Assessment of Marine Geohazards Activity in the Farasan Islands Using Acoustic, GIS, and Remote Sensing Techniques

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SUMMARY

This study focuses on investigating the tectonic activity of the Farasan Islands, located in the southern Red Sea, by utilizing advanced methods in Geographic Information Systems (GIS) and remote sensing, along with the analysis of morphotectonic indices. The primary objective is to assess neotectonic activity in the region through the examination of geomorphic features and their relationship with tectonic processes. We employed Digital Elevation Models (DEMs) and bathymetric data to derive key geomorphic indices, such as the Wetness Index (TWI), Terrain Ruggedness Index (TRI), Topographic Position Index (TPI), Slope-Length Gradient Factor (LS-factor) and Stream Power Index (SPI), and amplitude relief (Ar), and corresponding slope and aspect, which serve as indicators of tectonic deformation. By integrating these indices with GIS techniques and remote sensing data, this study offers a comprehensive spatial assessment of the tectonic features of the Farasan Islands. Field observations and previous geological reports were incorporated to ensure the accuracy of the analysis and provide ground-truthing for the remote sensing data. A multi-criteria decision analysis (MCDA) approach was used to assess the spatial distribution of neotectonic activity by combining different geospatial layers, such as lineament data and lithological information. The results show a clear spatial variation in tectonic activity across the region, with the central and eastern parts of the islands exhibiting signs of high tectonic activity, particularly linked to fault systems, while the northern and western regions display lower levels of tectonic deformation. This study highlights the importance of using integrated GIS and remote sensing techniques, particularly when combined with morphotectonic indices, to generate accurate tectonic hazard maps. The findings of this study have significant implications for understanding the tectonic processes that shape islands and coastal regions, with potential applications in disaster risk management, land-use planning, and environmental protection. The use of bathymetric data, alongside traditional land-based methods, further enhances the precision of tectonic assessments, offering a more holistic view of the interconnectedness between terrestrial and marine tectonic features. This study serves as a valuable contribution to the growing body of knowledge on tectonic hazards in the Red Sea region and provides a framework for similar geomorphic and tectonic studies in other coastal and islands areas globally.

Key words: Geomorphic indices, hydrography, multi sensor system, Red Sea, morphotectonic, GIS Modeling, remote sensing, Farasan Islands.

1. INTRODUCTION

The study of geomorphology and tectonics plays a pivotal role in understanding the dynamic processes that shape the Earth’s surface. In tectonically active regions, such as the Farasan Islands in the Red Sea, understanding the nature and extent of tectonic forces is crucial for assessing natural hazards, guiding land-use planning, and protecting human infrastructure. The Farasan Islands are situated along the boundary of the Arabian Plate, an area characterized by complex tectonic interactions including faulting, seismic activity, and volcanic phenomena. These processes contribute to geomorphological evolution of the region and present significant challenges for geospatial studies (Murphy & Wheeler, 2016; Zwoliński & Guth, 2017).

Recent advancements in remote sensing and Geographic Information Systems (GIS) technologies have revolutionized the way geoscientists study and monitor tectonic activities. GIS provides a platform for processing and analyzing the data, while Remote sensing enables the acquisition of high-resolution spatial data, enabling for the generation of detailed maps, calculation of geomorphic indices, and assessment of morphotectonic features in a more efficient and precise manner (Kerski, 2008; Breman, 2002). The combination of these technologies offers an unprecedented opportunity to study tectonic activity and geomorphic evolution in a systematic and quantifiable way.

The Farasan Islands, located approximately 50 kilometers off the western coast of Saudi Arabia, have been a focal point for geological studies due to their proximity to significant tectonic features. The islands lie at the intersection of two major tectonic domains: the Red Sea Rift and the Arabian Shield (Roberts et al., 2016). The tectonic forces associated with these domains have influenced the region’s faulting patterns, volcanic activity, and topographic features. While much of the islands’ tectonic history has been studied through traditional field methods, there remains a need for more advanced, systematic approaches that can offer new insights into the ongoing tectonic processes in the region.

This study aims to bridge that gap by utilizing remote sensing and GIS techniques to explore the tectonic activity on the Farasan Islands. Specifically, the focus is on the analysis of geomorphic indices derived from bathymetric data, as well as the assessment of morphotectonic susceptibility through the use of spatial models and multi-criteria decision analysis (MCDA). By digitally analyzing the drainage networks and geomorphological features of the islands, this study seeks to identify areas of active tectonic processes, map tectonic hazard zones, and contribute to a better understanding of the islands’ tectonic landscape.

The primary objective of this research is to evaluate the effectiveness of GIS and remote sensing technologies in the study of tectonic activity through geomorphic indices. These indices, such as the slope angle, slope aspect and curvature, Wetness Index (TWI), Terrain Ruggedness Index (TRI), Topographic Position Index (TPI), Slope-Length Gradient Factor (LS-factor) and Stream Power Index (SPI), and amplitude relief (Ar), are powerful tools in the identification of neotectonic activity and can help highlight regions that are more susceptible to geological hazards. Moreover, the study explores how GIS-based models can integrate various spatial variables, such as lithology, fault lines, and slope data, to assess the neotectonic dynamics of the Farasan Islands. The term of Lithology referees to the examination of the physical and chemical properties of rocks and the substances that constitute the Earth's crust. This study includes an analysis of the rocks' composition, texture, color, and other characteristics to gain insights into their formation, classification, and spatial distribution. Lithology plays a vital role in several geological fields, including sedimentology, paleoecology, and petrology, as it aids in deciphering geological history and understanding various geological processes.

Additionally, this research aims to establish a methodology for applying these advanced techniques to other tectonically active regions, thereby contributing to the broader field of geomorphology and tectonic studies. By examining the relationship between tectonic processes and geomorphic features in the Farasan Islands, this study hopes to provide valuable insights into the role of tectonics in shaping islands topography, which could be used to inform future geospatial studies and environmental monitoring efforts.

This introduction provides the necessary context for understanding the significance of this study, highlighting the region's tectonic importance and the potential of GIS and remote sensing to improve our understanding of geological processes. The following sections will detail the materials and methods employed in this research, as well as the results, discussions, and conclusions derived from the analysis.

