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Criteria for Selecting Areas to Identify Ecosystem Services Provided by Geodiversity: A Study on the Coast of São Paulo, Brazil

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Abstract: Ecosystem services are essential for life. Despite traditionally focusing on biodiversity, several studies have presented the ecosystem services provided by geodiversity. However, the choice of the study area is still a step that raises doubts for the researcher. Several elements of geodiversity must occur in the area so that different ecosystem services can be identified. Thus, the selection of the study area is a crucial step of the research. This work aims to determine the criteria for the selection of potential areas for the identification of ecosystem services by geodiversity in Baixada Santista, central coast of São Paulo, Brazil. The criteria established were (i) characterization of the physical environment based on the geodiversity index map and the watershed map and (ii) description of land use based on the characterization of land use and analysis of territorial planning instruments. As a result, the watershed with high levels of geodiversity and diversity of land uses was selected. The criterion was important, as it is an area already used in soil management and different land uses can provide a variety of ecosystem services. Thus, these criteria proved to be effective in the selection of areas for the evaluation of ecosystem services by geodiversity.

Keywords: ecosystem services; geodiversity; land use; watershed

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1. Introduction

Ecosystem services are the goods and services provided by nature that are essential for the maintenance of life, societies, and human well-being [1–3]. In the last decade, the amount of research on this topic has increased [4]. Traditionally, research regarding ecosystem services exclusively considers the benefits related to biodiversity, though more recently, ecosystem services have been approached from a geodiversity perspective. Works such as References [5,6] understand that abiotic elements of nature also provide goods and services that are enjoyed by society and nature.

The authors of Reference [4] present research on ecosystem services that, even without mentioning geodiversity by name, already addresses this topic. In these studies, the study areas are diverse, from administrative areas [7] to ecosystems [8,9], islands [10], hydrographic basins [11,12], and relief forms—valleys [13]. Research that directly addresses the ecosystem services provided by geodiversity also occurs in different contexts such as large territories [14,15], ecosystems [16], sedimentary basins [17], environmental preservation areas [18], and watersheds [19,20]. However, these surveys do not indicate how the study area has been chosen.

The selection of areas for the identification of ecosystem services has been a crucial stage of research. When working in a large area, the separation of a representative area from the point of view of geodiversity is important so that efforts can be directed in a region that will have the services identified. This selection should take place before the fieldwork stage, as it will serve as a guide to assist the researcher in the search for work already carried out in the region, as well as providing details for those who do not know the study area in detail.

This guidance should be made with the help of remote sensing products and cartographic material, and, in this sense, the geodiversity index map that evaluates the characteristics of the physical environment can be used to assist in this step. According to [21], this methodology allows the highlighting of potential areas to be the target of further research, besides being possible to apply at different scales [22].

However, the geodiversity index map is insufficient to delimit a study area for research on ecosystem services. Several studies have used the watershed to delimit a study area to analyze ecosystem services [11,12,19,20]; this natural boundary is an important tool because it is a management unit, which facilitates communication with decision-makers, besides being a region with similar physical characteristics. Moreover, adding other criteria that encompass land management and different land uses will contribute to the establishment of areas with greater possibility of diversity of ecosystem services.

On the basis of these assumptions, the aims of this research are (i) to establish which criteria to analyze for the selection of potential areas for the identification of ecosystem services provided by geodiversity and (ii) to apply them in a study area in the Baixada Santista, central coast of the State of São Paulo, Brazil. The definition of the criteria is essential to guide future research in objectively determining the sites that will be the target of methodologies for the analysis of ecosystem services provided by geodiversity.

2. Study Area

The Baixada Santista is an administrative region of the state of São Paulo, Brazil, located in the central part of the coast, composed of nine municipalities: Bertioga, Guarujá, Cubatão, Santos, São Vicente, Praia Grande, Mongaguá, Itanhaém, and Peruíbe (Figure 1).

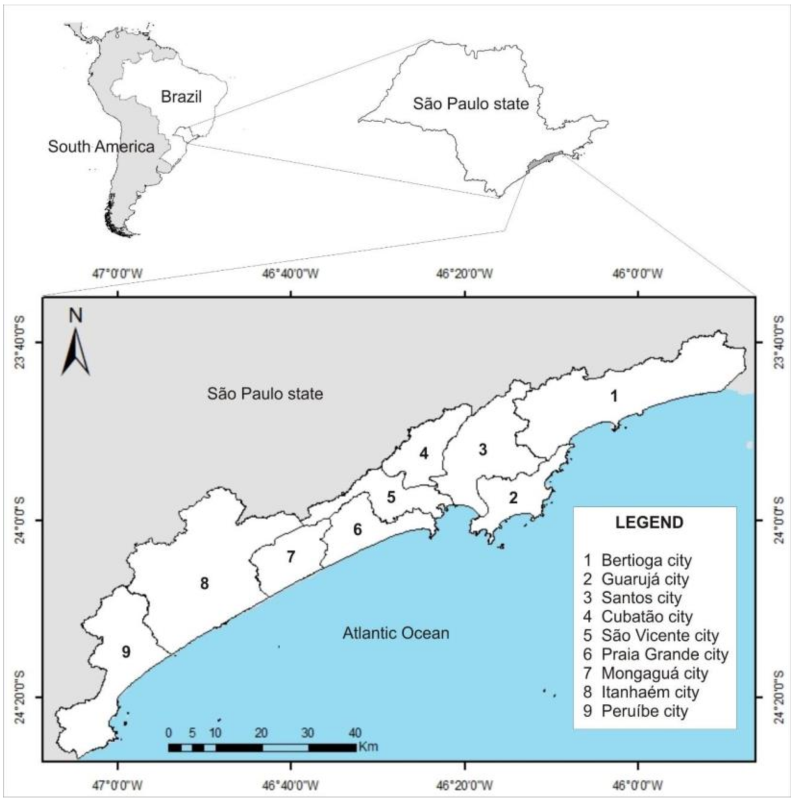

Figure 1. Location of the Baixada Santista, State of São Paulo, Brazil.

