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RESEARCH ON LANDSLIDE RISK MANAGEMENT IN THE DA LAT–LAC DUONG URBAN AREA, LAM DONG PROVINCE

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INTRODUCTION

1. Necessity of the Dissertation

At present, research on landslide risk management in Vietnam remains limited. Previous studies have mainly focused on landslide identification, hazard zonation, or the analysis of influencing factors, while comprehensive quantitative risk assessment frameworks have not been adequately developed. The lack of quantitative assessment tools, early warning systems, and integrated databases poses significant challenges for planning and investment activities in landslide-prone areas. Therefore, developing an effective landslide risk management system that integrates multiple factors and modern technologies is an urgent requirement to protect human lives and property and to support sustainable urban development in the context of climate change.

In response, the dissertation entitled "Research on Landslide Risk Management in the Da Lat–Lac Duong Urban Area, Lam Dong Province" aims to develop a scientifically based and practical framework for landslide risk assessment and risk control that can be applied to local conditions.

2. Objectives and Research Contents of the Dissertation

Objectives: 1) To identify the characteristics and assess landslide hazards in the Da Lat–Lac Duong urban area; 2) To quantitatively assess landslide risk and propose risk management measures for the Da Lat–Lac Duong urban area.

Research Contents: 1) Investigating the characteristics of landslides in the Da Lat–Lac Duong urban area; 2) Assessing landslide hazards in the Da Lat–Lac Duong urban area; 3) Evaluating the risk to the main elements exposed to landslides in the Da Lat–Lac Duong urban area; 4) Proposing measures for landslide risk reduction and risk management in the Da Lat–Lac Duong urban area.

3. Research Hypotheses

Hypothesis 1: Landslides in the Da Lat–Lac Duong urban area are primarily associated with rapid urbanization on steep terrain under complex geological conditions, resulting in an increase in high- and very high-hazard areas over time.

Hypothesis 2: Landslide risk in the Da Lat–Lac Duong urban area can be managed through a six-step framework: 1) landslide hazard identification and assessment; 2) landslide risk quantification; 3) landslide risk evaluation; 4) risk control planning; 5) proposal of risk reduction measures; and 6) monitoring and updating. Areas with unacceptable risk are concentrated mainly in newly developed urban zones.

4. Data Sources of the Dissertation

Collected data and documents: 1) Public information sources (newspapers, television, and social media) related to landslide events; 2) Government data obtained from provincial agencies and local authorities in Lam Dong Province, including disaster reports, geological hazard records, maps, and land-use planning documents; 3) National and international scientific publications related to landslides and risk assessment; 4) Databases and results inherited from research projects TN18/T13, ĐL0000.01/20-21, TN3/T04, TN3/T01, and the Da Lat Geological Investigation Project; 5) Population statistics (2012–2022), rainfall records (1978–2024), an inventory of 57 landslide locations, and planning documents of Lam Dong Province.

Data generated by the dissertation: 1) Investigation of 125 landslide sites; development of a database including field descriptions, photographs, and Google Earth image analyses to characterize spatial–temporal evolution, classify landslide types, and establish an Htb–Lv regression model for estimating impact extent and supporting landslide risk management; 2) Monitoring of two major landslide sites: (i) seasonal displacement monitoring in Da Lat City; and (ii) operation of an automated monitoring system in Lac Duong Town measuring rainfall, pore-water pressure (PWP), and displacement in real time to support the development of an early warning basis; 3) Analysis of 21 landslide events (2016–2020) and five years of daily rainfall records to determine rainfall thresholds and the probability of landslide occurrence over time; 4) Laboratory testing of 55 soil samples representing five colluvial soil types to determine shear strength parameters under natural, compacted, and saturated conditions, providing geotechnical data for slope stability assessment; 5) Development of 85 slope cross-sections for factor-of-safety (FS) analysis to evaluate optimum stability conditions and the influence of anthropogenic activities; 6) Analysis of changes in building distribution from 2016 to 2023 using the Google Open Buildings dataset to identify trends in construction expansion on steep slopes and encroachment on natural drainage systems, supporting the assessment of urbanization impacts on landslide hazard.

5. Key Contributions of the Dissertation

- The dissertation clarifies the distribution and development characteristics of the principal landslide types, including translational, rotational, and complex landslides, in relation to the urbanization process in the Da Lat–Lac Duong urban area, revealing an increasing trend in landslide risk over time under the influence of urban development.

- The dissertation proposes prioritized landslide risk management measures for administrative units within the Da Lat–Lac Duong urban area (hereinafter referred to as the study area), including areas with Unacceptable Risk (Ward 7, 8, 3, 6, 2, 9, and 11), Tolerable Risk (Ward 4, 10, and Lac Duong Town), and Acceptable Risk (Ward 12, 1, 5, and Xuan Tho, Xuan Truong, Ta Nung, and Tram Hanh Communies).

CHAPTER 1. OVERVIEW OF LANDSLIDE RISK MANAGEMENT RESEARCH, RESEARCH APPROACHES, AND METHODOLOGY

1.1. Overview of Landslide Risk Research

1.1.1. Concepts and Terminology

a. Urban Areas and Urbanization

An urban area is a settlement characterized by high population density, developed infrastructure, and predominantly non-agricultural activities.

Urbanization is the process of increasing urban population and expanding urban areas, accompanied by the development of infrastructure to support socio-economic growth.

b. Landslides and Earth Landslides

A landslide is the downslope movement of earth-, rock-, debris-slides, or a combination of these materials under the influence of gravity.

An earth landslide is a type of landslide involving predominantly cohesive or weakly cohesive soils.

c. Risk and Landslide Risk

Risk refers to the potential for loss, damage, injury, or other adverse consequences arising from hazardous events or uncertain conditions that may affect people, property, infrastructure, or the environment.

Landslide risk is characterized by the probability of losses or damages resulting from landslides within a specified period of time and is commonly quantified as the product of hazard and consequences.

d. Risk Management and Landslide Risk Management

Risk is the potential for loss or damage resulting from hazardous events.

Landslide risk is the probability of losses caused by landslides over a specified period, commonly quantified as the product of hazard and consequences.

