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Graduation Project Report

GIS-based Landslides Susceptibility Mapping (LSM) in the West Bank, Palestine

By

Sabri Ghassan Barham – Reg. No: 12029265

Rokon Ali Bawaqne – Reg. No: 11926676

Naser Oruoba Shurafa– Reg. No: 11926832

Under the supervision of: Dr. Sameer Shadeed

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DEDICATION

We dedicate this Project to all the people who have worked hard to help us complete this project.

This project is especially dedicated to the teachers who helped and guided us to complete this project work.

Also, I would like to dedicate this project to my dear father, who has been a wonderful supporter until my research was completed, and to my beloved mother, who has been encouraging me for months.

ACKNOWLEDGEMENT

In the name of God, the most gracious, the most merciful. Praise be to God, by whose grace good deeds are accomplished. Praise be to God, who has enabled us to complete this project. Special thanks go to my supervising Professor, Dr. Sameer Shadeed, for supervising and sharing his valuable lessons with me during this project. His valuable assistance with constructive comments and suggestions during the experimental work and preparing the project contributed greatly to the success of this project. Many thanks to Dr. Isam Jardaneh and Dr. Ahmed Ghadieh for providing important information and directing us to where to get some Important data, and to Dr. Radwan Al-Kalani for providing insightful guidance. We will not forget our thanks to our parents for their endless love, prayers, and encouragement throughout our journey. I also thank our brothers and friends for their help in writing this project. Thank you everyone.

DISCLAIMER

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GIS-based Landslides Susceptibility Mapping (LSM) in the West Bank, Palestine

ABSTRACT

Landslides are a significant geological hazard, threatening lives, properties, and environmental stability worldwide. This project focuses on the development of a Landslides Susceptibility Map (LSM) for the West Bank, Palestine, utilizing a Geographic Information System (GIS)-based Analytic Hierarchy Process (AHP). The West Bank's complex topography and geological diversity, characterized by its mountainous terrain and varied climatic conditions, increase its vulnerability to landslides. Recent events, such as the devastating landslide in Nablus, highlight the urgent need for effective land-use planning and risk mitigation.

This project employs a GIS-based multi-criteria decision analysis (MCDA) approach, integrating nine key criteria: soil, rainfall, land use, road distance, drainage distance, elevation, slope, aspect, and curvature. The AHP method is utilized to weigh these criteria, ensuring a comprehensive and reliable LSM. The project aims to inventory existing landslides, identify high-risk areas, and propose sustainable plans and mitigation strategies to protect the West Bank's population and infrastructure.

The study reveals that approximately 26% (1,464 km²) and 15% (828 km²) of the total area of the West Bank are highly and very highly susceptible to landslides, respectively. Meanwhile, areas with moderate susceptibility to landslides constitute about 26% (1,412 km²) of the total area of the West Bank. Finally, regions with low and very low susceptibility to landslides account for approximately 18% (1,023 km²) and 15% (822 km²) of the total area of the West Bank, respectively.

The resulting LSM provides a crucial tool for policymakers, planners, and stakeholders in Palestine, showing sustainable land use and enhancing public safety. It addresses the urgent need for a national spatial plan that considers landslide risks, aiding in the development of proactive measures to prevent future disasters. This project contributes significantly to the field of engineering geology and geomorphology, demonstrating the effectiveness of GIS and AHP in landslide susceptibility mapping and analysis.

1 Introduction

1.1 Background

One of the most damaging geological disasters in the world, landslides pose a threat to properties, resources, human lives, and the environment (Yu & Chen, 2020; Rotigliano et al., 2012). Due to their high frequency and widespread distribution, many scientists have focused on studying landslides, with some dedicating their careers to landslides susceptibility mapping (LSM) (Yu & Chen, 2020).

In mountainous areas, landslides are among the most devastating events that regularly occur (Panchal & Shrivastava, 2022). Maps that indicate the likelihood of landslides are necessary for planning and mitigation efforts. LSM denotes the potential of landslides occurring in a specified area. A profound understanding of the mechanisms triggering these landslides is essential for research assessing their potential risks (Panchal & Shrivastava, 2022; Bozzano et al., 2010).

By analyzing LSM, areas at high risk can be identified. Accordingly, the harmful impacts of landslides can be minimized by taking proper mitigation measures. Over the years, the development of LSM has made it an important topic in many fields such as engineering geology and geomorphology. (Yu & Chen, 2020; Bui et al., 2019; Liu et al., 2019).

Thus, LSM is vital for managing associated risks. These maps support authorities, practitioners, and decision-makers in developing sustainable strategies and risk mitigation measures, such as implementing monitoring and warning systems (Roccati et al., 2021; Dai et al., 2002; Cascin et al., 2005; Corominas et al., 2014).

This graduation project aims to develop an LSM for the entire West Bank using a GIS-based AHP approach. The developed map is of high value for different stakeholders to identify high landslides susceptible areas and accordingly develop strategies and mitigation measures for sustainable land use planning in Palestine.

1.2 Landslides

Landslides stand as a formidable natural phenomenon, marked by the displacement of soil, rock, and debris down slopes, driven by the force of gravity. This process is often triggered by a combination of natural events such as heavy rainfall, earthquakes, and volcanic eruptions, alongside human activities including deforestation, urban development, and mining (Highland & Bobrowsky, 2008).

Landslide classification is crucial for effective risk assessment and management, distinguishing between types based on movement (falls, slides, flows) and material (rock, earth, debris). This classification facilitates a targeted approach to landslide prediction, prevention, and response, tailored to the specific characteristics and risks of each landslide type. The adverse effects of landslides extend beyond immediate physical damage, contributing to longer-term challenges such as economic disruption, habitat loss, and reduced water quality, making the study of landslides a critical aspect of environmental and disaster management science (Hungr et al, 2014).

The risk management of landslides encompasses a comprehensive strategy that includes hazard identification, risk assessment, monitoring, early warning systems, and both structural and non-structural mitigation measures. Effective management strategies also emphasize the importance of community engagement and preparedness, aiming to enhance the resilience of communities to landslide hazards. Advances in technology and data analysis have significantly contributed to improvements in landslide monitoring and early warning, offering new tools for risk reduction and disaster response (Froude & Petley, 2018).

1.3 GIS Applications In Landslides Susceptibility Mapping

Geographic Information Systems (GIS) are pivotal in managing, analyzing, and displaying spatial and geographic data. Integrating hardware, software, and data, GIS captures, manages, analyzes, and displays geographically referenced information, enabling users to visualize, question, analyze, and interpret data to understand relationships, patterns, and trends. This integration is crucial across various domains such as urban planning, environmental science, and healthcare, demonstrating GIS's versatility and essential role in spatial analysis and decision-making processes (Longley et al., 2015).

ArcGIS, developed by ESRI, is a leading platform in the GIS sector that offers a comprehensive suite of software, enhancing GIS capabilities with advanced analytical tools, extensive databases, and sophisticated mapping features. Recognized for creating detailed geographical representations and conducting spatial analysis, ArcGIS facilitates decision-making in both public and private sectors (Esri, 2022).

The advent of GIS technology, particularly through platforms like ArcGIS, has revolutionized spatial data usage. Furthermore, ArcGIS's capabilities in real-time data analysis and cloud-based services provide scalable solutions for data collaboration, impacting smart city development, sustainable growth, and digital transformation across industries (Mitchell, 2012).

In recent years, Geographic Information System (GIS) technology has become a popular tool for mapping and analyzing LSM. This technology often includes data from innovative sources, like satellite data and light detection and ranging (LiDAR) images (Roccati et al., 2021). GIS-based models are efficient in managing vast amounts of data and enable spatial analysis of landslides susceptibility, which is crucial for effective land planning and risk mitigation (Roccati et al., 2021; Yalcin et al., 2011; Turconi et al., 2019).

