ЗАГАЛЬНА ТА ІСТОРИЧНА ГЕОЛОГІЯ

UDC 551.435.627
DOI: http://doi.org/10.17721/1728-2713.107.01

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SUSCEPTIBILITY MODELLING OF LANDSLIDES IN CENTRAL NEPAL

(Представлено членом редакційної колегії д-ром геол. наук, ст. дослідником О.І. Меньшовим)

Background. ***Landslide processes in the Himalayas represent a major hazard threatening both humans lives and the socio-economic development of the region. The main goal of the present study is to examine the main factors influencing landslides in Central Nepal, to understand their relative importance and connections, and demonstrate the potential of the integrated technique for the assessment of landslide hazards at the regional scale.***

Methods. ***The workflow used in this study consists of the following steps: (1) collection of the data for analysis (numerical topographies, remote sensing data, geological data, inventory of landslides); (2) identification of the main causes of landslides, determination of input parameters for modelling; (3) lineament extraction by using manual and automated approaches; and (4) susceptibility mapping and spatial modelling of landslides.***

Results. ***Based on the overlay analysis of geological and geomorphological data, the susceptibility modelling of landslides in Central Nepal helps to identify the landslide-prone areas (high to low). The analysis confirms the essential role of lineaments in the landslide formation and their relation with tectonic and erosion processes. Therefore, in the regional classification of landslides in the Central Nepal it is necessary to add the landslides associated with weak zones of various nature and orientations.***

Conclusions. ***The susceptibility modeling and landslide forecasting at the regional level are the main stage of the landslide risk evaluating and management. The results concern the general impact of geological-geomorphological and landscape factors on the formation of landslide phenomena in Central Nepal. Carrying out an analysis of landslides and studying their dynamics and regime is only possible with detailed studies and identifying the priority of the influence of each factor on the landslide formation. This study also aims to provide valuable insights for disaster preparedness, risk reduction, and sustainable land use practices in the region.***

Keywords: ***Nepal, landslide hazard, susceptibility, mapping.***

Background

Landslide processes in the Himalayas represent a major hazard threatening both human lives and the socio-economic development of the region located in the central Himalaya. Nepal is particularly vulnerable to landslide hazards: all its mountainous districts are affected. Nepal contribute 10 % of all rainfall-triggered landslide events to the Earth global dataset. The analysis of different databases (Petley et al., 2007; Froude, & Petley, 2018) suggest that there is a high level of variability in the occurrence of landslides from year to year in Himalaya, but that the overall trend is upward. This increase in landslide occurrences amplifies the importance of research and measures to mitigate these natural disasters. The complexity of factors influencing landslides in this region range from geological and topographical features to climate conditions.

Landslides hazard assessment and landslide management are based on various approaches and methodology among which the regional forecasting of landslides and the determination of the main causes and their possible associations is of great importance (Roy, & Saha, 2019; Biswakarma et al., 2020). Regional forecasts imply special zoning of the territory, which characterizes the spread of landslides, the conditions for their occurrence and activation, and determines the probability of occurrence within certain territories. The susceptibility modelling of landslides helps to identify the landslide-prone areas (high to low). This enables communities to implement mitigation measures across the landslide-induced zones (Dhungana et al., 2023). In the central Himalaya, many studies have attempted to document landslide susceptibility using different approaches, most of them based on multi-criteria zoning and statistical approaches. Four distinct approaches were applied in the Indrawati watershed, a high mountain area of Central Nepal: frequency ratio, logistic regression, artificial neural network, and support vector machine. Landslide susceptibility maps are prepared on the basis of available digital data of topography, geology, land-use and hydrology (Kayastha, Dhital, & De Smedt, 2013; Gautam et al., 2021). Regmi et al. (2014) have investigated the application of the frequency ratio (FR), statistical index (SI), and weights-of-evidence (WoE) approaches for landslide susceptibility mapping within the Lesser Himalaya and Siwalik zones of Central Nepal. With a success rate of 76.8 % and predictive accuracy of 75.4 %, the FR model performs better than the WoE and SI models. In most cases the validation of landslide susceptibility maps is carried out using receiver operating characteristic (ROC) curves (Devkota et al., 2013). It is important to note that comprehensive understanding of the primary factors influencing landslides and their intricate interrelations is of paramount importance for assessing landslide susceptibility and predicting future occurrences. Investigating the relationships among the factors is essential for developing accurate models that can assess landslide susceptibility.

The main goal of the present studies is to examine the main factors influencing landslides, to understand their combinations and priority, and finally to demonstrate the potential of the integrated technique for the assessment of the landslide hazards at the regional scale within the mountain areas. This study also aims to provide valuable insights for disaster preparedness, risk reduction, and sustainable land use practices in the region.