Regarding the geology, the study area is part of the Mantiqueira Province, which developed during the Neoproterozoic Brasiliano–Pan African cycle, as a result of the amalgamation of the Western Gondwana Paleocontinent [23]. The Mantiqueira Province is located parallel to the Atlantic coastline and aligned in a NE–SW direction [24,25] and is subdivided into mobile bands, which are composed of several terrains delimited by transcurrent shear zones. This province is segmented in three parts: northern segment (represented by the Araçuaí Belt), central segment (represented by the Ribeira Belt), and southern segment (represented by the Dom Feliciano and São Gabriel Bands) [23].

The Ribeira Belt is divided into five terrains: Embu, Curitiba, Luis Alves, Paranaguá, and Costeiro. Baixada Santista is inserted in the Embu and Coastal Terrane (Figure 2), which are limited by the Cubatão Shear Zone [26]. The Embu Terrane presents high-grade metamorphic rocks intruded by a series of granitic bodies elongated in the NE–SW direction. The authors of References [27,28] identified granitic magmatism of ca. 590 Ma and [29] dated the main metamorphic event at 790 Ma. In the Coastal Terrane, metasedimentary successions with high amphibolite to granulite facies are found [30], with metamorphism peaking at 745 Ma [31]. Granitic magmatism of about 630 Ma with a subsequent metamorphic event in 570 Ma was identified [32].

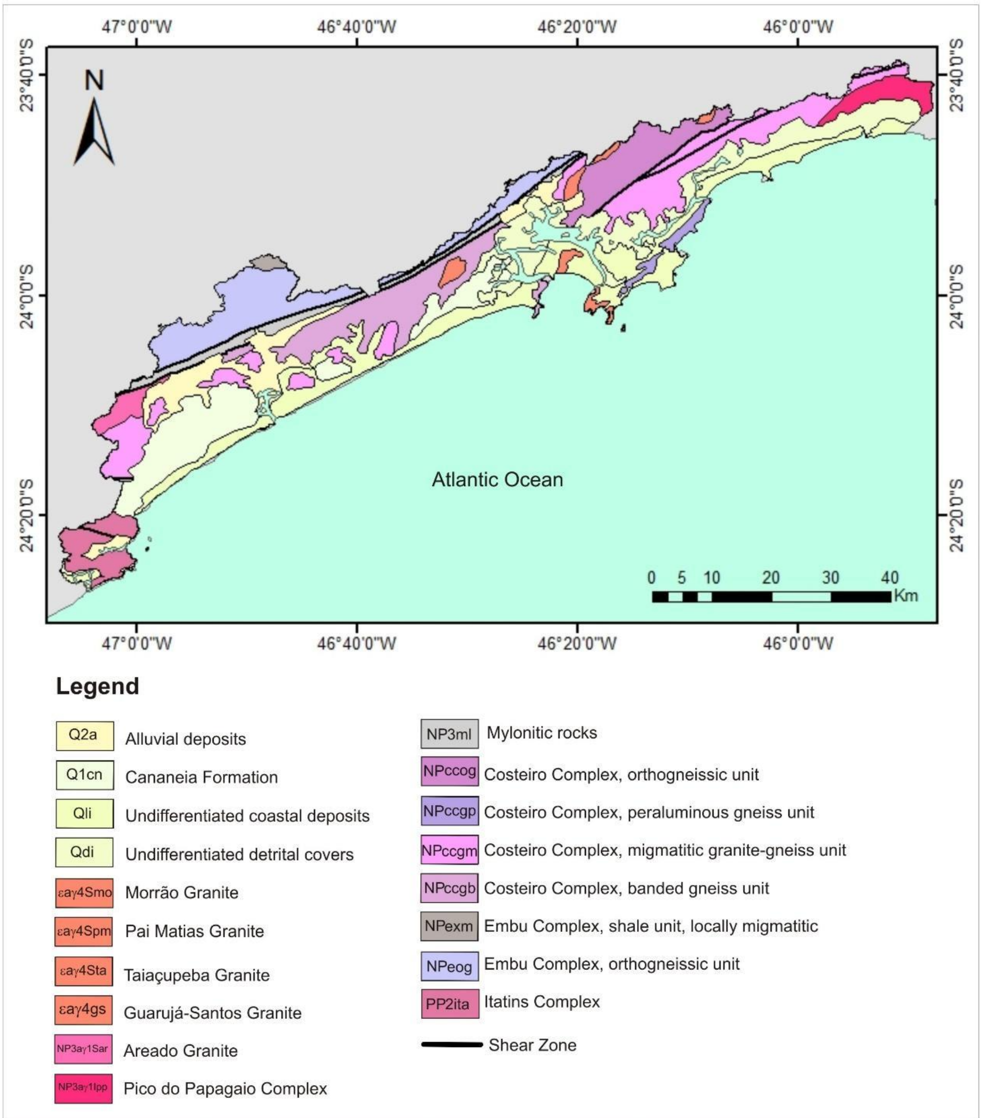

Figure 2. Geological map of the Baixada Santista, State of São Paulo, Brazil. Adapted from [33].