1.1.2. Overview of Urbanization on Sloping Terrain and Landslide Risk

Schuster and Highland (2007) highlighted the socio-economic impacts of landslide risk, identifying population growth, uncontrolled construction, inadequate drainage, and the lack of effective warning systems as key contributing factors. Di Martire et al. (2012) showed that extensive construction on unstable slopes in Naples and Ischia, Italy, continued despite hazard regulations, revealing limitations in integrating hazard information into urban planning. El Kechebour et al. (2015) demonstrated that increasing building density and building height reduce slope stability, particularly under seismic conditions.

1.1.3. Overview of Landslide Risk Management Worldwide

Landslide risk management requires the selection of appropriate assessment methods because landslide hazards exhibit complex spatial and temporal variability. At present, three principal approaches are widely applied: qualitative, semi-quantitative, and quantitative risk assessment

(QRA), with the choice depending on the study scale and data availability. Qualitative assessment is primarily based on descriptive analysis, expert judgment, and hazard–impact matrices, making it suitable for preliminary assessments or data-scarce areas. Semi-quantitative assessment assigns relative numerical values to risk factors and commonly applies the relationship $R = H \times V \times E$, enabling a more systematic quantification of risk. Quantitative risk assessment (QRA) requires detailed datasets to estimate risks to people and property and has been standardized through international guidelines and methodologies. In addition to assessment methods, the establishment of acceptable risk criteria is a fundamental basis for prioritizing mitigation measures and optimizing resource allocation. Globally, many developed countries have adopted proactive, quantitative, and GIS-based approaches to landslide risk management. These programs commonly focus on developing landslide databases, hazard and risk zoning for land-use planning, multi-level governance frameworks, and enhanced monitoring and early-warning systems.

1.1.4. Overview of Landslide Risk Management in Vietnam

Landslide risk management in Vietnam has been implemented within the framework of national disaster prevention and mitigation policies and strategies. The National Strategy for Natural Disaster Prevention and Control to 2030, with a vision to 2050, emphasizes disaster loss reduction, risk management capacity, and a five-level disaster risk classification system. Numerous national and provincial programs have focused on landslide investigation, hazard zonation, and the mitigation of landslide-prone areas. Recent studies have increasingly applied machine learning, physically based models, and geotechnical monitoring to support landslide prediction and early warning. Research has gradually evolved from qualitative assessments to quantitative and probability-based approaches. In the Central Highlands, landslide databases and hazard and risk maps have been developed at scales of 1:50,000 to 1:25,000; however, these results have not yet been fully integrated into land-use planning and urban development.

1.1.5. Research Gaps and Research Orientation of the Dissertation

In Vietnam, landslide studies have mainly focused on landslide inventories, hazard assessment, and qualitative risk evaluation, while quantitative approaches remain limited and are largely confined to linear infrastructure corridors. Consequently, landslide risk information has not been systematically integrated into urban planning. This dissertation focuses on the Da Lat–Lac Duong urban area, characterized by steep terrain, thick weathering profiles, intense seasonal rainfall, rapid urbanization, and frequent landslide events. The research aims to: (i) develop an integrated landslide risk assessment framework incorporating hazard (H), vulnerability (V), and exposed elements (E); (ii) quantify landslide risk using field and monitoring data; and (iii) propose a landslide risk management framework linked to GIS, urban planning, and early warning systems.

1.2. Research Approaches and Methodology

1.2.1. Research Approaches

This dissertation considers urban landslides as the result of interactions between natural conditions and human activities during urban development. Landslide risk management is viewed as a dynamic process for identifying, controlling, and reducing potential losses. The study adopts an integrated framework that analyzes the relationships among hazard, exposure, vulnerability, and risk. Four principal approaches are employed: interdisciplinary, modeling, engineering and forecasting, and management science. The research outcomes support decision-making and the integration of landslide risk into urban planning and construction management.

1.2.2. Research Methodology

1) multi-source data and information analysis and synthesis; 2) remote sensing; 3) landslide classification and field investigation; 4) expert judgment and mapping; 5) laboratory analysis and testing; 6) modeling; 7) monitoring, forecasting, and early warning; 8) landslide risk management assessment; and 9) landslide runout and impact-area determination.

1.2.3. Landslide Risk Management Process for Urban Areas

The landslide risk management framework adopted in this dissertation consists of six fundamental steps: 1) landslide hazard identification and assessment; 2) landslide risk quantification; 3) geological hazard risk evaluation; 4) risk control orientation; 5) risk control planning; and 6) monitoring and updating, as illustrated in Figure 1.5.

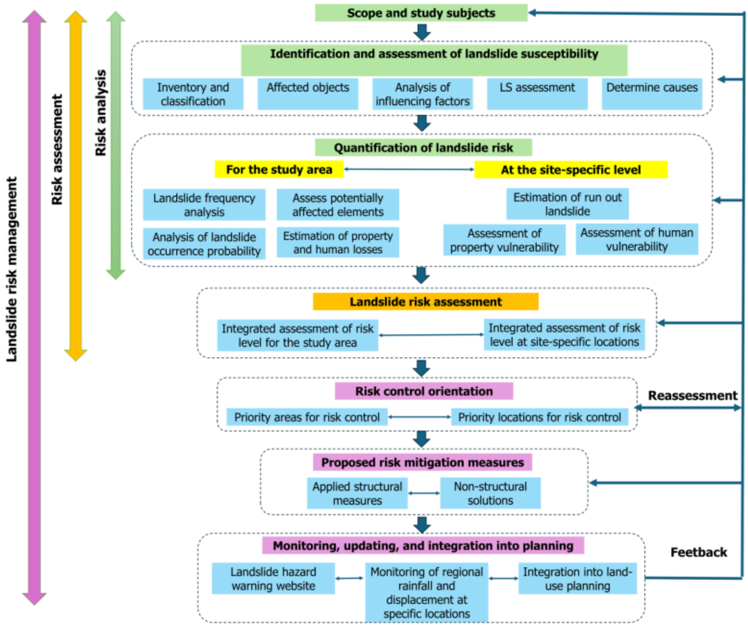

Figure 1.5. Workflow of the Landslide Risk Management Process in the Da Lat–Lac Duong Urban Area