One of the analytical techniques employed in the literature for LSM is the analytic hierarchy process (AHP) (Roccati et al., 2021; Cignetti et al., 2019). The AHP is a multicriteria decision analysis (MCDA) approach that is commonly used in natural hazard management (Roccati et al., 2021; Gamper et al., 2006; Paliaga et al., 2019).

1.4 Research Importance and Objectives

For proper and strategic land use planning, different natural hazards have to be identified. Landslides are one of the main hazards that need to be studied to avoid any misuse of land for different uses. In Palestine, some buildings were built in landslide-prone areas. In recent years, some landslides occurred as the one in Nablus (the white mountain), and as a result, several buildings were destroyed totally or partially. This situation has compelled the dire need to properly map landslides susceptible areas. Accordingly, the Palestinian national spatial plan can be improved to guide decision-makers (e.g., the Ministry of Planning and International Cooperation, the Ministry of Local Government, etc.) towards sustainable land use planning in Palestine and to offer valuable insights for minimizing potential damages and enhancing public safety.

The main goal of this graduation project is to develop an LSM for the entire West Bank. In light of the above, the following objectives are to be achieved:

1. To inventory the location of existing landslides in the different West Bank governorates.
2. To identify high landslides and susceptible areas in the different West Bank governorates.
3. To propose sustainable plans and mitigation measures to protect existing buildings in high landslides susceptible areas.

1.5 Study Area

The West Bank of Palestine is located in the Middle East region. Its area is about 5640 km^2. Land surface elevations range from 1,022 meters above mean sea level in the south (in Hebron) to 410 meters below mean sea level near the Dead Sea (in Jericho) (UNEP, 2003).

Administratively, the West Bank is divided into 11 districts (see Figure 1), and the total population is approximately 3.25 million people (PCBS, 2023).

Land use and land cover in the West Bank represent approximately the following percentages for each category: arable lands (14%), built-up areas (5%), irrigated agriculture (2.6%), Israeli settlements (1.4%), permanent crops (14%), rough grazing (62%), forests/woodlands (0.7%).

West Bank is a relatively small geographic area however the soils are remarkably diverse in their properties. This diversity is due to the variation in climatic, origin (parent material), and topographic features (Dudeen Basem, 2001). The types of soils in the West Bank are divided into four categories based on the maps we have each type includes a description of the nature of the soil it encompasses. Clay loam (35.8%), Loamy (9%), Sandy loam (8%), and Clay (46.6%).

Palestine is distinguished by the diversity of its climatic regions despite its small area. It belongs to the temperate Mediterranean region and has a tropical climate and a desert and semi-desert climate. The Mediterranean Sea had a prominent impact on the diversity of its climate, which is affected by the westerly winds accompanying the low air, especially in the northern regions of Palestine. The climate of Palestine is considered moderate climate compared to the Middle East region, but there is a clear difference in the climate of Palestine between its south and north and between the coastal plains and the Jordan Valley which shows rainfall in the West Bank (PMD, 2023).

West Bank, is sedimentary rock composed of limestone, dolomite, and marly limestone rock, while the others are composed of evaporates of Lisan formations (Ghanem Marwan, 2022).

The region of Palestine has been experiencing landslide hazards due to its topographical and geological conditions. Most of Palestine consists of mountainous areas, which have great steep slopes and the type of soil is mainly grayish to yellowish silty clay (Marl Soil). Due to the above-mentioned factors, many landslides have occurred from Negev south to the northern borders of Palestine. An example of huge and destructive landslides in a Palestine authority is the landslides in the White Mountain area in the city of Nablus (Alwahsh, 2013).

An example of huge and destructive landslides in Palestine is the landslide in the White Mountain in the city of Nablus, which occurred due to soil movement in the area, which led to the collapse of entire homes and damage to several nearby homes (Jardaneh et al, 2022).

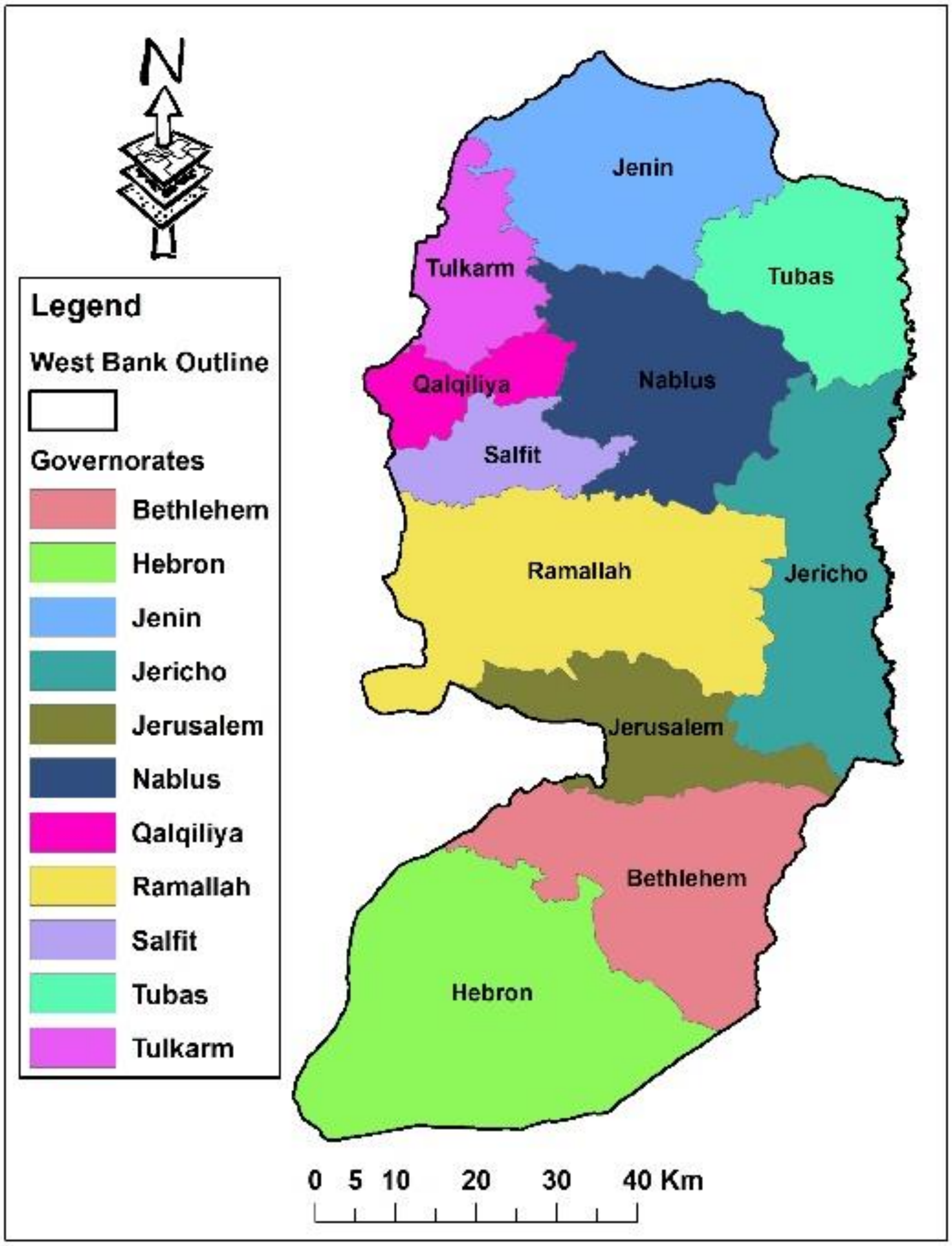

Figure 1: The West Bank of Palestine

2 Design Methodology

2.1 Landslides Selected Criteria

The following are the selected criteria for the development of LSM for the West Bank (see Figure 2).

