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Landslide Susceptibility Assessment Using Frequency Ratio (FR) Model in the Upper Koyna River Basin, Western Maharashtra, India

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Research Article

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Abstract

Landslides represent a significant geo-environmental hazard in mountainous and tectonically active regions, posing threats to human life, infrastructure, and ecosystems. This study assesses landslide susceptibility in the upper Koyna River basin, Maharashtra, using the Frequency Ratio (FR) model, a bivariate statistical method that correlates historical landslide occurrences with various causative factors. The study area, extending from the Koyna River's source in Mahabaleshwar to Patan town, is characterized by rugged ridge topography, steep gradients, and substantial rainfall, making it inherently vulnerable to slope failures. Anthropogenic influences, including dam construction, deforestation, mining, and road development, have further aggravated the instability of the landscape.

The FR model was applied to integrate and analyze multiple thematic layers such as slope, lithology, soil type, land use/land cover (LULC), lineament density, rainfall distribution, and proximity to rivers and roads. The model calculates the ratio of landslide occurrence within each class of these factors relative to their spatial distribution across the study area, allowing for the identification of zones with varying degrees of susceptibility. Results classified the region into four susceptibility zones: low, moderate, high, and very high. The central and southern parts of the basin exhibited the highest vulnerability, mainly due to steep gradients, weak geological formations, poor drainage conditions, and intense human intervention.

Validation of the susceptibility map using the Receiver Operating Characteristic (ROC) curve yielded an Area Under the Curve (AUC) value of 0.788, indicating strong predictive accuracy of the model. The generated landslide susceptibility map is a vital tool for local authorities, planners, and policymakers for risk assessment, disaster mitigation, and sustainable land use planning. The findings emphasize the need for regulated development and targeted conservation measures in high-risk zones to mitigate future landslide hazards effectively.

1. Introduction

Landslides represent the third most significant natural disaster globally, resulting in substantial damages (Zillman, 2000). They are responsible for increasing human casualties, infrastructure damage, and disruptions to settlements across the world. Globally, landslides account for billions of dollars in economic losses and thousands of fatalities and injuries each year. In Iran, the topography and relief—characterized predominantly by mountainous terrain—make large areas particularly susceptible to mass movements, including landslides, rockfalls, earth flows, and soil creep.

This study focuses on a 250 km² area in the western part of Iran, specifically in Kermanshah Province. The region's susceptibility to landslides arises from a combination of geological, climatic, geomorphological, and anthropogenic factors. Numerous villages and agricultural areas in this region are situated on unstable slopes, emphasizing the need for accurate landslide susceptibility mapping. Such maps are essential tools for informed land-use planning and disaster mitigation, potentially guiding the relocation of structures from hazardous zones.

Landslide hazard evaluation involves analyzing the ground conditions in areas with a history of landslide events (Carrara et al., 1999). The primary objective of this study is to develop a landslide inventory and generate a susceptibility map using the **Frequency Ratio (FR)** method. Statistical approaches such as the FR method have proven effective in predicting and classifying environmental hazards (Paliwal & Kumar, 2009).

Landslide zonation mapping techniques can be broadly classified into three categories: **statistical or quantitative methods** (e.g., Guzzetti et al., 1999; Rautela & Lakhera, 2000; Lineback et al., 2001; Cevik & Topal, 2003; Gorsevski et al., 2003; Lee, 2004; Tangestani, 2004; Sakellariou & Ferentinou, 2005; Ayalew & Yamagishi, 2005), **deterministic approaches** (e.g., Gökceoglu & Aksoy, 1996), and **qualitative or expert-based methods** (e.g., Ives & Messerli, 1981; Rupke & Veilleux, 2011; Regmi et al., 2010).

The methodology for landslide hazard analysis in this study includes the creation of a spatial database, extraction of relevant conditioning factors, and evaluation of landslide potential through statistical correlation between these factors and known landslide occurrences. Validation of results was performed using the Receiver Operating Characteristic (ROC) curve, ensuring the reliability of the model. The FR method operates on the fundamental assumption that the future distribution of landslides can be predicted based on past occurrences (Pradhan & Lee, 2010).

The main objectives of this research are to apply the Frequency Ratio method to delineate landslide-prone areas and to assess the model's predictive accuracy through ROC analysis, while also highlighting the strengths and limitations of this technique.