Geological settings. The Nepal Himalayas is located in the central part of the Himalayan arc. The range is a consequence of the collision between Indian and Eurasian plates during the Cenozoic and is bounded by Indus Tsangpo Suture Zone (ITSZ) to the north and the Ganga basin to the south. The Nepal Himalayas display the highest peaks on Earth. They are characterized by steep slopes, rugged relief, and deep valleys, and one of the most tectonically active continental regions in the world (Adhikari, & Ojha, 2021).

This region is marked by a gradient of heavy rainfall increasing from south to north with intense monsoon precipitation peaking at 4 m/y along the southern flank of the High range (Putkonen, 2004). This area presents steeper slopes, active microseismic activity (Ni, & Barazangi, 1984; Pandey et al., 1995), with strong ground shaking events by major earthquakes like during the Gorkha earthquake (Mw ~7.8, 25/04/2015). This topographic, climatic and seismic setting induces some of the highest regional erosion rates in the Himalayas (Lavé &Avouac, 2001), particularly through intense monsoon-induced and co-seismic landsliding (Petley et al., 2007; Morin et al., 2018; Roback et al., 2018; Marc et al., 2019; Jones et al., 2021). The landslides affect all the geologic units of the central Himalaya. This geology is traditionally divided into four main E–W trending geological units (Colchen, Le Fort, & Pécher, 1986), including from North to South: 1 – the Tethyan Sedimentary Series (TSS: medium to low-grade detrital and carbonate metasediments of Paleozoic to Eocene age); 2 – the High Himalayan Crystalline (HHC: high-grade metamorphic gneisses and migmatites; both formations are intruded by Miocene leucogranites); 3 – the Lesser Himalayan formations (LH: metamorphosed Precambrian to Palaeozoic metasediments of the Indian craton); 4 – the Siwaliks corresponding to the Neogene foreland basin deposits of the Ganga plain, exhumed by Late Cenozoic thin skin tectonics. At the longitude of Kathmandu area, the southern prolongation of the High Himalayan Crystalline units is expressed by a klippen (the so-called Kathmandu klippen) that overrides the Lesser Himalayan units and which is made of high grade methamophosed units at its base to unmetamorphosed sediments at its top.

These geologic units are bounded by major thrusts: the Main Central Thrust (MCT) that overthrusted HHC units on top of LH units, the Main Boundary Thrust (MBT) that overthrusted LH units on top of Siwaliks sedimentary units, and the Main Frontal Thrust (MFT), that marks the most frontal topographic expression of the Himalayan wedge north of the modern Ganga plain. Most of the units present large scale folds, secondary folds as well as internal secondary faulting and fracturing mostly due to Himalayan active shortening over at least 20 Ma. Most of them are usually underlined by a geomorphic signature like break in slopes, linear valleys, or lineaments.

These tectonic features are usually associated to larger internal deformation and fracturing, which is presumed to have a direct impact on landslide susceptibility and on landscape erodibility. Structural elements as faults, folds and lithological boundaries and other structural weakness zones have therefore an imprint on erosional forms and landscape, that can be expressed in many cases by lineament features (Bhattarai, 1984).

Methods

Landslide risk assessment on a regional scale requires a special classification of the area in order to characterize landslide distribution, triggering factors and occurrence probabilities.

The workflow used in this study consists of the following steps:

1) collection of the data for analysis, – e.g. SRTM/DSM numerical topographies, Landsat images, geological data, inventory of landslides. For the Central Nepal recently compiled 30-year mass-wasting inventory (Jones et al., 2021) has been used. This database includes mass-wasting over an area of ~42,000 km^2 extending over central and eastern Nepal, between 1988 and 2018. Of the 12,920 moderate to large (>1000 m^2) landslides mapped, 10,138 were new failures and 2782 reactivations or remobilisations of previous failures (Fig. 1). The inventory does not include co-seismic or anthropogenic mass movements, but includes rainfall-induced landslides as well as reactivations/remobilisation during monsoon of co-seismic mass wasting (Jones et al., 2021);

2) identification of the main preparatory factors of landslides, determination of input parameters for modelling from existing geological and geomorphological data;

3) lineament extraction by using manual and automated approaches (ArcGIS and RockWorks17), and subsequent comparison of the results (Poliakovska et al., 2022);

4) susceptibility mapping and spatial modelling of landslides using the weighted overlay method.

To determine in step 3 the impact of the structural-tectonic factor on the formation of landslides, detailed studies of lineaments were carried out and the priority influence of tectonic factor on the reactivation/remobilization of landslide phenomena was determined. The lineament features were mapped using remote sensing and topography data. Such method is applied for different geological research (Bhattarai, 1984; Kassou et al., 2012; Thapa et al., 2023). The workflow used for the lineaments analysis is composed of four main steps (Poliakovska et al., 2022): (i) selection of the most suitable data for analysis, – e.g. SRTM/DEM/Landsat images; (ii) data processing and enhancements; (iii) lineament extraction by using the manual and automated approaches and their further comparison. (iv) comparison of the final map with available geological and tectonic data and geospatial analysis (density, direction, intersection length, and orientation analysis). For lineament analysis of the Central Nepal the LANDSAT 8 images were used. A specific geomodelling software packages were applied for the analysis: RockWorks17, ArcGIS, and Stereonet. Remote sensing and GIS techniques enable the process of analyzing and interpreting the topography data.