1. **Soil (S)**
   The soil composition in a specific region significantly influences landslide occurrences, encompassing factors such as particle size, shape, and pore characteristics, consequently impacting slope stability. Understanding soil characteristics is valuable in the assessment of landslides (Das, 2011; Rossi & Reichenbach, 2016; Makonyo & Zahor, 2023) and

plays a crucial role in managing specific types of landslides in the area. Additionally, soil type determines water infiltration, water movement, and the soil's water retention capacity (Silalahi et al., 2019; Makonyo & Zahor, 2023). Soils like clay, characterized by larger pore spaces, tend to retain a higher volume of water, making them more susceptible to landslides (Lepore et al., 2012; Makonyo & Zahor, 2023). Conversely, soils with shallow depths exhibit an increased vulnerability to landslides (Das & Lepcha, 2019; Makonyo & Zahor, 2023).

2. Rainfall (R)

High-intensity rainfall emerges as a predominant factor contributing to landslides in diverse global regions (Jennifer et al., 2021; Youssef, 2015; Makonyo & Zahor, 2023). Functioning as an active catalyst, it directly impacts the stability of surface slopes within specified areas. Additionally, both intense, brief episodes and prolonged rainfall periods govern surface runoff, thereby energizing soil pore water pressure. Consequently, this process triggers the attenuation of soil strength, posing a threat to the stability of the terrain (Jennifer et al., 2021; Makonyo & Zahor, 2023). Rainfall has been a central focus in landslide research for various scholars (Gheshlaghi & Feizizadeh, 2021; Hong et al., 2018; Jennifer et al., 2021; Makonyo & Zahor, 2023), with consistent findings highlighting it as the primary influential factor in landslide occurrence.

3. Land Use (LU)

Land use emerges as a critical factor influencing landslides, as it contributes to the removal or addition of loads in a stable environment. Areas with inadequate cultivation practices, including bare lands, regions with sparse vegetation, and grass-covered lands, exhibit heightened vulnerability to soil degradation, mass wasting, and slope instability. To delve into these dynamics, a comprehensive land use map was crafted for the study (Asmare et al., 2023). the land use map of the study area was methodically classified into seven distinct categories: Arable Land (supporting grains), Built-up Areas, Irrigated Farming (supporting vegetables), Israeli Settlements, Permanent Crops, Rough Grazing/Subsistence Farming, Woodland/Forest.

4. Road Distance (RD)

The proximity to roads is significantly linked to landslide occurrences, often arising from slope excavation during road construction. This excavation disrupts the geological and slope structure of a specific area, consequently contributing to slope instability and potential landslides (Kavzoglu et al., 2014; Makonyo & Zahor, 2023). This association, emerges as a key contributing factor to slope instability, leading to slope failures (Jennifer et al., 2021; Makonyo & Zahor, 2023). It is a widely utilized parameter in landslide research, significantly influencing the understanding of landslide occurrence (Chen et al., 2019; Moragues et al., 2021; Ozioko & Igwe, 2020; Makonyo & Zahor, 2023).

5. Drainage Distance (DD)

The stability of slopes is intricately linked to the drainage density of the catchment (Asmare, 2022b; Asmare et al., 2023). Streams play a dual role in affecting land stability by eroding slopes and saturating the Earth's materials, leading to a loss in shear strength and an ensuing enhancement of slope instability. Consequently, areas located farther from streams tend to exhibit greater stability. To explore this relationship further, the distance to the drainage map was meticulously reclassified into five distinct classes: 0-440.6, 440.6-881.3, 881.3-1445.3, 1445.3-2044.5, and 2044.5-4494.5 (Asmare et al., 2023).

6. Elevation (E)

Elevation above mean sea level has a direct impact on both biological and natural elements (Kavzoglu et al., 2014; Makonyo & Zahor, 2023) and serves as a key determinant in landslide occurrences (Hong et al., 2018; Makonyo & Zahor, 2023). This influential factor typically shapes various geological and geomorphological aspects of the Earth's surface (Ayalew & Yamagishi, 2005; Makonyo & Zahor, 2023). Elevation controls the direction of streams and the density of drainage networks, significantly influencing soil moisture and slope gradient (Yilmaz, 2009; Zhao et al., 2022). Lower altitudes often indicate stable surfaces, while higher grounds tend to exhibit increased instability (Devkota et al., 2013; Makonyo & Zahor, 2023).

7. Slope (SL)

The slope is defined as the degree of elevation change over a specified area. Lower slope values indicate relatively flat surfaces, while higher values signify elevated areas (Rahaman & Aruchamy, 2017; Makonyo & Zahor, 2023). The slope plays a pivotal role in Landslide Susceptibility Mapping LSM assessments (Hong et al., 2018; Nguyen et al., 2019; Makonyo & Zahor, 2023). Consequently, it directly influences shear forces (Lee & Min, 2001; Makonyo & Zahor, 2023). In a theoretical context, the susceptibility to landslides is projected to increase in regions characterized by steeper slopes (Dou et al., 2015; Zhao et al., 2022), as the acceleration of mass removal becomes notably pronounced when the surface inclination angle surpasses a critical threshold of 30° (Tofelde et al., 2017; Makonyo & Zahor, 2023). Conversely, the risk diminishes to zero in areas with slopes less than 5° (Dou et al., 2015; Zhao et al., 2022).

8. Aspect (A)

The term 'Aspect' refers to the directional orientation of the slope angle and holds significance as a key factor influencing landslides (Tesfa and Woldearegay 2021; Asmare et al., 2023). This influence stems from various conditions, encompassing the weight of the slope, exposure to sunlight, effects of cold and hot winds, rainfall patterns, and the presence of discontinuities (Awawdeh et al. 2018; Bera et al. 2019; Asmare et al., 2023). The slope aspect significantly impacts moisture retention, vegetation cover, and subsequently, soil strength, collectively contributing to the occurrence of landslides (Asmare et al., 2023). Aspect determination utilized Digital Elevation Model (DEM) data in ArcGIS software, classified into ten distinct classes.

9. Curvature (C)

Curvature refers to the variation in slope along a small arc of the surface curve. This factor has been identified as a triggering element in landslides, influencing the velocity and direction of mass motion (Kornejady, 2017; Zhao et al., 2022). The curvature map of the designated area was generated using Digital Elevation Model (DEM) data and classified into five categories: very concave, concave, flat , convex, and very convex surfaces (Asmare et al., 2023). Positive or negative curvature values indicate a higher probability of landslide occurrence. In flat areas, the likelihood of landslide occurrence is very low. A positive curvature signifies an upwardly convex surface at that grid, while a negative curvature indicates an upwardly concave surface. A curvature value of zero denotes a flat surface (Mersha and Meten, 2020).