2. Study area

The Koyna River, a tributary of the Krishna River, originates in Mahabaleshwar, Satara district, Maharashtra. Unlike many other rivers in the region that flow in an East-West direction, the Koyna River flows from North to South. The study area selected for this research extends from the source region of the Koyna River to Patan town. This area is characterized by a rugged ridge topography with numerous runoff channels and significant gradients, making it highly susceptible to landslides.

Various anthropogenic activities, such as mining, quarrying, dam construction, road building, and agriculture practices, have extensively modified the topography of the study area. Covering an area of 1417 square kilometers in the Deccan traps region, the elevation ranges from 953 to 1,409 meters above mean sea level (MSL). The study area spans from 17° 15″ N to 17° 54″ N latitude and 73° 48″ E to 73° 57″ E longitude.

The Koyna River initially flows in a North-South direction from its source to Helvak, where it then takes an eastward turn, flowing in a West-East direction. The river is impounded by the Koyna Dam at Koynanagar, forming the Shivsagar reservoir. The subtropical monsoon climate prevails in the study area, characterized by heavy rainfall. The catchment area of the river, up to Helwak, receives an average rainfall of above 5000 millimeters, extending up to the Koyna Dam.

This description outlines the geographical and climatic characteristics of the study area, emphasizing its susceptibility to landslides and the influence of anthropogenic activities on its topography and hydrology. Such insights are essential for understanding the dynamics of landslide hazards and formulating effective mitigation strategies.The major tributaries of Koyna River are Kera, Wang, Morna and Mahind. The study area is located in major earthquake prone zone of India (Fig. 1).

3. MATERIALS AND METHODS

To analyze landslide susceptibility, a comprehensive geospatial database was developed using a combination of remote sensing data, topographic maps, geological surveys, and field observations. Various thematic layers were prepared, including slope, lithology, soil, rainfall, lineament density, land use/land cover (LULC), and distance from rivers and roads. A Digital Elevation Model (DEM), such as SRTM or ASTER with 30-meter resolution, was used to derive slope and aspect layers, while geological and soil maps were obtained from relevant government agencies and field validation. Rainfall data was collected from the Indian Meteorological Department (IMD) or nearby weather stations, and LULC information was extracted using supervised classification of satellite imagery, such as Landsat-8 or Sentinel-2. River and road layers were digitized from topographic sheets and recent satellite images. A landslide inventory map was created based on historical data, remote sensing interpretation, and ground truth verification.

All the thematic layers were processed and standardized to a common coordinate system and raster resolution using GIS software, primarily ArcGIS and QGIS. Each factor was categorized into relevant classes based on field knowledge and literature review. For example, slope was classified into five categories: 0–12°, 13–18°, 19–24°, 25–30°, and above 30°. Lithological units were grouped according to rock type, such as basalt and laterite, while soils were classified based on texture and drainage characteristics. Rainfall was divided into classes based on natural breaks in distribution, and Euclidean distance tools were used to generate proximity maps for rivers and roads, which were later reclassified into distance zones. Lineament density was calculated from mapped faults and fractures using spatial density analysis tools.

The Frequency Ratio (FR) model was applied to quantify the relationship between each causative factor class and the spatial distribution of past landslides. FR is a bivariate statistical method that calculates the ratio of the occurrence of landslides in a particular class to the occurrence of that class in the entire study area. It is expressed as:

$$\varvec{F}\varvec{R} = \frac{(\varvec{L}\varvec{a}\varvec{n}\varvec{d}\varvec{s}\varvec{l}\varvec{i}\varvec{d}\varvec{e}\ \varvec{p}\varvec{i}\varvec{x}\var}{(\varvec{A}\v}$$

An FR value greater than 1 indicates a higher likelihood of landslide occurrence in that class, while values less than 1 indicate lower susceptibility. The landslide susceptibility index (LSI) map was generated by summing the FR values of the classes for each thematic layer using raster calculations in GIS. This map was then classified into susceptibility zones ranging from very low to very high.

To validate the model's performance, the Receiver Operating Characteristic (ROC) curve was used along with the Area Under the Curve (AUC) value. The landslide inventory data was divided into two subsets: 70% was used for training the model, and the remaining 30% for validation. The FR model achieved an AUC value of 0.786, indicating a strong ability to predict landslide-prone areas based on historical and spatial factor correlations. Software tools such as ArcGIS, QGIS, and ERDAS Imagine were used for geospatial analysis, while Microsoft Excel and R were used for statistical calculations and ROC curve plotting. Overall, the FR model provided a robust framework for understanding and mapping landslide susceptibility in the region.

