geographies

Article

Qualitative-Quantitative Assessment of Geodiversity of Western Samoa (SW Pacific) to Identify Places of Interest for Further Geoconservation, Geoeducation, and Geotourism Development

Vladyslav Zakharovskyi [1] and Károly Németh [1,2,3,*]

[1] School of Agriculture and Environment, Massey University, Palmerston North 4442, New Zealand; v.zakharovskyi@massey.ac.nz
[2] Institute of Earth Physics and Space Science, 9400 Sopron, Hungary
[3] The Geoconservation Trust Aotearoa, Opotiki 3122, New Zealand
* Correspondence: k.nemeth@massey.ac.nz; Tel.: +64-27-479-1484

Abstract: The assessment of geodiversity is a relatively new field of research connecting abiotic aspects of nature to the wider environment. The study of geodiversity is still in development, so a uniform and complete paradigm remains to be defined. Therefore, an assessment of geodiversity may be highly dependent on the nature of the territory subject to study, available databases, and the researchers' field of specialization. The main quantitative method for the assessment of geodiversity was proposed to the scientific world only few years ago and may only be relevant to some places in the world, rather than all, which would be desirable. However, while similarities in research methods may be apparent, the directions, scales, and data utilized are clearly different. This article demonstrates a quantitative-qualitative method for an assessment of geodiversity, based on a five-point evaluation system and the utilization of widely available standard databases such as geological maps, SRTM models, and satellite images. Western Samoa Islands (Savai'i and Upolu Islands) were selected for assessment, as a typical example of basaltic ocean island volcanism generating relatively homogenous rock formations and subject to gradual geomorphology (e.g., shield volcano). While initially appearing as a region of simple geology and morphology, complexity is added by considering rock ages, the position and type of eruptive centres, and the coastal geoenvironment. By considering these factors, the assessment becomes specifically tailoring for geodiversity assessment of the islands of Samoa. In conclusion, it has been demonstrated a simple methodology of general assessment of geodiversity with additional improvements to take account of variability in other abiotic factors.

Keywords: geodiversity; Samoa; quantitative-qualitative assessment; QGIS; SRTM; slope

check for updates

Citation: Zakharovskyi, V.; Németh, K. Qualitative-Quantitative Assessment of Geodiversity of Western Samoa (SW Pacific) to Identify Places of Interest for Further Geoconservation, Geoeducation, and Geotourism Development. *Geographies* **2021**, *1*, 362–380. https://doi.org/10.3390/geographies1030020

Academic Editor: Luca Salvati

Received: 28 October 2021
Accepted: 16 December 2021
Published: 17 December 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Geodiversity assessment is a field still in development and is strongly associated with the physical area of study and associated materials such as maps, GIS data bases, LiDAR files, thematic maps, and other models. The term geodiversity is based on collaborative ideas presented by Gray, Kozłovski, Serrano, and others [1–5]. They claimed that geodiversity is a feature/attribute of abiotic nature, which includes geology, geomorphology, hydrology, soil science, climate and connected weathering processes, and human and biological impacts. Geodiversity became a starting point for two other terms: geosite and geoheritage. These terms may be subject to slightly different descriptions between researchers. In general, a geosite refers to a place with several geological features representing the most typical geological asset in the specific region (e.g., rocks, minerals, fossils, landscape, and others). As part of the geosphere, geosites hold importance in documenting the Earth's history [6–8]. Meanwhile, geoheritage refers to the values describing geosites with some uniqueness and significance in recording the Earth's history and demonstrating the interplay between abiotic factors and the evolution of the living world, including humans and their society [7,8]. Hence, geodiversity is the value describing several elements, which combine themselves, creating abiotic nature, while a geosite is a place displaying geodiversity at the studied location, then geoheritage is the overall value applied to a group of rare and/unique geosite(s) with significance for the Earth's evolution (Figure 1).

