

Machine Learning Techniques for Landslide Susceptibility Mapping in Choman District, Iraq

Kaifi Chomani¹ * 

¹ Civil Engineering Department, University of Raparin, Ranya, Sulaymaniyah, Kurdistan Region 46012, Iraq.

Article History

Received: 17.10.2024

Revised: 21.11.2024

Accepted: 06.12.2024

Published: 09.12.2024

Communicated by: Prof. Dr. Ayad M.

Fadhil Al-Quraishi

*Email address:

kaifi.chomani@gmail.com

*Corresponding Author



Copyright: © 2023 by the author. Licensee Tishk International University, Erbil, Iraq. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution-NonCommercial 2.0 Generic License (CC BY-NC 2.0) <https://creativecommons.org/licenses/by-nc/2.0/>

Abstract:

The geographic information system (GIS) and remote sensing techniques used in this study with an integration of different machine learning techniques such as support vector machine (SVM), Random Forest and Decision Trees (RT), and K-Nearest Neighbor (KNN) to generate accurate and reliable map of areas susceptible to landslides for Choman District in Kurdistan region of Iraq. Residents and infrastructures can be damaged dramatically by landslides, emphasizing the critical need for accurate susceptibility map of landslides for effective disaster management and risk mitigation procedures. High resolution imagery from Google Earth Pro and field trips were used to collect historical landslide data to assess and validate the generated results. 14 different geological and environmental factors were considered as the primary contribution factors for landslides that used as to establish an effective susceptibility model. The research categorized Choman District into four vulnerability zones: very low, low, medium, and high susceptibility. The results highlighted that steep slope regions with proximity to geological faults and main roads are most vulnerable regions to landslides in Choman district. The results of landslide susceptibility mapping for SVM, RT, and KNN algorithms showed that 165.8 km² (19.3%), 278.2 km² (32.3%), 306.5 km² (35.6%) of Choman District is highly susceptible to landslides, however, only 96.1 km² (11.2%), 111.5 km² (12.9%), and 182.8 km² (21.2%) of Choman District were located in very low landslide susceptible areas. The area under the curve (AUC) were used to assess the accuracy of each machine learning techniques. AUC values for SVM, RT, and KNN techniques were 91.9%, 96.4% and 75%, respectively. The assessment indicated that SVM and RT showed better performance than KNN to generate the landslide susceptible areas. The results of this study provide valuable insights for urban planners and policy makers to perform sustainable planning and robust mitigation strategies.

Keywords: Landslide, Geographic Information System, Machine Learning, Choman District.

1. Introduction

The downward movement of rock or earth is considered as landslides which are a severe natural hazards. Environmental and geological conditions can significantly affect these landslide occurrences in different ways. Landslides could make human settlements, infrastructure, and natural ecosystems face serious challenges, leading to catastrophic consequences like loss of life, property damage, and environmental degradation. The landslides can have serious impacts, which makes the assessment and mapping of landslide-susceptible areas necessary to mitigate its risks and enhance preparedness. Iraq's diverse geological conditions, rainfall patterns, terrain slope, soil composition, and seismic activity have a huge contribution to the landslides frequency, resulting in severe damage to structures and human life. For instance, a landslide in Karbala resulted in the death of eight people in 2022 [1]. The Kurdistan region which is located in the north of Iraq within the Zagros series, specifically the Choman District due to its diverse mountainous formations and lithological units, is highly susceptible to landslides. Recent research has highlighted the necessity for more detailed and region-based landslide

analysis and assessments to face these challenges effectively. There were 3,190 different types of landslides, such as rock falls, translational slides, and slumps in the region [2, 3].

The Hamilton Road, starting from Haji Omran to Soran District, is a significant economic and strategic road between Iran and Iraq borders. Every year, Kurdistan region faces huge economic losses because of landslide occurrences from the mountains during the heavy rain seasons, which frequently block the route and causing people injuries, and impacting trucks, and cars [4]. These landslides also caused the damage of water pipes in Soran city, resulting in disruptions in the drinking water supply [5]. Additionally, landslides caused substantial damage on roads, vehicles, and properties around Choman areas. As an example, a huge landslide in 2022 which occurred during night and heavy rainfall, buried a house full of sheep, resulting in their dramatic deaths. Furthermore, a landslide on the side roads caused damage to a car, injuring the driver and passenger in Dukan District [6]. Similarly, a tragic landslide event near Darbandikhan District in southern of Sulaymaniyah province caused the deaths of two individuals and injury to a third one. The victims suffered fatal head wounds, they were mountaineers caught in the Tuni Baba gorge. The heavy rains were identified as the main cause of the landslide occurrence days [7].

These incidents emphasize the critical need to create accurate landslide prone areas, and plan accordingly to increase such risks to protect life of people and infrastructure for more sustainable environment. For effective disaster management and land-use planning accurate and reliable landslide susceptibility mapping of Choman and its surroundings are needed. Because having the risk map areas is helpful to identify areas that are prone to landslides and enables decision makers to create different strategic planning to reduce the impacts of landslides, saving properties, and protect lives of people. There are plenty of important researches that assessed and created landslide risk maps in Iraq, by using different types of approaches to improve our understanding related to the causes and impacts of landslides. In 2023, Al-Dhahi successfully used analytical hierarchy process (AHP) and geographic information system (GIS) to create a map of vulnerable areas to landslides for the Zurbatiya region in Wasit Governorate. This research used various parameters to create susceptible areas that have significant contribution to landslide events [1]. Similarly, in Kurdistan region of Iraq, Fatah integrated both frequency ratio (FR), AHP, and an ensemble FR-AHP model to create accurate map of landslide risk areas in the Akre District of the Kurdistan Region [8]. This research highlighted the effectiveness of different statistical model combinations together to enhance the accuracy of the landslide risk areas. Moreover, contributions of Othman was pivotal related to landslides in Kurdistan region if Iraq. In 2013, Othman used remote sensing techniques to automatically extract landslides in the Kurdistan region and analysed historical landslides in detail. Then, he applied different model statistics to create map of areas susceptible to landslides in the Mawat area, highlighting the significant contribution of various techniques in landslide-prone areas. Further in his research, a contribution to landslides, in 2017, Othman analyzed and created landslide vulnerable map for the Qala Dize area using remote sensing and GIS applications [2, 3, 9].