4. Factors related-landslide

In the study area, several key factors were found to significantly influence landslide susceptibility. Slope emerged as a critical determinant, with steep slopes showing a higher likelihood of failure due to increased gravitational forces, especially when combined with intense rainfall or human interventions such as excavation and deforestation. Lithology also played an important role; regions dominated by basaltic rocks were more vulnerable to landslides as these rocks are often highly weathered, jointed, and fractured, resulting in reduced structural stability. The soil characteristics further contributed to landslide occurrence, particularly in areas with moderately shallow and excessively drained soils on steep terrains. Such soils typically have poor water retention and low cohesion, making them unstable during heavy rainfall events.

Another significant factor was lineament density, where areas with a high concentration of faults, joints, and fractures exhibited increased susceptibility. These structural discontinuities weaken the rock mass and facilitate water infiltration, leading to enhanced weathering and slope instability. The analysis of Land Use/Land Cover (LULC) revealed that vegetated and open land areas were more prone to landslides compared to built-up or agricultural zones. This is likely due to the impact of human activities such as deforestation, which disrupt the natural balance and reduce the binding capacity of roots in the soil. Lastly, the distance from rivers and roads showed a noteworthy correlation with landslide events. Areas situated at moderate distances from rivers were susceptible due to toe erosion and water seepage, while roads contributed to instability through slope cutting and alterations in drainage patterns. Collectively, these factors interact in complex ways, amplifying the overall landslide risk in the region.

5. RESULTS AND DISCUSSION

The application of the Frequency Ratio (FR) model in the present study yielded significant insights into the spatial distribution of landslide susceptibility across the study area. The model quantitatively assessed the correlation between historical landslide occurrences and various thematic factors, effectively identifying zones most vulnerable to future landslides.

One of the most prominent findings was the high correlation between steep slopes and landslide occurrences. Areas with slopes greater than 24° exhibited the highest FR values, indicating that steep terrain plays a dominant role in triggering slope failures. This is attributed to the increased gravitational force acting on unconsolidated or weathered material on steep slopes, especially under saturated conditions during heavy rainfall events.

Figure 1.2. Landslide Susceptibility map Using FR Model of the Study Area

Rainfall emerged as another critical factor, with regions receiving annual rainfall in the range of 1551–1650 mm showing the highest susceptibility. These areas tend to experience significant soil saturation, resulting in reduced shear strength and increased pore water pressure, which collectively contribute to landslide initiation. The spatial analysis also revealed that lithological composition significantly influences slope stability. Basaltic rock formations, which are prevalent in the study area, were associated with high landslide frequencies. This can be attributed to their weathered and fractured nature, which weakens the rock structure and makes it more prone to failure under stress or infiltration.

Soil characteristics further contributed to the susceptibility pattern. Moderately shallow and excessively drained soils, particularly on steep slopes, were found to be highly vulnerable. Their limited water retention capacity, when combined with slope gradient, reduces cohesion and increases the risk of mass movement. Lineament density was another factor with strong influence; areas with high lineament density recorded a higher incidence of landslides. This suggests that the presence of fractures and faults in the rock enhances water infiltration and weakens the slope's structural integrity.

Land use and land cover (LULC) also played a notable role in landslide vulnerability. Vegetated regions and open lands were identified as more susceptible compared to built-up or agricultural areas. This could be due to human-induced changes such as deforestation and slope modification, which destabilize the land surface. Furthermore, the model identified moderate distances from rivers and roads as zones of elevated landslide risk. This is likely due to erosional processes along riverbanks and slope disturbances caused by road construction activities, including slope cutting and inadequate drainage.

The final Landslide Susceptibility Index (LSI) map, derived from the sum of FR values for all thematic layers, was classified into five zones: very low, low, moderate, high, and very high susceptibility. The spatial distribution indicated that a considerable portion of the study area fell under moderate to high susceptibility zones, highlighting the need for targeted mitigation strategies.

Model validation using the Receiver Operating Characteristic (ROC) curve yielded an Area Under the Curve (AUC) value of **0.788**, indicating a strong predictive performance. This high AUC value confirms the model's robustness in distinguishing between landslide-prone and stable areas, thereby reinforcing the reliability of the FR model for hazard zonation. The validation results suggest that the thematic factors selected for this study are appropriate and that the statistical approach effectively captures their influence on landslide occurrences.

