

GIS Application for the Quantitative Assessment of Geodiversity in Santa Elena, Ecuador

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Abstract

Geodiversity is defined as the variety of geological, geomorphological, and mineral elements present in a given territory. However, despite its importance in understanding the processes that govern the functioning of the planet and maintain environmental balance, its study remains limited in many regions. In this context, the present study aimed to evaluate the geodiversity of the Santa Elena Province through a quantitative analysis of the geodiversity index, obtained by integrating five components (geological, geomorphological, mineralogical, paleontological, and pedological) to characterize the province's abiotic diversity spatially. The research was structured in three phases: (i) definition of geospatial variables, (ii) calculation of the geodiversity index, and (iii) identification of areas of heritage interest. The results show that 30.92% of the studied territory has a geodiversity index classified as high to very high, indicating a greater variety of geological features in this area. These areas primarily coincide with regions of high biodiversity, which will enhance future tourism development in the territory. This study establishes an initial framework for geotourism promotion and geological heritage conservation strategies, focusing on establishing geotourism routes that incorporate community participation. The resulting cartographic product and estimated index represents a fundamental input for land-use planning, geotourism promotion, and development of effective geoconservation strategies for the province.

Keywords

Cartography, Geoconservation, Geosites, Geotourism, spatial analysis

1. Introduction

Geodiversity is a relatively new concept that has been defined in various ways by different authors since the 1990s [1]. It emerged from the need for a concept that encompassed the abiotic components of the natural environment, such as rocks, minerals, landforms, soils, and geological processes [2]. According to Nieto [3], geodiversity is "the number and variety of structures (sedimentary, tectonic) and geological materials (minerals, rocks, fossils, and soils) that constitute a region's substrate, upon which organic activity including human activity is based." Gray [4] defines geodiversity as "the natural range of diversity of geological features (rocks, geomorphological features—including landforms, minerals, and fossils—terrain, and processes) and relationships, interpretations, and systems" This definition

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has become the international benchmark for geodiversity studies, particularly in the fields of ecology, biodiversity, and conservation [5].

Geodiversity is the abiotic equivalent of biodiversity [6] and provides society with numerous goods and services that are fundamental to human well-being and development [7]. However, it was not until after 2010 that the number of studies on geodiversity experienced significant growth, approaching the subject from multiple perspectives, thereby establishing it as an emerging topic within the earth and environmental sciences [8].

Geodiversity is assessed based on two analytical criteria: (i) data provenance, comprising direct and indirect approaches, and (ii) the type of analysis employed: qualitative, quantitative, or mixed (quantitative-qualitative) [9]. Direct methods rely primarily on fieldwork for geodiversity assessment, whereas indirect methods utilise pre-existing information such as geological, geomorphological, soil, and hydrological maps, digital terrain models, and databases; the latter are the most common, as data acquisition is simpler and considerably less costly [10]. Qualitative approaches describe and evaluate a territory's abiotic elements based on criteria of importance; quantitative approaches estimate abiotic diversity using derived variables, mathematical indices, and spatial analyses; and mixed approaches combine both methods [9].

The assessment procedure is based on measuring and numerically analysing components within a specific area. It employs indices and spatial variables to evaluate the diversity of abiotic elements—such as geology, geomorphology, soils, hydrology, and mineral resources. This approach enables the comparison of zones, the establishment of geodiversity levels, and support for decision-making regarding land-use planning and conservation [11, 12]. To this end, map algebra techniques within geographic information systems (GIS) are utilised, allowing for spatial operations between variables to generate indices that represent the territory's abiotic diversity and its spatial distribution [12, 13].

Numerous studies on calculating the geodiversity index have been conducted worldwide. Carruana Herrera and Martínez Murillo [14] evaluated the geodiversity index of the Sierras Subbéticas Natural Park and Geopark (Cordoba, southern Spain) using map algebra. Parrot et al. [15] calculated the geodiversity index for the Republic of Mexico based on three sub-indices: geology, geomorphology, and soils. Pereira et al. [12] evaluated the geodiversity index for the State of Paraná (Brazil) using five main components: geology (stratigraphy and lithology), geomorphology, palaeontology, soils, and mineral occurrences. Silva et al. [11] assessed the geodiversity of the Xingu River basin (Amazonia, Brazil) by quantifying and integrating abiotic characteristics represented in thematic maps.