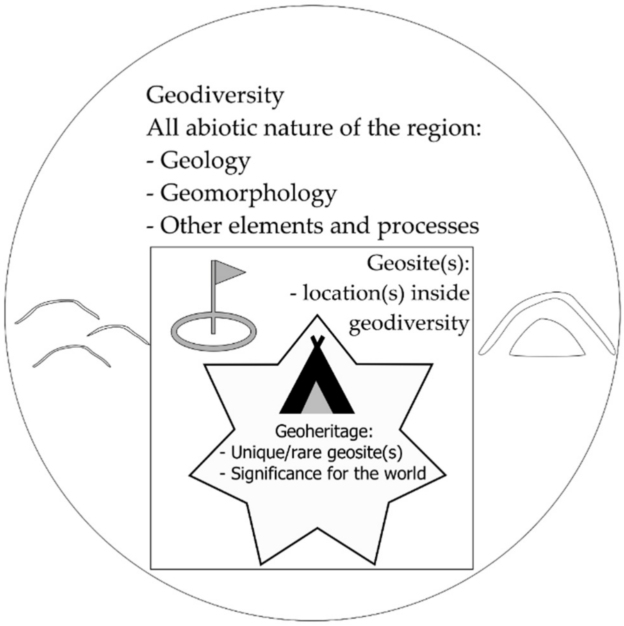

Figure 1. Connection between geodiversity, geosite, and geoheritage. Geodiversity includes all elements of abiotic nature. Geosite is a specific location in geodiversity. Geoheritage is unique/rare geosite(s) with significance for the world as demonstrated in other works elsewhere [9,10].

Utilizing systematic methodologies based on geoheritage databases, researchers may collaborate with government agencies and community organisations to develop strategies for geoeducation, planning for geoconservation, and facilitating niche tourism, including geotourism [7,8,11]. In the research, a methodology was established to recognise geodiversity's value, utilizing a qualitative-quantitative methodology. If displaying a high value, locations of interest were flagged as potential geosites.

In 2018, Zwoliński described the differences between three types of assessment of geodiversity and provided examples: quantitative, qualitative, and qualitative-quantitative models [12]. Qualitative methodology is based on the expert knowledge and relies on a subjective view of the value system of geodiversity [13,14]. Meanwhile, the quantitative method is the most popular type of assessment of geodiversity as it is based on a simple algorithm. Even though the algorithm may be simple, it does require a large database (instrumental measurements, numerical calculation, and geoinformation analyses). The methodology for the quantitative assessment of geodiversity was described by Serrano and Ruiz-Flaño [5,15] and applied calculations derived from the study of biodiversity (calculation of the population of organism(s) from the area of its spreading). However, geodiversity is currently considered a far more complex theory, and there is no final consensus between various schools of thought [16,17]. Currently, most specialists in geodiversity agree that it includes geo features interacting with factors such as in geomorphology, geology, hydrology, soil science, and climate. Subsequently, the quantitative method has been utilized to calculate the number of geological features in a chosen area, where a high variety of features defines locations of potentially high geodiversity values that would benefit from further research utilizing geoconservation, geotourism, and geoeducation approaches [1,4,5,12,18]. This method is popular in studies of geodiversity and has been used in a number of assessments in Brazil [6,19,20], Hungary [21], Italy [22–27], and other countries. For example, da Silva and do Nascimento utilized quantitative assessment of geodiversity in Seridó Geopark Project, Northeast Brazil [19], and Bétard and Peulvast used it to highlight the geodiversity hotspots in the Ceará State (Northeastern Brazil) [28]. However, a shortcoming of this methodology is information access and lateral differences according to the territory of research. It is unlikely that the methodologies applied to different territories of research and the subsequent results and their implications would be comparable, essentially meaning every assessment is unique and can only be viewed in its own context.

This article presents a qualitative-quantitative method with low requirements for material and tools, and utilizes a methodology developed previously through application to the Coromandel Peninsula, New Zealand [18]. This methodology combines characteristics of qualitative and algorithmic quantitative models [12]. A five-point evaluation system was used for the geo units based on a common recognition of geodiversity, where one is the lowest and five is the highest value or mark. The system is applicable for research applied to the assessment of geomorphology and geology elements of geodiversity presented as core parameters. The geological element is presented as a qualitative parameter of Earth's materials (e.g., rocks) "enriched" with geomorphological element, thereby describing its forms (relief). Meanwhile, all other features of abiotic nature are products of rocks' weathering processes and transformations. Hence, geological features (e.g., eruptive centres) and coastal areas of the Western Samoa in the SW Pacific (Figure 2) were included into assessment as additional values, thereby improving the methodology. However, this study does not show a complete diversity of the abiotic nature of the chosen area but rather demonstrates a method that highlights places with high values. Potential value as geosites can be further defined through more precise research leading to future geoconservation, geotouristic, and geoeducational projects.