Fig.no. 1.3. ROV-AUC Curve

6. Conclusion

The Frequency Ratio (FR) model proved to be a reliable and effective tool for landslide hazard zonation by quantifying the relationship between past landslide occurrences and multiple contributing factors. The study demonstrated that steep slope, high rainfall, basaltic lithology, shallow and drained soils, high lineament density, vegetated/open land cover, and proximity to rivers and roads are the primary drivers of landslide susceptibility in the region. The spatial patterns derived from the FR model provide critical information for identifying high-risk areas, which is essential for disaster preparedness, risk reduction, and land use planning.

The model's high predictive accuracy, confirmed by an AUC value of 0.786, indicates that the FR-based approach can effectively guide mitigation efforts in landslide-prone regions. Moreover, the methodology is data-driven, relatively simple to implement, and can be adapted to other regions with similar environmental settings. Future work may incorporate more refined temporal rainfall data, subsurface geotechnical information, and higher-resolution remote sensing products to further enhance model accuracy and applicability. Overall, this study emphasizes the importance of geoinformatic techniques and statistical modeling in understanding and managing landslide hazards for sustainable development.

Declarations

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Ethics, Consent to Participate, and Consent to Publish: Both authors contributed to the conception and design of the study, research methodology, data collection, data processing, GIS-based analysis, application of the Frequency Ratio (FR) model, preparation of maps and figures, interpretation of results, and manuscript preparation. Both authors critically reviewed the manuscript and approved its final version for publication. Both authors agree to be accountable for all aspects of the research.