Research focused on assessing geodiversity in Ecuador remains limited; among the most significant studies is that conducted by Carrión-Mero et al. [13] at a regional scale, which evaluated the geodiversity of mainland Ecuador by estimating a geodiversity index based on partial indices (lithological, geomorphological, paleontological, pedological, and mineral occurrence). Additionally, Vera et al. [16] quantified the geodiversity of the Napo Amazon region using spatial indices to support a UNESCO geopark bid, evaluating five components: geology, geomorphology, hydrology, soil, and mineral resources.

In 2025, Ecuador increased the number of UNESCO Global Geoparks to three with the addition of Napo Sumaco and Volcan Tungurahua, joining the Imbabura Global Geopark. According to UNESCO [17], this recognition positions Ecuador as the country with the second-highest number of recognised global geoparks in Latin America and the Caribbean relative to its territory, strengthening its regional leadership in geoconservation.

Furthermore, UNESCO recognises geoparks as spaces that contribute to the conservation of geological heritage, environmental education, and the development of geotourism, while simultaneously promoting sustainable development alternatives with the active participation of local communities. From this perspective, the Santa Elena Peninsula Geopark Project represents an opportunity to strengthen the appreciation and protection of the coastal region's geodiversity, given that this territory currently lacks a UNESCO Global Geopark.

The Santa Elena Province possesses high geological potential and significant geodiversity, resulting from its complex geological evolution and diverse geomorphological features. Against this backdrop, various studies have focused on geosite assessment, geotourism, the Santa Elena–Ancon Geopark project,

and the valuation of the province's geological and paleontological heritage [18, 19, 20]. However, existing studies focus on the characterisation and assessment of individual geosites rather than conducting a quantitative spatial evaluation of geodiversity using a geodiversity index at the provincial scale. This lack of information limits the understanding of the spatial distribution of geodiversity and hinders the identification of areas with high geological value, as well as their integration into strategies for conservation, land-use planning, environmental management, and the sustainable use of geological heritage.

Against this backdrop, the following questions arise: Which areas of the province exhibit the greatest geological diversity for the development of geotourism and geoconservation strategies that foster the sustainable use of natural resources? And how can connections be established with other biodiversity and historical-cultural values? Therefore, this study aims to assess the geodiversity of Santa Elena province by calculating a geodiversity index—integrating geological, geomorphological, pedological, paleontological, and mineral occurrence components using GIS tools for spatial analysis and to propose strategies that contribute to land-use planning and the conservation of geological heritage.

2. Materials and methods

2.1. Study area

The Santa Elena province is located at the westernmost point of mainland Ecuador, within the Coastal region. It is bordered to the north by the province of Manabí, to the south by the Guayas province and the Pacific Ocean, to the east by the Guayas province, and to the west by the Pacific Ocean (Figure 1) [21]. The province comprises three cantons—La Libertad, Salinas, and Santa Elena—and has a population of approximately 186,687 inhabitants and a land area of roughly 3,690.17 km² [22, 23], with an average elevation of 40 meters above sea level. It features a hot, arid climate, with a mean annual temperature of 23.1°C [21].