CHAPTER 2. LANDSLIDE INVENTORY AND CAUSATIVE FACTORS IN THE DA LAT–LAC DUONG URBAN AREA

2.1. Overview of the Study Area

2.1.1. Geographical Location

Prior to July 1, 2025, the Da Lat–Lac Duong urban area was located in northeastern Lam Dong Province. It was bounded by Lat and Da

Sar communes to the north, Don Duong District to the east and southeast, Lam Ha District to the west, and Duc Trong District to the southwest. The study area is located between 11°48′34″–12°04′32″ N and 108°18′49″–108°35′28″ E, covering approximately 416.2 km². It comprises 17 administrative units, including Da Lat City with 12 wards and four communes (Ta Nung, Tram Hanh, Xuan Tho, and Xuan Truong), and Lac Duong Town with an area of 70.6 km² (Figure 2.1).

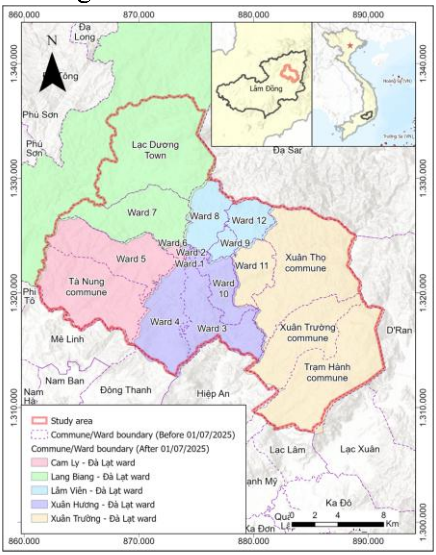

Figure 2.1. Location Map and Administrative Units of the Da Lat–Lac Duong Urban Area

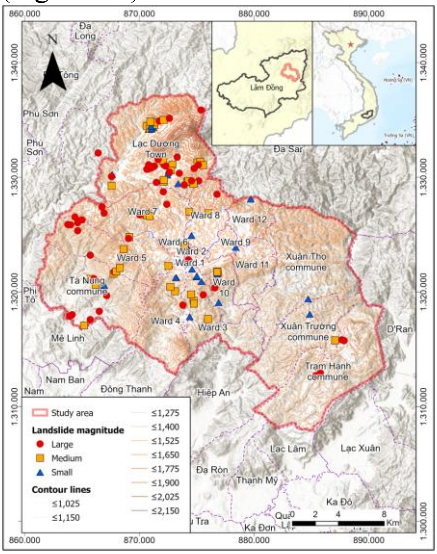

Figure 2.9. Landslide Inventory Map by Landslide Magnitude in the Study Area

2.1.2. Topographic and Geomorphological Characteristics

The Da Lat–Lac Duong urban area is located on the Lam Vien Plateau and is characterized by diverse topographic and geomorphological conditions. Da Lat is a relatively flat basin surrounded by mountains at elevations of about 1,700 m, with mountainous hills, upland plains, streams, and narrow valleys. In contrast, Lac Duong is a narrow depression surrounded by the LangBiang Range, with elevations of 2,064–2,167 m, steep slopes (20°–35°), and strongly dissected terrain.

2.1.3. Stratigraphic Characteristics

The study area comprises sedimentary, volcanic, and intrusive rock formations. Sedimentary and volcanic units account for approximately 2/3 of the area, while intrusive rocks occupy the remaining one-third. The stratigraphy is dominated by Late Mesozoic formations, whereas Cenozoic deposits have a more limited distribution. A completely weathered mantle, composed mainly of clay, silty clay, sandy clay, and gravelly materials, has developed over the bedrock. The principal geological units include the La Nga Formation (J_2ln), consisting mainly of siltstone, claystone, and sandstone; the Dakrium Formation (K_2dr); the Don Duong Formation (K_2đd); the Xuan Loc Formation (βQIIxl); the Dinh Quan Complex (J_3đq); and the Ca Na Complex (K_2cn). Quaternary deposits, including alluvial, alluvial-swamp, and alluvial-proluvial sediments, are distributed along stream valleys and form first- and second-order fluvial terraces.

2.1.4. Tectonic Characteristics

The Da Lat–Lac Duong area is situated within the Da Lat magmatic–tectonic zone. The regional geological structure is controlled by three principal fault systems: the NW–SE system, characterized mainly by left-lateral strike-slip movement; the NE–SW system, which controls the regional geological structure and has undergone late-stage reactivation; and the N–S to submeridional system, characterized mainly by right-lateral strike-slip movement.

2.1.5. Climatic and Hydrological Characteristics

Climate: The Da Lat–Lac Duong area has a subtropical highland climate with mild temperatures, two distinct seasons, and an average annual temperature of 18–21°C. The rainy season lasts from April to October, while the dry season extends from November to March..

Hydrology: The study area contains 16 reservoirs and a drainage network controlled by topography. Streams drain into Suoi Vang Lake, the Da Nhim River, and the Datanla–Da Prenn drainage system. Cam Ly Stream, about 20 km long, is the principal stream, while many small streams experience reduced or temporary dry flow during the dry season.

2.1.6. Population Development Characteristics

Between 2010 and 2022, the population of Da Lat City increased from 209,170 to 232,407 (13.7%), while Lac Duong Town increased from 5,137 to 11,184 (117.74%). Population growth was more rapid during 2010–2016 than 2016–2022, with the total population of the study area increasing by 29,281 people over the 12-year period.

2.2. Landslide Identification and Hazard Assessment

2.2.1. Landslide Inventory and Classification

A total of 125 landslides were identified within the study area, including 83 recorded before 2016 and 42 occurring between 2016 and 2023. Landslides are concentrated in three main zones: (i) the northwestern sector (Lac Duong Town, Ward 7, Ward 5, and Ta Nung Commune); (ii) the central Da Lat area (Wards 1, 2, 5, 6, and 10), mainly along transportation corridors and construction areas; and (iii) the southern and southeastern sectors (Wards 3, 4, and 11, Xuan Tho Commune, and Tram Hanh Commune), where they occur sporadically on lower slopes and in urban–agricultural transitional areas (Figure 2.9). Landslide movement types are presented in Table 2.2.