These researches together show the significant role of advanced geospatial technologies and statistical models in developing mapping landslides and risk assessment approaches in the Kurdistan region. Using different approaches of machine learning with remote sensing and GIS help a lot to create reliable and accurate identification of landslides, which contribute noticeably in enhancing the disaster preparedness and mitigation strategies in the region. However, despite the high susceptibility to landslides in the Kurdistan region, there is a lack of comprehensive studies that integrate multiple methodologies to assess landslide susceptibility accurately. Existing research often lacks the integration of advanced remote sensing techniques with robust machine learning techniques, leaving significant gaps in understanding and preparedness [10]. Moreover, no freely available high resolution satellite imagery are available to identify historical landslides accurately, also the administrations in Choman and Kurdistan region did not collect the historical landslides and there is no a proper database to depend on. This issue makes the researchers depend on very high resolution satellite imagery to identify landslides. However, the Google Earth Pro helped the process by providing the historical

imagery of entire earth with very high resolution images which are freely available. This have a great contribution to create a database with reliable detail and accuracy for landslides events in the past, and solving the challenge of gaps in historical data and expensive high-resolution satellite imagery. This is one of the few researches that used Google Earth imagery as a reliable source for collecting and identifying historical landslide in Choman District.

The generation of an accurate map of landslide vulnerable areas in Choman District using machine learning techniques is the objective of this research, to have significant insights on the landslide vulnerable areas. The outcome of this research will be used as a source to plan accordingly to mitigate the impact of landslide events on people, infrastructures and the environment.

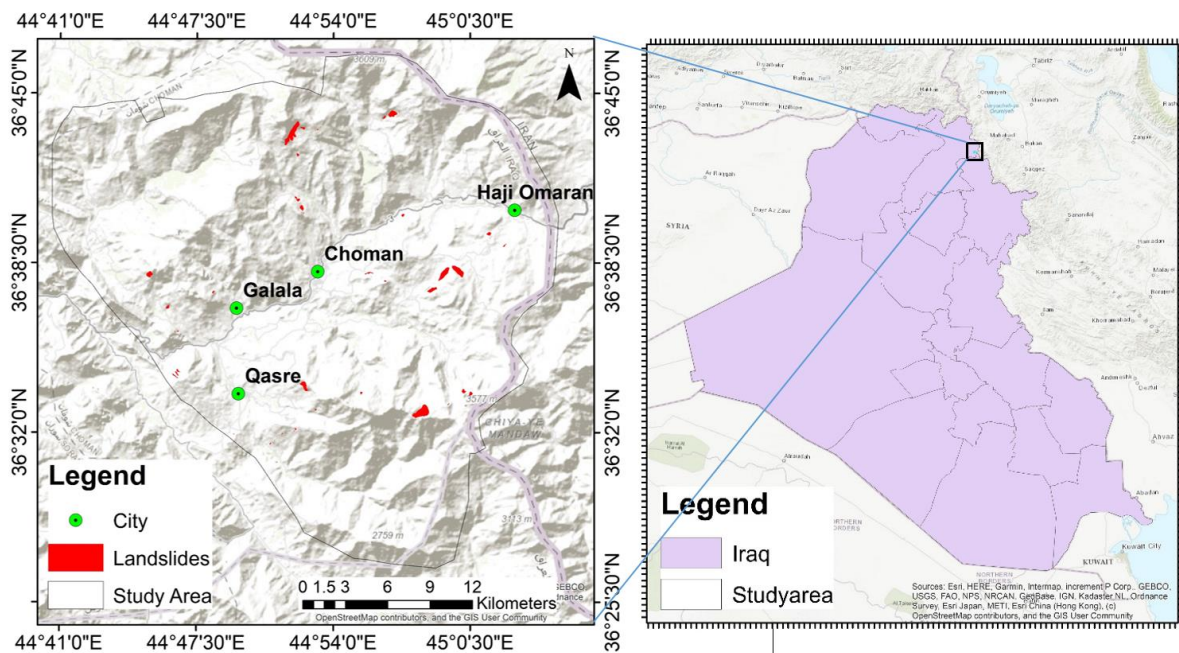


Figure 1: Study area (Choman District, Iraq).

2. Methodology

2.1 Study Area

Choman District is located in the east of Erbil Governorate in the Kurdistan Region in Iraq, which is an ideal region to assess and analyse the impact of landslides and susceptible areas, because of its geographical and environmental condition. It's located along the Iraqi-Iranian border, and it covers 4 other sub-districts like Galala, Haji Omeran, Samilan, and Qasre, along with 166 villages, with 861.7 km². The Choman District is characterized by its beautiful nature and it's a recommended place for tourists especially due to its cool weather in hot summer. It has complex mountainous terrain and there are Zagros Mountain range in the area, which is the most important peaks such as Halgurd Mountain, the highest in Iraq at 3,609 meters is located in Choman area. This diverse topography have critical contribution to landslides and made the areas vulnerable to landslides [11].

In the other hand, Choman is a critical region for landslide studies due to its diverse climate and geological conditions make. The district have a critical rain and snow particularly in the Halgurd-Sakran Mountain range, resulting in landslide event occurrences in the area and threatening properties and life of people every years. The Choman region is also active for its contribution in agricultural activities, which have a huge impact on erosion and slope instability of the land. Furthermore, historical and environmental significance of Choman the district, including the Halgurd-Sakran National Park and numerous archaeological sites, necessitates the process of creating the landslide vulnerable areas to save both natural and cultural resources in the region. That is why Choman District

is a place that needs immediate mapping and continues assessment of landslide susceptible areas. The unique geological conditions, climatic patterns, and socioeconomic activities have a significant impact on landslides and considering these factors have role in creating an enhanced and detailed landslide susceptibility mapping and risk assessment research [11].