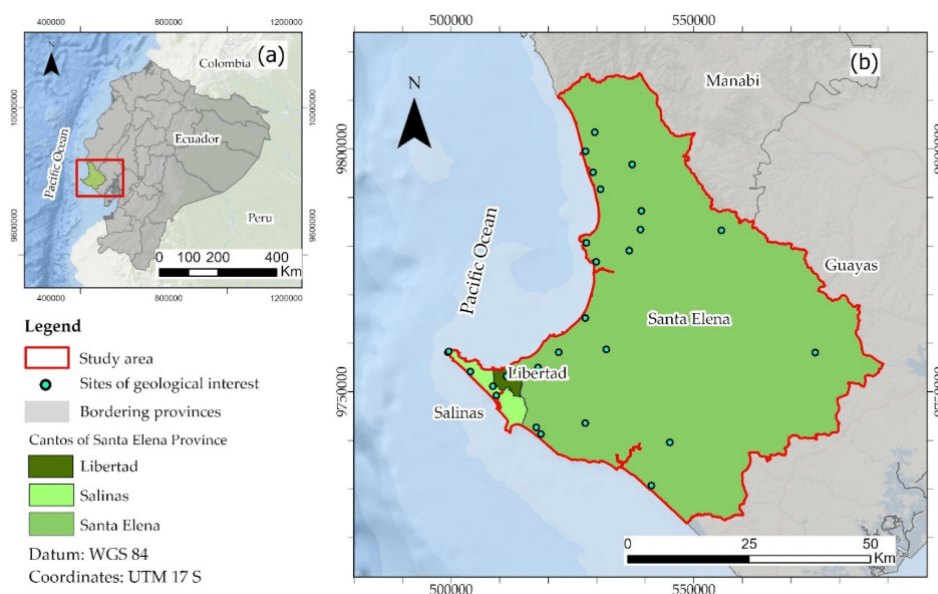


Figure 1: Location of the study area. (a) Location of the study area relative to mainland Ecuador. (b) Delimitation of the study area corresponding to the Santa Elena province, its cantons, and neighboring provinces.

The Santa Elena Canton lies primarily over the Progreso Basin, one of the most important sedimentary basins on the Ecuadorian coast. This basin developed as a forearc basin between the continental margin and the Andean volcanic arc [22], resulting from the subduction of the Nazca Plate beneath the South American Plate [23]. This process has controlled the tectonic evolution of the southwestern Ecuadorian continental margin since the Late Cretaceous [24].

The configuration of the relief in the Santa Elena province is primarily influenced by two major geological structures: the Chongon–Colonche mountain range, located in the northern sector, and the Azucar–Playas horst, situated to the south [22]. The interaction of these structural elements has given rise to various geomorphological units, including coastal plains, marine terraces at different levels (high, intermediate, and low), and landforms associated with the evolution of the Chongon–Colonche range [25]. The formation of these landforms is the result of a dynamic geological history, in which processes such as tectonic activity, sediment accumulation, and marine erosion have played a role in the progressive transformation of the province's landscape [24].

The geological basement consists primarily of Cretaceous rocks of oceanic and volcanosedimentary origin, represented by the Piñon and Cayo formations, which form part of the structural complex of the Chongon–Colonche mountain range [26] (Figure 2). Overlying these Cretaceous units are Tertiary and Quaternary sedimentary deposits comprising marine and continental sequences, including alluvial and colluvial deposits and marine terraces [25], formed through the interaction of subduction processes and coastal sedimentary evolution associated with the active Pacific continental margin [23]. The study area exhibits a complex evolution shaped by subduction, marine sedimentation, tectonic uplift, and coastal geomorphic processes, accounting for the diversity of geological and geomorphological units found in the region [23].

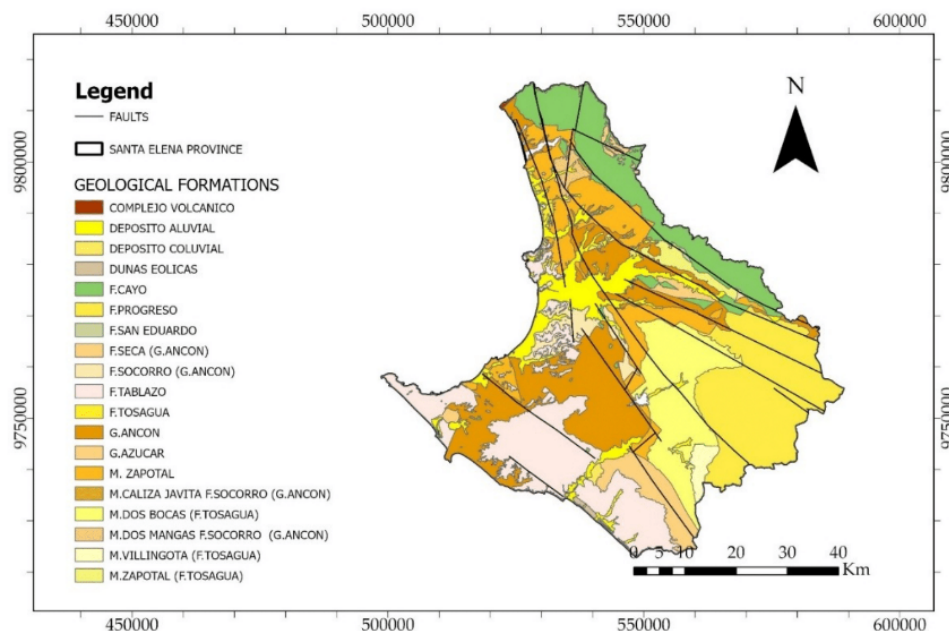


Figure 2: Geological map of Santa Elena province. Based on the Ministry of Agriculture, Livestock and Fisheries (MAGAP, acronym in Spanish) [27].