Table 2.2. Classification of Landslides in the Da Lat–Lac Duong Urban Area (Modified after Varnes, 1978)

No.	Landslide Type	Symbol	Scale			Total	Percentage (%)
			Small	Medium	Large		
1	Translational Landslide	Tr	23	23	16	62	**49,6**
2	Rotational Landslide	Ro	2	10	21	33	**26,4**
3	Complex Landslide	Co	0	6	13	19	**15,2**
4	Flow Landslide	Fl	1	4	6	11	**8,8**
	Total		**26**	**43**	**56**	**125**	**100**

2.2.2. Elements Affected by Landslides

The inventory of 125 landslides shows that impacts are mainly associated with five categories of exposed elements: buildings and structures (CTXD), transportation infrastructure (DGT), cultivated land and agricultural gardens (VHM), planted forests (RTR), and bare land (DTR). Their distribution is presented in Table 2.4.

Table 2.4. Statistics of Elements Affected by Landslides in the Da Lat–Lac Duong Urban Area

No.	Affected Element	Symbol	Number of Landslides	Scale			Dominant Triggering Factor
				Small	Medium	Large	
1	Building	CTXD	33	11	10	12	Anthropogenic
2	Road	DGT	31	7	19	5	Anthropogenic
3	Bare Land	DTR	27	6	9	12	Natural and Anthropogenic
4	Agricultural Gardens	VHM	20	2	4	14	Anthropogenic
5	Planted Forests	RTR	14	0	1	13	Anthropogenic
	Total		**125**	**26**	**43**	**56**	-

2.2.3. Factors Influencing Landslides and Landslide Hazard Zonation

The factors influencing landslide occurrence were ranked according to their relative importance as follows: (1) slope gradient, (2) rainfall, (3) lithological characteristics, (4) weathering profile type, (5) distance to faults, (6) land use, (7) vertical dissection density, and (8) horizontal dissection density. Slope gradient directly controls slope stability, while rainfall is the principal external triggering factor. Lithology, weathering profile, and fault proximity determine the mechanical behavior and strength of slope materials. Land use represents anthropogenic influences, whereas vertical and horizontal dissection density reflect terrain morphology and erosion intensity that contribute to landslide susceptibility.

2.2.4. Landslide Hazard Assessment

A comparison of the landslide hazard assessment results for 2016 and 2023 indicates a clear shift toward higher hazard levels. Specifically, the area classified as very low hazard decreased from 55.30 km² to 42.27 km², while the low-hazard area decreased from 107.57 km² to 98.88 km². The moderate-hazard class remained the most extensive category but declined slightly from 156.82 km² to 148.37 km². In contrast, the high-hazard area increased substantially from 100.43 km² to 128.53 km², and the very high-hazard area increased slightly from 44.03 km² to 46.10 km². Overall, the period from 2016 to 2023 demonstrates a clear trend toward increasing landslide hazard across the study area.

The total number of buildings and structures increased from 147,800 in 2016 to 192,283 in 2023, an increase of 44,483 buildings (approximately 30%). Most new development occurred within high and very high landslide hazard zones, indicating continued urban expansion into areas with elevated landslide susceptibility (Figure 2.15).

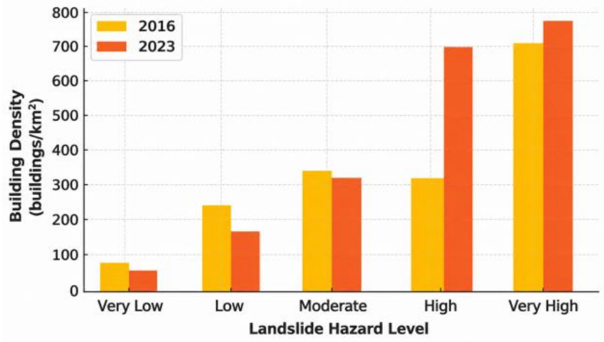

Figure 2.15. Comparison of building density across landslide hazard levels in 2016 and 2023

2.2.5. Causes of Landslides

1) Rainfall-induced landslides: Under unsaturated conditions, increasing soil moisture reduces cohesion and shear strength, causing colluvial and residual slopes to become unstable during prolonged rainfall. During 2016–2020, 19 rainfall-induced landslides were analyzed, with most events occurring during the rainy season (April–November). A Poisson-based analysis indicated that the relationship between daily rainfall (Pm) and three-day cumulative rainfall (P3) provided the most effective discrimination between landslide and non-landslide conditions. The proposed rainfall threshold is $P = 62.4 - 0.178P3$, which is more suitable for early warning than deterministic prediction. Laboratory tests on five representative soil groups showed a marked reduction in shear strength when moisture content exceeded 25%, particularly under saturated conditions, with variations related to mineralogical composition.

2) Rapid urbanization: Rapid urban expansion has increased landslide susceptibility through construction on steep slopes, encroachment upon natural drainage channels, and slope modification associated with cut-and-fill activities and structural loading. Between 2016 and 2023, the number of buildings increased from 147,800 to 192,283 (30.1%), with the

highest growth on slopes of 35–45° (66.1%) and >45° (98.7%). Buildings encroaching upon natural drainage channels increased from 1,674 to 2,693, while the length of affected channels nearly doubled from 49,541 m to 97,907 m. Landslide sites within 50 m of encroaching structures increased from 8 to 23, and the total number of affected sites increased from 40 to 61. Slope stability analyses showed that terrain modification and structural loading reduced the factor of safety, particularly under saturated conditions, with many modified slopes exhibiting FS < 1.0, indicating a high likelihood of failure.