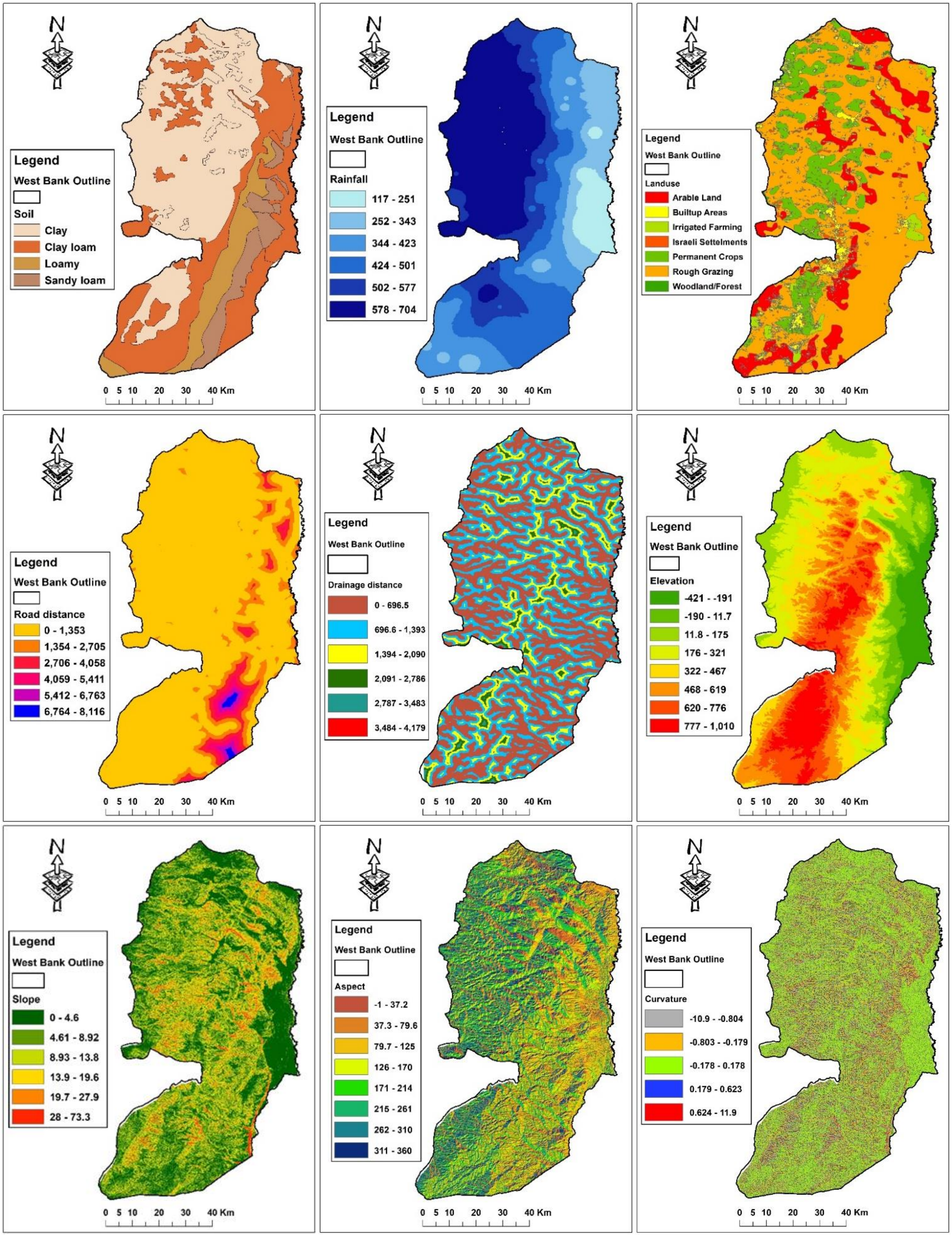

Figure 2: The 9 criteria for LSM

2.2 Methodological Approach

In this project, the LSM was created using the GIS-based multi-criteria decision analysis (MCDA) approach. 9 influential criteria were selected to make the LSM (see Table 1). More details of these criteria are presented in section 2.1.

Table 1: LSM criteria

Criteria	Description	Data Source
S	Soil	Geomolg[1]
R	Rainfall	
LU	Land Use	
RD	Road Distance	
DD	Drainage Distance	
E	Elevation	USGS[2]
SL	Slope	
A	Aspect	
C	Curvature	

1 Geoportal for Geospatial Information in Palestine.
2 The United States Geological Survey Earth Explorer.

The general methodological framework for developing the LSM is shown in (see Figure 3). To give proper weights for the selected LSM criteria, the AHP pairwise comparison matrix approach (Saaty, 1980) was used (see Table 2). Consequently, the reliability of the defined weights was verified based on the consistency ratio (CR) as follows (Saaty, 1980):

$$\mathbf{CR = CI/RI \ \ldots\ldots\ldots\ldots\ (1) \qquad CI = (\lambda - n)/(n-1) \ \ldots\ldots\ldots\ldots\ (2)}$$

Where CI is the consistency index, RI is a random consistency index that depends on the number of criteria, λ is the maximum eigenvector of the matrix, and n is the number of criteria. The maximum allowable value of CR is 0.1 (Malczewski, 1999). In this project, an estimated value of 0.05 was obtained for the CR. This indicates that the LSM criteria matrix is consistent.

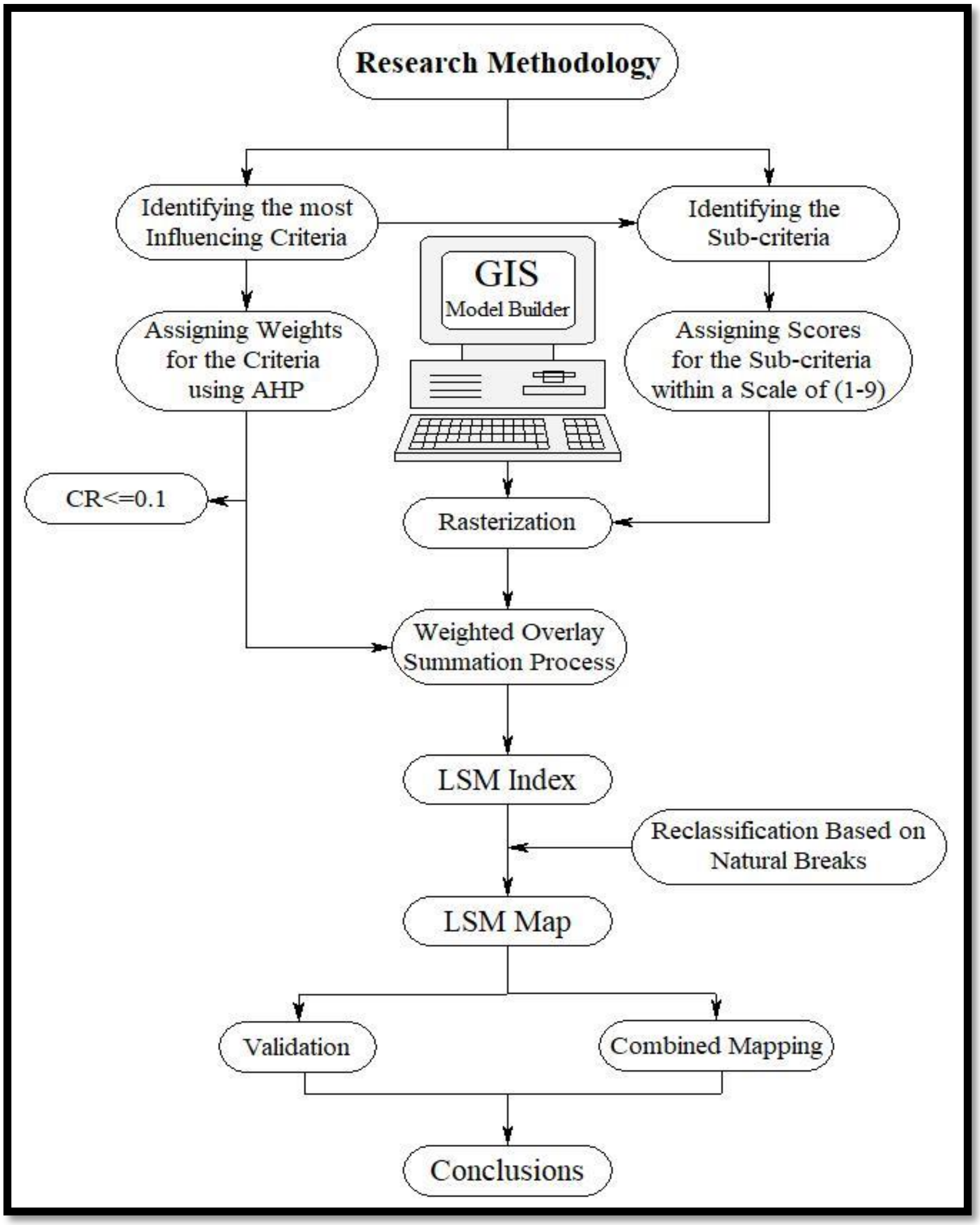

Figure 3: General methodological framework

In a GIS environment and using the weighted overlay sum process (WOSP), the LSM index (Malczewski, 1999) is estimated for various selected parameters by combining the weighted cell values. Then we multiply all the input raster data by their weight and the results are combined as follows:

$$\mathrm{LSM}i\sum_{i}^{\square} \mathrm{W}i \times Sij$$

Where LSMi is the overall cell index, Wi is the standardized weight ($\sum \mathrm{W}i = 1$), Sij is the score value of the ith cell of the raster j, and n is the number of cells in each raster j. The overall LSMi indices are then reclassified through the use of natural breaks (Jenks) in GIS to produce the final LSM of the entire West Bank.

Table 2: AHP pairwise comparison matrix for the LSM mapping in the West Bank

Criteria	S	R	LU	RD	DD	E	SL	A	C	Weight
S	1.0	1.8	2.3	4.3	2.8	2.7	2.8	6	3.8	27.5
R	0.6	1.0	1.3	2.4	1.5	2	1.8	3.4	1.7	15.7
LU	0.4	0.8	1.0	1.9	1.3	1.3	1.1	2.6	1.4	11.8
RD	0.2	0.4	0.5	1.0	0.7	0.7	0.4	1.4	1.0	6.4
DD	0.4	0.7	0.8	1.4	1.0	0.4	0.4	1.2	2.0	8.2
E	0.4	0.5	0.8	1.4	2.5	1.0	0.6	2.2	0.9	10.3
SL	0.4	0.6	0.9	2.5	2.5	1.7	1.0	3.4	2.4	15.3
A	0.2	0.3	0.4	0.7	0.8	0.5	0.3	1.0	0.5	4.6
C	0.3	0.6	0.7	1.0	0.5	1.1	2.0	2.0	1.0	9.2

Each criterion used in developing an LSM map is classified into several scores, and user-specified cell values (scores) were subjectively assigned from 1 to 9 for each one (see Table 3 and Figure 4). Theoretically, values which are close to 9 have the highest hazard, whereas the lowest hazard areas have values close to 1.

Table 3: Scores for criteria

#	Criteria	Sub-criteria	Score
1	Soil (S)	Sandy loam	3
		Loamy	5
		Clay loamy	7
		Clay	8
2	Rainfall (R)	117 – 269	1
		270 – 370	2
		371 – 453	4
		454 – 552	5
		553 – 704	8
3	Land Use (LU)	Woodland/Forest	3
		Agricultural areas	5
		Rough Grazing	7
		Built-up Areas	9
4	Road Distance (RD)	≥ 4,903	1
		2,961 – 4,902	3
		1,592 – 2,960	5
		542 – 1,591	7
		541 ≥	9
5	Drainage Distance (DD)	≤ 344	1
		345 – 918	3
		919 – 1,426	5
		1,427 – 2,049	7
		2,050 ≤	9
6	Elevation (E)	-421 – -89.4	4
		-89.3 – 197	2
		198 – 422	4
		423 – 658	6

		659 ≤	8
7	Slope (SL)	0 – 4.9	1
		5 – 10	3
		11 – 16	5
		17 – 24	8
		25 ≤	9
8	Aspect (A)	-1 (flat)	6
		0 – 67.5 (north, northeast)	8
		67.5 – 157.5 (east, southeast)	3
		157.5 – 247.5 (south, southwest)	4
		247.5 – 360 (west, northwest, north)	9
9	Curvature (C)	-11 – -0.8	8
		-0.79 – -0.18	6
		-0.17 – 0.18	3
		0.19 – 0.62	7
		0.63 –12	9

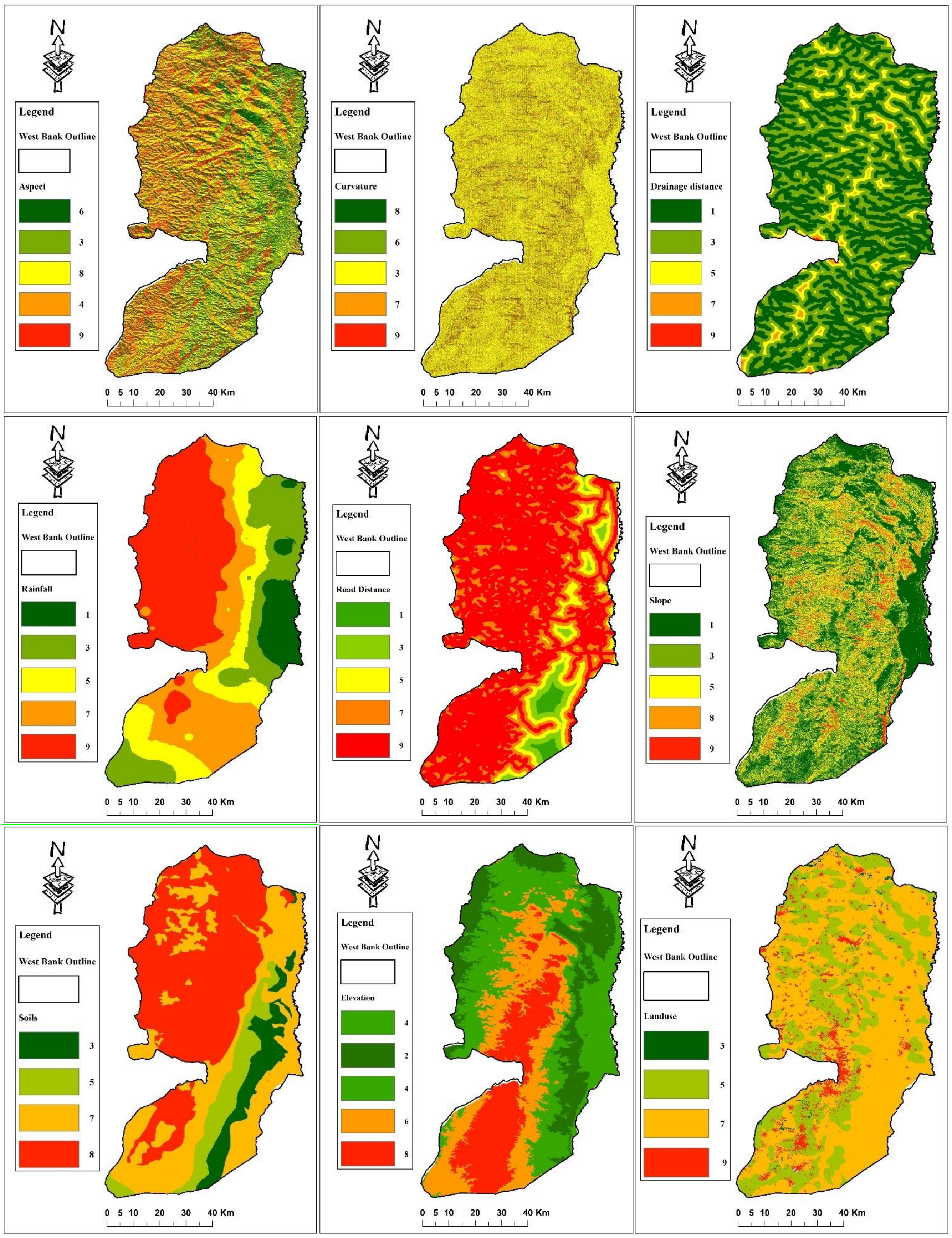

Figure 4: The scored raster grids of the nine criteria for the study area.