2.2. Method

This study is based on the quantitative geodiversity assessment methodology proposed by Pereira et al. [12]. This method allows for the quantification of geological diversity by integrating five sub-indices and using geographic information system (GIS) tools to analyse the spatial distribution of geodiversity. The process comprised three phases: i) definition of geospatial variables; ii) calculation of the geodiversity index based on the method of Pereira et al. [12], applying the variable normalisation process proposed by Carrión-Mero et al. [13]; and iii) identification of areas of heritage interest (Figure 3).

2.2.1. Phase I: Definition of the geospatial variables

The first phase consisted of gathering, reviewing, and organising the information required to conduct this study. Initially, a literature review was conducted covering research related to geodiversity,

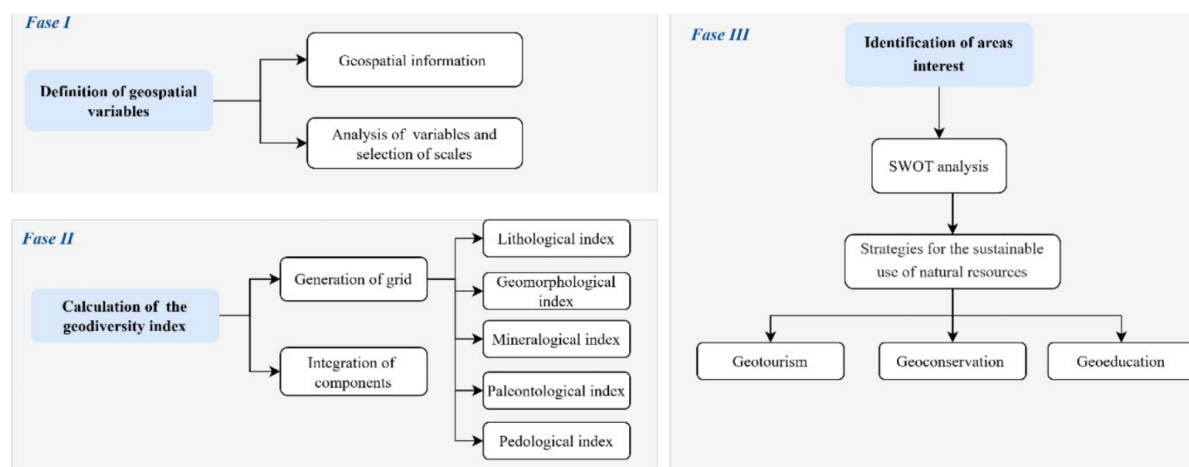


Figure 3: Flowchart of the methodology used for the assessment of geodiversity in the Santa Elena Province.

methodologies for calculating the geodiversity index, geosites, and geoconservation strategies; this review considered both national and international studies, enabling the definition of the methodological approach and an understanding of its application in the assessment and conservation of geological heritage [2, 7, 12, 28].

Subsequently, the available geospatial information for the study area was reviewed and systematised, including lithological, geomorphological, pedological, mineralogical, and paleontological mapping, as well as other base mapping required for the analysis (Table 1). The various information layers were evaluated for quality, scale, format, and spatial reference systems to ensure their compatibility.

Table 1

Specifications of the thematic maps used to calculate the Geodiversity Index.

Index	Data	Scale	Type of GIS geometry	Source
Lithological	Hydrogeology (Formations, lithology)	1:100000	Polygons	[27]
Geomorphological	Geomorphology (landforms)	1:25.000	Polygons	[29]
	River drainage system	1:1"000.000	Lines	[30]
Paleontological	Paleobiology Database	–	Points	[31]
Pedological	Geopedological units.	1:25.000	Polygons	[32]
Mineralogical	Map of no metallic mineral occurrences	1:1"000.000	Points	[33]
	Map of oil zones in Ecuador	1:1"000.000	Polygons	[34]
	Thermal Mineral Springs in Santa Elena	–	Points	[35]