The relief of the region is marked by two compartments: the Serra do Mar and the Coastal Plain. The Serra do Mar is a topographic step in the NE–SW direction parallel to the coastline [34]. The scarps of this geomorphological feature were developed in the

Cenozoic by tectonic events with vertical movements. The Coastal Plain is represented by the Itanhaém-Santos and Bertioga-Ilha de São Sebastião units [35]. These units are formed by fluvio-marine sediments of the Quaternary age, in which Cananeia (Pleistocene) and Santos (Holocene) transgressive events generated the most recent sedimentary coverings of the region.

The climate of the study area is classified as tropical [36] and presents average temperatures of the warmest month above 18 °C and average annual precipitation between 1600 mm and 2000 mm. The climate favors a dense drainage network composed of 21 subbasins. According to [37], the rivers are not very extensive; they are born in the Serra do Mar and flow toward the ocean. The vegetation is characteristic of the Atlantic Forest and beach ecosystems (mangroves and spits forests).

Due to its physical characteristics, the Baixada Santista region began to be urbanized in the 16th century with the arrival of the Portuguese in Brazil, as the coastline allowed ships to anchor. Traditionally, this region served as the entrance and exit of people and goods to the Brazilian territory and currently stands out for the Port of Santos, the largest port in Brazil. Urban settlements are concentrated near the beaches and estuaries. The urbanization process used rocky outcrops to provide stone materials for the constructions, a fact that generated impacts on the elements of local geodiversity [38].

3. Methodology

The selection of potential areas for analysis of ecosystem services was carried out according to the following steps: (i) delimitation of the study area; (ii) characterization of the physical environment through cartographic material based on the geodiversity index map (distribution and frequency of the elements of geodiversity) and the drainage network; (iii) land use characterization and analysis of land use planning instruments; (iv) selection of a watershed with high geodiversity and ecosystem services analysis through the diversity of land uses.

The methodology proposed by [39] was used in the geodiversity quantitative assessment. Using ESRI ArcGIS software, a geodiversity index map was produced, based on the physical environment maps of the region (Table 1) and a 2 × 2 km cell-size grid that resulted in the lithology, geomorphology, soils, and mineral resource subindices. The cells size was defined according to [40]; thus, 48 rows and 74 columns and a total of 836 cells were obtained.

Table 1. Data used for the elaboration of the geodiversity index map of the Baixada Santista, State of São Paulo, Brazil.

Subindex	Map	Scale	Reference
Lithology	Rocks	1:750,000	[33]
	Structures	1:750,000	[33]
Geomorphology	Relief	1:500,000	[41]
	Hydrography, rivers	1:750,000	[33]
	Hydrography, water bodies	1:750,000	[33]
Soils	Soils	1:500,000	[42]
Mineral resources	Mineral resources	1:750,000	[33]

The lithology subindex was calculated based on information on rock types and structures (faults) taken from the geological map of the State of São Paulo [33]. The geomorphology subindex is composed of two parts: relief and hydrography. The relief diversity was calculated from the geomorphological map of São Paulo State [41], computing the information referring to the relief classification. To calculate the hydrographic diversity, the information from [33] that encompasses rivers and water bodies was added.

The soils subindex was based on the soil map of the State of São Paulo [36]. The mineral resources subindex is composed of the information referring to mineral occurrences and mines, contained in [33]. The authors of Reference [39] elaborate on the paleontology subindex; however, this was not calculated because the area does not present mapped fossil records. Subsequently, the subindices were added to compose the geodiversity index. Thus, the map was organized into 5 classes that represent the geodiversity indices: very low, low, medium, high, and very high.

Cartographic data referring to rivers and water bodies were extracted from [33] for the elaboration of the watershed map. These data were inserted in the ESRI ArcGIS software and analyzed together with the limits of the sub-basins that compose the Baixada Santista. The boundary data were provided by the Watershed Committee of the Baixada Santista [43].

Land use planning is based on guidelines that take into account the land use and occupation, environmental characteristics, and socioeconomic development of a region. In this sense, the ecological economic zoning (ZEE) is an important management tool that delimits a certain region into territorial units with the attribution of uses and restrictions on human activities.

The ZEE of Baixada Santista establishes seven zones (Table 2). Each zone presents the activities that can be implemented according to the carrying capacity of the environment and the social development that is expected in each area.

Table 2. Territorial units and uses and activities allowed by ecological economic zoning (ZEE) of the Baixada Santista, State of São Paulo, Brazil. Source: modified from [44].

Zones	Allowed Uses and Activities
Z1	Scientific research; environmental education; self-sustained management of natural resources, conditioned to the elaboration of a specific plan; ecotourism organizations that maintain the environmental characteristics of the zone; artisanal fishing; low-impact human occupation.
Z1AEP	Those set forth in: Federal Law 9.985 of 18 July 2000; the decree creating the full-protection conservation unit and the respective management plan; and specific regulations, in the case of indigenous lands.
Z2	In addition to those established for Z1: aquaculture; mining, based on the guidelines established by the regional mining master plan, if any; processing, craft processing, and commercialization of products resulting from subsistence activities of the populations residing in the area.
Z3	Besides those established for Z1 and Z2: agriculture and livestock, including integrated processing, storage, and marketing units; forestry; commerce and support services to activities permitted in the zone; rural tourism; educational, sport, assistance, religious, and cultural activities; human occupation with rural characteristics.
Z4	In addition to that established for Z1, Z2, and Z3: occupation for urban purposes; commerce and services to support the permitted uses; beneficiation and processing of products to attend local residents.
Z5	In addition to those established for Z1, Z2, Z3, and Z4, all other uses and activities, as long as the relevant legal and regulatory norms are met.
Z5E	In addition to those established for Z1, Z2, Z3, and Z4: low-impact industrial developments; commerce and services; storage, packaging, transportation, and distribution of products and goods; technological parks.