2.3 Building of a GIS-Based Model

To automate the development of LSM based on the aforementioned methodology, the Model Builder was used. Model Builder in ArcGIS is a graphical interface designed to facilitate the creation, editing, and management of models, streamlining repetitive tasks and complex analyses in GIS projects. This tool enables users to visually construct workflows that integrate various datasets and perform spatial analyses systematically.

One of the significant advantages of Model Builder is its ability to simplify complex workflows. ESRI (2018) states that Model Builder allows users to string together geoprocessing tools to create intricate models, which is particularly useful in tasks such as landslide susceptibility mapping. Additionally, Model Builder enhances efficiency by automating repetitive tasks, reducing the time spent on these tasks and ensuring consistency and accuracy in the analysis (Mitchell, 2012). Another important aspect is the reproducibility and sharing capability of Model Builder. Models can be easily shared and reused, ensuring that analyses are consistent across different users and datasets, which is crucial for collaborative projects (Longley et al., 2015). Furthermore, Model Builder facilitates the integration of various data types and enhances data visualization. It allows users to integrate raster and vector data, apply spatial analysis techniques, and visualize results coherently, which is essential for comprehensive spatial analysis and decision-making (Nyarko, 2002). For this graduation project, sequential procedures for the development of LSM by the use of Model Builder can be depicted in Figure 5.

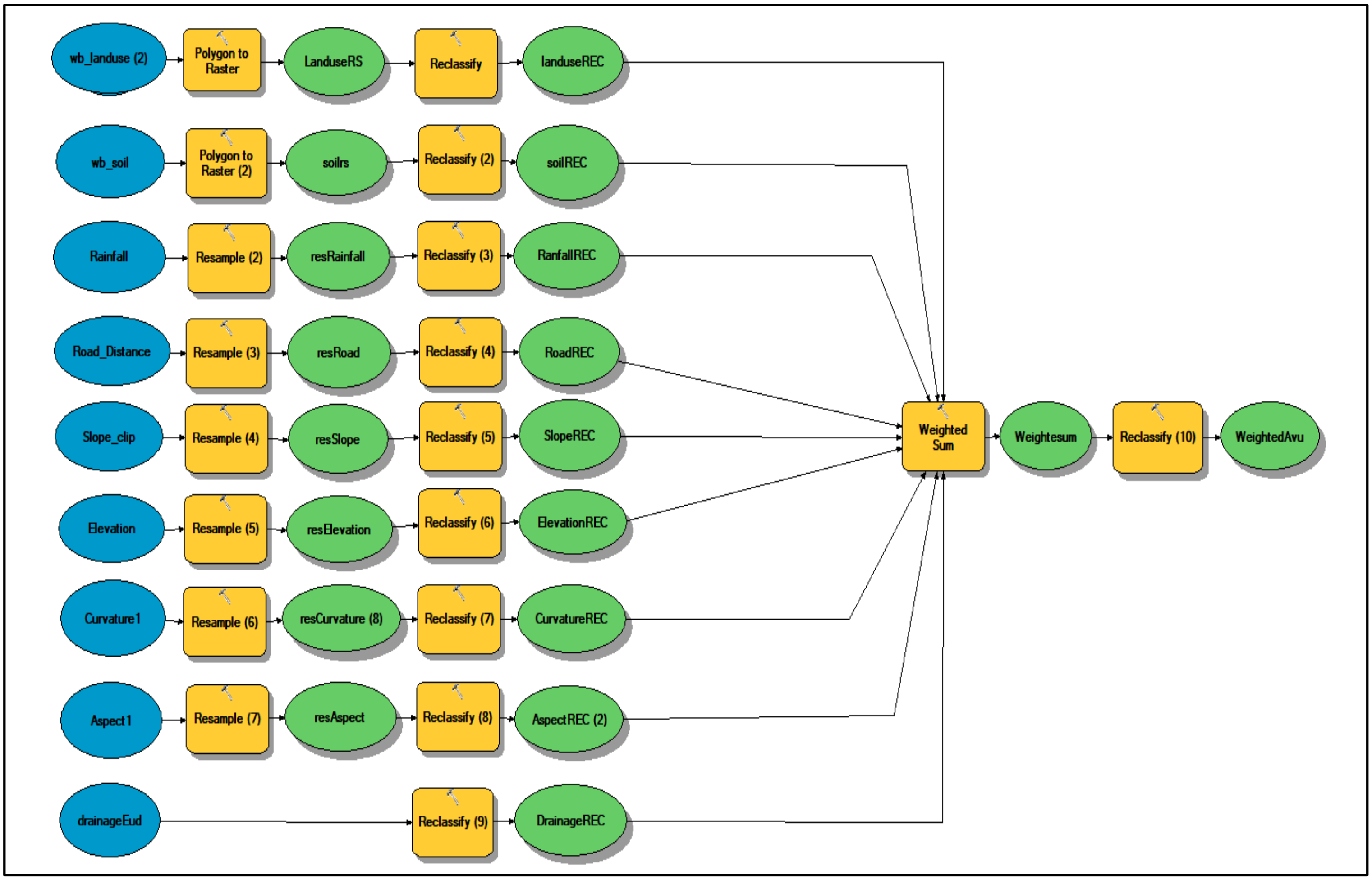

Figure 5: LSM model builder process

3 Results and Discussion

3.1 The Developed Landslides Susceptibility Map

Based on the theoretical framework of the LSM, and after performing the weighted sum and then reclassifying it, the LSM index is produced for the entire West Bank governorates. The map was classified into five susceptibility classes (very low, low, medium, high, and very high) by the natural breaks (Jenks) approach (see Figure 6). As such, ArcMap identified breaks by recognizing the intrinsic classification scheme of the input data. Thus, datasets are classified where breaks are set where notable jumps exist in the data values (Nerantzis et. al., 2015; Shadeed, 2018).