2.2.2. Phase II: Calculation of the Geodiversity Index

In this phase, the geodiversity assessment methodology proposed by Pereira et al. [12] was applied and adapted to the scale of the Santa Elena province. To this end, thematic layers that had been previously compiled, standardised, and clipped to the study area boundaries were used. A regular grid was generated using the "Create Fishnet" tool in ArcGIS Pro, consisting of 2×2 km cells covering the entire province. This cell size was selected based on the extent of the study area, the spatial distribution of the elements, and the scales of the available cartographic data [36]. Unlike the study by Pereira et al. [12], which used a 25×25 km grid to assess a region of approximately 200,000 km², the 2×2 km

grid allowed for a more detailed representation of the spatial distribution of geodiversity components without causing excessive data fragmentation, thereby enabling a homogeneous spatial analysis [36].

As a first step, the ArcGIS Pro Dissolve tool was used to homogenise thematic units with similar attributes across the various map layers. This procedure reduced spatial data fragmentation and prevented double-counting of the same category. Subsequently, the Spatial Join tool was employed to determine the number of categories for each geodiversity component within each grid cell by counting the distinct thematic units associated with each component. The hydrographic network was included in the geomorphological index; rivers were classified by hierarchy and valued according to the methodology proposed by Pereira et al. [12]. The results enabled the calculation of sub-indices for lithology (IL), geomorphology (IGM), palaeontology (IPa), mineralogy (IM), and pedology (IPe). Subsequently, the sub-index values were normalised by dividing them by the maximum recorded value for each component (Equation 1), following the approach used by Carrión-Mero et al. [13]. Finally, the geodiversity index (IG) was obtained by summing the five component sub-indices proposed by Pereira et al. [12] (Equation 2); this index was then normalised (Equation 1) and classified into five categories: very low (1), low (2), medium (3), high (4), and very high (5) [37, 38].

$$IN = \frac{V_{Obs} * 5}{V_{Max}} \quad (1)$$

$$IG = IL + IM + IM + Ipa + Ipe \quad (2)$$

Where

- V_{Obs} : Number of occurrences of quantified elements in each cell for each subscript.
- V_{Max} : Maximum value of each subscript.

Finally, to generate a continuous representation of the spatial distribution of the geodiversity index, thereby helping identify areas of high and low geodiversity, geostatistical interpolation was performed using the Ordinary Kriging method in ArcGIS Pro. The quality of the interpolation model was evaluated through cross-validation.

2.2.3. Phase III: Identification of areas of interest

Priority areas were identified based on the spatial distribution of the geodiversity index, specifically targeting zones with high and very high index values that also spatially coincide with the locations of previously inventoried and studied geosites. This process enabled the identification of sectors with significant geological and geomorphological richness, representing areas of interest for proposed geotourism routes. Additionally, an analysis and validation of geotourism routes proposed in earlier studies were conducted, considering criteria such as i) connectivity between geosites, ii) approximate route length, iii) main access roads and available services, and iv) complementary tourist attractions, including cultural, archaeological, gastronomic, and recreational resources.

Finally, based on the generated geodiversity index map and existing research on the study area's geoheritage. SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) was conducted as a strategic diagnostic tool to evaluate the area's potential for geotourism, geoconservation, and geoeducation activities [19, 39]. This analysis was carried out based on the judgment of authors with expertise in fields such as geology, geoheritage, land use planning, and the environment. Drawing on the SWOT analysis, the study proposed a set of "3G" strategies (Geotourism, Geoconservation, and Geoeducation) as a tool to foster the sustainable development of coastal communities in the Santa Elena Province.

3. Results and discussion

The analysis of the geodiversity index made it possible to identify the spatial distribution of abiotic diversity within the study area (Figure 4). The sub-index maps (Figure 4 a–e) reveal distinct spatial

patterns. The sub-indices shown in Figures 4a and 4b exhibit a relatively homogeneous distribution, characterised by predominantly low values across most of the territory and only small areas with higher values. In contrast, sub-indices c, d, and e display greater spatial variability, reflecting a more heterogeneous distribution of the elements considered and contributing significantly to the composition of the final index.