If the study area is large, the delimitation of a smaller area that is representative from the point of view of local geodiversity can be advantageous. The intersection of the geodiversity index map and the hydrographic basins of the region allows the selection of potential sub-basins with high geodiversity values. After this step, data regarding land use planning were inserted, leading to the selection of an area that contemplates the greatest diversity of land uses.

4. Results

4.1. Geodiversity Index Map

The geodiversity index map (Figure 3) is the result of the integration of the lithology, geomorphology, soils, and mineral resources subindices. The lithology subindex (Figure 3A) ranges from 0 to 6. Among all the subindices, this was the one that achieved the greatest variety. The highest values are distributed in the NE–SW direction, and the cell with the highest value (6) is located in the northern part, where there is a variety of different lithological units and lineaments. The cells with the lowest value are distributed in the areas near the coast.

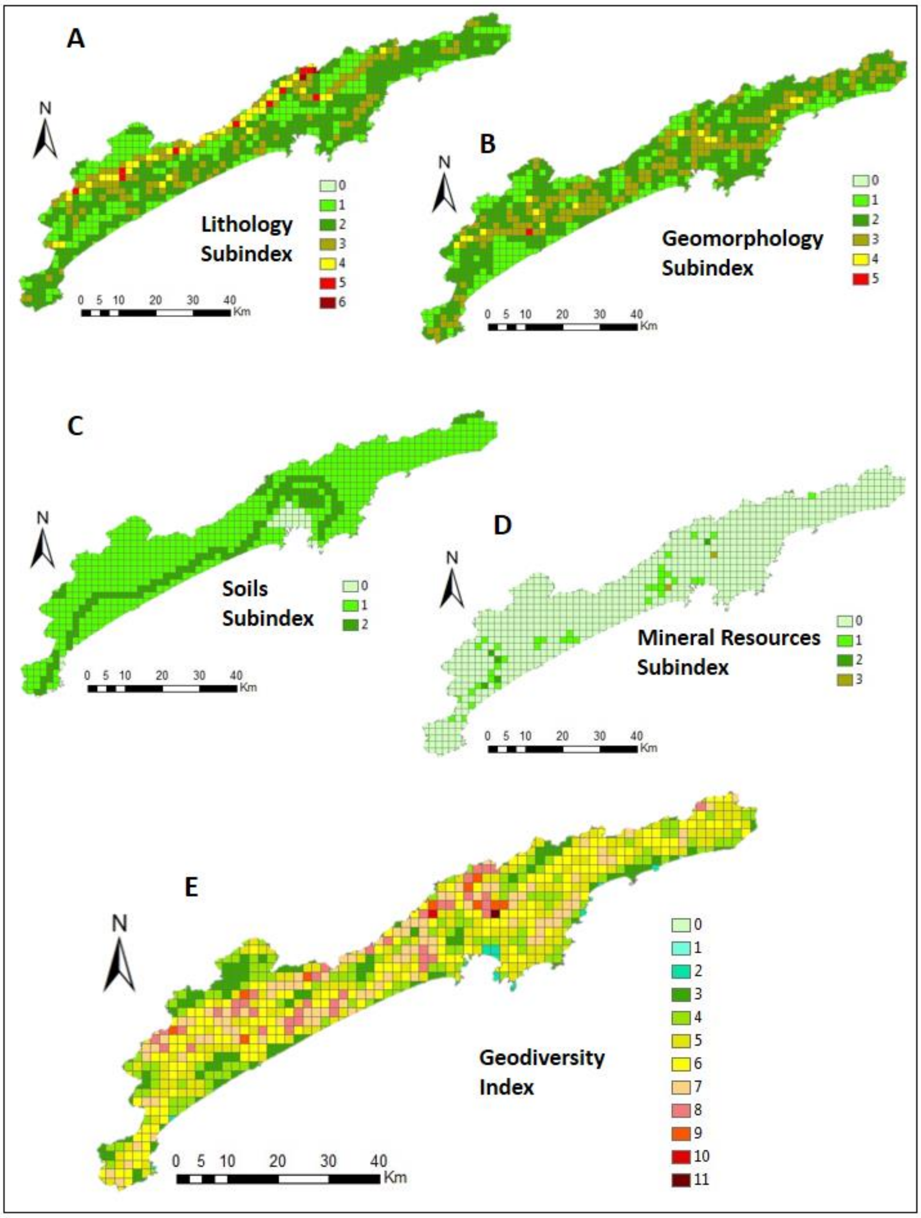

Figure 3. Geodiversity index and subindices of the Baixada Santista, State of São Paulo, Brazil: (**A**) lithology subindex; (**B**) geomorphology subindex; (**C**) soils subindex; (**D**) mineral resources subindex; (**E**) geodiversity index.