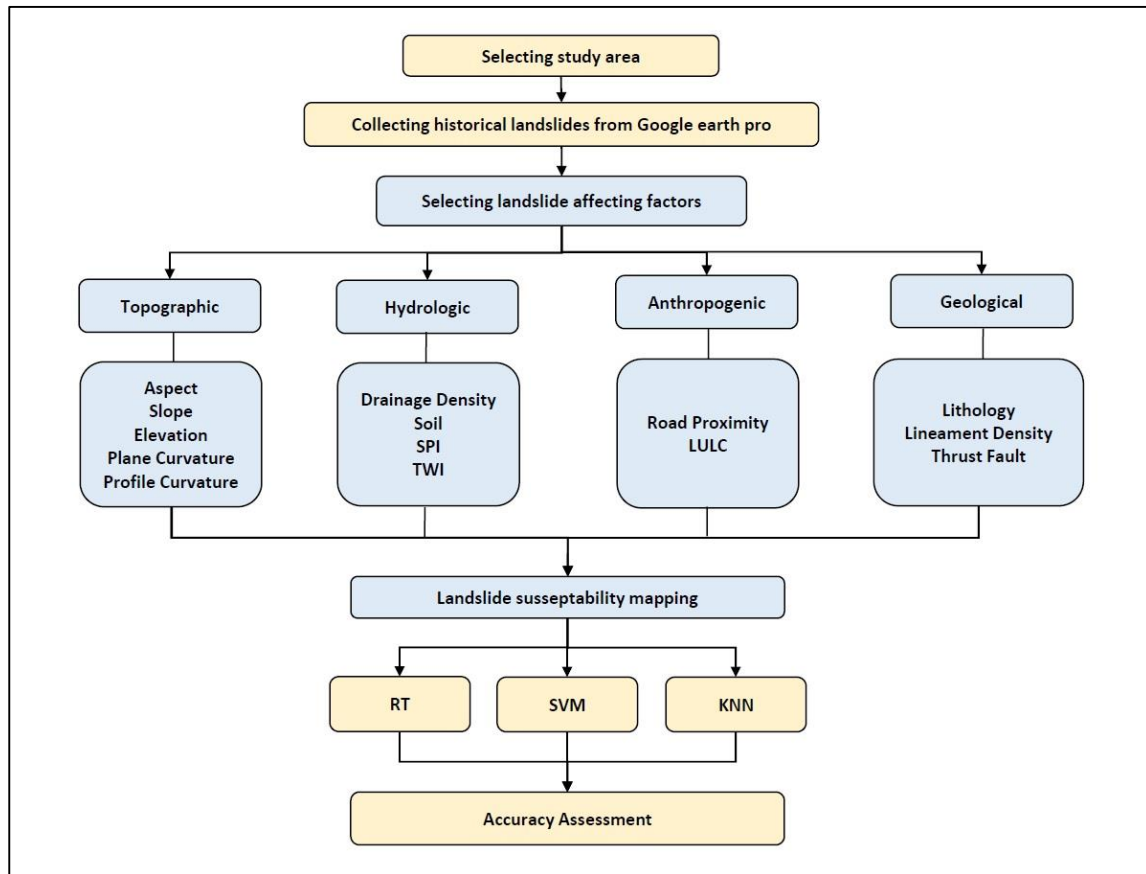


Figure 2: The flowchart of the study.

2.2 Data Collection

The freely available historical high-resolution satellite imagery from Google Earth Pro used with trip fields to collect landslides, which is a necessary step to have detailed and accurate information related to landslides for assessing landslide susceptibility. Google Earth Pro is significant platform for researchers which have cost-effective and efficient way to gather topographical and geological data to all world by providing freely available high resolution satellite imagery, especially for remote and complex regions such as the Choman District. However, the most updated satellite imagery available from Google Earth Pro was for December 2022, and to have more historical landslide data, field surveys were conducted to collect and validate the Google Earth Pro collected data and to identify new landslides that occurred after December 2022. 60 landslides were collected in total in the study area from both satellite imagery and field data (Fig. 1). The collected data were divided into training (70%) and test data (30%). The training data were used to train the machine learning techniques, while the test data were used to assess the performance of the results. To ensure that recent landslide events has included, and collected data from satellite imagery were accurate, this process was done to provide a strong base for mapping the reliable susceptible area to landslides [12].

Table 1: The factors used for landslide susceptibility mapping

Category	Factor	Resolution/type	Source
Topographic	Aspect	Raster (12.5m)	DEM from ALOS PALSAR satellite (https://asf.alaska.edu/)
	Slope		
	Elevation		
	Plane Curvature		
	Profile Curvature		
Hydrologic	Drainage Density	Digitized image	Ministry of Agriculture in Bagdad [13]
	Soil		
	SPI (Stream Power Index)	Raster (12.5m)	DEM from ALOS PALSAR satellite (https://asf.alaska.edu/)
	TWI (Topographic Wetness Index)		
Geological	Lithology	Digitized image	Study of Stevanovic. and Markovic. (2003) [14]
	Lineament Density	Raster (12.5m)	DEM from ALOS PALSAR satellite (https://asf.alaska.edu/)
	Thrust Fault	Digitized image	[14]
Anthropogenic	Road Proximity	Raster (10 m)	Generated from Sentinel 2 imagery.
	LULC (Land Use and Land Cover)	Raster (10 m)	Sentinel 2 imagery using support vector machine for classification.

2.3 Selection of Factors

Due to the complexity and large numbers of factors that contribute landslide, prediction and mitigation of landslides become more challenging process. These factors include geological setting of the area, which is related to the type of rock and soil; geomorphological conditions which means the slope angle, aspect, and elevation of the region; and environmental variables including vegetation cover, land use, and hydrological characteristics (Table 1, Fig. 3). The mixture of these factors have a significant impact of possibility and frequency of landslide events, emphasizing the need for use complex approaches that considers all factors. To create an accurate the landslide vulnerable map in the Choman District, factors like topographic, hydrologic, geological, and anthropogenic were considered based on their critical impact on landslide occurrences as used in previous studies. Each factors were analysed to understand the influence of each one on the slope stability within the region. The flowchart of the study illustrated in Fig. 2. Machine learning techniques can be used effectively to analyse and assess the multiple factors that have impact on landslide events, leading to more accurate map of areas with risk of landslides [15-17].