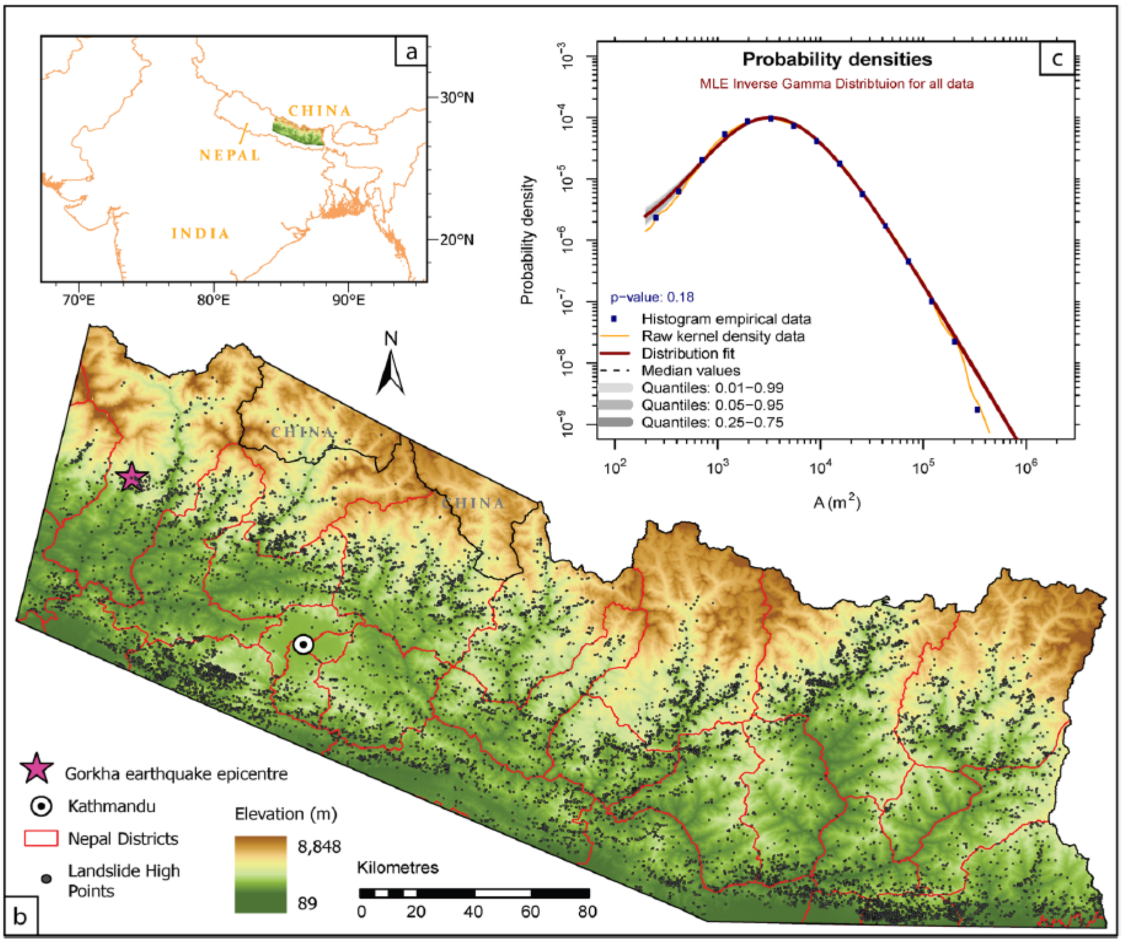

Fig. 1. (a) Regional location of the study region. (b) The location of the 12,838 mapped landslide points used within this study. Kathmandu and the 2015 Gorkha earthquake epicenter are represented by a circle and a pink star respectively. (c) The inverse-gamma distribution fitted to the probability density function of landslide area for all mapped landslides (reproduced from Jones et al., 2021)

Results

Analysis of the factors favoring the occurrence of landslides and landslide susceptibility mapping. An analysis of the factors favoring the occurrence of landslides is performed on the basis of existing geological and remote sensing data. Various data can be involved in the overlay analysis, which determine the priority factors of mass movements and their possible combinations. This method allows to take into account simultaneously the different factors to be considered in order to obtain spatial information and to implement a multi-factor model for a comprehensive landslide hazard assessment.