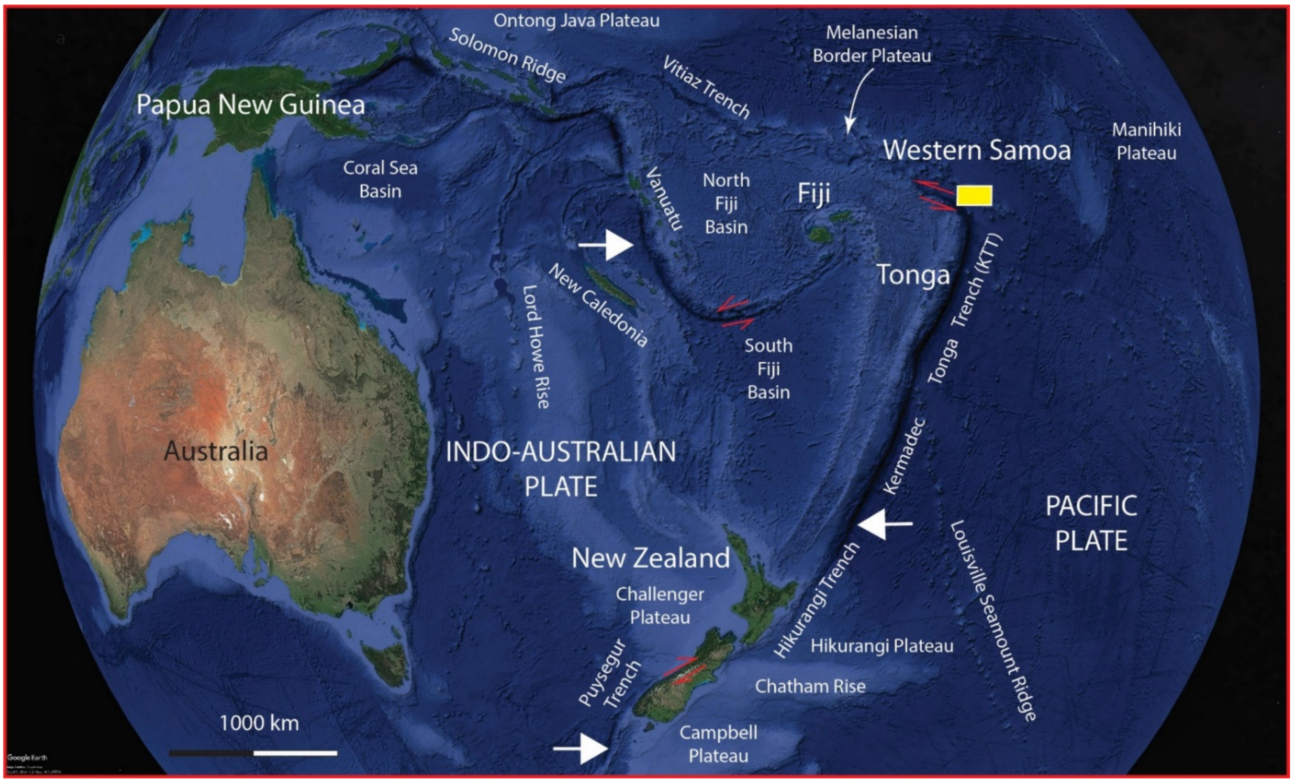

Figure 2. Overview of the geotectonic situation in the SW Pacific and Western Samoa on Google Earth Pro satellite imagery. Study area of Western Samoa is highlighted by a yellow rectangle. Relative tectonic plate movements are marked by arrows. White arrows show the subducting plate move direction. Double opposing red arrows refer to transform plate boundaries, e.g., major strike slip fault systems such as the Alpine Fault in New Zealand. Major geotectonic elements, continents, and islands are named.

The Western Samoa islands (Savai'i and Upolu) (Figure 2) were chosen as a location of interest, although they may display relatively low geomorphological and geological diversity due to its relatively simple volcanic evolution. The islands' volcanic eruption history formed two major shield volcanos with geochemically and petrologically similar rock types such as various basalts [29,30]. Hence, to increase the variety of features and refine the assessment, the information about the islands' rock ages and identified eruptive centres were included as additional geological parameters. Coastal areas were added as an additional parameter into geodiversity estimates. This is justified by the presence of intact Pleistocene to Holocene volcanic cones (e.g., scoria cones and associated lava flow fields) and the diversity of dynamic coastal realms ranging from coral sand beaches to lagoons and steep lava field cliffs. The validation of coastal morphology variations is based on the touristic potential of a tropical island coastal region.