2. MATERIALS AND METHODS

In this study, remote sensing and Geographic Information System (GIS) technologies were employed to analyze and map the tectonic activity of the Farasan Islands. This section outlines the study area, the morphotectonic indices used to assess tectonic activity, and the collected data, including remote sensing datasets, bathymetric data, and field observations.

2.1 The Study Area

The Farasan Islands, a group of islands in the southern Red Sea, are part of Saudi Arabia's territorial waters and are located approximately 50 kilometers off the coast of Jizan, along the western shore of the Arabian Peninsula. The islands group consists of over 100 islands (Roberts et al., 2016), with Farasan Island being the largest and most geologically significant. Fig 1 shows the location of the Farasan Islands. The Farasan Islands are situated at the intersection of the Red Sea Rift and the Arabian Shield, two major tectonic regions that are characterized by faulting, seismic activity, and volcanic processes (De Golyer & MacNaughton, 1953). The tectonic environment of the Farasan Islands is influenced by the opening of the Red Sea and the associated extensional tectonics, as well as the compressive forces resulting from the ongoing collision between the Arabian Plate and the African Plate. The islands' geological history includes the development of various structural features such as fault lines, uplifted plateaus, and deep marine basins, all of which are indicative of active tectonic processes.

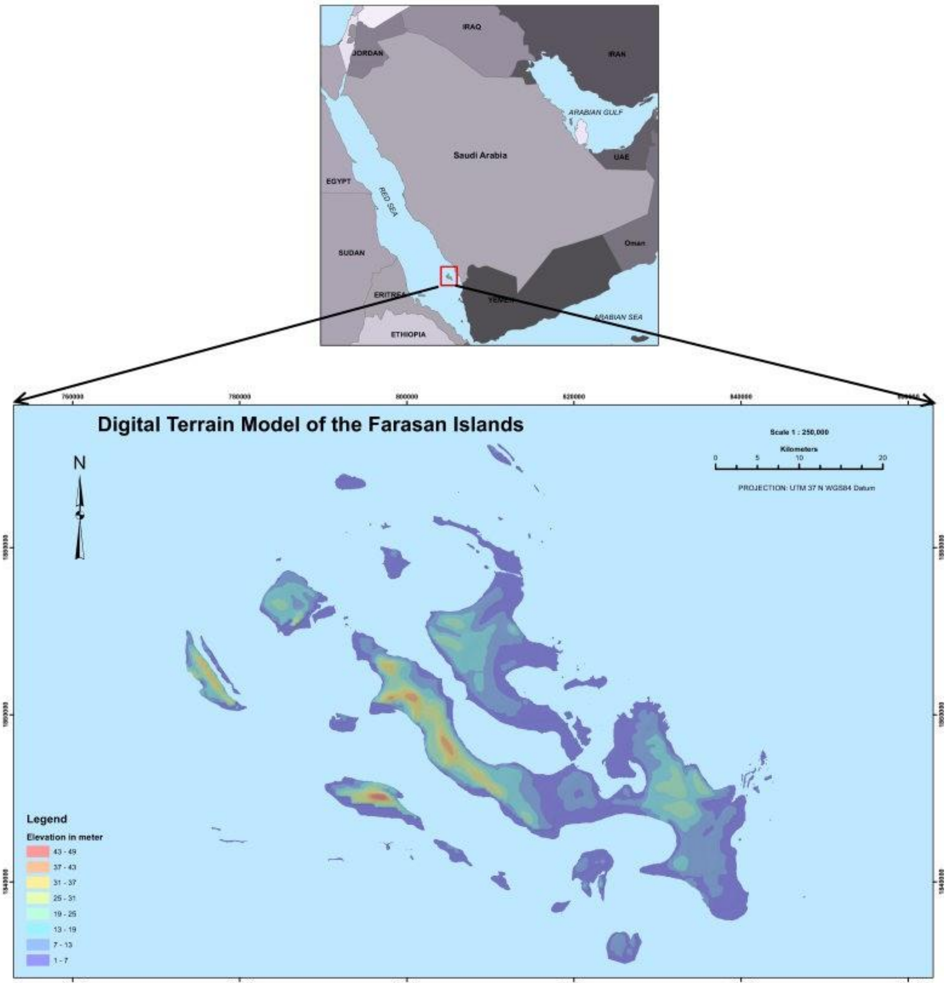


Figure 1: Satellite image depicting the location of the Farasan Islands. Adopted from (Almalki et al., 2017).

To analyze the tectonic activity in this region, this study focused on the geomorphological features that reflect neotectonic movements, such as changes in drainage patterns, slope morphology, and faulting. The study area was selected based on its tectonic significance, its proximity to major fault zones, and the availability of high-resolution satellite imagery and bathymetric data for GIS analysis (Bohannon & Eittreim, 1991).

2.2 Morphotectonic Indices

Morphotectonic indices are quantitative measures that help assess the influence of tectonic activity on the surface morphology of a region. These indices are derived from topographic and bathymetric data and reflect the degree of tectonic deformation. The most commonly used morphotectonic indices in this study are the slope angle, slope aspect, TWI, TRI, TPI, LS-factor, SPI, and Ar, which provide insights into the intensity and type of tectonic activity. Slope is defined as the rate of change of elevation, expressed as a gradient (in percentage) or in degrees. Using the finite difference approach, slope in any direction is expressed as the first derivative of the elevation in that direction. The deterministic eight-neighborhood (D8) algorithm estimates the slope by calculating the rate of change of elevation in the steepest downslope direction among the eight nearest neighbors. This approach is generally preferred when the channel slope is required (Moore, 1996). When gridded DEMs are used for the analysis, each of the grids is compared to its nearest eight neighbors and the slope is derived for each grid. Aspect is the direction that a slope faces. It identifies the steepest downslope direction at a location on a surface. It can be thought of as the slope direction or the compass direction a hill faces. Aspect is calculated for each cell in rasters (Wilson & Gallant, 2000; Deng, Wilson, & Bauer, 2007). It is measured clockwise in degrees from 0 (due north) to 360 (again, due north, coming full circle). The TWI evaluates the distribution of moisture across a landscape by considering its topographical features. It demonstrates how the configuration of landforms affects water accumulation by considering the contributing area and slope. Elevated TWI values suggest regions that have a higher capacity for retaining water, indicating wetter conditions (Qin et al., 2011). The TRI quantifies the roughness of a terrain by analyzing the variation in elevation within a specific region. It provides an assessment of how uneven the landscape is; higher TRI values signify more rugged areas that are typically characterized by prominent landforms such as hills and valleys. This index is beneficial for studies in ecology and hydrology (Evans, 2013; Dai et al., 2011). The TPI evaluates how a particular location fits within its surrounding landscape by comparing its elevation to adjacent areas. This index aids in identifying landforms and their relative placements, such as ridges, valleys, or slopes, thereby offering insights into the geomorphological processes that shape the environment. It is crucial for understanding different habitat types and ecological conditions (Jenness, 2006). The LS-factor integrates both the length and steepness of slopes to assess the likelihood of soil erosion due to water. This index helps illuminate how the arrangement of terrain influences erosion risk, as longer and steeper slopes are generally associated with a higher potential for erosion. It is frequently applied in soil conservation and land management strategies (Moore and Wilson, 1992) . The SPI quantifies the energy available for erosion within a stream, considering the water flow and the slope of the streambed. This index reflects the potential for sediment transport and erosion, which can be affected by both the topography and the hydrological conditions. The SPI is valuable in hydrology and fluvial geomorphology for comprehensively understanding river dynamics and sedimentation processes (Conesa-García et al., 2022). The Ar denotes the maximum difference in elevation within a specified area, indicating the vertical range of topographical variation. It serves as a straightforward measure of relief that captures the extent to which a landscape's height varies. This metric can yield insights into geological processes, the development of landforms, and the characteristics of erosion (Yang et al., 2018).