As a result of geological and geomorphological studies and analysis of mass movements, a complex relationship between geomorphological and geological factors in the formation of these hazardous processes has been established for the study area.

In Central Nepal topographic characteristics are one of the most important criterion and prognostic indicator for the formation of landslides. The main factors that traduce the impact of the topography are: absolute elevation of the landslides, slope and aspect of the hills (Regmi et al., 2014; Petley et al., 2007). To study the relief parameters USGS DEM model representing 3D elevation data has been used. The vast majority of landslides are confined to steep slopes, the degree of which varies from 36 to 89 (Fig. 2).

The lithology appears also to control the occurrence of the landslide phenomena. For spatial analysis of existing landslides, the large-scale geological map of the Central Nepal was used (Dhital, 2015).

Geographically, the majority of landslide processes are confined to the Himal group (two mica gneisses, granitic gneisses, banded gneisses, kyanite bearing gneisses) and Ranimatta formation (phyllites, grillstones with conglomerates and massive quartzites). A large number of landslides correspond to the rocks of the Upper Lesser Himalaya group represented by quartzites interbedded with phyllites, carbonaceous slates and green shales, calcareous quartzites and quarzitic limestones, and dark grey slates (Fig. 3). Based on the results of the overlay analysis, the location of landslides within a certain polygon of the specified vector layers was identified and a statistical calculation of the occurrence of landslides in a specific polygon was carried out by combining the attribute tables of landslides and the specified layers. A procedure was carried out to rank the territory by the number of landslides within each polygon.

To determine the impact of the structural-tectonic factor on the formation of landslides, the detailed analysis of lineaments was carried out and the priority influence of tectonic factor on the reactivation/remobilization of landslide phenomena was determined. The lineament features were mapped all over the mountainous areas including the Siwaliks (Fig. 4a). The High Himalaya and the Mahabarat range display a higher density of lineaments than the Lesser Himalaya and the Siwalik belt.

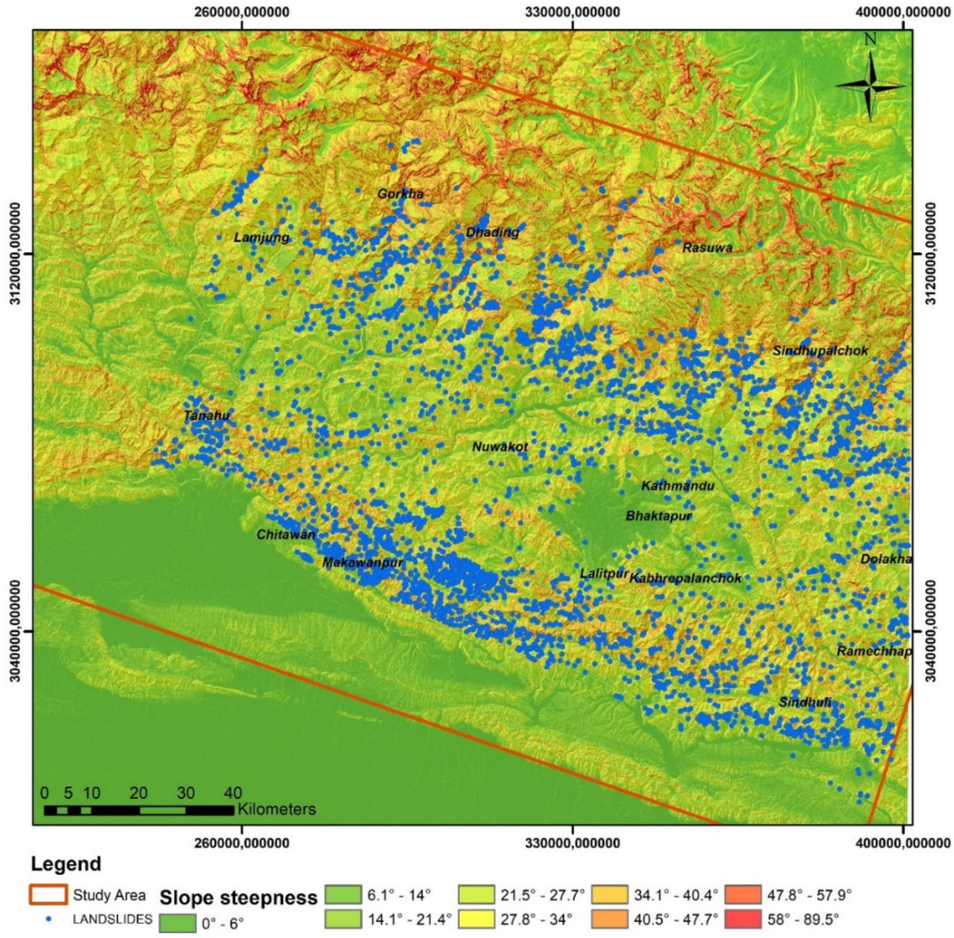

Fig. 2. Distribution of the monsoon-induced landslides (Jones et al., 2021) superimposed on the slope map of Central Nepal

The corresponding determination of the influence of lineaments of different nature on the formation of landslides is shown on the Fig. 4. A significant number of landslides are localized within a distance of 0 – 1000 m from lineaments (Fig. 4b and 5).

