planning using landslide hazard, vulnerability and risk assessment approaches. In Nepalese context, landuse zoning and risk sensitive landuse planning are two major policy instruments formulated by the Nepal Government, to provide regulations for efficient management and balanced development of an area by preserving land characteristics and minimizing disaster risk (GoN, 2015; GoN, 2018). Disaster Risk Reduction National Strategic Plan of Action, 2018-2030, Nepal has also identified 'understanding the risk through hazard-specific risk assessment' as the foremost priority area (GoN, 2018) for mainstreaming disaster risk reduction from national, regional and local level.

Earlier studies on landslide hazard assessment pointed out data availability as the major limitation and suggested proxy data variables (Kincey et. al., 2024). A study adopted population density and population census grid data as a proxy weight factors, which necessarily do not always represent population (Dahal, 2017). But now, with the unrestricted availability of up-to-date high-resolution satellite data of built-up area and building footprints which are more representative, enhances reliability. Further studies need to be carried out considering different methods and their limitations, the number of characteristics parameters, data and its reliability finally spatial scale at which analysis will carried out spatial resolution of data.

Conclusion

Geo-spatial tools facilitated landslide susceptibility mapping using different methods. The Method A consideration on the selection of method and determining triggering and conditional factors for location-specific analysis is dependent on data availability and provision with the selected method. Hence, the selection of method and corresponding data should be a major factor when using tools for landslide mapping. Irrespective of methods adopted, landslide susceptibility maps and output data provide useful tools for landslide hazard risk identification and management. Landslide susceptibility mapping needs to be recognized as a creditable tool by disaster risk management and development planning authorities albeit limitations and advantages of the approach, methods, and data are clearly stated and results verified at a micro spatial scale. This necessitates robust and universally applied guidelines at different geographic scales.

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Annex1: Calculated frequency ratio

S. N.	Factor	Class	Class Pixel	Landslide Pixel	No. of Landslide	Frequency ratio (FR)	RF (Relative frequency)	Prediction ratio (PR)
1	Aspect	Flat	854	0	0	0.00	0.00	
		North	166056	21600	24	1.99	0.09	
		North East	127940	37800	42	2.34	0.11	
		East	131568	79200	88	2.65	0.12	
		South East	183622	259200	288	3.02	0.14	
		South	219065	570600	634	3.29	0.15	
		South West	180615	501300	557	3.32	0.15	
		West	156246	106200	118	2.70	0.13	
		North West	159816	26100	29	2.09	0.10	
						21.39	1.00	0.14
2	Curvature	<-0.05	610888	834300	927	3.01	0.34	
		-0.05-0.05	119757	99000	110	2.79	0.32	
		>0.05	595136	668700	743	2.92	0.34	
3						8.72	1.00	0.06
	Distance to Fault line	<100	23265	25200	28	0.00	0.00	
		100-200	19654	50400	56	3.28	0.26	
		200-500	62594	166500	185	3.30	0.26	
		500-1000	97761	124200	138	2.98	0.24	
		>1000	1122778	1235700	1373	2.91	0.23	
						12.47	1.00	0.08
4	Distance to Stream	<100	580622	675900	751	2.94	0.21	
		100-200	315061	387900	431	2.96	0.22	
		200-500	349726	432900	481	2.96	0.22	
		500-1000	68349	104400	116	3.06	0.22	
		>1000	12003	900	1	1.75	0.13	
						13.67	1.00	0.09

5	Land Use	Waterbody	22890	25200	28	2.91	0.16	
		Agriculture	668560	639900	711	2.85	0.16	
		Forest	540609	501300	557	2.84	0.16	
		Others	47921	389700	433	3.78	0.21	
		Public Use	31538	38700	43	2.96	0.16	
		Residential	13214	7200	8	2.61	0.15	
		Cultural & Archeological	194	0	0	0.00	0.00	
		Commercial	364	0	0	0.00	0.00	
		Industrial	311	0	0	0.00	0.00	
		Mine & Minerals	165	0	0	0.00	0.00	
						17.96	1.00	0.12
6	Lithology	Quartzite	677326	1062900	1181	3.07	0.35	
		Gneisses	110042	166500	185	3.05	0.35	
		Slate	534766	372600	414	2.72	0.31	
		Schists	3632	0	0	0.00	0.00	
						8.83	1.00	0.06
7	Slope	0-5	50214	11700	13	2.24	0.16	
		5-15	198644	141300	157	2.72	0.19	
		15-30	727003	738900	821	2.88	0.20	
		30-45	317050	581400	646	3.14	0.22	
		< 45	32871	128700	143	3.46	0.24	
						14.44	1.00	0.10
8	Soil Erosion	Low	772279	866700	963	2.92	0.25	
		Medium	439321	580500	645	2.99	0.25	
		Very High	33459	90000	100	3.30	0.28	
		High	78318	36000	40	2.53	0.22	
						11.75	1.00	0.08
9	NDVI	<0	22890	25200	28	2.91	0.19	
		0-0.15	93707	435600	484	3.54	0.23	
		0.15-0.30	668560	639900	711	2.85	0.19	
		0.30-0.45	117091	175500	195	3.05	0.20	
		>0.45	423518	325800	362	2.76	0.18	
						15.11	1.00	0.10

10	Distance to Road	<200	867375	877500	975	2.88	0.24	
		200-500	243556	320400	356	2.99	0.25	
		500-1000	85667	122400	136	3.03	0.25	
		>1000	129106	281700	313	3.21	0.27	
						12.11	1.00	0.08
11	Elevation	<1000	403968	266400	296	2.69	0.17	
		1000-2000	657782	768600	854	2.94	0.19	
		2000-3000	187642	374400	416	3.17	0.21	
		3000-4000	55676	133200	148	3.25	0.21	
		4000-5000	20624	59400	66	3.33	0.22	
		>5000	90	0	0	0.00	0.00	
						15.39	1.00	0.10

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