CHAPTER 3. LANDSLIDE RISK MANAGEMENT IN THE DA LAT–LAC DUONG URBAN AREA

3.1. Quantification of landslide risk

3.1.1. Quantification of Landslide Risk in the Study Area

1) Landslide Frequency and Probability. The Poisson distribution was applied to estimate the annual probability of landslide occurrence under the assumptions of independent events and a constant average occurrence rate. During 2016–2022, the average annual landslide frequency was $\lambda = 6$ events/year. The highest probabilities corresponded to 5–6 events/year (16.06%), while lower and higher frequencies occurred with progressively smaller probabilities. The average annual occurrence rate was then allocated to each hazard class to estimate the probability of at least one landslide occurring within 1-, 3-, and 5-year periods. The results show that landslide probability increases rapidly over time across all hazard classes, approaching 1.0 after 3–5 years. Using the ratio between the average landslide-affected area and the corresponding hazard-zone area, the estimated number of buildings potentially affected by landslides increased from 3.49 within 1 year to 10.46 within 3 years and 17.43 within 5 years.

2) Assessment of Elements Potentially Subject to Loss and Damage. Human life and buildings were identified as the primary elements at risk. Population and building densities were analyzed for the 17 administrative units to evaluate exposure and support risk-control

prioritization. Very high population and building densities are concentrated in the central urban wards (Wards 1, 2, 6, and 9), whereas peri-urban and rural areas generally exhibit lower densities. The estimated number of buildings potentially affected by landslides increases from 3.49 within 1 year to 10.46 within 3 years and 17.43 within 5 years. More than 95% of the affected buildings are located within medium-, high-, and very high-hazard zones, with the medium-hazard class accounting for the largest share. Wards 7, 8, 3, 4, 5, 10, and 11, together with Lac Duong Town, exhibit the highest estimated numbers of affected buildings, whereas Ta Nung, Tram Hanh, Xuan Tho, and Xuan Truong show comparatively lower potential impacts (Figure 2.16).

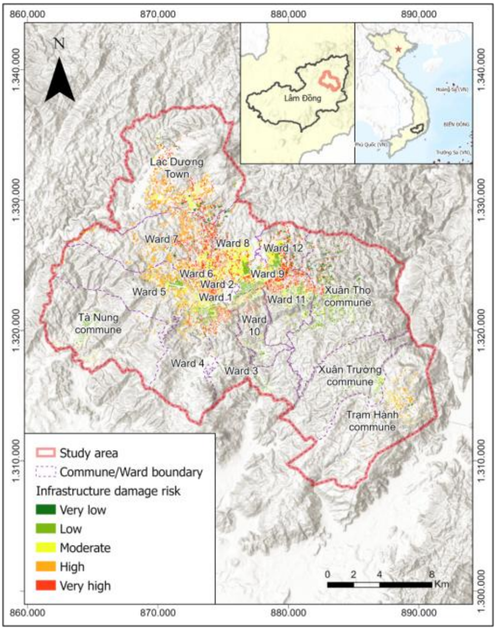

Figure 2.16. Spatial Distribution of Buildings across Landslide Hazard in 2023

3) Estimation of Property and Human Risk

Property Risk Estimation: Property risk (R_p) was estimated using local construction costs and the average floor area of buildings in each administrative unit. Construction values were assigned according to building density and predominant building grades, with average costs of approximately VND 7.8 million/m² for high-density urban areas and VND 6.4 million/m² for low- to medium-density areas. The potentially affected area and the number of vulnerable buildings were estimated based on hazard-zone extent, landslide probability, building distribution, and vulnerability coefficients. The results indicate that approximately 1.61 buildings per year are expected to sustain damage, increasing to 4.84 buildings over 3 years and 8.06 buildings over 5 years. Property risk was calculated using the following equation: $Rts_{i,1} = n_{i,1} \times S_{CTXD} \times G_{XD}$

The total estimated property loss is approximately VND 732.6 million per year, increasing to VND 2.2 billion over a three-year period and VND 3.7 billion over a five-year period. Property risk is concentrated primarily in Ward 7, with an estimated loss of approximately VND 516.7 million over five years, followed by Wards 8, 11, and 9, reflecting the high density of buildings located within medium-, high-, and very high-hazard zones. A moderate-risk group comprises Wards 3, 4, 10, and 12, together with Lac Duong Town, whereas the peripheral communes of Xuan Truong, Ta Nung, and Tram Hanh exhibit comparatively low levels of property risk.

Human Risk Estimation: Human risk (R_h) was estimated based on the number of buildings potentially affected within each administrative unit, combined with vulnerability coefficients for human exposure according to hazard level, (V(L/T)=1.0,;0.7,;0.4,;0.1) (from very high to low hazard levels), and the average number of occupants per building (φ). This approach assumes that the probability of casualties increases with both the severity of the hazard and the concentration of exposed population within potentially affected buildings. Human risk was calculated using the following equation: $Rcn_{i,1} = n_{i,1} \times V(L/T) \times \varphi_i$

The estimated human risk for the study area is approximately 1.75 potential fatalities per year, increasing to 5.26 over three years and 8.77 over five years. High-risk areas are concentrated in Wards 2, 3, 6, 7, 8, and 9, and Lac Duong Town, with values ranging from 0.46 to 0.94 potential fatalities over five years. Wards 6 and 7 show the highest values (approximately 0.94 over five years). Moderate-risk areas include Wards 1, 4, 5, 10, 11, and 12 (0.31–0.64 over five years), whereas the peripheral communes of Ta Nung, Tram Hanh, Xuan Tho, and Xuan Truong exhibit very low risk (<0.2 over five years).

3.1.2. Quantification of Landslide Risk at Specific Sites

1) Identification of Landslide-Prone Sites. The study proposes a data structure for site-specific landslide risk assessment, including area code–coordinates, landslide hazard level (LSI), slope characteristics (height and slope angle), building function, building class, construction materials, and impact extent. The system is quantified using a priority scoring method, in which five principal components (hazard level, building type, building class, construction materials, and vulnerability level) determine the overall score. The total score serves as the basis for determining the spatial priority for landslide risk control, while the remaining information is considered supplementary data for future expansion.