The spatial analysis confirms (Fig. 4) the essential role of lineaments in the landslide formation and the relation between tectonic heritage and pre-conditioning factors for landslides. Certain combinations of geological and tectonic conditions can result in a complex interplay of erosion processes and tectonic zones, which essentially affects the dynamics and morphology of landslides. Within tectonized units associated to active or formerly active faults, rheologic weaknesses favour the manifestation of landslide phenomena. The constructed map of the distances of the landslides in relation to the lineaments became the basis for creating a raster model of the study area with ranking of zones, and where the distances to the lineaments are reflected (four classes characterizing these distances were identified, respectively).

Thus, based on cartographic modeling, a comprehensive analysis of the factors for the formation of landslide processes was carried out. Each above described factor was ranked according to its degree of correlation with the density of recent landslides. The objects of each layer (factor) were classified creating a unified scale for all classes (ranking from 1 to 4) to assess their impact on the landslide hazard. In order to determine the impact of each factor on the formation of landslides, calculations of weighting coefficients (informativeness coefficients) were performed. All characterized factors are combined to create a common integrated hazard map. It should be noted that the assignment of weighting coefficients at the analysis stage required some clarifications and adjustments. This is dictated by the need for a step-by-step grouping of factors and the use of the results of expert assessment, taking into account data from analytical studies. The integrated landslide susceptibility map (Fig. 5) was created by the method of overlay analysis, which makes it possible to simultaneously take into account the considered factors, obtain a new spatial information and the corresponding implementation of a model for a comprehensive assessment of landslide hazard in the region. A landslide susceptibility map depicts areas that have the potential for landsliding. These areas are determined by correlating some of the principal factors that contribute to landsliding with the past distribution of landslides. Susceptibility measures the degree to which a terrain can be affected by future slope movements (Shahabi, & Hashim, 2015). In other words, it is an estimate of "where" landslides are likely to occur. In mathematical language, susceptibility can be defined as the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions. Susceptibility does not consider the size e.g., the length, width, depth, area or volume of the landslides, but susceptibility assessments can be prepared for different-sized landslides.

These maps indicate only the relative stability of slopes; they do not make absolute predictions.

The results concern the general impact of geological-geomorphological and landscape factors on the formation of landslide phenomena in Central Nepal. Carrying out an analysis of landslides and studying their dynamics and regime is only possible with detailed studies and identifying the priority of the influence of each factor on the landslide formation. The significance of dynamic factors can radically change their combinations and the corresponding weight of each in the process of landslide formation. It should be noted that the analysis of landslide formation factors was carried out to study the natural factors of the landslide phenomena. The impact of anthropogenic factors, which are usually unpredictable and cannot be considered as forecasting and reference criteria, introduces a variable component into the overall analysis process, the consideration of which in each specific case requires additional research and a corresponding change in the complex landslide hazard model.