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Figures

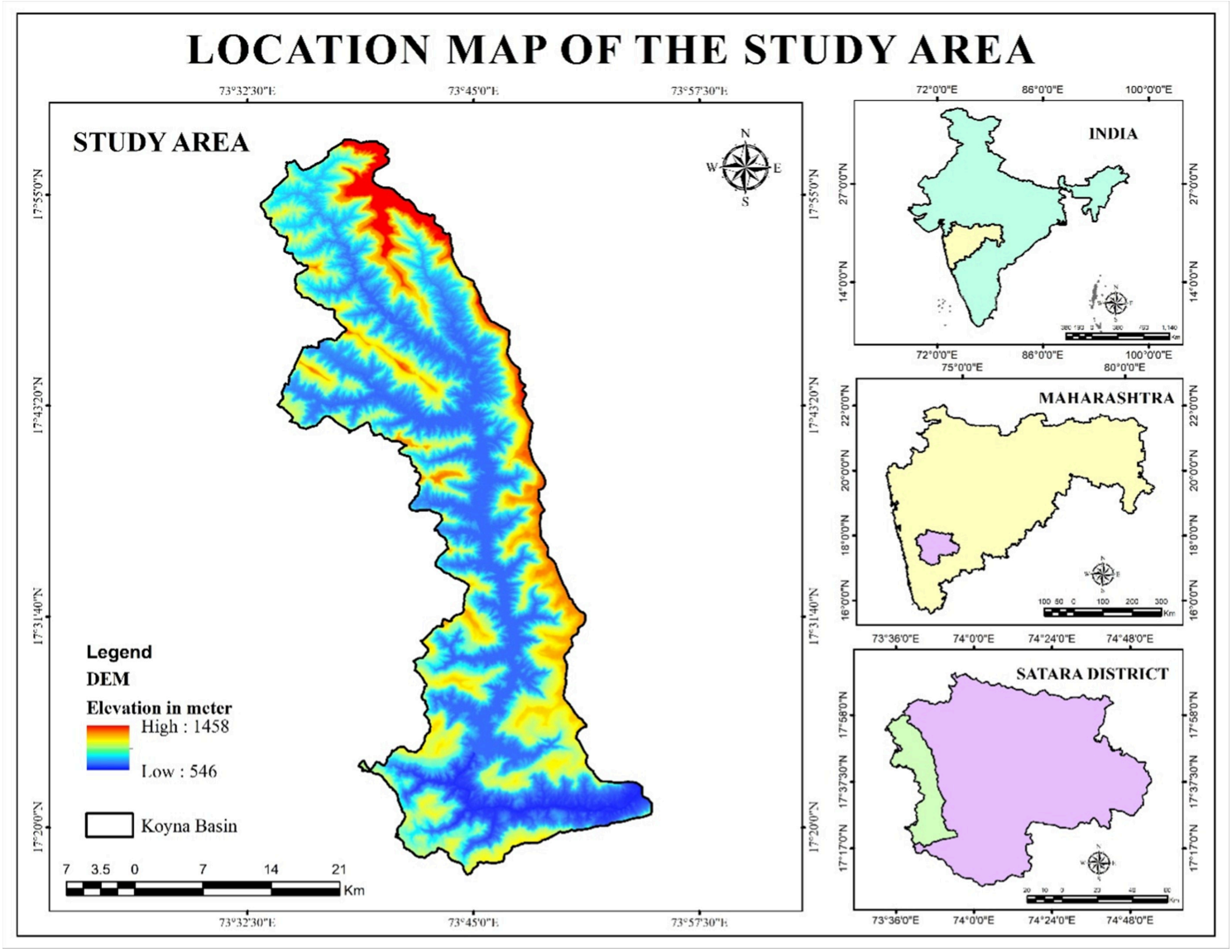


Figure 1

Fig. 1.1. Map of the study area

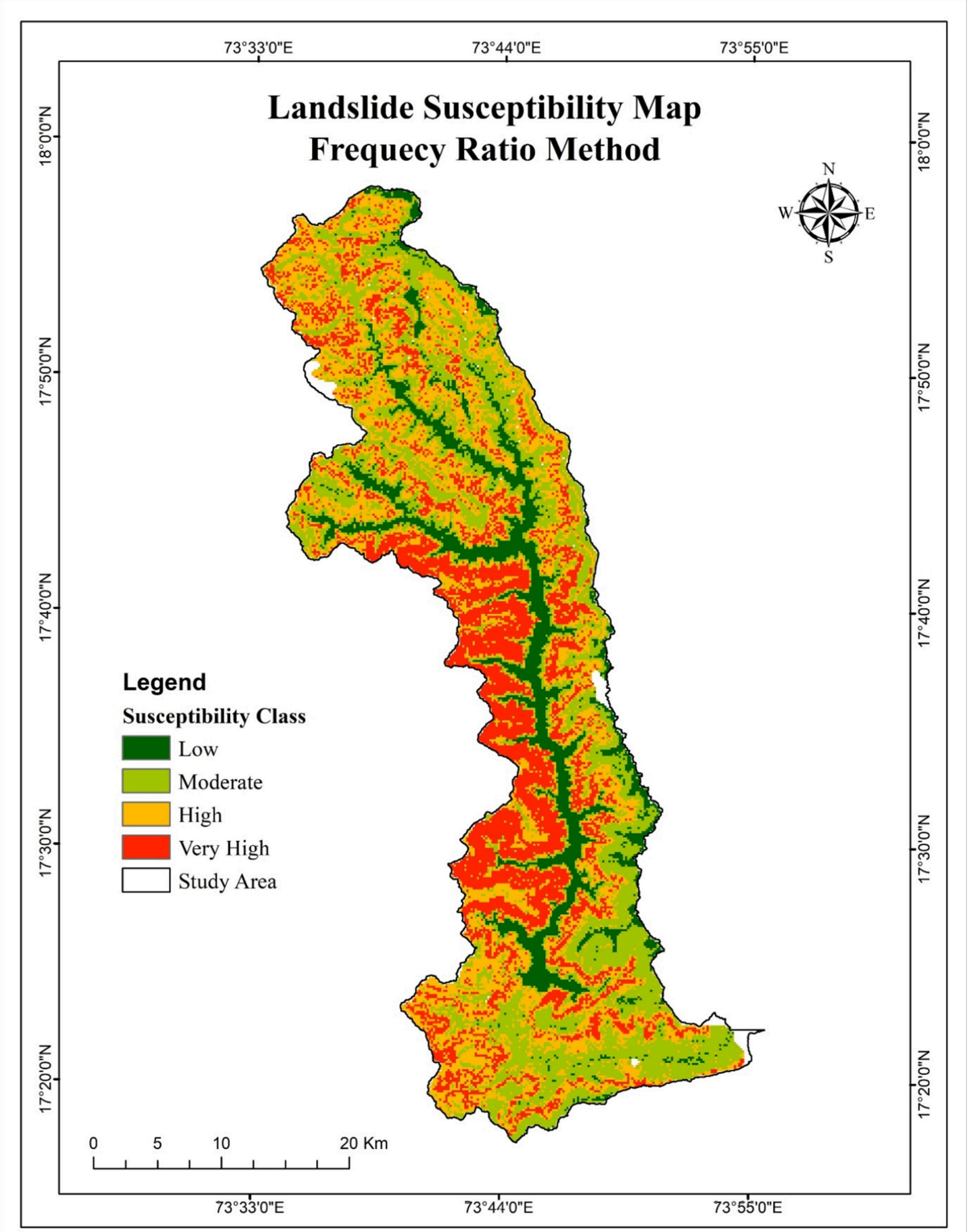