The geomorphology subindex (Figure 3B) ranges from 0 to 5. The calculated elements are distributed along the area, with the smallest values near the coastline and in the western part of the region; the grid cell with the highest value is located in the SW part and represents the confluence between the Preto and Itanhaém rivers. The soils subindex

(Figure 3C) presents the lowest values (between 0 and 2) because in each grid cell, a maximum of two types of soils can be found. The subindex mineral resources (Figure 3D) presents most of the cells with values of 0, because the occurrence of mineral resources in Baixada Santista is sparse. The grid cells with values between 1 and 3 correspond to regions of the study area with mineral exploration, mainly rocks for civil construction, which are concentrated in the SW and central parts of Baixada Santista.

With the sum of the subindices, the geodiversity Index was calculated (Figure 3E). The map of the geodiversity index of the Baixada Santista (Figure 4) presents a variant index between 0 and 11, which is classified into five classes: very low (<2), low (3–4), medium (5–6), high (7–8), and very high (>9). The lower index classes are concentrated along the coastline and in the W part of the study area. The intermediate class is predominant in the central part of the map. The high and very high geodiversity classes are aligned in the NE–SW direction and concentrated in the upper central part of the map, due to the high number of lithology, geomorphology, and mineral resources elements.

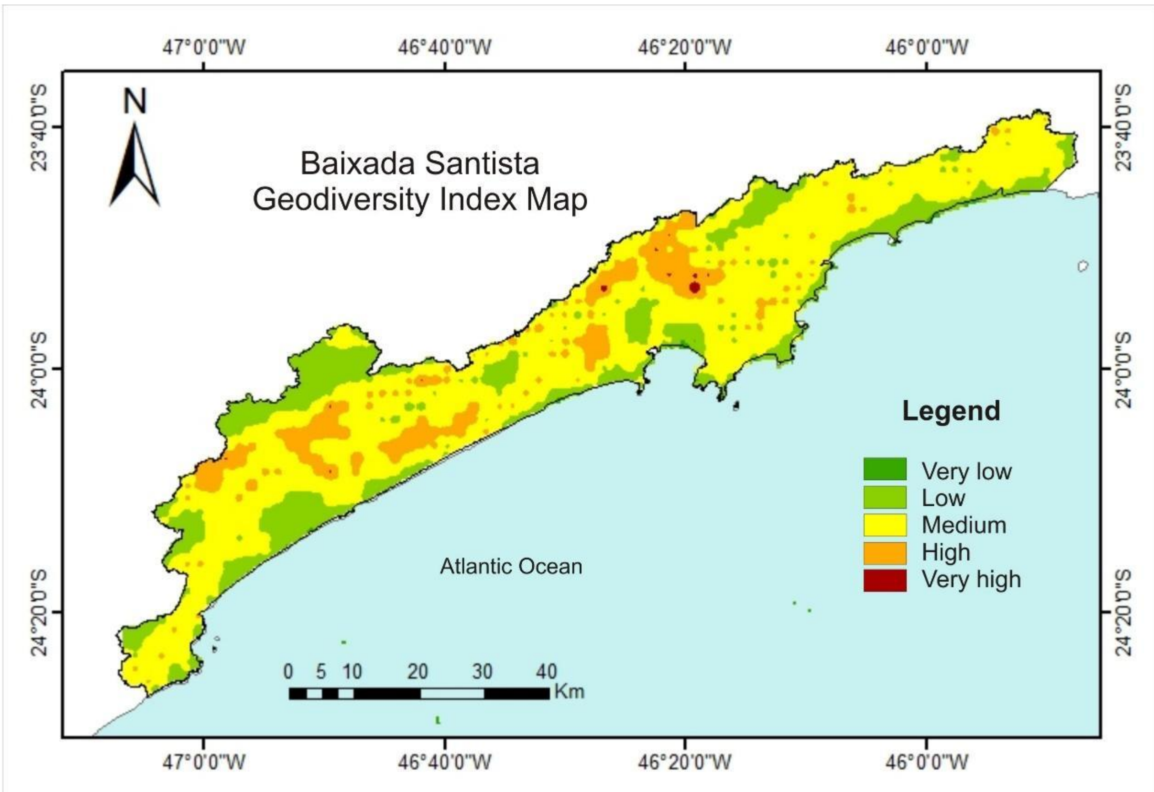

Figure 4. Geodiversity Index map of the Baixada Santista, State of São Paulo, Brazil.

4.2. Hydrographic Basin Map

The hydrographic basin map (Figure 5) is defined according to the main rivers of each sub-basin. In all, 21 sub-basins were identified, which present varied territorial extensions (Table 3), with the largest, Rio Branco, having an area of 416 km^2 and the smallest, Praia do Una, 33 km^2. In addition, the Rio Preto Sul, Rio Branco, Rio Cubatão, Rio Mogi, Rio Itatinga, and Ribeirão Sertãozinho sub-basins have limits that go beyond the Baixada Santista area.