2.3 Collected Data

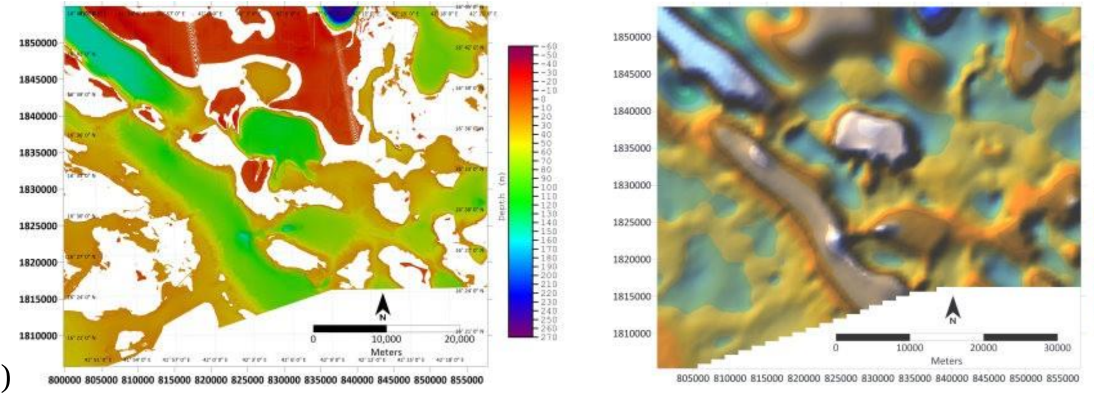
The primary data sources for this study included satellite imagery, bathymetric data, field observations, and previous geological reports. The data collection process is divided into the following key categories:

2.3.1 Bathymetric Data

Bathymetric data for the region were obtained from marine acoustic surveys and public geospatial databases. These data were essential for assessing underwater topography and identifying submarine fault lines, depressions, and ridges, which are indicative of tectonic activity beneath the ocean surface. The bathymetric data were integrated into the GIS platform to create a seamless model of the study area, combining both land and marine features (Fig 2a).

2.3.2 Satellite imagery

High-resolution satellite imagery was acquired from platforms such as Landsat and SPOT, which provided up-to-date data on the surface features of the Farasan Islands. The imagery was processed in GIS software to extract relevant morphometric features, including drainage patterns and fault lines. The satellite imagery also enabled the analysis of land cover and vegetation types, which were useful in assessing the spatial distribution of tectonic features (Fig 2b).



(a) (b)

Figure 2: a) Combined collected Swath bathymetry data with all acquired 10-, 20-, 50- and 100-m depth resolutions for the mapped region. **b)** Combined collected Swath bathymetry data and ASTER digital elevation model data for the mapped region.

3. GIS AND REMOTE SENSING ANALYSIS

The GIS platform used in this study was ArcGIS, which allowed for the integration, processing, and analysis of various spatial datasets (Jenson & Domingue, 1988, Wang & Liu, 2006). The analysis was carried out in several steps:

- **Data Preprocessing:** The satellite imagery, DEMs, and bathymetric data were preprocessed to reduce noise. The data were then geo-referenced to ensure spatial alignment and accuracy (Schilling et al., 2008).
- **Calculation of Geomorphic Indices:** Using GIS tools, the morphotectonic indices (drainage density, stream frequency, and basin elongation ratio) were calculated for each drainage basin in the study area. These indices were mapped to assess the spatial distribution of tectonic activity.
- **Multi-Criteria Decision Analysis (MCDA):** To assess neotectonic susceptibility, a multi-criteria decision analysis was performed by integrating data from various sources, including geomorphological features, fault lines, and lithological characteristics. This analysis allowed for the identification of areas with varying levels of tectonic hazard.

The final output from the GIS and remote sensing analysis included spatial maps that visualized the distribution of geomorphic indices and neotectonic activity across the Farasan Islands. These maps were further analyzed to identify areas of high tectonic risk and to assess the potential impact of tectonic processes on the region's infrastructure and environment.

4. RESULTS

The results of the GIS and remote sensing analysis are presented in terms of the spatial distribution of geomorphic indices and the identification of areas with varying levels of neotectonic activity. These results are based on the calculation of drainage density, stream frequency, and basin elongation ratio, along with the integration of bathymetric data and field observations. The study also incorporated multi-criteria decision analysis (MCDA) to assess the susceptibility of different regions to tectonic hazards.