Figure 2

Fig.1.2. Landslide Susceptibility map Using FR Model of the Study Area

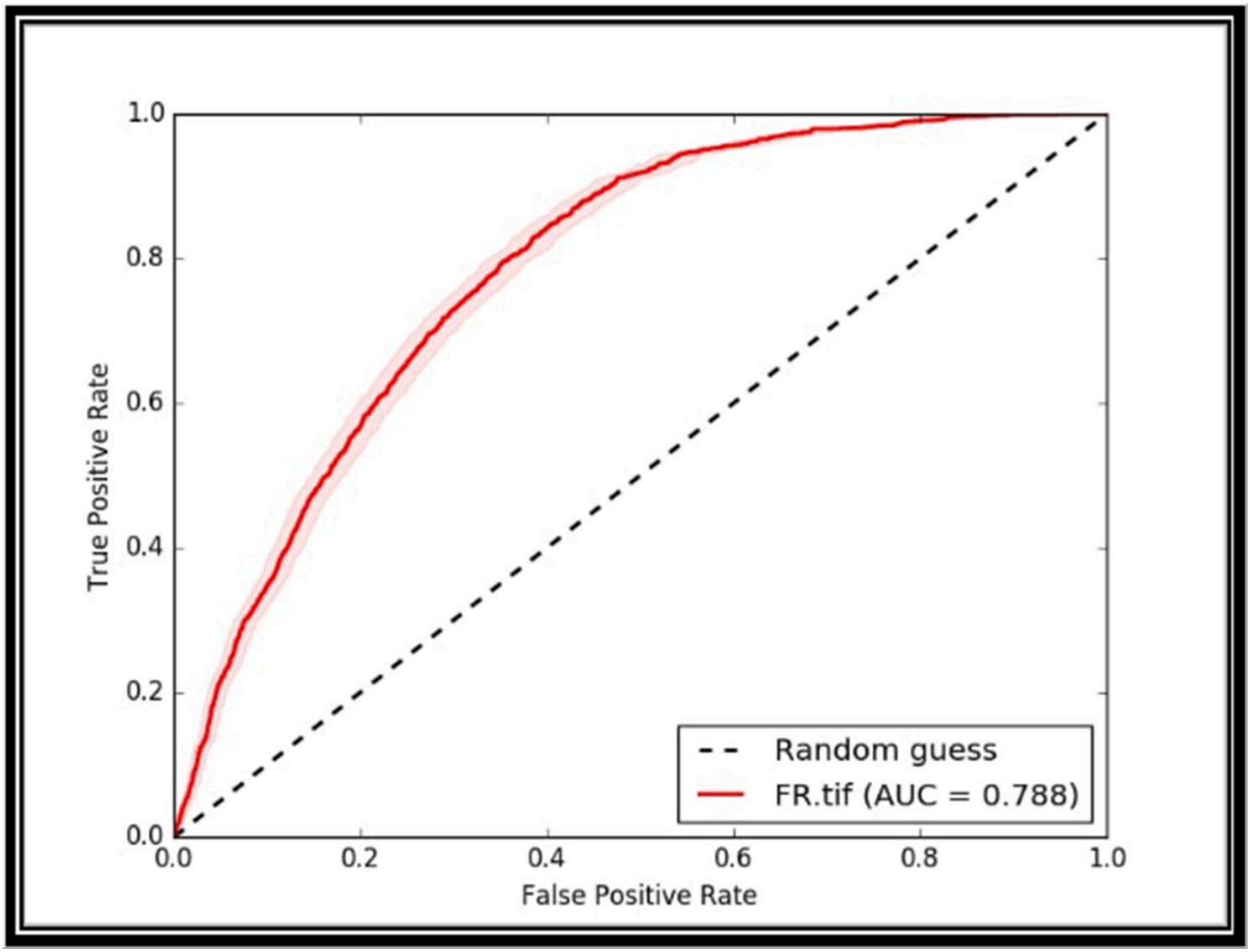


Figure 3

Fig.no. 1.3. ROV-AUC Curve