This paper demonstrates an example of geodiversity assessment geodiversity with minimal data requirements (that is freely available to any users) applied to the Western Samoa Islands. The data include geomorphological data as SRTM (Shuttle Radar Topographic Mission) model [31] and a 1 to 100,000 scale geological map of Savai'i and Upolu Islands. For assessment, the analysis used the free software QGIS (3.16 "Hannover") (https://qgis.org/en/site/forusers/download.html (accessed on 16 September 2021)), with its plugin "SRTM-Downloader" (https://plugins.qgis.org/plugins/SRTM-Downloader/ (accessed on 16 September 2021)). Additionally, it is demonstrated the inclusion of associated information for the specific area in cases where the area of research may initially appear poor in variety. The database may be made readily accessible to a variety of stakeholders and used for the further study of the region from geotourism and geoconservation perspectives.

2. Materials and Methods

2.1. Aim

The main goal of the research is to create the most acceptable and uncomplicated method of assessment of geodiversity for any kind of territory throughout the world and accessible to any users or stakeholders. Accessibility and simplicity of the research and database will provide access to a simple methodology providing a global perspective on geodiversity. This methodology utilizes free GIS software (e.g., QGIS), satellite images (e.g., Google Earth or similar satellite imagery), digital terrain models (e.g., SRTM), and common maps (e.g., geology and various thematic maps). Additionally, the assessment of coastal areas and eruptive centres have been included into calculations to expand the equation with parameters accessible from satellite images.

2.2. Volcanic History of the Western Samoa Islands

Western Samoa is a challenging location for this kind of assessment, as this area displays a relatively low variety of geological and geomorphological features. The geological history of the Samoa Islands is represented in 6 periods of volcanic processes occurring from the Pliocene through to Historical time. All these periods of volcanism are represented by basaltic rock types [29,30] (Figure 3). The first event created rocks grouped in the Fagaloa lithostratigraphy unit, which is the least visible throughout Savai'i Island in the north part. In contrast, nearly a third of Upolu Island is covered by rocks associated with this unit (Pliocene to Mid-Pliocene). The Fagaloa volcanism resulted in a lava shield building phase, when large shield volcanoes emerged from the sea floor reaching an estimated height of around 1800 m above sea level. During the early to middle Pleistocene, these shield volcanoes eroded significantly, partly in response to global climatic changes and glaciation, leaving behind subdued volcanic terrains with steep valleys and volcaniclastic debris aprons. The second major lithostratigraphy unit of the volcanism formed the Salani Unit, mostly located in the eastern part of Savai'i Island and southeast and central parts of Upolu Island [29,30] (Figure 3). The Salani lavas occupied the deeply incised volcanic landscape following valley filling patterns. Erosion of the Salani volcanic terrains took place in a warm climate and formed amphitheatre-like morphological features. During the last glacial period, the Mulifanua event produced eruptive products that spread through the Savai'i Island from its western to central parts, while on Upolu Island, it can only be in the surface in the northwest. During the post-glacial sea level rise, barrier reefs formed and in the interior of the islands, small-volume volcanism produced sporadic eruptive products and formed the rocks mapped into the Lefaga Unit. This unit represents eruptive products of volcanism of the Early Holocene and its eruptive products are visible only in southwestern part of Savai'I Island. The Aopo lithostratigraphy unit is formed by eruptive products of the young volcanism, and they can only be seen cropping out in the northern part of the Upolu Island. The rocks associated with the Puapua volcanic phase were formed in the Middle to Late Holocene and cover a large area from central to south and then to the east part of the Savai'i Island. In contrast, on Upolu Island, they are only present as small area in the south. Additionally, some Holocene Alluvium deposits can be found in the western part of the Upolu Island, and Vini Tuff from the Last Interglacial period forms two small islands from the western and eastern parts of Upolu Island, Apolima and Nu'utele, respectively. Both are associated with the same magma–water explosive interaction-driven eruptions forming tuff cones in shallow water. Intact, young eruptive centres were also included into the assessment and most of them are located along the east–west axis of both Islands.