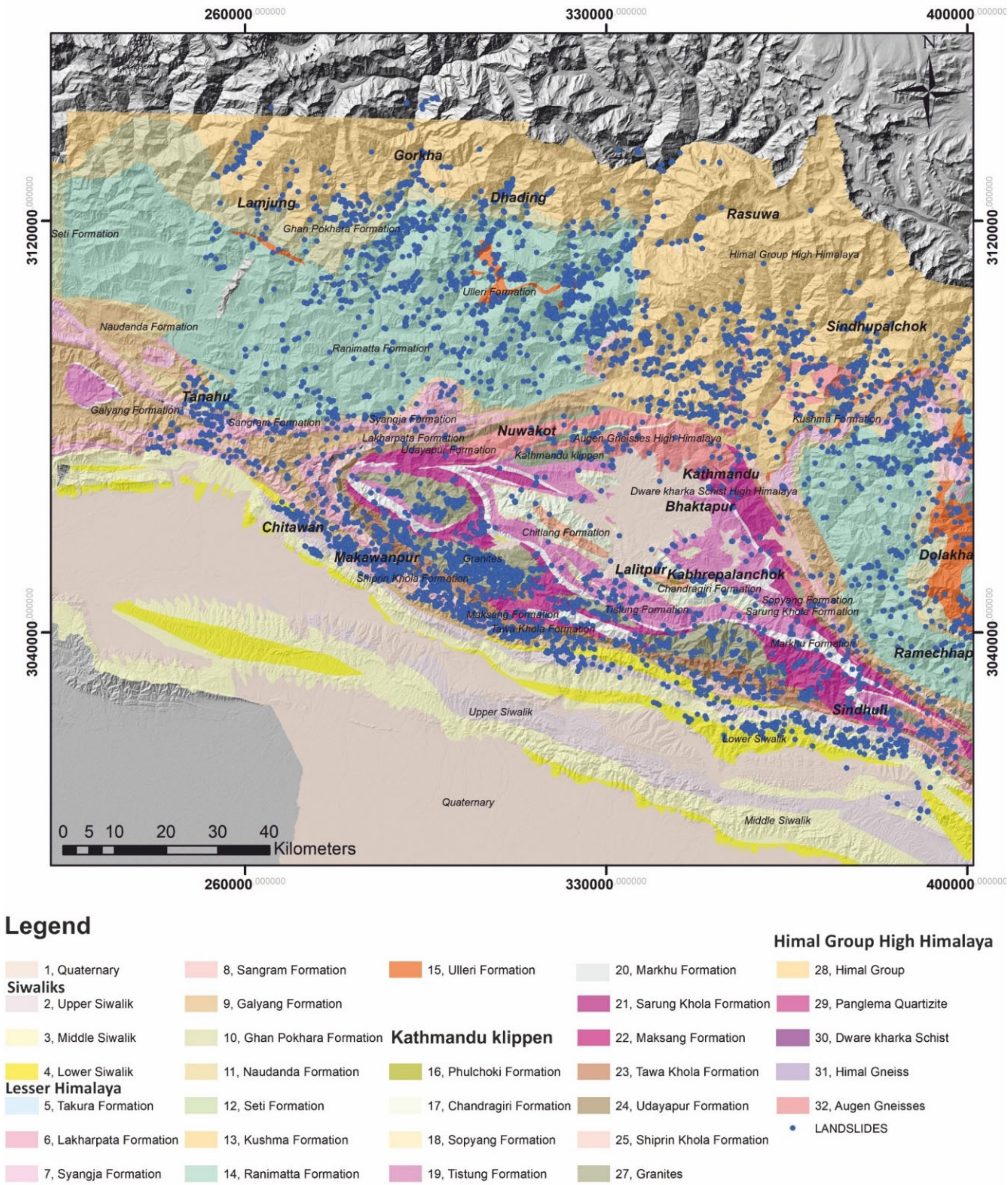

Fig. 3 Distribution of the monsoon-induced landslides (Jones et al., 2021) superimposed on the geologic map of Central Nepal (Department of Mines and Geology of Nepal)