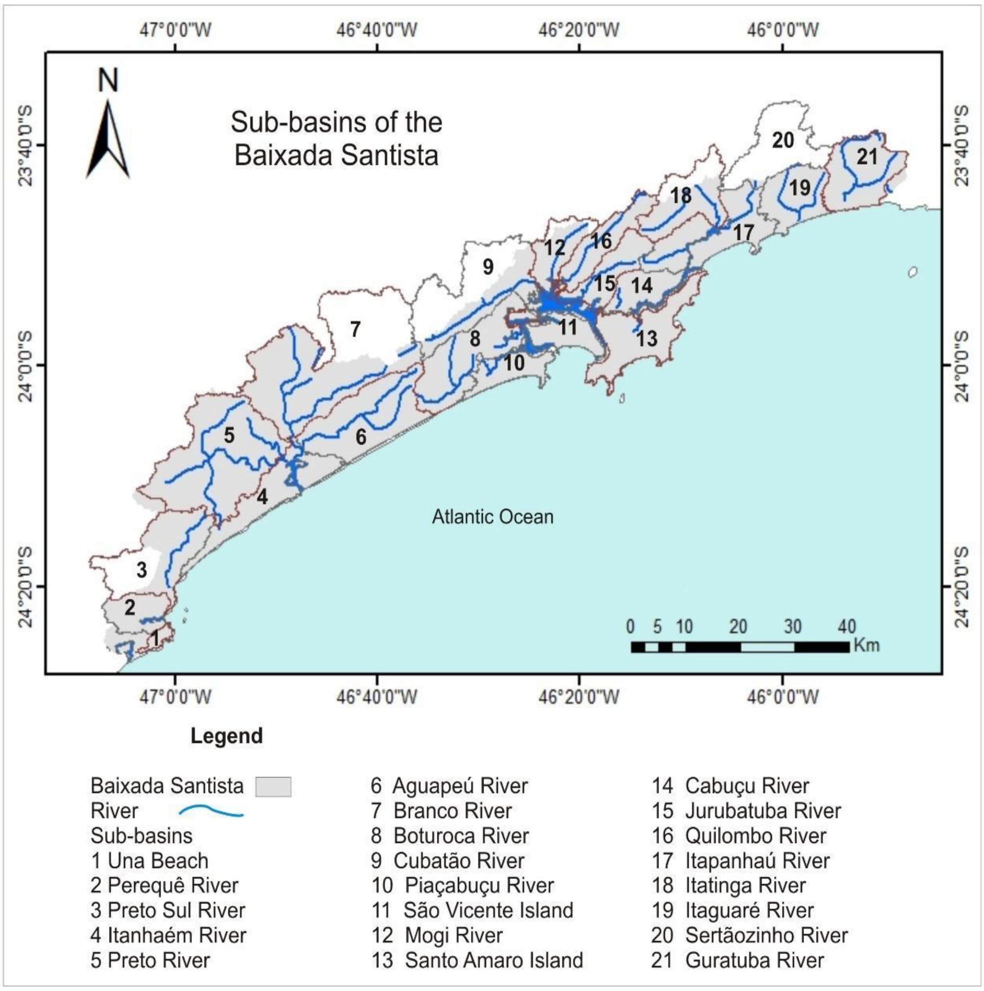

Figure 5. Sub-basins of the Baixada Santista, State of São Paulo, Brazil.

Table 3. Sub-basin drainage areas of the Baixada Santista, State of São Paulo, Brazil. Source: [43].

Sub-Basin	Drainage Area (km^2)	Municipalities
Una Beach	33.44	Peruíbe
Perequê River	65.03	Peruíbe
Preto Sul River	102.91	Peruíbe
Rio Itanhaém River	103.66	Itanhaém
Preto River	328.07	Itanhaém
Aguapeú River	190	Itanhaém/Mongaguá
Branco River	416.03	Itanhaém
Boturoca River	184.78	Praia Grande
Cubatão River	177.41	Cubatão
Piaçabuçu River	59.23	Praia Grande
São Vicente Island	86.72	São Vicente/Santos
Mogi River	69.11	Cubatão
Santo Amaro Island	144.21	Guarujá
Cabuçu Island	70.39	Santos
Jurubatuba River	80.20	Santos
Quilombo River	87.80	Santos
Itapanhaú River	150.90	Bertioga
Itatinga River	116.10	Bertioga
Alhos River	109.42	Bertioga
Ribeirão Sertãozinho	133.06	Bertioga
Guaratuba River	109.93	Bertioga

4.3. Selection of an Area for Ecosystem Services/Land Use Analysis

The Aguapeú River drainage basin (Figure 6) was selected for ecosystem services/land use analysis, according to the criteria of physical environment and land use types. It is a hydrographic basin that presents low, medium, and high geodiversity values, with the most expressive spot corresponding to the medium and high geodiversity indices.