4.1 Spatial Distribution of Geomorphic Indices

The analysis of geomorphic indices facilitated the identification of regions within the Farasan Islands that demonstrate varying degrees of tectonic activity. The spatial distribution maps created using GIS technologies revealed clear patterns of tectonic influence throughout the study area, as illustrated in Figures 3 a-d. The local slope calculated from a gridded DEM decreases with an increase in the DEM grid size. This is because, as the grid size increases, the grids represent larger areas. In the slope calculation, the spatial averages of the elevation for such larger areas are used, the result tends to be a smoother or less steep surface (Wilson et al., 2007). The extracted slope map from the gridded DEM of the area is shown in Fig 3a. On the other hand, the extracted aspect map from the gridded DEM of the area is shown in Fig 7b. The value of each cell in an aspect dataset indicates the direction in which the cell's slope faces (Wilson & Gallant, 2000; Deng, Wilson, & Bauer, 2007). Flat areas with no downslope direction are given a value of -1, as can be seen in Fig 3b.

The observed spatial distribution of Ar in the mapped area can indicate active or recent vertical displacements. Clusters of the observed Ar shown in Fig 3c were estimated using the geostatistical approach of Ar (the maximum difference in elevation within unit areas of 1 km2), which is considered a powerful indicator for active tectonics assessment (Ciotoli et al., 2003).

Information associated with recent vertical displacements of uplifted or subsidence blocks can be identified by the spatial distribution of the amplitude relief (Fig 3c). In the study area, the Ar values range from 0-130 m. Values higher than 80 m can be found mainly in the southern drainage basins. Relatively high values of Ar form an alignment with NW-SW and NE-SW extension zones. Highly increased values with regard to the surrounding neighborhood region can be found across the entire study area, indicating tectonically active regions.

Additionally, slope angle and slope length are the most important parameters in slope stability and are directly related to erosion rate and processes (Moore & Wilson, 1992). LS-factor demonstrates the fact that erosion increases with slope angle and slope length (Zhang et al., 2017). Many erosion models, including Universal Soil Loss Equation (USLE), used LS factor as a parameter to calculate the influence of terrain on potential soil loss and deposition. In this study, LS factor (dimensionless) was computed by applying the topographic indices module in SAGA GIS following a numerical model developed by (Moore & Wilson, 1992). As has been studied by (Zhang et al., 2017), the index corresponds to areas with the highest probability of erosion. Topographically, higher values of the LS factor are found in steep slopes and complex contours near river banks and cliffs. The Slope Length and Steepness factor, or the LS-factor, has the greatest effect on soil loss and morphotectonics. The S-factor measures the effect of slope steepness, and the L-factor defines the impact of slope length. The combined LS-factor describes the effect of topography on soil erosion and tectonics. LS was estimated for the mapped region as can be seen in Fig 3d. The LS-calculation was performed using the System for Automated Geoscientific Analyses (SAGA), which incorporates a multiple flow algorithm and contributes to a precise estimation of flow accumulation. The LS-factor dataset was calculated using a high-resolution (10-m) Digital Terrain Model for the entire region (see Fig 3d), resulting in an improved delineation of areas at risk of soil erosion and rifting. This combined approach involving the use of GIS software tools and high-resolution DTMs has been successfully applied in regional assessments in the past. It is now being applied for the first time in the mapped region. Overall, the geomorphic indices provided valuable insights into the tectonic processes at play across the Farasan Islands, with distinct patterns emerging that underscore the relationship between landforms and tectonic activity (Makrari et al., 2022).

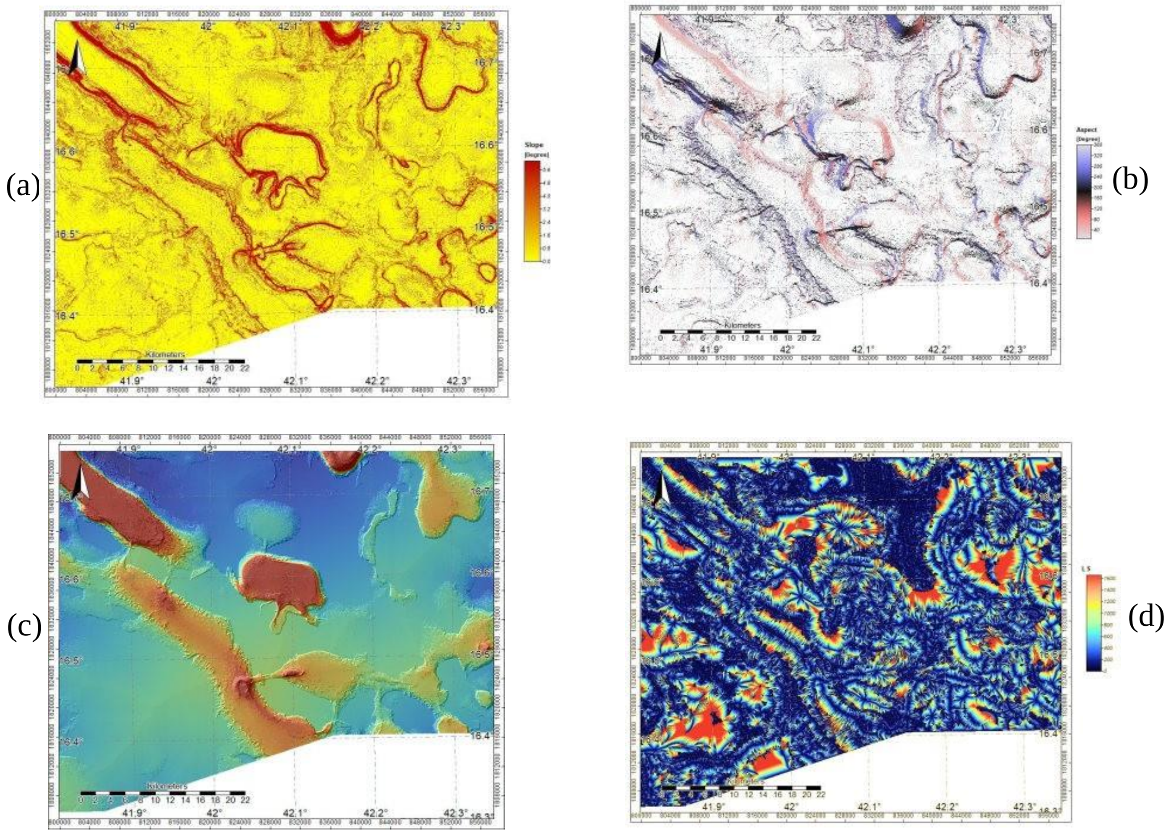


Figure 3: a) Slope map derived from the gridded Digital Elevation Model (DEM) of the area. **b)** Aspect map obtained from the gridded DEM of the area. **c)** Estimated Amplitude Relief (Ar) for the region. **d)** Calculated Slope Length and Steepness Factor, referred to as the LS-factor, for the mapped area.