2) In the Da Lat–Lac Duong urban area, only a small number of Grade II buildings (high-rise buildings) are located on relatively gentle terrain and are therefore less susceptible to landslides. Grade III and Grade IV buildings constitute the majority and are predominantly distributed on steep terrain and in close proximity to slopes, making them more vulnerable to landslide impacts. Accordingly, this study proposes assessing vulnerability at specific sites based on the burial extent (Lv), which is classified into four impact zones (Zones 1, 2, 3, and 4). Vulnerability values are quantified separately for property (Vb) and human life (Vp), with Zone 4 representing the highest level of vulnerability (complete destruction and a very high probability of fatality), decreasing progressively to Zone 1 (minor impact with limited casualties). Grade IV buildings generally exhibit higher vulnerability because of their weaker structural characteristics, whereas Grade III buildings and above have greater resistance to landslide impacts.

3.2. Landslide Risk Assessment

3.2.1. Landslide Risk Levels in the Study Area

The chart illustrates the distribution of property risk and human risk over a five-year period across the 17 administrative units, highlighting clear spatial differences in landslide risk distribution (Figure 3.4).

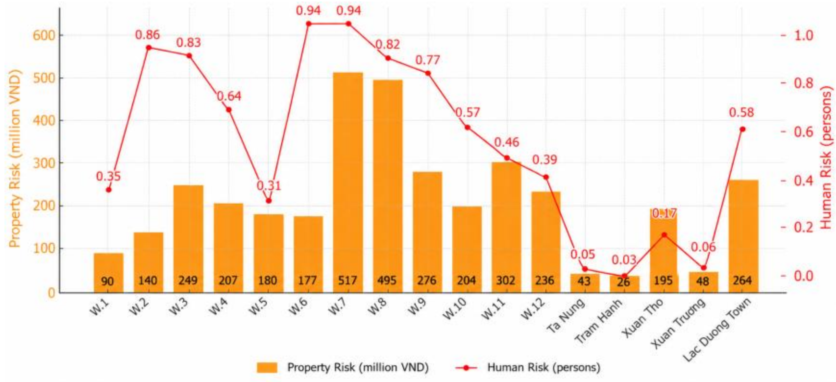

Figure 3.4. Estimated property and human risk across the administrative units over a five-year period.

Property risk (Rts) and human risk (Rcn) were quantified separately and classified into five levels, ranging from very low to very high. The values were standardized into scores ranging from 1 to 5, and the overall landslide risk (Rth) was calculated using the equation $Rth = 0.7 \times Rcn + 0.3 \times Rts$, in which greater weight was assigned to human risk.

Over the five-year period, the overall landslide risk classification indicates that Ward 7 falls within the very high-risk category; Wards 6, 2, 3, 8, 9, and 11 are classified as high risk; Ward 4, Ward 10, and Lac Duong Town as moderate risk; Wards 12, 1, and 5, together with Xuan Tho Commune, as low risk; and Xuan Truong, Ta Nung, and Tram Hanh Communes as very low risk.

3.2.2. Landslide Risk Levels at Specific Sites

Based on information provided by the local authorities and the landslide hazard zoning results, 33 landslide-prone sites were identified from 59 inventoried locations. A multi-criteria scoring method was applied to prioritize landslide risk control, with higher scores indicating higher priority. The method was developed with reference to the risk assessment frameworks of Fell et al. (2008) and UNDRR (2015) to ensure that risk-control priorities are consistent with local management capacity. Landslide risk is classified into four levels (Table 3.20).

Table 3.20. Classification of Landslide Risk Levels for Buildings

No.	Total Score Range	Risk Level	No. of Buildings	Description
1	≥ 38	Very High	12	Buildings with very high landslide risk and severe vulnerability require detailed assessment and early intervention.
2	32 - 37.9	High	6	Buildings with high landslide risk and significant vulnerability require reinforcement, warning measures, and periodic inspections
3	24 - 31.9	Moderate	7	Buildings with moderate landslide risk require regular monitoring and appropriate mitigation measures.
4	< 24	Low	8	Buildings with low landslide risk require routine monitoring and maintenance

3.3. Landslide Risk Control Strategy

3.3.1. Landslide Risk Levels in the Study Area

1) Classification of Landslide Risk Zones: Landslide risk in the Da Lat–Lac Duong urban area is classified into three categories: acceptable, tolerable, and unacceptable risk. The classification is based on the overall landslide risk index (Rth), which integrates property risk (Rts) and human risk (Rcn), with greater weight assigned to human risk (Table 3.22).

Table 3.22. Landslide Risk Acceptability Classification and Risk Control Strategy

No.	Risk Category	Overall Risk Level	Component Risk Values	Administrative Units	Risk Control Strategy
1	Unacceptable Risk	Rth > 3.5	Rcn = 0.77–0.94 potential fatalities Rts = 249.3–516.7 million VND	Wards 7, 8, 3, 6, 2, 9, and 11	Immediate intervention: Implement structural and non-structural measures, establish early warning systems, and relocate at-risk residents where necessary.
2	Tolerable Risk	Rth = 2.5 – 3.5	Rcn = 0.46–0.64 potential fatalities Rts = 204.3–302.5 million VND	Ward 4, Ward 10, and Lac Duong Town	Proactive risk control: Adjust land-use planning, upgrade disaster prevention infrastructure, construct mitigation, and strengthen community preparedness.
3	Acceptable Risk	Rth < 2.5	Rcn = 0.03–0.39 potential fatalities Rts = 39.2–236.4 million VND	Ward 12, 1, 5 , and Xuan Tho, Xuan Truong, Ta Nung, and Tram Hanh Communes	Routine monitoring: Maintain periodic monitoring, implement basic warning measures, and manage urban development to minimize landslide risk.

2) Identification of Priority Administrative Units for Landslide Risk Control: Priority levels were determined based on the overall landslide risk (Rth), with human risk (Rcn) given priority and property risk (Rts) considered where particularly high. This approach supports prioritization by integrating potential impacts on human life and property (Table 3.23).