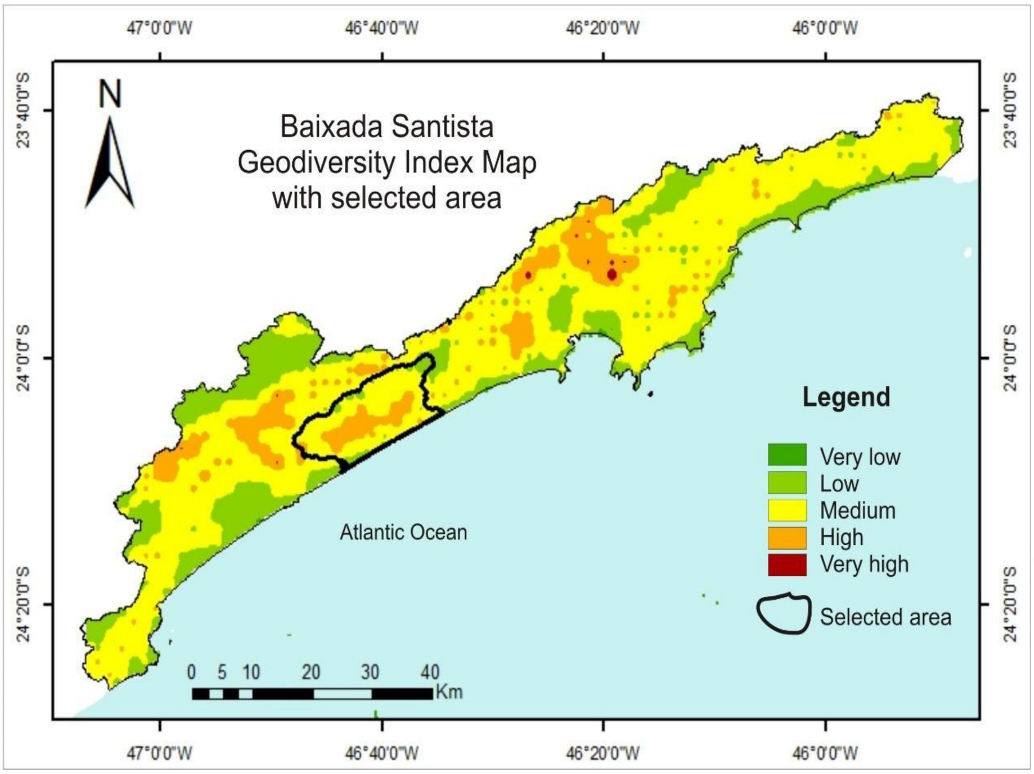

Figure 6. Delimitation of the Aguapeú River drainage basin over the geodiversity index map of the Baixada Santista, State of São Paulo, Brazil, as the selected area for ecosystem services/land use analysis.

Regarding land use, the ZEE presents several uses represented by the Z1, Z1AEP, Z2, Z3, Z4, Z5, and Z5E zones (Figure 7 and Table 2): Z1 and Z1AEP are areas destined for environmental preservation; Z2 is an area where mining-related activities are permitted; Z3 is characterized by agricultural activities; Z4 is destined for urbanization; and Z5 and Z5EP are characterized by commerce and mining. The presence of environmental protection areas, mineral extraction sites, urbanization, commercial areas, and tourism and fishing areas is reflective of the various ecosystem services provided by the geodiversity of the region.

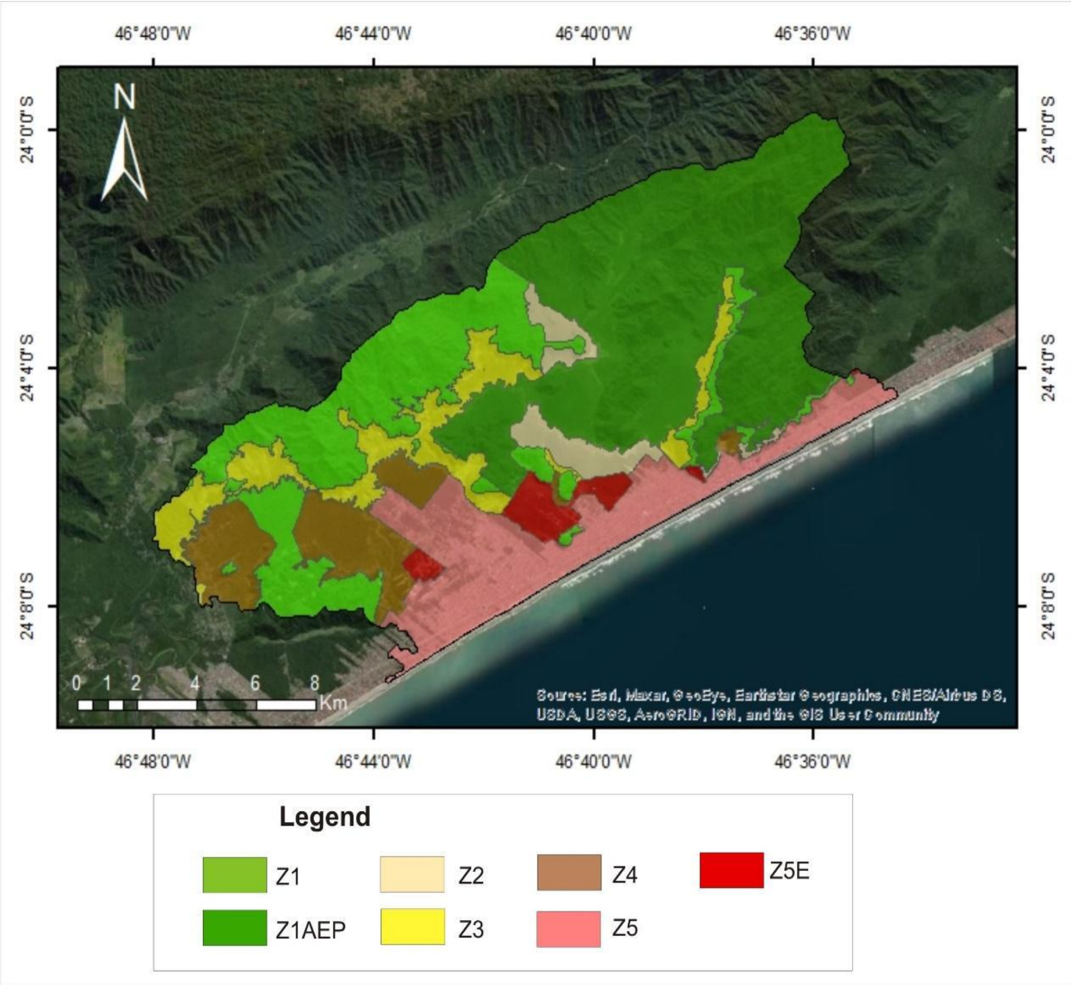

Figure 7. Sub-basins of the Baixada Santista, State of São Paulo, Brazil.