2.4 Description of the used algorithms

2.4.1 K-Nearest Neighbor (KNN)

The K-Nearest Neighbor (KNN) machine learning is an effective machine learning technique in analyzing spatial data and predicting areas at risk of landslides. KNN is a non-parametric algorithm which can handle complex and high-dimensional datasets, making it suitable technique for landslide

susceptibility mapping [18, 19]. Recent studies suggested that the integration of KNN with GIS techniques significantly enhance the accuracy of landslide susceptibility maps [20]. A research indicated that the combination of KNN with different machine learning techniques improved the predictive performance of risk areas, leading to more reliable results of areas with risk of landslides [21]. Additionally, the ArcGIS Pro with its user-friendly interface facilitated the implementation of KNN algorithms, resulting in more data processing efficiency and visualization, providing invaluable insights for decision-making in land use planning and disaster risk management [22]. Combining KNN technique within the ArcGIS environment not only make the mapping process easier, but also improves the accuracy and interpretability of results, making it a significant tool for geospatial analyst and urban planners [23].

2.4.2 Support Vector Machine (SVM)

Support Vector Machine (SVM) used in different researches a powerful tool for mapping susceptible areas to landslides. The SVM algorithms significantly facilitate the process of analyzing various geospatial data layers, enhancing the predictive accuracy of land slide susceptibility [24]. Diverse datasets were integrated with SVM which effectively used for landslide predictions. Multiple factors such as geological, topographical, and environmental conditions significantly contribute in landslide risk assessments [25]. Additionally, integrating SVM with optimization techniques, including the Gray Wolf Optimization algorithm, enhanced the accuracy of the results in different researches [26]. Using SVM in ArcGIS pro facilitate the landslide mapping process and also provides robust framework for assessing susceptible landslide areas, offering valuable insights for urban planners and policy makers [27].

2.4.3 Random tree (RT)

The analyzing complex spatial data and predict landslide occurrences made the Random Forest and Decision Trees (RT) machine learning technique as one of the effective algorithms for landslide susceptibility mapping. Recent studies proved the RT performance in enhancing the accuracy of landslide susceptibility assessments. A research successfully integrated machine learning with geospatial techniques to generate landslide prediction systems economically, particularly in regions with limited data sources [28]. Additionally, the study of Shahabi et al., (2019) indicated that RT algorithm was better than other machine learning techniques in mapping landslide susceptibility, specifically in mountainous areas, due to its effectiveness in processing diverse environmental parameters [29]. Additionally, capturing the non-linear relationships between landslide occurrences and their contributed parameters is another effective characteristics of RT algorithm [30]. Using machine learning techniques improved the reliability of the susceptibility mappings, specifically in landslide assessments, providing significant help for disaster management and mitigation strategies.

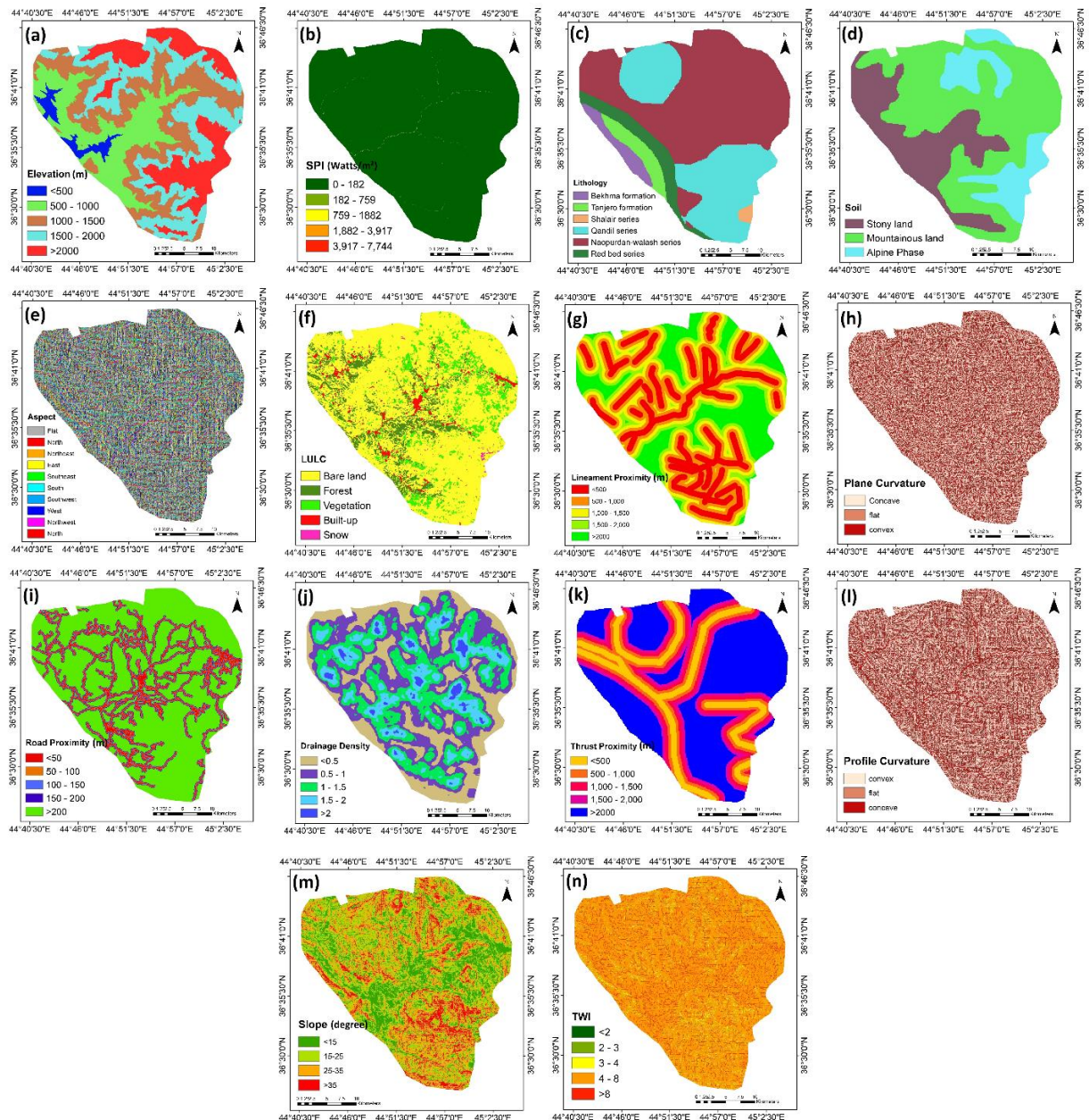


Figure 3: The factors used to map the landslide susceptibility in the Choman District, including: (a) Elevation, (b) SPI, (c) Lithology, (d) Soil, (e) Aspect, (f) LULC, (g) Lineament proximity, (h) Plane curvature, (i) Road proximity, (j) Drainage density, (k) thrust proximity, (l) Profile curvature, (m) Slope, and (n) TWI.