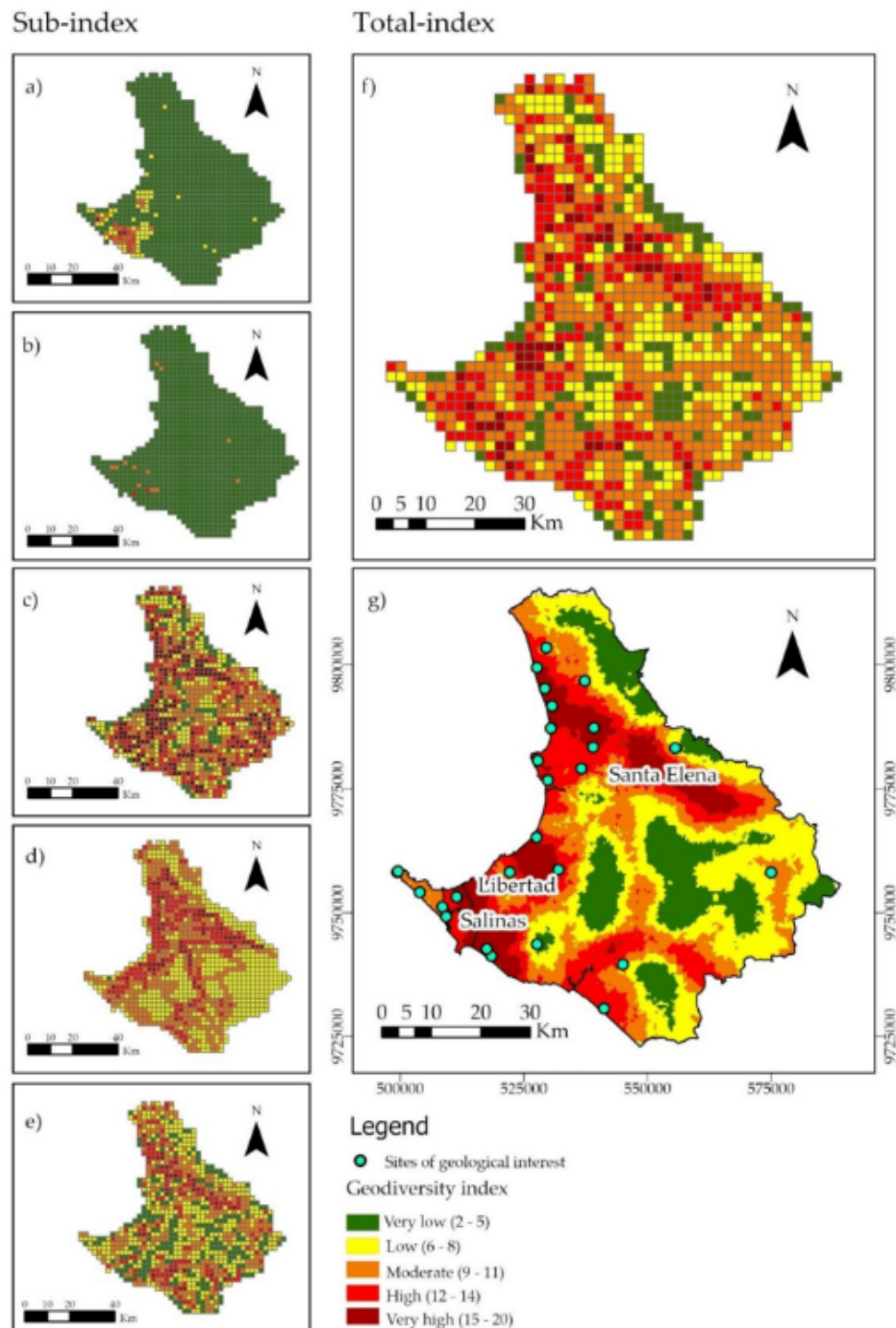


Figure 4: Map of the geodiversity index of the province of Santa Elena: a) mineralogical index; b) paleontological index; c) geomorphological index; d) lithological index; e) pedological index; f) map of the geodiversity index; g) Geodiversity index interpolation map.

Quantitative assessment of the GI revealed that 30.92% of the provincial territory (18.41% high and 12.51% very high) consists of zones with greater abiotic diversity [12]. These areas are distributed primarily across the western sector of the province, associated with the coastal strip, as well as in central

and south-central areas, where high index values exhibit greater spatial continuity. These values are linked to the presence of coastal plains, terraces (high, intermediate, and low), and structural landforms associated with the Chongon Colonche range, shaped by tectonic processes, sedimentation, and marine erosion, which have collectively moulded the current landscape [24, 25].