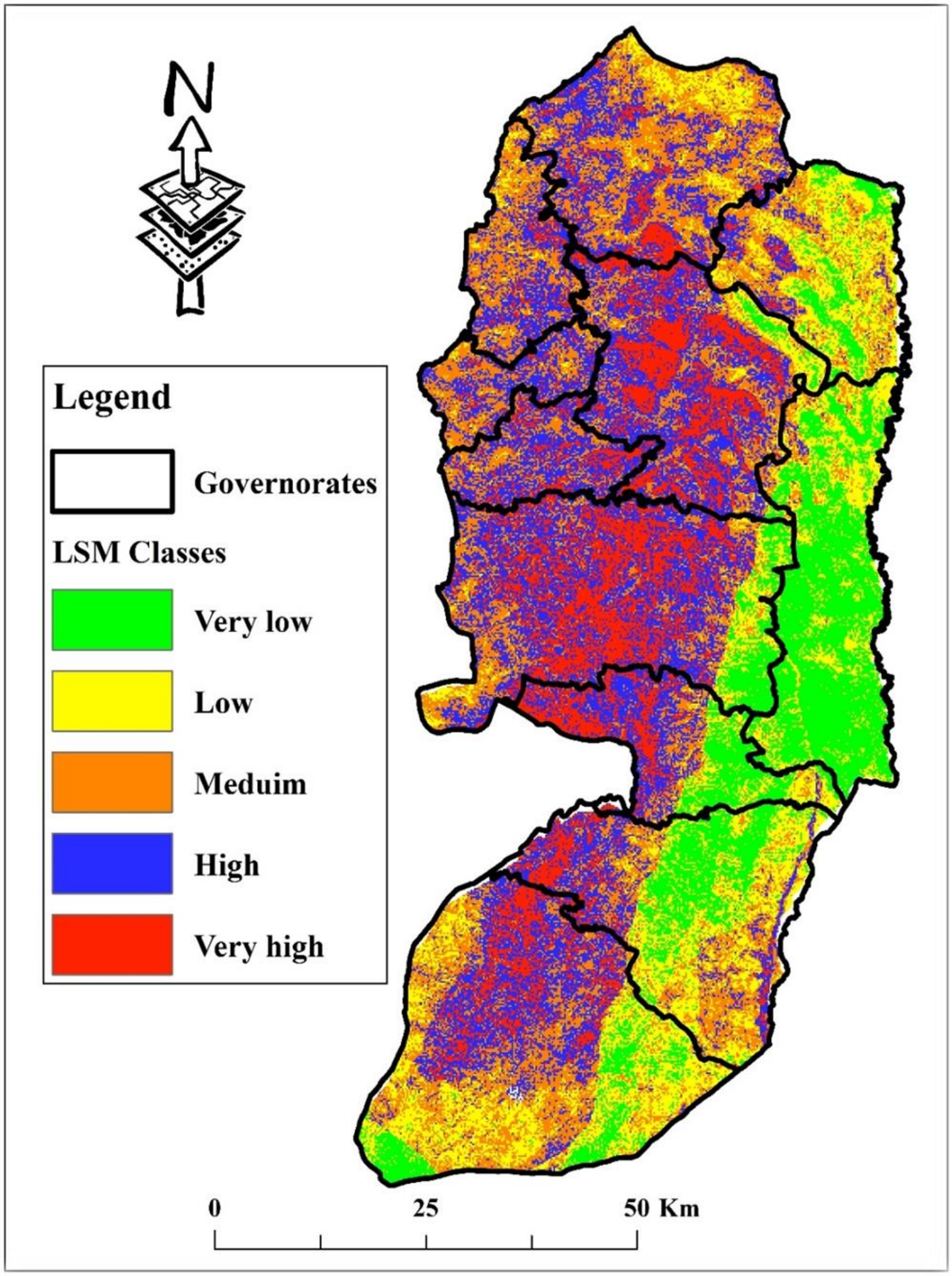

Figure 6: The developed LSM

The developed map indicates that the susceptibility classes of medium to high landslides make up the West Bank's largest areas (51%). Moreover, very high landslides susceptibility areas are mostly located in the middle parts with some concentrated regions in the northern and southern parts, and, high landslides susceptibility areas are in general sparsely distributed in the western parts of the West Bank with some concentrated regions of the middle parts (in Jerusalem district) and the north (in Tulkarm, Qalqiliya, Jenin and Nablus districts) and in the south (in the Hebron). whereas the very low and low ones are located in the eastern with some concentrated areas in the southern parts. This spatial trend is matched with the spatial distribution of mountain sequence with its elevation, slopes, and distance to drainage and all factors effective (Shadeed, 2018). Figure 7 presents, the areas, and percentages of the landslide's susceptibility regions in the West Bank.

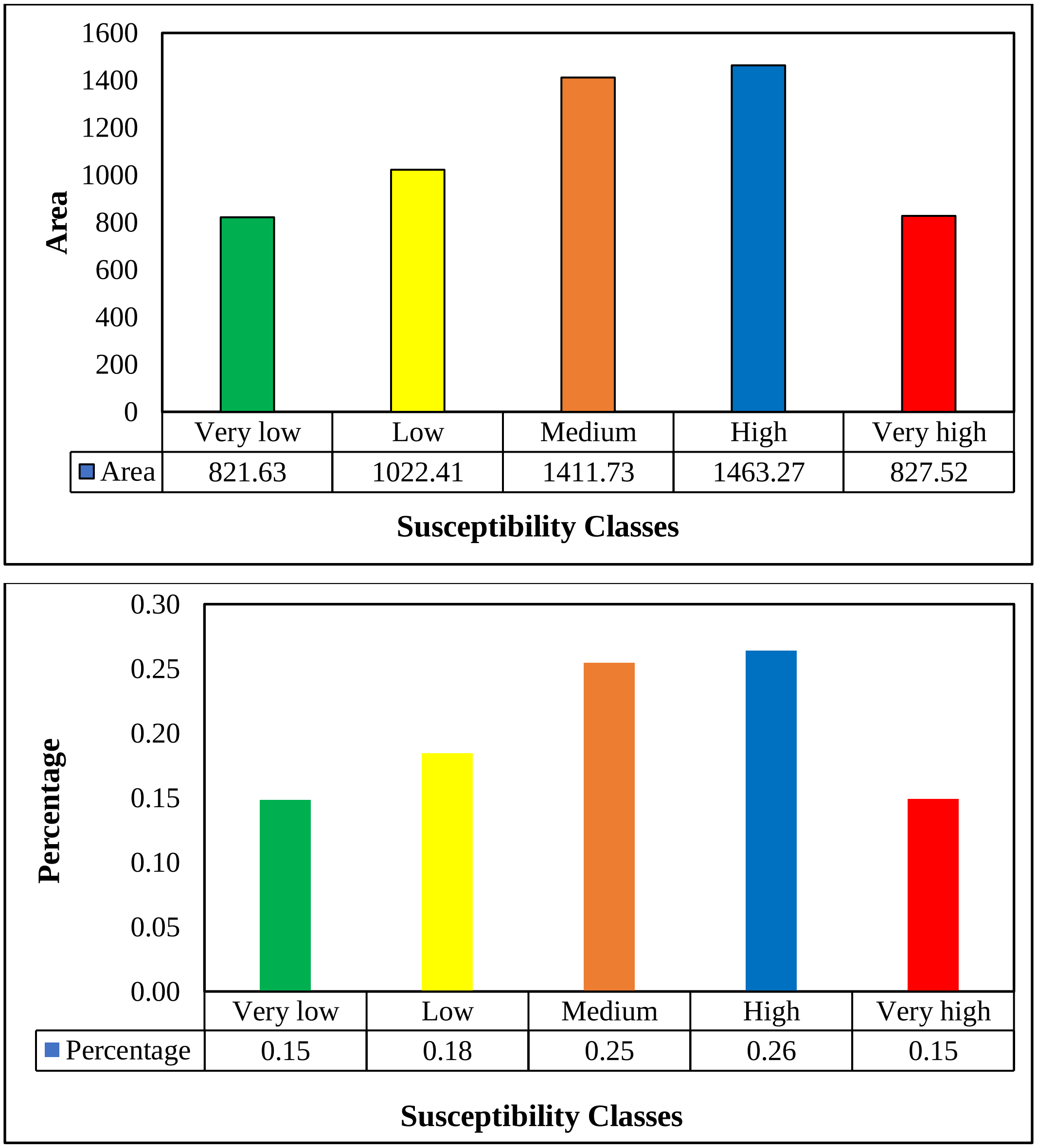

Figure 7: Landslides susceptibility areas and percentages in the West Bank

From the figure, it can be concluded that about 26% (1464 km^2) and 15% (828 km^2) of the total West Bank area are high and very high vulnerable to landslides susceptibility, respectively. This, in turn, confirms the urgent need to enhance sustainable planning (such as structural plans) in these areas to remove buildings and population centers from these areas vulnerable to landslides and thus mitigate their catastrophic consequences. Whereas land having medium landslides susceptibility forms about 26% (1412 km^2) of the total West Bank area. In such areas, attention should be also taken to infrastructure development to avoid unfavorable consequences. Finally, low and very low landslides susceptibility areas form about 18% (1023 km^2) and 15% (822 km^2) of the total West Bank area, respectively (Shadeed, 2018).