3. Results

The historical landslides in Choman District were collected using both high-resolution Google Earth Pro imagery and field trips, which the data were used for validating the generated landslide susceptibility mappings. Multiple factors were considered for mapping landslide risk areas, such as aspect, slope, elevation, plane curvature, profile curvature, drainage density, soil map, stream power index, topographic wetness index, lithology map, lineament density, thrust fault proximity, road proximity and land use land cover. Using remote sensing and GIS techniques allowed for the identification of landslide vulnerable regions, also field surveys offered ground truth data to assess the generated landslide maps. The historical data collection illustrated that study area witnessed 3.1 km² (0.36%) of landslides. The largest landslide was 0.6 km² in the south-east of the Choman district. The generated landslide maps for Choman District were categorized into four different risk zones: very

low, low, medium, and high susceptibility. The integration of remote sensing, GIS and machine learning methodologies provided a robust framework to assess landslide risk areas with reliable results . The outcome of SVM, RT, and KNN algorithms showed that 19.3% (165.8 km²), 32.3% (278.2 km²), 35.6% (306.5 km²) of Choman District is highly susceptible to landslides, which the plenty of the regions in high risk zones are located in regions with high slopes and near to roads and rivers, however, only 11.2% (96.1 km²), 12.9% (111.5 km²), and 21.2% (182.8 km²) of Choman District were located in very low landslide susceptible areas (Figs. 4, 6). The results indicated that a great amount of regions are at risk of landslides, which significantly have the impact on the safety of residents and passengers in the study area, specifically during winter season.

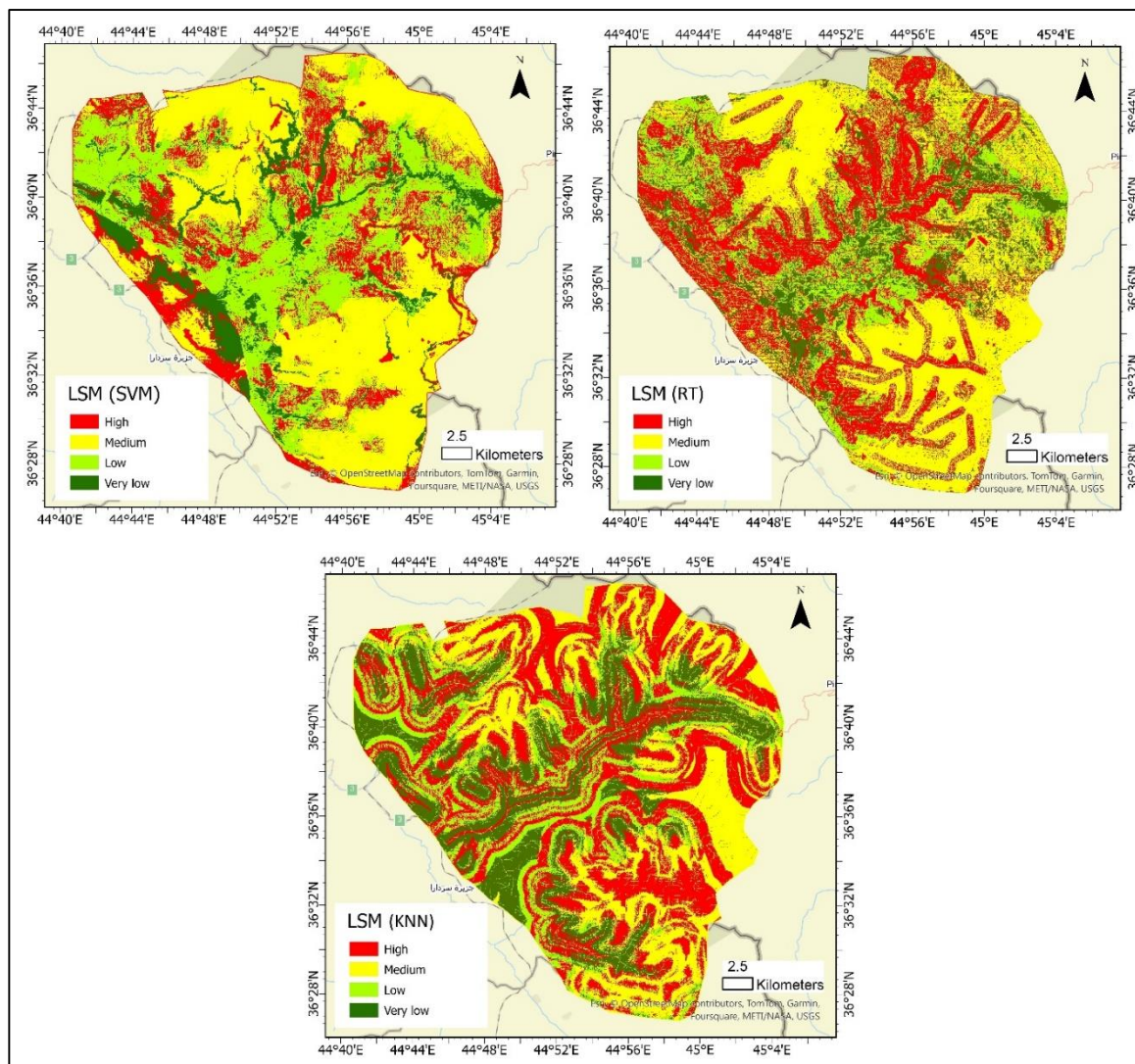


Figure 4: Result of landslide susceptibility using SVM, RT, and KNN.