Unlike previous research conducted in the Santa Elena province, which focused on the assessment of geosites, geotourism, and the Santa Elena Geopark Project [18, 19, 20], this study incorporated a spatial and quantitative assessment of geodiversity by applying a geodiversity index at the provincial scale, enabling the identification of priority areas for sustainable land management.

The resulting map (Figure 4g) shows that several sites of geological interest are located within or near areas classified as having high and very high geodiversity values, demonstrating a direct relationship between the concentration of abiotic elements and the presence of geosites with scientific, educational, and tourism potential [18, 19, 40]. These areas are priorities for implementing geoconservation strategies aimed at protecting geological heritage and sustainably using natural resources.

Table 2

SWOT analysis results regarding the geodiversity of Santa Elena Province.

Strengths (S)	Weaknesses (W)
S1. High geodiversity of the territory (30.92%).	W1. Lack of ongoing strategies for the protection, monitoring, and proper management of geological heritage.
S2.. Most sites offer favourable accessibility conditions.	W2. Low
S3. Complementary natural and cultural richness.	W3. Limited government funding for the development and promotion of geosites.
S4. Coastal tourism routes with the highest tourist traffic in the country.	W4. Progressive loss of ancestral knowledge regarding natural resource management.
S5. Significant number of inventoried and evaluated geosites.	W5. Lack of dissemination of geological wealth by the local academic sector.
S6. Community interest in sustainable development alternatives.	
Opportunities (O)	Threats (T)
O1. Development of geoconservation and environmental education projects (geopark project).	T1. Prioritisation of conventional forms of tourism over geotourism, reducing institutional interest.
O2. Integration of geoheritage into territorial planning and local development strategies.	T2. Unplanned urban expansion and uncontrolled extraction of natural resources.
O3. Socio-economic development alternatives for rural communities.	T3. Loss of geological heritage due to natural and anthropogenic processes.
O4. Participatory geotourism approaches involving the community, academia, and government bodies.	T4. Impact of territorial insecurity levels on tourism.
O5. Preservation and transfer of ancestral knowledge in the country's coastal regions.	T5. Inconsistent environmental and conservation policies.
O6. National and international partnerships to access funding for projects.	

The cross-validation results showed a mean error (ME) of -0.0013 and a standardised mean error of -0.0015, both close to zero, indicating the absence of systematic bias in the predictions. The root mean square error (RMSE = 0.5248) was very similar to the average standard error (ASE = 0.5335), demonstrating an adequate estimation of uncertainty. Furthermore, the root mean square standardised error (RMSSE = 0.981) was very close to the ideal value of 1, indicating that the model adequately

represented the spatial autocorrelation structure of the data. Overall, these results support the use of Ordinary Kriging to generate the continuous IG surface for the study area. The choice of this method is based on its ability to estimate values in the spaces between data points using spatial autocorrelation, thereby producing a continuous surface that more realistically represents the spatial variability of the geodiversity index [41, 42].

The results of the SWOT analysis show that Santa Elena possesses favourable conditions for leveraging its geological heritage. These include a diversity of geological and geomorphological features, easy access to various geosites, and natural and cultural resources that can enhance its tourism value, all supported by opportunities such as the Geopark project. Establishing partnerships with various institutions offers a valuable opportunity to promote and strengthen geotourism throughout the province. However, some factors could limit its development, such as the lack of continuous management and promotion of geo-heritage, insufficient financial support, and the gradual loss of traditional and ancestral knowledge, which may be exacerbated by external factors like urban expansion, the deterioration of sites of geological importance, and changes in environmental policies and regulations (Table 2).

Based on the SWOT analysis, a set of "3G" strategies (Geotourism, Geoconservation, and Geoeducation) was formulated to strengthen the sustainable use of Santa Elena province's geological heritage. The proposed strategies include strengthening the Santa Elena Geopark Project through strategic alliances, developing new georoutes that integrate with existing tourism offerings, enhancing community participation in geotourism activities, implementing monitoring and conservation measures for geosites, and promoting education programs as well as the dissemination and promotion of geoheritage and geological heritage conservation efforts (Table 3).