4.2 Multi-Criteria Decision Analysis (MCDA)

The multi-criteria decision analysis (MCDA) was employed to evaluate the neotectonic susceptibility (or susceptibility maps) of the Farasan Islands in a spatial context. By integrating diverse data layers, including geomorphological features, fault lines, and lithological properties, the MCDA produced a detailed susceptibility map (see Figures 4 a-d). The findings from the MCDA indicated that the central and eastern sections of the islands, characterized by high drainage density, frequent streams, and elongated basins, are at significant risk for tectonic activity. These regions were categorized as having a high susceptibility to neotectonic hazards such as faulting, landslides, and ground deformation (Bribiesca, 1997). This underscores the importance of monitoring these areas for potential geological threats. In contrast, the northern and western parts of the islands, displaying lower drainage density and more stable geomorphological characteristics, were classified with moderate to low susceptibility to neotectonic hazards. The MCDA results emphasized the central region as the most critical zone for observing tectonic activity and assessing associated risks.

The results of this analysis are illustrated in Figures 4 a-d. The Stream Power Index (SPI) was computed using the Standard Terrain Analysis tool from the Terrain Analysis module within SAGA GIS software. This tool generates numerous raster layers related to terrain, including slope, aspect, curvature, hill shading, and watershed basins, along with a vector layer representing the watershed channel network (Fig. 4a). The Stream Power Index reflects the erosive strength of streams and was derived from a Digital Elevation Model (DEM) with a spatial resolution of 10 x 10 meters (Fig. 4a). The Topographic Wetness Index (TWI), also known as the Compound Topographic Index (CTI), is a steady-state indicator of wetness that considers the upslope contributing area along with certain geometric functions. The TWI values are based on the flow accumulation raster corresponding to the DEM (see Fig. 4b). The construction of the TWI index accounts for two types of slope shapes: concave and convex. A concave slope in low-gradient areas tends to collect water, resulting in a lower TWI value, while a convex slope in steep areas tends to shed water, contributing to a higher TWI index (see Fig. 4b). The estimated TWI thus serves as a straightforward mathematical representation of potential soil moisture in the mapped region, as evidenced by the digital terrain data shown in Fig. 4b. The Topographic Ruggedness Index (TRI) was calculated to quantify elevation differences between adjacent cells in the DEM. It determines the elevation variations from a central cell by comparing it to the eight surrounding cells. The calculation involves squaring the elevation differences, averaging the squared values, and then taking the square root of that average. The TRI was derived for the mapped region (see Fig. 4c) to quantify topographic heterogeneity resulting from nearby tectonic activity related to rifting in the Red Sea. Various physical and biological processes that affect the landscape correlate closely with topographic position such as hilltops, valley bottoms, ridges, and slopes. The Topographic Position Index (TPI) assesses the elevation of each cell in a DEM relative to the average elevation of neighboring cells within a defined area. An annulus neighborhood is commonly used, although other geometric forms can be applied. The TPI can be generated easily from a digital elevation model, requiring only the radius of neighboring cells and their geometric arrangement based on varying scales. In this study, a radius ranging from 50 to 1000 meters was employed to determine slope positions, utilizing Gaussian and exponential weighting with a bandwidth value of 75 was used. The resulting TPI values are presented in Fig. 4d. The integration of these analytical methods and indices allows for a comprehensive understanding of the neotectonic susceptibility across the Farasan Islands, facilitating effective monitoring and management of geological hazards.