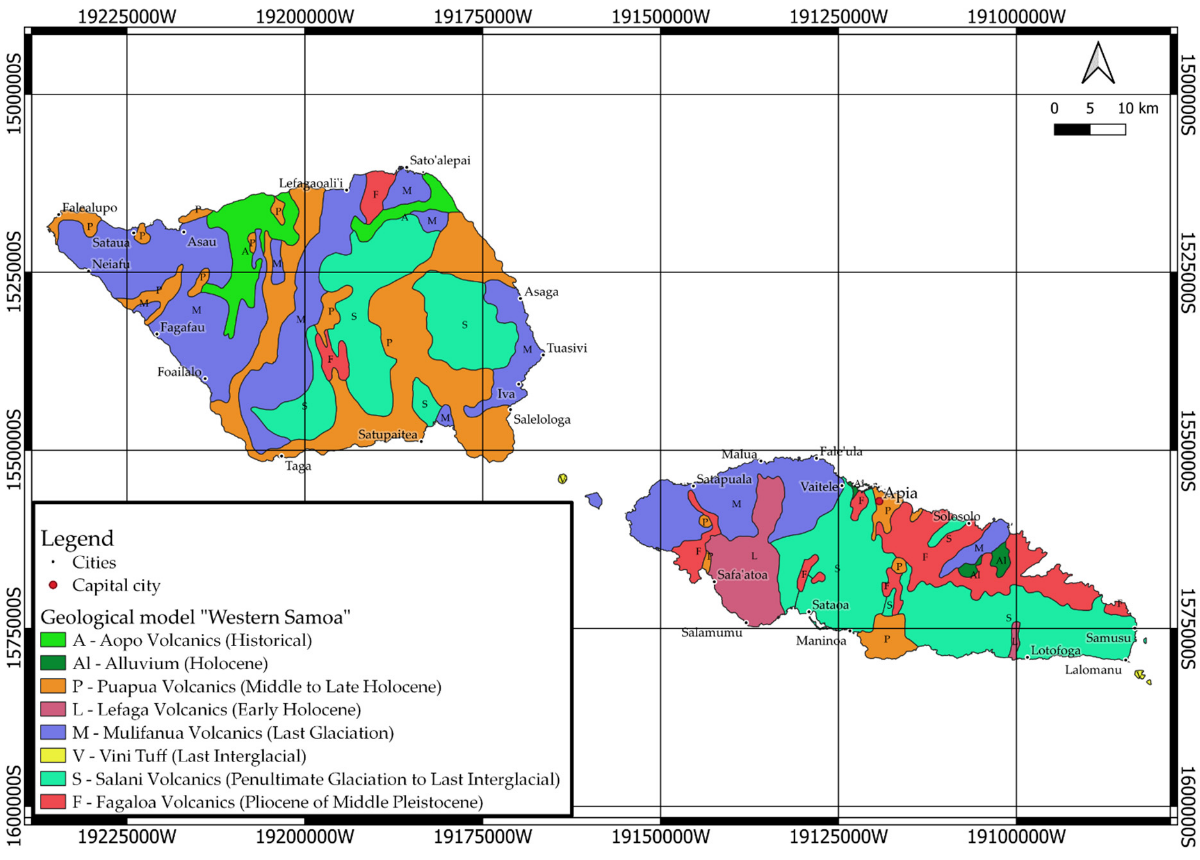

Figure 3. Geological model of the Western Samoa adopted from the geological map of Western Samoa [30]. Letters on the map are the first letter of geological units' names. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

From a geomorphological perspective (Figure 4), both islands display a gradual increase in elevation from the coastal area to their central parts as a reflection that the main volcano morphology asset of the islands is associated with lava shield building phase of the ocean islands. However, some steep cliffs near the centre directed towards the south in the Savai'i Island can be identified, while rugged surfaces on the east part of the Upolu Island can be explained by erosion processes (because of river flows) creating the valley system. This area displays gradually exposed older lava flow sheets forming a step-like morphology. Hence, the Western Samoa Islands are geologically and geomorphologically diverse enough, with clearly visible unique features. Therefore, this reason can be included the data about coastal areas and eruptive centres into the geodiversity estimate equation, which will increase the variety for geological assessment.