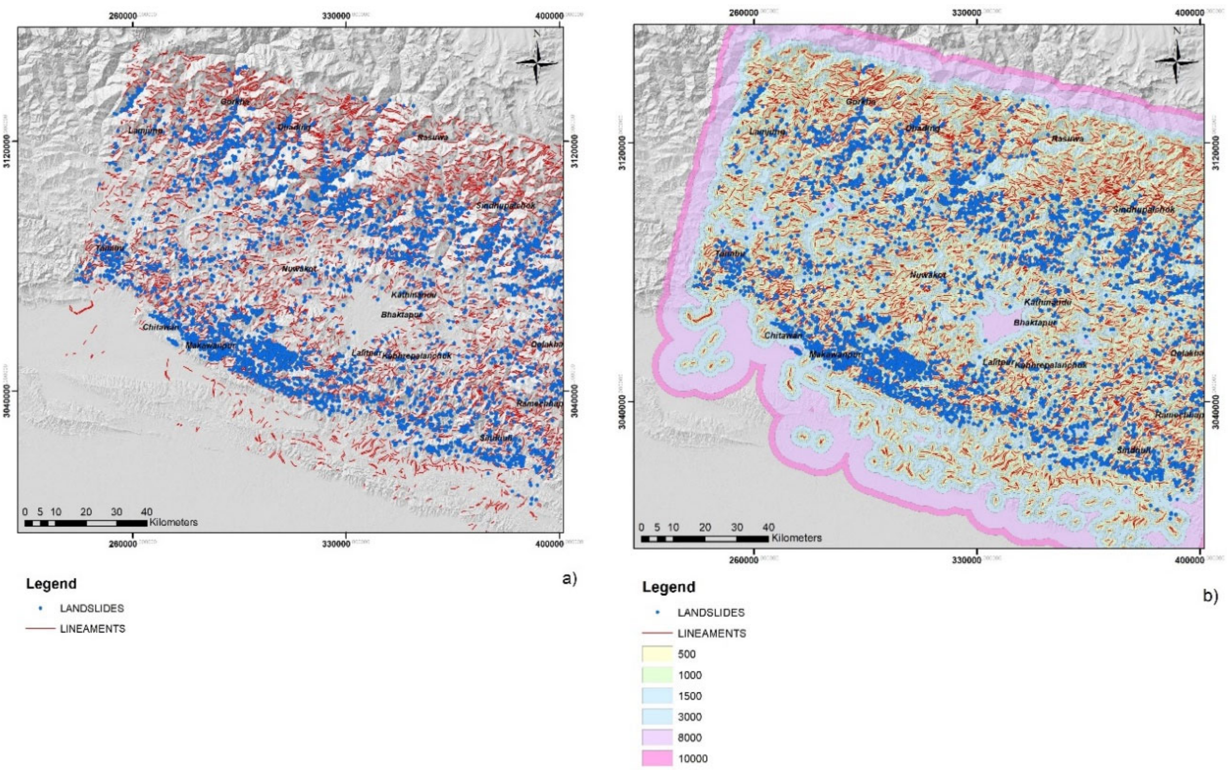

Fig. 4. Monsoon induced landslides superimposed on the maps of lineaments (a) and of distance to lineaments (b) in Central Nepal

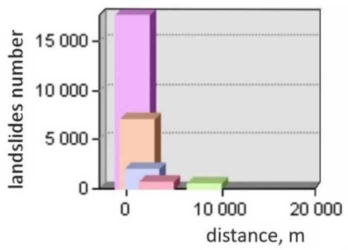

Fig. 5. Graph of number the landslides and their distributions within zones of distance to lineaments

Discussions and conclusions

The article's emphasis on susceptibility modeling as a preliminary step in predicting landslides is an important perspective in geology and natural disaster risk assessment. Susceptibility modeling indeed plays a crucial role in identifying areas where landslides are likely to occur, and it provides a valuable tool for prioritizing areas for further investigation and mitigation efforts. However, it's essential to recognize that susceptibility modeling has limitations and should be complemented with more detailed, site-specific information. One key point made in the article is that susceptibility modeling can effectively highlight regions with a high risk of landslides. This is particularly useful for large-scale planning, such as zoning regulations, infrastructure development, and disaster preparedness. Identifying these susceptible areas at a broad scale allows for proactive measures to be taken, such as land use planning, risk assessment, and the implementation of early warning systems (Sim, Lee, & Wong, 2022).

Nonetheless, the article correctly points out that susceptibility modeling alone cannot provide a complete understanding of landslide dynamics. To comprehensively assess the risk and predict the behavior of landslides, it is necessary to delve into the local geological and geotechnical conditions. This involves conducting in-depth geological research to understand the specific characteristics of the soil and rocks, the geological structure of the slopes, groundwater conditions, and other factors that influence slope stability. In essence, while susceptibility modeling helps to identify potential landslide-prone areas on a regional level, it cannot replace the importance of detailed, site-specific geological research for a comprehensive assessment. Only through local-scale investigations we can understand the unique factors that contribute to landslide formation and develop effective mitigation strategies. This comprehensive approach is crucial for minimizing the potential consequences of landslides, including loss of life and property damage.

Susceptibility modeling is a valuable tool in landslide risk assessment, but it should be viewed as just the initial step in landslide forecasting. Local-scale geological research is essential for understanding the specific characteristics of landslide-prone areas and providing more accurate predictions and effective strategies for landslide risk reduction. Both approaches, when used in conjunction, contribute to a more holistic and robust approach to landslide management and disaster prevention. It is crucial to increase landslide management and risk assessment capacity at the local and regional level. The comprehensive analysis of landslide risks will increase the accuracy of landslide resilience identification.