Bảng 3.23. Criteria for identifying priority administrative units for landslide risk control

No.	Risk Control Priority Group	Identification Criteria
1	First Priority	Areas with Rth > 3.5, and: – Rcn > 0.80 potential fatalities or Rts ≥ 400.0 million VND
2	Second Priority	Areas with Rth > 3.0, and: – Rcn = 0.40–0.79 potential fatalities or Rts ≥ 200.0 million VND
3	Third Priority	Areas with Rth > 1.0, and: – Rcn = 0.10–0.39 potential fatalities or Rts ≥ 100.0 million VND
4	Fourth Priority	Areas with Rth < 1.0, and: – Rcn < 0.10 potential fatalities or Rts ≥ 50.0 million VND

3.3.2. Determination of Landslide Risk Control Priorities at Specific Sites

Based on a set of criteria that simultaneously reflects both the likelihood of landslide occurrence and the potential consequences. The main criteria include: (i) the landslide hazard level (LSI) at the building location; (ii) building characteristics, including building function, building class, and construction materials, to assess vulnerability; (iii) topographic conditions at the site, including slope height and slope angle, which influence the landslide mechanism and magnitude; and (iv) the potential impact extent of landslides on buildings and occupants. These factors are quantified using a scoring system and integrated into a building risk index to objectively rank intervention priorities and enable comparison among different sites. For convenient management, monitoring, and periodic updating, each site is assigned a standardized identification code comprising the administrative area (KV), survey year (YY), identification number (ID), and priority level (UT). The classification results of landslide risk control priorities at specific sites are summarized in Table 3.26.

Bảng 3.26. Results of the Classification of Landslide Risk Control Priorities

No.	Priority Level	Total Score Range	Number of Buildings
1	A – First Priority	≥ 38	12
2	B – Second Priority	32 - 37.9	6
3	C – Third Priority	24 - 31.9	7
4	D – Fourth Priority	< 24	8

3.4. Landslide Risk Control Plan

3.4.1. Limitations of Local Disaster Prevention and Mitigation

The Da Lat–Lac Duong area still exhibits limitations in land-use planning, technological application, and landslide mitigation. Urban development has expanded onto hillslopes, stream corridors, and other high-risk areas, while landslide hazard information has not been fully integrated into land-use and construction planning. Slope modification has altered natural drainage and increased slope instability. Risk management and communication remain inadequate because of delayed warning dissemination, limited inter-agency coordination, and insufficient local technical capacity. Existing mitigation works are small-scale and site-specific, often lacking adequate drainage systems. In addition, surface drainage infrastructure has deteriorated and is frequently obstructed, while subsurface drainage remains at the pilot stage.

3.4.2. Planning and Construction Measures

Planning and construction measures focus on integrating landslide hazard information into land-use planning and construction management to reduce risk and support sustainable urban development. Measures are differentiated according to hazard level. Very high-hazard zones require relocation, prohibition of new construction, safety buffer zones, and slope stabilization. High-hazard zones require slope reinforcement, strict construction control, and early warning systems. Moderate-hazard zones should prioritize green spaces, improve drainage, and strengthen community warning. Low- and very low-hazard zones mainly require periodic monitoring and slope maintenance. Planning should be implemented from master planning to detailed planning, supported by geological investigations at 1:2,000–1:500 scales. Based on landslide risk zoning, construction should be prohibited in very high-risk areas, restricted in high-risk areas with detailed geological investigation and mitigation design, and controlled in the remaining areas.

3.4.3. Engineering and Infrastructure Measures

Engineering and infrastructure measures for landslide risk control are compiled based on current technical standards (TCVN 9861:2013, TCVN 11823-1:2017, 22TCN 171-87, and 22TCN 263-2000) and classified into five main groups according to their intervention objectives: (1) mechanical stabilization measures, including retaining walls, counterfort berms, piles, anchors, and reinforced earth walls for high slopes requiring long-term stability; (2) slope unloading measures, including slope cutting, benching, and slope flattening to reduce driving forces; (3) surface drainage control measures, including drainage ditches, stepped channels, and impermeable covers to minimize erosion and surface runoff concentration; (4) subsurface drainage measures, including drainage trenches, wells, and drainage boreholes or tunnels to reduce pore water pressure; and (5) slope reinforcement and surface protection measures to improve the stability of the surficial soil layer.

3.4.4. Social and Community-Based Measures

Community-based disaster risk management is an effective, sustainable, and low-cost approach. Key measures include: (i) establishing local disaster risk management committees and community core groups with clear coordination mechanisms; (ii) conducting participatory risk assessments (RRA) to identify landslide-prone areas and vulnerable groups; (iii) developing community disaster preparedness plans, including evacuation routes and task assignments; (iv) providing regular communication, training, and emergency drills; and (v) establishing community monitoring and early warning systems using crack markers, rainfall observations, and warning loudspeakers linked to meteorological and sensor data.

3.4.5. Periodic Monitoring and Updating of Landslide Risk Information

The study proposes an integrated WebGIS-based landslide monitoring and early warning system that combines topographic data, landslide inventory, hazard maps, and real-time monitoring data (horizontal displacement, pore water pressure, and rainfall). The system supports spatial and temporal monitoring and early warning for authorities and local communities. It consists of two components: (i) regional monitoring and warning through WebGIS, with periodic updates to landslide risk maps, priority areas, and safety buffer zones; and (ii) monitoring and forecasting of the LangBiang deep-seated landslide using integrated sensors for horizontal displacement, pore water pressure, rainfall, and soil moisture.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1) Landslides in the Da Lat–Lac Duong area were identified as four main types: translational slides, rotational slides, complex slides, and flow slides. Among these, translational (shallow) landslides predominate, generally occurring at small to medium scales within completely weathered soil and are most common in urbanized areas strongly affected by slope cutting, land leveling, and structural loading. Rotational (deep-seated) landslides are typically large in scale and occur on natural slopes where completely to highly weathered profiles are thick and capable of retaining large amounts of water. Complex slides and flow slides are mainly distributed in water-concentrating areas and develop within mixed soil–rock materials during prolonged heavy rainfall.

2) Urbanization is closely associated with the increasing occurrence of landslides. Slope cutting, land leveling, and structural loading reduce the strength of soil and rock masses, creating favorable conditions for landslide initiation, particularly when combined with heavy rainfall. The results indicate that the degree of urbanization is one of the major controlling factors contributing to increased landslide hazard in the study area.