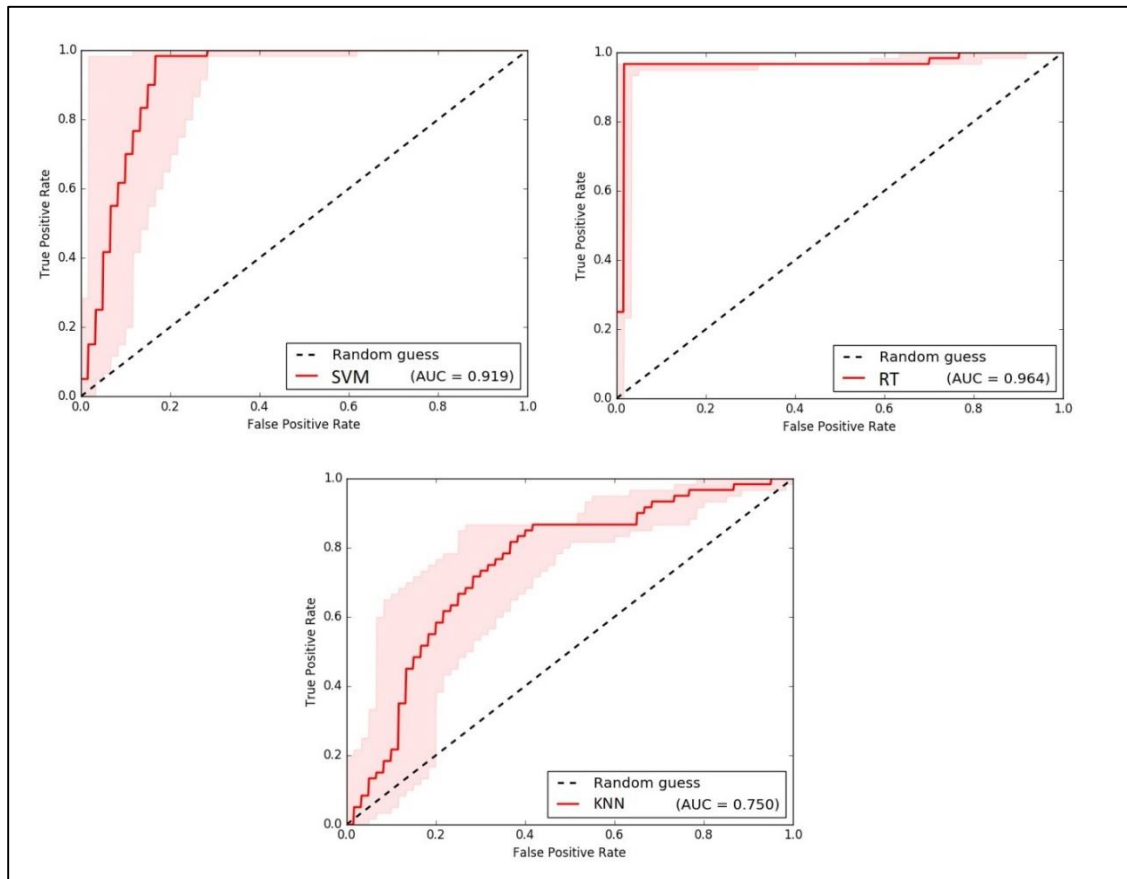


Figure 5: Result of ROC-AUC values for SVM, RT, and KNN algorithms.

The number of landslides which were located in the very high susceptibility class of landslides were divided by the total number of all landslides in the Choman District to find the accuracy of the SVM, RT, and KNN algorithms. The results of SVM showed that the 96.7% of historical landslides were located in high susceptible areas, also 91.7% and 83.3% for RT and KNN, respectively, indicating the effectiveness and accuracy of machine learning techniques. Additionally, the area under the curve (AUC) were used to assess the performance of each techniques. AUC values for SVM, RT, and KNN were 91.9%, 96.4% and 75%, respectively (Fig. 5). The results indicated that machine learning techniques generated reliable and accurate maps of landslide susceptible regions in Choman District, specifically both SVM and RT methods. This accuracy assessments emphasize the effectiveness of machine learning approaches to create accurate mapping of landslide risk areas, which provide significant insights for urban planners and developing disaster management strategies for Choman District.

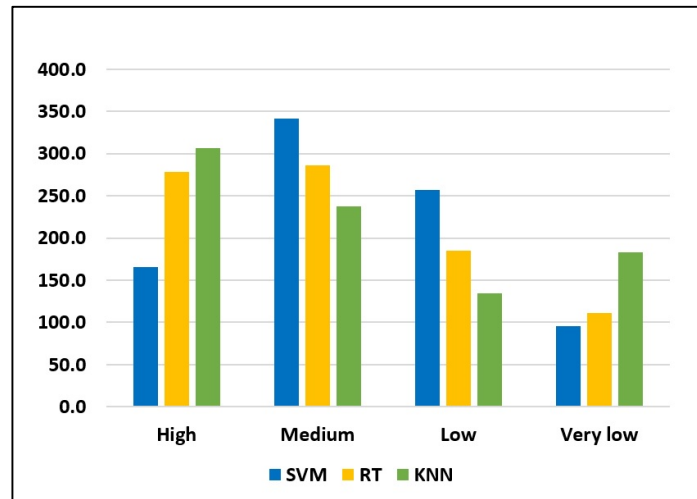


Figure 6: The landslide area in km² for SVM, RT, and KNN algorithms.

4. Discussions

The results indicated that the regions with high susceptible to landslides are those which have steep slopes and near to geological faults in Choman District. During rainy seasons the landslides triggered due to the instability conditions of the area. This parameters emphasize the significant of considering slope and fault proximity for risk mitigation strategies and disaster management procedures to reduce the landslide events in the region. The outcome of this research supports the previous studies that have been done in different environmental characteristics, which slope conditions and lithological formations considered as primary factors contributing to landslide hazards. As a comparison to the literature, the results of our study showed consistency with existing research findings. The RT technique showed the highest accuracy with 96.4%, exceeding the accuracy of 90% which was recorded in previous studies, demonstrating its effective ness in landslide mapping [31, 32]. Additionally, SVM accuracy with 91.9% was within the existing range of 85-95% documented in various case studies, indicating its suitability for landslide modeling [33, 34]. Moreover, KNN techniques achieved the lowest accuracy with only 75%, which aligns with existing literature indicating the lower performance of KNN compared to RT and SVM in complex scenarios [30, 35]. These comparative results showed the consistency of our study with literature, where RT indicated its superior performance, followed by SVM, while KNN showed its lower accuracy in landslide susceptibility mapping. On the other hand, future contributions could use the integration of advanced techniques like machine learning and deep learning approaches to enhance the accuracy of generated landslide vulnerable areas. The maps created by this research serve significant insights for policymakers and planners in the Choman District. It can be used as a valuable guide for natural resource and disaster management in the area along with better land-use decision makings to avoid high-risk areas in the future. Categorizing the region into different level of landslide susceptibility, offers a critical help to prioritize high susceptible areas for detailed investigation, infrastructure development, and developing immediate mitigation strategies for these areas. This procedures can significantly ensure the safety of people and properties, also mitigating the possible damages from landslide.