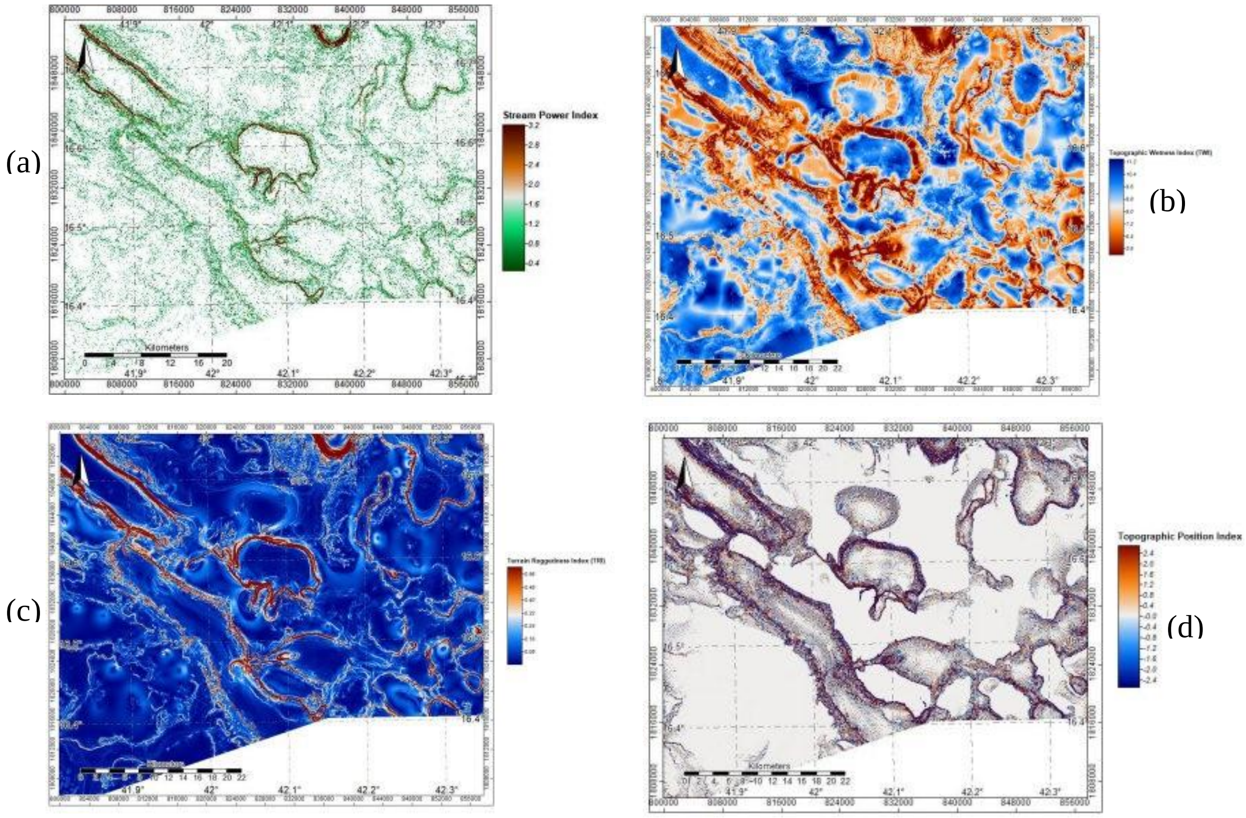


Figure 4: a) Stream power index (SPI) map for the area. **b)** Topographic Wetness Index (TWI) for the mapped region. **c)** Terrain Ruggedness Index (TRI). **d)** Topographic Position Index (TPI).

4.3 Bathymetric Data Analysis

The bathymetric data analysis provided valuable insights into the underwater topography of the Farasan Islands and its relationship to tectonic activity. Submarine fault lines, ridges, and basins were identified in the bathymetric data, particularly along the eastern and southern coasts of the islands. These underwater features are indicative of tectonic deformation beneath the ocean floor, which is consistent with the patterns of land-based tectonic activity observed in the geomorphic indices (Saaty, 1994).

The bathymetric data also revealed the presence of deep marine basins and fault zones in the Red Sea, which are aligned with the tectonic features on land. The spatial correlation between the bathymetric features and the geomorphic indices further supports the conclusion that tectonic activity is actively shaping both the land and marine environments surrounding the Farasan Islands. Based on the estimated TPI cluster values, the geomorphological units were identified (Fig. 5).

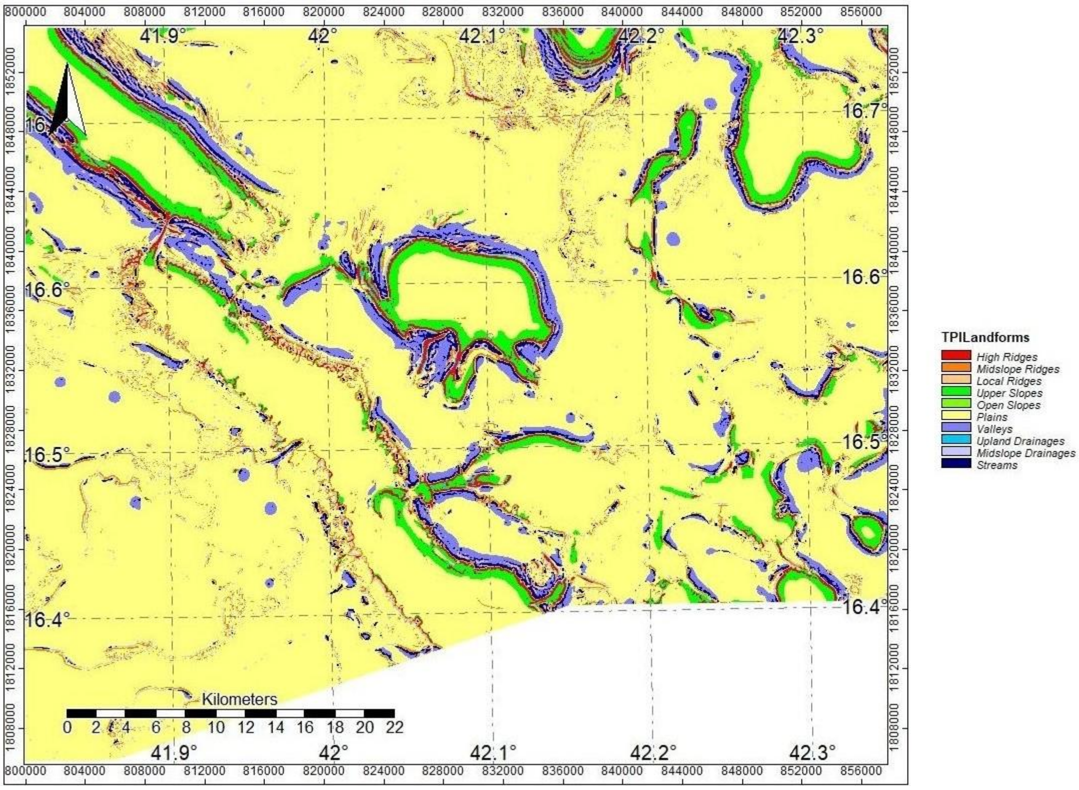


Figure 5: Geomorphological units for the area.

4.4 Tectonic Activity Zones

The integration of geomorphic indices has enabled the identification of distinct zones of tectonic activity within the Farasan Islands. The conclusive assessment of tectonic indicators is illustrated in Figure 6. This figure underscores the efficacy of the geomorphic indices derived from Digital Elevation Models (DEMs) through GIS methodologies in recognizing neotectonic activity across the Farasan Islands landscape.

Based on the analysis of drainage density, stream frequency, and basin elongation ratio (ESRI, 2011), the identified zones were classified into varying levels of tectonic activity: The central and eastern regions of the Farasan Islands were classified as zones of high tectonic activity. These areas are characterized by elevated drainage density, a high frequency of streams, and elongated drainage basins all indicative of active tectonic processes such as faulting and uplift. The presence of crucial tectonic features, including fault lines and fractures, reinforces the classification of these areas as high-risk zones for tectonic activity. Consequently, these regions are particularly susceptible to recent neotectonic movements, which may result in land deformation, landslides, and various other tectonic hazards. The northern and western parts of the Farasan Islands were designated as zones of moderate tectonic activity. These areas display lower drainage densities, less frequent stream flow, and more circular-shaped drainage basins. While there is evidence of some tectonic influence in these regions, they are not as significantly affected by recent faulting and uplift compared to the central and eastern zones. The moderate level of tectonic activity suggests that while tectonic movements may have occurred historically, the northern and western areas are currently experiencing a more stable geological environment. A smaller portion of the study area, particularly along the coastlines at the northernmost and southernmost extremes of the islands, was identified as low tectonic activity zones. These regions exhibit low drainage density, infrequent streams, and nearly circular or symmetrical drainage basins. Such characteristics indicate that these areas are largely unaffected by recent tectonic movements and likely experience minimal neotectonic deformation. The integration of geomorphic indices has provided a robust framework for assessing and delineating tectonic activity across the Farasan Islands. This classification not only enhances our understanding of the geological dynamics of the region but also informs potential risk assessment and management strategies for neotectonic hazards. The results reinforce the need for ongoing monitoring and research to mitigate the impacts of tectonic activity, particularly in areas identified as high-risk zones. In the Figure 6 legend, the inclusion of both "very high" and "very low" classifications suggests that the analysis has been nuanced enough to capture a more detailed range of tectonic activity levels. This differentiation may be based on distinct numerical thresholds or unique combinations of the evaluated criteria that are not covered by the general "high," "moderate," and "low" classifications.