3) The integrated model combining the spatial, temporal, and event-scale probabilities of landslide occurrence with vulnerability and exposed elements enables the quantitative assessment of landslide risk to people and property. This multi-criteria approach simultaneously considers both the likelihood of landslide occurrence and the expected consequences, thereby clearly distinguishing landslide risk from hazard. It is well suited to

local data conditions and effectively reveals the spatial distribution of landslide risk, providing a scientific basis for risk management and the prioritization of risk control measures.

4) The results show that landslide risk in the Da Lat–Lac Duong area exhibits clear spatial variation, with the overall landslide risk index (Rth) ranging from <2.5 to 5.0. Administrative units classified as unacceptable risk include Ward 7, 8, 3, 6, 2, 9, and 11 ($Rth \geq 3.5$); those classified as tolerable risk include Ward 4, Ward 10, and Lac Duong Town ($Rth = 2.5–3.5$); and those classified as acceptable risk include Ward 12, 1, 5, Xuan Tho Commune, Xuan Truong Commune, Ta Nung Commune, and Tram Hanh Commune ($Rth < 2.5$). The application of a higher weighting factor for human risk ($w_1 = 0.7$) highlights the importance of population and building density and provides a scientific basis for prioritizing landslide risk control.

5) The classification and coding of 33 buildings indicate a clear variation in risk levels: 12 buildings (36%) are classified as Very High Risk, 6 buildings (18%) as High Risk, 7 buildings (21%) as Moderate Risk, and 8 buildings (24%) as Low Risk. The application of the coding system (KV–YY–ID–UT) not only standardizes information and facilitates the retrieval and management of individual sites but also provides a scientific basis for comparing, synthesizing, and integrating spatial and temporal risk data. In practice, the coding system supports resource prioritization, intervention planning, construction planning control, and enhances local early warning and disaster risk management.

6) Landslide risk control is implemented through a systematic process that integrates regional-scale risk assessment with quantitative risk evaluation at specific sites. This approach is based on local data, ensuring practical applicability while providing a scientific basis for prioritizing risk control measures. It therefore contributes to improving landslide risk management in mountainous urban areas and can be applied to other regions with similar conditions.

7) The dissertation proposes a comprehensive landslide risk management framework covering all stages from hazard analysis, risk assessment, and risk quantification to risk control, monitoring, and periodic

updating. The proposed framework ensures continuity, adaptability, and integration into urban development planning, thereby enhancing the capacity for landslide prevention and loss reduction.

8) The dissertation still has several limitations: (i) historical landslide and monitoring data are incomplete, and the observation period remains relatively short; (ii) the hazard assessment mainly relies on the AHP method and statistical analysis and is therefore influenced by expert judgment; and (iii) the study does not fully cover all types of geological hazards and indirect losses. In addition, the rainfall thresholds were established using daily rainfall data and therefore do not fully capture short-duration, high-intensity rainfall events. The limited number of landslide events also introduces uncertainty in determining rainfall thresholds for landslide initiation. Nevertheless, the results provide valuable practical implications and serve as a foundation for further improving landslide risk assessment and early warning models in future studies.

RECOMMENDATIONS

- Integrate the landslide hazard and risk maps developed in this dissertation into urban planning and development management in the Da Lat–Lac Duong area, with particular attention to areas where $R_{th} \geq 3.5$, in order to control land modification, slope cutting, and building construction.

- Prioritize the implementation of the engineering and non-engineering measures proposed in this dissertation, including drainage systems, slope stabilization, vegetation cover restoration, and the establishment of a periodic monitoring network integrated with a WebGIS platform for monitoring, early warning, and risk information updating.

- Local authorities should allocate sufficient resources for disaster prevention and mitigation while applying the risk classification results (Rth, Rcn, and Rts) to prioritize risk control, mitigation, or relocation measures in hazardous areas.

- The findings and proposed framework of this dissertation can be applied to other mountainous urban areas in Vietnam, contributing to both the scientific basis and practical implementation of landslide risk management.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

1) **Nguyen Viet Tien**, Nguyen Trong Tai, Tran Trong Hien, Ha Ngoc Anh, Do Minh Duc, 2022, Characteristics of Large-Scale Landslides in B'Lao Ward, Bao Loc City, Lam Dong Province. *Proceedings of the 2021 ACEA-VIETGEO National Scientific Conference on Geological Hazards* (ISBN: 978-604-67-2296-0), pp. 497–504.

2) **Nguyen Viet Tien**, Ha Ngoc Anh, Hoang Hai Yen, Nguyen Trong Tai, Tran Phu Hoang, 2024, Effects of Slope Morphology Modification and Structural Loading on Slope Stability in the Da Lat–Lac Duong Urban Area, Lam Dong Province. *Journal of Geotechnical Engineering (ISSN - 0868 - 279X)*, No. 4, pp. 29–38.

3) Pham Le Hoang Linh, Nguyen Trung Kien, Duong Van Binh, **Nguyen Viet Tien**, Nguyen Quoc Thanh, Vy Thi Hong Lien, Do Thang, Nguyen Trong Tai, 2025, Landslide Hazard in the Ta Xua Area, Bac Yen District, Son La Province, and Its Potential Impact on Buildings. *Journal of Construction (ISSN - 2734 - 9888)*, No. 2, pp. 46–49.

4) **Viet-Tien Nguyen**, Trong-Tai Nguyen, Mai Nguyen Thi, Yen Hoang Hai, Lien Vi Thi Hong, Do Minh Ngoc, Indra Prakash, Tran Van Phong, 2025, Forecasting deep-seated landslide displacements based on the application of machine learning models using automatic monitoring data. *Journal of Science and Transport Technology (ISSN: 2734-9950)*, 5(4), tr. 87-106.

5) **Nguyen Viet Tien**, Nguyen Kim Hung, Hoang Hai Yen, Nguyen Van Huong, Nguyen Trong Tai, Ha Ngoc Anh, 2026, Data-driven forecasting of landslide displacement using machine learning and real-time monitoring. *VNU Journal of Science: Earth and Environmental Sciences (e-ISSN 2588-1094)*, tr. 1-12.