5. Conclusion

The GIS and remote sensing technologies effectively used in this research with different machine learning techniques to generate accurate landslide susceptibility map for Choman District in Kurdistan region of Iraq. The results categorized the Choman region into four risk levels, low, medium high, and very high susceptible area of landslides. 14 factors from different categories were considered to create landslide vulnerable areas. 60 landslides were collected using google earth pro and field trips, and the study found that approximately 16% of the Choman District is highly susceptible to landslide hazards,

resulting in high risk to the local population, specifically during rainfall seasons. The outcome indicated that steep slope and regions near geological faults and roads are prone to landslide events. The result of this research offers invaluable insights about the factors that significantly contribute in landslide events, and emphasizing the necessity of considering these factors in disaster reduction strategies. The results of SVM, RT, and KNN algorithms indicated that 165.8 km² (19.3%), 278.2 km² (32.3%), 306.5 km² (35.6%) of Choman District is highly susceptible to landslides, however, only 96.1 km² (11.2%), 111.5 km² (12.9%), and 182.8 km² (21.2%) of Choman District were located in very low landslide susceptible areas. The area under the curve (AUC) were used to evaluate the performance of each algorithms. AUC values for SVM, RT, and KNN techniques were 91.9%, 96.4% and 75%, respectively. The assessment indicated that SVM and RT showed better performance than KNN to generate the landslide susceptible areas.

Furthermore, the map can offer a significant help for early warning systems and could be used as a consideration for infrastructure planning projects by policymakers, ensuring the location of new constructions in safer areas and reducing the risks caused by landslide. Communities and infrastructures in Choman district which is a highly susceptible region to landslides could be protected by doing continues researches and investment in landslide susceptibility assessment. By developing our understanding of factors that contribute in landslides and enhancing the integrated approaches to generate accurate map of those places prone to landslides, we can reduce the risks of landslide events and prepare more effectively to reduce the impacts of natural hazards and safe people and resources to have more sustainable environment.

6. Conflict of Interest

The authors declare no conflict of interest.

References

- [1] Al-Dhahi AD, Hussain AI, Al-Shwaily AK. Assessment of Landslide Susceptibility Using the AHP and GIS Techniques for the Zurbatiya Region, East of Iraq. The Iraqi Geological Journal. 2023;201-13. <https://doi.org/10.46717/igj.56.2D.16ms-2023-10-22>.
- [2] Othman AA, Gloaguen R, Andreani L, Rahnema M. Landslide susceptibility mapping in Mawat area, Kurdistan Region, NE Iraq: a comparison of different statistical models. Nat Hazards Earth Syst Sci Discuss. 2015;2015:1789-833. <https://doi.org/10.5194/nhessd-3-1789-2015>.
- [3] Othman AA, Gloaguen R. Automatic extraction and size distribution of landslides in Kurdistan region, NE Iraq. Remote Sensing. 2013;5(5):2389-410. <https://doi.org/10.3390/rs5052389>.
- [4] Rudaw. Erbil2024 [Available from: <https://www.rudaw.net/sorani/kurdistan/1601201618>].
- [5] Qallam. 2024 [Available from: <https://qallam.net/posts/14187>].
- [6] Kurdiu. Erbil2023 [Available from: <https://www.kurdiu.org/ku/b/527004>].
- [7] Rudaw. 2023 [Available from: <https://www.rudaw.net/english/kurdistan/200520231>].
- [8] Fatah KK, Mustafa YT, Hassan IO. Geoinformatics-based frequency ratio, analytic hierarchy process and hybrid models for landslide susceptibility zonation in Kurdistan Region, Northern Iraq. Environment, Development and Sustainability. 2024;26(3):6977-7014. <https://doi.org/10.1007/s10668-023-02995-7>.
- [9] Othman AA, Al-Jaff AU, Al-Manmi DA, Al-Maamar AF. Landslide susceptibility mapping using remote sensing and GIS application: A case study in Qala Diza and surrounding area, Kurdistan region, NE Iraq. Iraqi Bulletin of Geology and Mining. 2018;14(1):65-90.
- [10] Abedini M, Ghasemyan B, Rezaei Mogaddam M. Landslide susceptibility mapping in Bijar city, Kurdistan Province, Iran: a comparative study by logistic regression and AHP models. Environmental earth sciences. 2017;76:1-14. <https://doi.org/10.1007/s12665-017-6502-3>.
- [11] Gov.org. Hawler gov; 2024 [Available from: <https://www.hawlergov.org/app/en/node/387>].