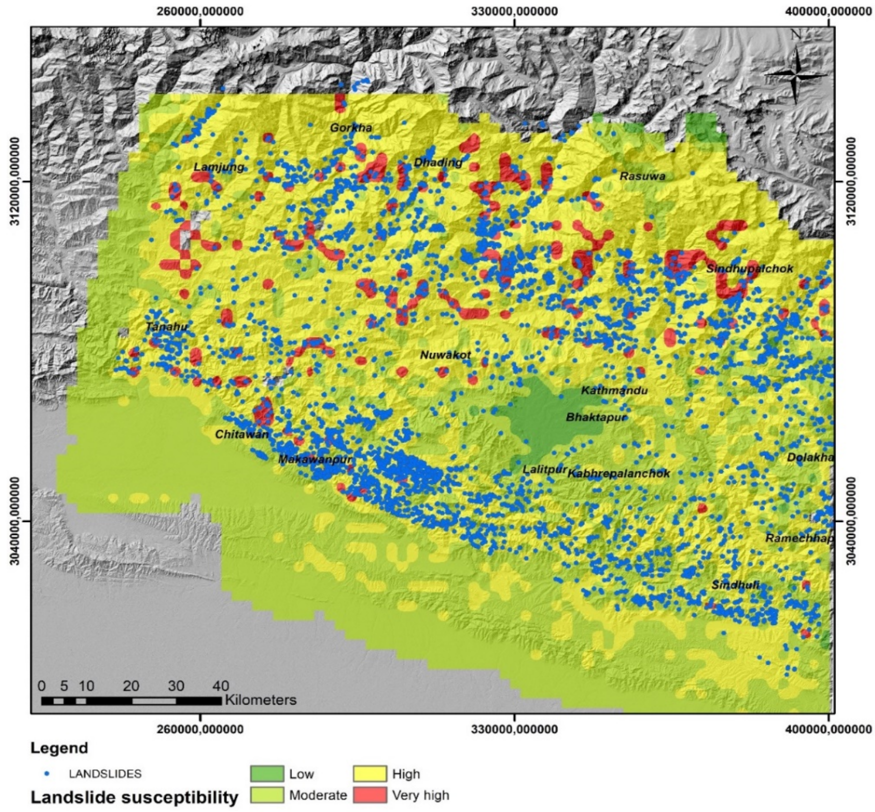

Fig. 6. Landslide susceptibility map, Central Nepal

The developed prognosis models could be applied for better understanding of vulnerability of areas, and to apply the methods of local predictions of landslides within areas with the highest hazards. It enables to develop the appropriate protective measures to withstand the impact of potential landslides in Central Nepal. The Government of Nepal committed to the implementation of the new Sendai Framework for Disaster Risk Reduction 2015–2030 to enhance efforts to strengthen disaster risk reduction to reduce losses of lives and assets from disasters, increase the capacity for understanding the disaster risks, strengthen the global cooperation. Therefore the susceptibility modeling and landslide forecasting at the regional level are the first stage of the landslide risk evaluating and management and could be a part of the Disaster Risk Reduction (DRR) cycle. This cycle includes preparation, mitigation, response, and recovery in term of the landslide hazards (Sawalha, 2020; Van den Hurk et al., 2023; Tian, & Lan, 2023).

Authors' contribution: Olena Ivanik – concept and methodology, preparation of the manuscript; Jerome Lave – concept and methodology, preparation and revising of the manuscript; Kateryna Hadiatska – databases and data analysis; Dmytro Kravchenko – data analysis and revising of the manuscript; Eduard Petrushenko – data analysis.

Acknowledgments, sources of funding. This research has been done in the framework of project "Risk assessment of landslide hazards and impact on communities" funded by PAUSE program (France).

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Отримано редакцією журналу / Received: 17.06.24
Прорецензовано / Revised: 24.09.24
Схвалено до друку / Accepted: 20.12.24

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МОДЕЛЮВАННЯ ЗСУВНОЇ СПРИЙНЯТЛИВОСТІ ЦЕНТРАЛЬНОГО НЕПАЛУ

В с т у п . ***Зсувні процеси в Гімалаях становлять велику небезпеку, яка загрожує як життю людей, так і соціально-економічному розвитку регіону. Мета цього дослідження – дослідити основні фактори, що впливають на формування зсувів у Центральному Непалі, зрозуміти їх пріоритетність та взаємовідношення, а також продемонструвати ефективність застосування комплексної методики для оцінки небезпеки зсувів у регіональному масштабі.***

М е т о д и . ***Методика, яка використовується в цьому дослідженні, включає такі етапи: (1) збір даних для аналізу (дані топографії, дані дистанційного зондування, геологічні дані, інвентаризація зсувів); (2) визначення основних факторів зсувної небезпеки, аналіз вхідних параметрів для моделювання; (3) створення карт лінеаментів за допомогою ручного та автоматизованого підходів; (4) картографування зсувної сприйнятливості та просторове моделювання зсувів.***

Р е з у л ь т а т и . ***Ґрунтуючись на аналізі співвідношення геологічних і геоморфологічних даних, моделювання сприйнятливості зсувів у Центральному Непалі дає змогу визначити зони, найбільш схильні до прояву зсувної небезпеки. Аналіз підтверджує істотну роль лінеаментів у формуванні зсувів та їх зв'язок із тектонічними та ерозійними процесами. У зв'язку із цим в регіональну класифікацію зсувів Центрального Непалу необхідно включити зсуви, пов'язані з ослабленими зонами різної природи та орієнтації.***

В и с н о в к и . ***Моделювання сприйнятливості та прогнозування зсувів на регіональному рівні є основним етапом оцінки та управління зсувними ризиками. Результати стосуються загального впливу геолого-геоморфологічних і ландшафтних факторів на формування зсувних явищ у Центральному Непалі. Проведення аналізу зсувів та вивчення їх динаміки та режиму можливе лише за умови детальних досліджень та виявлення пріоритету впливу кожного фактора на зсувоутворення. Це дослідження також має на меті надати додаткову інформацію щодо готовності до стихійних лих, мінімізації природних ризиків та забезпечення практики сталого землекористування в регіоні.***

К л ю ч о в і с л о в а : ***Непал, зсувна небезпека, сприйнятливість, картографування.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; in the decision to publish the results.