Table 3

Strategies derived from the SWOT analysis of the geodiversity of Santa Elena Province.

Strategies: Strength + Opportunities	Strategies: Strength + Threats
S1.S3.O1.O6. Strengthen the Santa Elena Peninsula Geopark project through national and international partnerships that enable access to funding.	S5.T2. Use GIS-based predictive models to identify areas at higher risk of geological heritage loss due to urban expansion and anthropogenic activities.
S2.S4.O2.O4. Design smart, interactive geotourism routes that complement existing routes and are managed by local communities.	S2.S4.T4. Strengthening geotourism routes by implementing safe tourism corridors, leveraging the accessibility of geosites, and integrating them with major coastal tourism routes.
S6.S3.O3.O6. Establish community-based geotourism ventures linked to local culture, gastronomy, and artisanal products through partnerships and external funding.	S2.S4.T4.T5. Diversifying geotourism routes and establishing adaptive management protocols that consider safety, accessibility, and changes in environmental policies.
Strategies: Weakness + Opportunities	Strategies: Weakness + Threats
W2.W5.O3 Promotion of geoheritage through digital marketing and smart platforms to boost tourism and the sector's socioeconomic development.	W1.T1.T3. Regulate the tourism carrying capacity of the most sensitive sites to minimise the risk of degradation.
W1.W4.W5.O5. Establish a permanent program for training, monitoring, and dissemination of geological heritage that integrates scientific knowledge and ancestral wisdom.	W4.W5.T1.T5. Develop local policies for geoheritage education and communication to strengthen social valuation and ensure continuity amid institutional changes.
W5.O4. Design and implement coastal geotourism development plans that integrate geoheritage through coordinated participation of the community, academia, and government institutions.	W1.W5.T2.T3. To design a system of early warning indicators that enables the identification of changes in the conservation status, accessibility, safety, and anthropogenic pressure of the geosites.

According to G. Herrera-Franco et al. [19] protecting these sites alongside promoting their scientific and heritage value fosters public wellbeing by strengthening social development through the responsible

use, planning, and management of the territory. This research analyses the geodiversity of the Santa Elena province using geospatial indices to identify and characterise areas featuring geological and geomorphological elements of special interest. The results provide criteria to facilitate the identification and prioritisation of areas for geoconservation, while also offering information to support the design of georoutes and strengthen initiatives aimed at developing sustainable geotourism. This research provides a methodological basis for future geodiversity assessments in other regions of Ecuador and emphasises the importance of improving national geoscientific inventories to strengthen the management and conservation of geological heritage.

The geospatial index used in this study enabled the evaluation of Santa Elena province's geodiversity and the identification of areas with significant geological and geomorphological attributes. These results contribute to decision-making processes related to geoconservation, georoute planning, and the promotion of sustainable geotourism initiatives. The availability of geospatial datasets varied considerably among the variables included in this study. Mineralogical information was particularly difficult to compile because records describing the location of oil wells and other geological resources were incomplete and available from different sources. A similar situation was found for the paleontological sub-index, where the limited number of georeferenced national records required the use of international scientific databases to complement the analysis. These constraints influenced the compilation of the datasets and underline the value of developing more complete and consistently updated national geological inventories for future studies on geological heritage.

4. Conclusion

This study demonstrated that the province of Santa Elena exhibits high geodiversity, with 30.92% of its territory classified within the "high" and "very high" categories reflected in the diversity of geological, geomorphological, and pedological units that constitute an area of significant scientific, educational, and scenic value. The methodology employed proved suitable for representing the spatial distribution of geodiversity at the provincial scale, providing an objective basis for prioritising areas with potential for conservation and research.

Based on the results of the SWOT analysis, strategies aimed at the territory's geotourism development are proposed, organised into three lines of action: i) strengthening and management of geo-heritage; ii) diversification and promotion of geotourism activities; and iii) conservation, education, and monitoring of the geological values present in the territory. Their implementation relies on the active participation of the community, academia, and local governments, thereby offering socioeconomic alternatives to the population. Overall, the research findings highlight that geodiversity is a fundamental component of Santa Elena Province natural heritage and a key tool for territorial planning, conservation of geological resources, and promotion of sustainable development that integrates environmental and scientific criteria. Future research could address the risk of natural and human-induced degradation in areas of the territory characterised by high geodiversity and significant tourist influx.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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