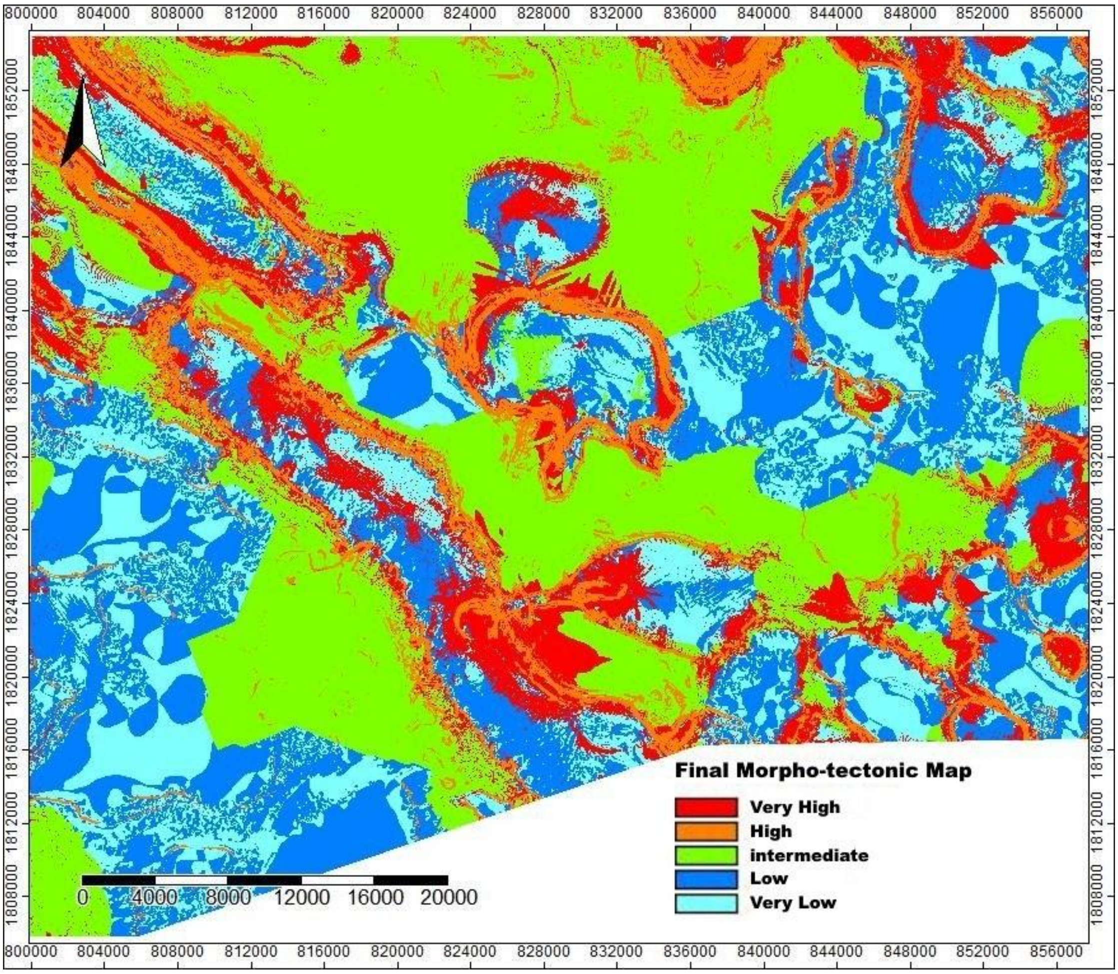


Figure 6: Relative morphotectonic index map for the mapped region.

5. DISCUSSIONS

The results of this study highlight the potential of GIS and remote sensing technologies to assess and monitor tectonic activity in regions like the Farasan Islands, where tectonic deformation plays a significant role in shaping the landscape (Jenness, 2006). The spatial distribution of geomorphic indices and the use of multi-criteria decision analysis (MCDA) have provided a comprehensive overview of the tectonic susceptibility in the region. The following discussion examines the implications of these results, their consistency with previous studies, and the broader significance of using GIS and remote sensing techniques in tectonic hazard assessment (Argyriou et al., 2016).

5.1 Interpretation of Geomorphic Indices

The geomorphic indices, particularly drainage density, stream frequency, and basin elongation ratio, were effective in delineating areas of varying tectonic activity across the Farasan Islands. These indices are commonly used in morphotectonic studies to identify regions affected by recent tectonic movements. The higher drainage density and stream frequency observed in the central and eastern parts of the islands suggest active faulting and tectonic uplift, which are consistent with the results of other studies conducted in tectonically active regions. The elongation of drainage basins, especially in the central area, further supports the hypothesis of extensional tectonic activity, which is commonly observed in regions subjected to normal faulting and rifting (Nazish, n.d.).

In contrast, the northern and western parts of the Farasan Islands, with their lower drainage density and more rounded basins, exhibit characteristics of more stable geomorphological environments. These areas may be less influenced by recent tectonic movements, possibly indicating that the tectonic forces in these regions have either been weaker or have been dormant for an extended period.

The results also align with earlier studies in other regions where similar indices were used to analyze neotectonic activity. For instance, studies in the Mediterranean region have shown that drainage density and stream frequency are sensitive indicators of tectonic activity, particularly in areas of active faulting and land deformation (Larroque et al., 2011).