3.2 LSM Validation

The validation process is crucial in assessing the accuracy and reliability of the developed LSM in this project. By comparing the obtained results with actual landslide occurrences, we can evaluate the reliability of the developed LSM for the entire West Bank. In this study, several known landslide sites, such as Silat Dhahar Road, Sebastia, White Mountain, Kafr Qalil, Wadi Al Badan Road, and Beit Ur al-Tahta - Wadi Griot, were used for validation (see table 7). These sites, identified by their specific coordinates, were cross-referenced with the landslide susceptibility map to verify that they fall within regions classified as "Very High" susceptibility. This step ensures that the accurately of the obtained results reflect real-world conditions and can reliably predict areas at high risk for landslides.

Validation is not only a means of checking the results performance but also a way to convince potential stakeholders and policymakers regarding the effectiveness of the developed LSM. By demonstrating that the results predictions align with actual data, the validation process underscores the map's utility in guiding land use planning and risk mitigation strategies. This alignment between predicted and actual landslide events confirms the robustness of the GIS-based MCDA approach used in the study, reinforcing the map’s credibility and practical application in enhancing public safety and sustainable development in the West Bank.

Table 7: Points validation

Location Name	X	Y
Silat Dhahar Road	167538	190754
Sebastia	167829	186973
White Mountain	176005	182293
Kafr Qalil	176894	178032
Wadi Al Badhan Road	179290	183752
Beit Ur al-Tahta - Wadi Griot	163270	143796

3.3 Combined Mapping

The combined mapping approach in this project involved the integration of various criteria to assess landslide susceptibility across the West Bank. Utilizing GIS and the MCDA method, this process allowed for a comprehensive classification of areas based on their susceptibility to landslides. Specifically, the analysis was performed by examining the relationship between landslide-prone areas and the administrative boundaries of the governorates as well as built-up areas. By incorporating multiple influential factors, the resulting maps offer a detailed understanding of the spatial distribution of landslide risks, which is essential for effective land use planning and disaster risk management.

Tables 4 and 5 provide landslides susceptibility areas and percentages respectively, for the West Bank governorates.

Table 4: LSM areas

Governorate	Landslides Susceptibility Class (Area, km^2)					
	1	2	3	4	5	Total Area
Bethlehem	137.9	194.5	149.9	101.7	50.2	634.1
Hebron	87.1	268.1	282.4	224.7	114.6	976.9
Jenin	0.1	70.1	264.3	183.0	58.1	575.5
Jericho	385.6	150.5	31.3	6.1	0.4	573.9
Jerusalem	72.9	46.1	43.5	96.5	78.2	337.2
Nablus	13.9	38.8	125.6	238.7	187.9	604.9
Qalqiliya	-	5.4	77.5	70.3	11.4	164.4
Ramallah	67.5	61.6	152.6	309.4	256.8	847.9
Salfit	-	1.6	56.8	102.1	42.5	203.0
Tubas	56.7	169.7	112.9	38.9	8.1	386.2
Tulkarm	-	16.1	115.1	92.0	19.5	242.6

Table 5: LSM percentage

Governorate	Landslides Susceptibility Class (%)					
	1	2	3	4	5	Total %
Bethlehem	0.22	0.31	0.24	0.16	0.08	1
Hebron	0.09	0.27	0.29	0.23	0.12	1
Jenin	0.00	0.12	0.46	0.32	0.10	1
Jericho	0.67	0.26	0.05	0.01	0.00	1
Jerusalem	0.22	0.14	0.13	0.29	0.23	1
Nablus	0.02	0.06	0.21	0.39	0.31	1
Qalqiliya	0.00	0.03	0.47	0.43	0.07	1
Ramallah	0.08	0.07	0.18	0.36	0.30	1
Salfit	0.00	0.01	0.28	0.50	0.21	1
Tubas	0.15	0.44	0.29	0.10	0.02	1
Tulkarm	0.00	0.07	0.47	0.38	0.08	1

From the Tables, it is clear that the districts of Nablus, Ramallah& Bireh, Jerusalem, and Salfit have the highest very high landslides susceptibility areas which account for about 31%, 30%, 23%, and 21% of the total districts' areas, respectively. Moreover, very low and low landslides susceptibility classes take up more than 93% of the total Jericho district area (Shadeed, 2018).

The areas of built-up likely to be affected by different landslides susceptibility classes are determined as summarized in Table 6.

Table 6: LSM classes of areas built-up

Landslides Susceptibility Class	Area of built-up (Km^2)	Percentage (%)
Very low	20.23	5.68
Low	22.29	6.26
Medium	77.33	21.73

High	140.33	39.43
Very high	95.72	26.90
Total	355.90	100.00

It is clear from the table that about 66.33% of the total buildings in the West Bank are exposed to high and very high landslide risks. About 21.73% of the buildings belong to the moderate landslide hazard zone. While the rest, 11.94% of the buildings, belong to low-lying and very low-lying areas at risk of landslides. This information is critical for planners in developing landslide warning systems and controlling areas where people can be allowed to build (Shadeed, 2018).

4 Conclusions and Recommendations

This project successfully employed a GIS-based MCDA to create a LSM for the West Bank, offering a vital tool for hazard assessment and risk management. The integration of 9 criteria (soil, rainfall, land use, road distance, drainage distance, elevation, slope, aspect, and curvature) allowed for a detailed and nuanced evaluation of landslide risks. The results emphasize the efficacy of using GIS and MCDA methodologies in environmental studies, providing critical insights for planners and decision-makers.

The study reveals that approximately 26% (1,464 km²) and 15% (828 km²) of the total area of the West Bank are highly and very highly susceptible to landslides, respectively. Meanwhile, areas with moderate susceptibility to landslides constitute about 26% (1,412 km²) of the total area of the West Bank. Finally, regions with low and very low susceptibility to landslides account for approximately 18% (1,023 km²) and 15% (822 km²) of the total area of the West Bank, respectively.

The combined mapping approach in this project involved the integration of various criteria to assess landslide susceptibility across the West Bank. Utilizing GIS and the MCDA method, this process allowed for a comprehensive classification of areas based on their susceptibility to landslides. Specifically, the analysis examined the relationship between landslide-prone areas, the administrative boundaries of the governorates, and built-up areas. By incorporating multiple influential factors, the resulting maps offer a detailed understanding of the spatial distribution of landslide risks. This comprehensive approach is essential for effective land use planning and disaster risk management, ensuring that high-risk areas are accurately identified and prioritized for mitigation efforts.

Based on the study results, the following recommendations are of utmost importance:

1. Consider geological, hydrological, and geomorphological factors when planning and implementing engineering projects and structures.
2. Identify and restrict future urban expansion directions in the study area to avoid areas with high landslide susceptibility.
3. Stabilize roadside slopes with concrete walls whose foundations extend below the slip surface.
4. Construct rainwater drainage channels to prevent water from reaching rock masses that are prone to falling.
5. Ensure collaboration between institutions and all relevant entities in addressing natural disasters.

6. Consider soil type and its bearing capacity in the building system and land zoning projects.
7. Ensure periodic and continuous updating of data to achieve the highest possible accuracy.

Finally, although the available data are limited, the work provides a comprehensive and valuable picture of the extent to which various areas of the West Bank are susceptible to landslides. This in turn indicates that even with scarcity of data and limited resources, much can be done to assist decision makers by providing essential information for mapping potentially very high landslides susceptibility areas and thus formulating appropriate corrective and preventive strategies including e.g. Not limited to emergency warning and preparedness plans, improvements to engineering structural plans to control slides, improving the distribution of people by improving the distribution of buildings, and protocols for managing catastrophic risks to people's lives and property.

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6 Appendices