-
- [12] Pro GE. 2024 [Available from: <https://www.google.com/earth/about/versions/>].
- [13] Buringh P, cartographer Exploratory soil map of Iraq. Bagdad: Ministry of Agriculture, Directorate General of Agricultural Research and Projects, Division of Soils and Agricultural Chemistry.; 1957. <https://esdac.jrc.ec.europa.eu/content/exploratory-soil-map-iraq-map-1>.
- [14] Stevanovic ZM, M. Hydrogeology of Northern Iraq, Climate, Hydrology, Geomorphology & Geology. FAO. 2003;1:1–122
- [15] Shano L, Raghuvanshi TK, Meten M. Landslide susceptibility evaluation and hazard zonation techniques – a review. *Geoenvironmental Disasters*. 2020;7(1):18
<https://doi.org/10.1186/s40677-020-00152-0>.
- [16] Barman J, Soren DDL, Biswas B. Landslide Susceptibility Evaluation and Analysis: A Review on Articles Published During 2000 to 2020. In: Das J, Bhattacharya SK, editors. *Monitoring and Managing Multi-hazards: A Multidisciplinary Approach*. Cham: Springer International Publishing; 2023. p. 211-20. https://doi.org/10.1007/978-3-031-15377-8_14.
- [17] Sujatha ER, Sudharsan JS. Landslide Susceptibility Mapping Methods—A Review. In: Panda GK, Shaw R, Pal SC, Chatterjee U, Saha A, editors. *Landslide: Susceptibility, Risk Assessment and Sustainability: Application of Geostatistical and Geospatial Modeling*. Cham: Springer Nature Switzerland; 2024. p. 87-102. https://doi.org/10.1007/978-3-031-56591-5_4.
- [18] Adnan MSG, Rahman MS, Ahmed N, Ahmed B, Rabbi MF, Rahman RM. Improving spatial agreement in machine learning-based landslide susceptibility mapping. *Remote Sensing*. 2020;12(20):3347. <https://doi.org/10.3390/rs12203347>.
- [19] Ganesh B, Vincent S, Pathan S, Benitez SRG. Integration of GIS and machine learning techniques for mapping the landslide-prone areas in the state of Goa, India. *Journal of the Indian Society of Remote Sensing*. 2023;51(7):1479-91. <https://doi.org/10.1007/s12524-023-01707-y>.
- [20] Wang Z, Liu Q, Liu Y. Mapping landslide susceptibility using machine learning algorithms and GIS: A case study in Shexian County, Anhui Province, China. *Symmetry*. 2020;12(12):1954. <https://doi.org/10.3390/sym12121954>.
- [21] Benmakhlouf M, El Kharim Y, Galindo Zaldívar J, Sahrane R. Landslide susceptibility assessment in western external rif chain using machine learning methods. 2023. <https://doi.org/10.28991/CEJ-2023-09-12-018>.
- [22] Rabby YW, Hossain MB, Abedin J. Landslide susceptibility mapping in three Upazilas of Rangamati hill district Bangladesh: application and comparison of GIS-based machine learning methods. *Geocarto International*. 2022;37(12):3371-96. <https://doi.org/10.1080/10106049.2020.1864026>.
- [23] Huang W, Ding M, Li Z, Zhuang J, Yang J, Li X, et al. An efficient user-friendly integration tool for landslide susceptibility mapping based on support vector machines: SVM-LSM toolbox. *Remote Sensing*. 2022;14(14):3408. <https://doi.org/10.3390/rs14143408>.
- [24] Edrich A-K, Yildiz A, Roscher R, Bast A, Graf F, Kowalski J. A modular framework for FAIR shallow landslide susceptibility mapping based on machine learning. *Natural Hazards*. 2024;1-30. <https://doi.org/10.1007/s11069-024-06563-8>.
- [25] Xing Y, Chen Y, Wang P, Huang S, Xiang Y. Research on landslide master control factor identification and susceptibility prediction modelling. *EGUsphere*. 2024;2024:1-24. <https://doi.org/10.5194/egusphere-2023-3134>, 2024.
- [26] Liu H, Ding Q, Yang X, Liu Q, Deng M, Gui R. A Knowledge-Guided Approach for Landslide Susceptibility Mapping Using Convolutional Neural Network and Graph Contrastive Learning. *Sustainability*. 2024;16(11):4547. <https://doi.org/10.3390/su16114547>.
- [27] Huang Y, Zhao L. Review on landslide susceptibility mapping using support vector machines. *Catena*. 2018;165:520-9. <https://doi.org/10.1016/j.catena.2018.03.003>.
-

-
- [28] MOHAPATRA R. Landslide susceptibility modelling in a part of Himachal Pradesh, India: An integrated method based on machine learning and geospatial techniques. *Nova Geodesia*. 2023;3(1):63-. <https://doi.org/10.55779/ng3163>.
- [29] Shahabi H, Ahmadi R, Alizadeh M, Hashim M, Al-Ansari N, Shirzadi A, et al. Landslide susceptibility mapping in a mountainous area using machine learning algorithms. *Remote Sensing*. 2023;15(12):3112. <https://doi.org/10.3390/rs15123112>.
- [30] Tien Bui D, Shirzadi A, Shahabi H, Geertsema M, Omidvar E, Clague JJ, et al. New ensemble models for shallow landslide susceptibility modeling in a semi-arid watershed. *Forests*. 2019;10(9):743. <https://doi.org/10.3390/f10090743>.
- [31] Cristina Dias H, Henrique Sandre L, Satizábal Alarcón DA, Henrique Grohmann C, Alberto Quintanilha J. Landslide recognition using SVM, Random Forest, and Maximum Likelihood classifiers on high-resolution satellite images: A case study of Itaóca, southeastern Brazil. *Revista Brasileira de Geociências*. 2021;51(4). <https://doi.org/10.1590/2317-4889202120200105>.
- [32] Sharma A, Prakash C, Manivasagam V. Entropy-based hybrid integration of random forest and support vector machine for landslide susceptibility analysis. *Geomatics*. 2021;1(4):399-416. <https://doi.org/10.3390/geomatics1040023>.
- [33] Nhu V-H, Shirzadi A, Shahabi H, Singh SK, Al-Ansari N, Clague JJ, et al. Shallow landslide susceptibility mapping: A comparison between logistic model tree, logistic regression, naïve bayes tree, artificial neural network, and support vector machine algorithms. *International journal of environmental research and public health*. 2020;17(8):2749. <https://doi.org/10.3390/ijerph17082749>.
- [34] Pradhan B. A comparative study on the predictive ability of the decision tree, support vector machine and neuro-fuzzy models in landslide susceptibility mapping using GIS. *Computers & Geosciences*. 2013;51:350-65. <https://doi.org/10.1016/j.cageo.2012.08.023>.
- [35] Jari A, Khaddari A, Hajaj S, Bachaoui EM, Mohammedi S, Jellouli A, et al. Landslide susceptibility mapping using multi-criteria decision-making (MCDM), statistical, and machine learning models in the Aube Department, France. *Earth*. 2023;4(3):698-713. <https://doi.org/10.3390/earth4030037>.
-