5.2 Role of Multi-Criteria Decision Analysis (MCDA)

The use of multi-criteria decision analysis (MCDA) in this study added a layer of sophistication to the tectonic hazard assessment. By integrating multiple data layers, including geomorphic indices, fault lines, and lithological features, the MCDA provided a more nuanced understanding of tectonic susceptibility across the Farasan Islands. The susceptibility map generated through MCDA revealed that the central and eastern parts of the islands are at the highest risk of tectonic hazards, including faulting, landslides, and ground deformation (Bribiesca, 1997).

The central and eastern regions, identified as areas of high tectonic activity, exhibit high drainage densities, frequent streams, and elongated basins, all of which indicate the presence of active fault lines and recent tectonic movements. This corresponds well with field observations and bathymetric data, which suggest that these areas are undergoing significant deformation due to ongoing tectonic forces. Furthermore, the use of MCDA allowed for a more comprehensive evaluation of spatial relationships between various tectonic features, enhancing the reliability of the susceptibility map.

In comparison, the northern and western parts of the islands, classified as moderate to low susceptibility zones, demonstrated lower tectonic activity. These regions may experience occasional seismic activity but are less prone to the kind of large-scale tectonic deformations observed in the central and eastern areas.

The MCDA approach used in this study provides a robust tool for assessing tectonic susceptibility in regions where traditional methods, such as field surveys or qualitative geomorphic analysis, may be limited by accessibility or data constraints. MCDA allows for the systematic integration of diverse datasets, facilitating more accurate and comprehensive hazard assessments.

5.3 Integration of Bathymetric Data

The inclusion of bathymetric data in this study was essential for understanding the broader tectonic context of the Farasan Islands, especially in terms of marine geology (Fig 2a). The bathymetric analysis revealed a number of underwater features, such as submarine ridges and fault lines, which correlate with the tectonic activity observed on land. These features suggest that the tectonic processes affecting the islands are not confined to the terrestrial environment but extend to the seafloor, providing further evidence of ongoing tectonic deformation in the region (CARIS, 2017).

The presence of deep marine basins and fault zones in the Red Sea, which are aligned with the tectonic features on the islands, reinforces the idea that the Farasan Islands are situated in a tectonically active region. The interaction between land-based and marine tectonic features underscores the importance of considering both terrestrial and submarine data when assessing tectonic hazards, particularly in coastal and islands regions.

While bathymetric data can be challenging to obtain and analyze, its integration with land-based remote sensing data offers a more holistic view of tectonic activity (Fig 2b). The results of this study suggest that similar approaches can be applied to other islands or coastal regions, where the combination of bathymetric and geomorphic data can provide critical insights into the tectonic dynamics of the area.

5.4 Implications for Tectonic Hazard Assessment

The findings of this study have significant implications for tectonic hazard assessment in the Farasan Islands and similar regions. The ability to accurately identify areas of active tectonic deformation and assess their susceptibility to future tectonic events is crucial for disaster risk reduction and land-use planning (Hrvatin, Perko, & Petek, 2006). By using GIS and remote sensing techniques, coupled with MCDA and bathymetric analysis, this study provides a framework for conducting similar assessments in other tectonically active regions.

The results also emphasize the need for continuous monitoring of tectonic activity in regions like the Farasan Islands. Given the dynamic nature of tectonic processes, regular updates to the geomorphic indices and susceptibility maps are essential for tracking changes in the landscape and anticipating potential hazards. Remote sensing technologies, such as satellite imagery and bathymetric data, offer valuable tools for monitoring these changes over time, providing decision-makers with the information needed to mitigate risks and plan for future events.The results also align with earlier studies in other regions where similar indices were used to analyze neotectonic activity. For instance, studies in the Mediterranean region have shown that drainage density and stream frequency are sensitive indicators of tectonic activity, particularly in areas of active faulting and land deformation.

The classification of tectonic activity zones can be performed using both numerical scoring systems and subjective assessments, depending on the methodologies employed in the analysis. Typically, a combination of both approaches is used to achieve a more comprehensive and objective classification.

6. CONCLUSIONS

This study demonstrates the effectiveness of combining GIS, remote sensing, and morphotectonic indices for assessing tectonic activity in the Farasan Islands. The results suggest that the application of geomorphic indices derived from DEM data, along with advanced techniques like multi-criteria decision analysis (MCDA), offers a robust method for mapping and analyzing tectonic susceptibility in islands and coastal regions, offer an effective and comprehensive method for analyzing tectonic hazards. The findings contribute to the growing body of knowledge on tectonic hazard assessment and provide valuable tools for future research and practical applications in disaster risk reduction and environmental management.

The findings of this research highlight several key points:

- **Tectonic Activity Distribution:** The GIS-based analysis of geomorphic indices revealed clear spatial patterns of tectonic activity across the Farasan Islands. The central and eastern parts of the islands exhibit high levels of tectonic activity, characterized by active faulting and deformation. These areas show high drainage densities, frequent stream patterns, and elongated basins, indicating ongoing tectonic forces at play. In contrast, the northern and western regions display lower levels of tectonic activity, suggesting relative stability.
- **Role of Multi-Criteria Decision Analysis (MCDA):** The integration of MCDA into the study provided a sophisticated framework for assessing tectonic susceptibility. By incorporating multiple data layers, including geomorphic indices, fault lines, and lithology, the MCDA approach produced a detailed susceptibility map that effectively identified areas of high and low tectonic activity. This highlights the power of MCDA in synthesizing diverse datasets for more accurate hazard assessments.
- **Bathymetric Data Integration:** The study also emphasizes the value of integrating bathymetric data in tectonic hazard assessments. The bathymetric analysis revealed significant underwater tectonic features, including ridges and fault zones, which align with the terrestrial tectonic features on the islands. This reinforces the idea that the Farasan Islands are part of a larger tectonic system that includes both land-based and marine features.
- **Potential for Future Applications:** The methodologies developed and tested in this study provide a valuable framework for assessing tectonic activity in other tectonically active regions. By combining GIS, remote sensing, and morphotectonic analysis, it is possible to develop accurate susceptibility maps that can inform disaster risk management and land-use planning in regions vulnerable to tectonic hazards. Furthermore, the integration of

bathymetric data adds an additional layer of insight, making this approach adaptable for coastal and islands regions where both land-based and marine tectonic features are present.

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BIOGRAPHICAL NOTES

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