5. Discussion

The selection of the study area is a crucial step in research that addresses ecosystem services, requiring, first, the identification of areas with a high diversity of services provided. In this sense, the criteria should include both the physical characteristics and the land use in the area.

Regarding the characteristics of the physical environment, the geodiversity index map has proved to be an important tool because it presents in a visual and quick way the distribution of the components of the physical environment of the region. The areas with high geodiversity indices have a concentration of abiotic elements of nature that theoretically provide more ecosystem services and should have priority in the land management. It should also be noted that areas with few elements of geodiversity, although not the target of priorities, may also need management plans for the conservation of some valuable geodiversity elements, since the occurrence of geoheritage elements is not directly related with high values of geodiversity. Moreover, areas with low levels of geodiversity should be analyzed in more detail because they may also be providing essential services to society.

The Baixada Santista region presents a strong structural control due to the intrinsic characteristics of the local geology. From the subindices calculated, the lithology subindex may be the most relevant for the total geodiversity index because it presents the highest number of attributes per cell. Due to the characteristics of the rocks and lineaments of the region, a NE–SW alignment of high geodiversity values matches the geological data. These areas are, therefore, concentrated in the upper central part of the map (Figure 4) and are due to the geological events that generated different structures and lithotypes. These characteristics are also connected with distinct landforms and the occurrence of mineral resources. Extraction industries are located in this region, which benefit from the proximity to the port area. The intermediate values of geodiversity are represented in the central part of the region. It is a homogeneous region from the physical environment point of view, standing out due to the transition from the beach environment to the higher-altitude areas. The lowest geodiversity indices in the Baixada Santista are located at the coast and in the western region. These are, nevertheless, important areas for land use and nature conservation, since the urban and port areas are located in the coast, and the environmental protection areas, such as the Serra do Mar State Park, are located in the western region.

The geodiversity index map represents the areas with higher geodiversity, which may be connected with greater diversity of ecosystem services provided by geodiversity to society. That allows the remote delimitation of smaller areas to perform an analysis on land use and ecosystem services provided by geodiversity. To assist in this selection, data on the sub-basins and land use planning data were inserted. By superimposing the indices generated on the watershed map, the basins presenting the highest values of geodiversity were pre-selected, and the size and variety of geodiversity spots for each basin were analyzed. This distinction is essential for a greater possibility of occurrences of several ecosystem services provided in the selected area.

In addition, we consider that data regarding land use is essential, since the different uses and occupation of land can be linked to the various ecosystem services provided in the region. Thus, the data of the ZEE were overlaid with the geodiversity index to identify the Aguapeú River drainage basin as the area with more variety in land use and, simultaneously, high geodiversity values.

The use of natural boundaries to select an area of research on ecosystem services is recurrent, as in the case of hydrographic basins [11,12,19,20], relief units [13], sedimentary basins [17], and islands [10]. The watershed is an important criterion for the theme of ecosystem services, as it eases communication with land managers. In addition, the hydrographic basin is a territorial management spatial tool used in several countries, which allows the implementation of this criterion in different locations. In this sense, several types of research are found on geodiversity assessment methods [45–47] and ecosystem services [19,20,48] that use the hydrographic basin as a study area.

The assessment of ecosystem services is widespread in studies on biodiversity, though the ecosystem services provided by geodiversity still require further research [4]. Previous works have tried to fill this gap [16,17]; these simply focused on methodologies to quantify the ecosystem services provided by geodiversity and did not specify how to define the areas to be assessed. Bounding these areas is an essential step to support these assessment procedures, as it will allow more ecosystem services to be identified. The selection of priority areas based on the characteristics of the physical environment and land use is, therefore, considered as a procedure to support the identification and evaluation of ecosystem services provided by geodiversity in the Baixada Santista region.

6. Conclusions

Ecosystem services provided by geodiversity are essential for life. Identifying and evaluating these services has been the subject of previous studies. In delimiting an area that will be the target of research on ecosystem services provided by geodiversity, it is noted that the use of the geodiversity index map, watershed map, and tools for land use planning have proven effective. The index map is an important methodology for the evaluation of geodiversity to present the components of the physical environment of a region, contributing to the identification of places with a higher frequency of geodiversity elements. Several researchers have used the map to make descriptions and analyze the studied region. Moreover, this approach has the potential to assist, also, in the delimitation and selection of priority areas for different uses.

This research shows that, by using the geodiversity index map and adding the watershed map, it is possible to select areas essential for territorial management, since the watersheds boundaries are already widely used in land management. Another relevant factor is the ease of communication that the superposition of these two approaches generates between geoscientists and decision-makers, as it is possible to select areas that are already used by managers, even if they do not have in-depth knowledge of geodiversity. Furthermore, the use of a land use planning tool, such as ecological economic zoning, allows the selection of areas with diverse land uses, which can provide a diversity of ecosystem services.

As the delimitation of the area occurs remotely, it can be done before the field stage, directing the researcher who does not know the region in detail to choose an area that is representative from the geodiversity point of view. Thus, the use of the geodiversity index map, the hydrographic basins map, and the ecological economic zoning are configured as important tools for the selection of potential areas for the evaluation of ecosystem services in a large area.

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