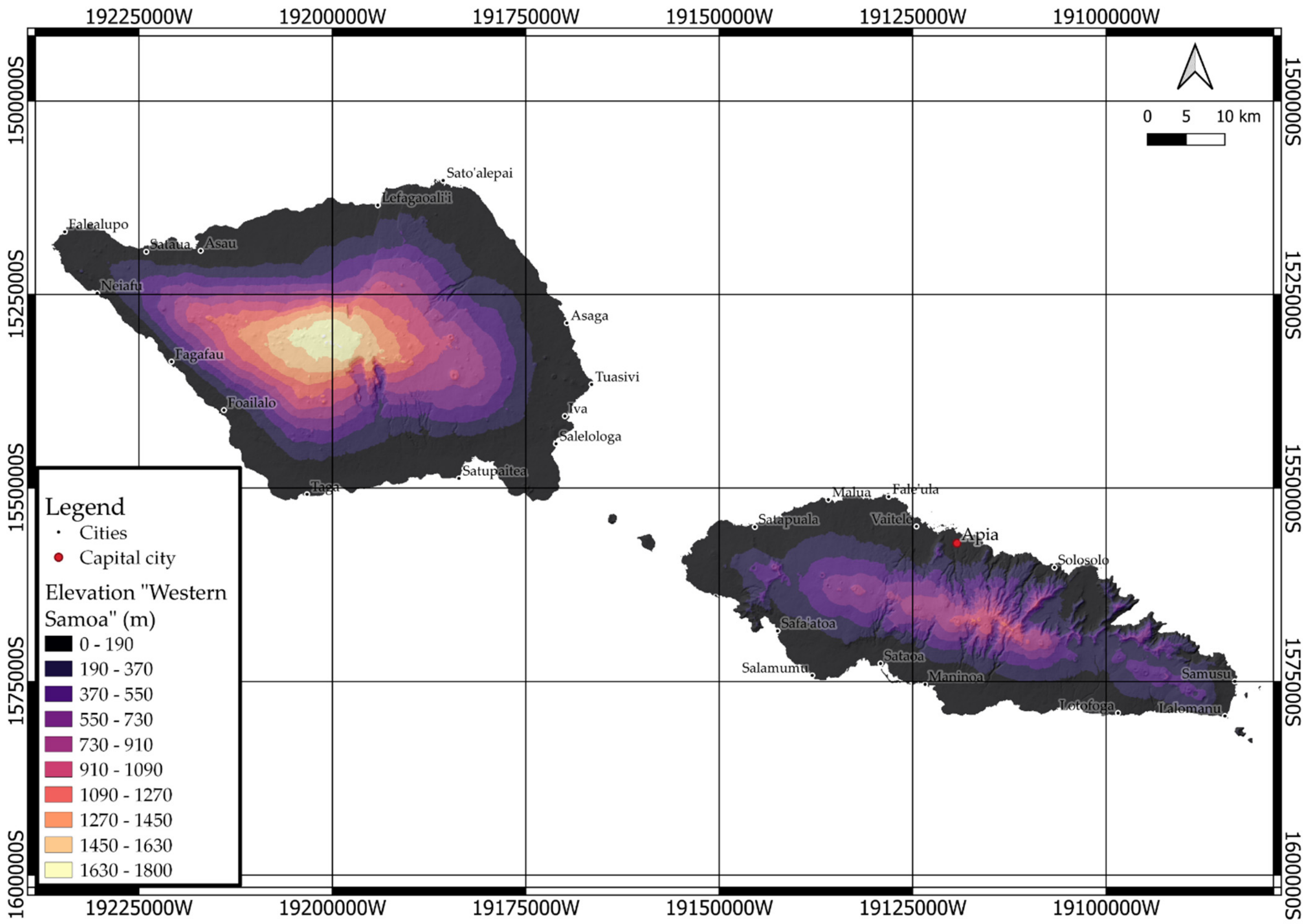

Figure 4. Geomorphological model of Western Samoa based on SRTM data available for Western Samoa (Figure 2) (citation). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

2.3. Methodology

Our method is concentrated on the assessment of the average arithmetic value of geodiversity for the studied area. Marks are based on the 5-point evaluation system for each element (Table 1). The main value of geodiversity consists of the range of geological features, which together form the core values of geodiversity: geology, geomorphology, soil science, and weathered material, (volcanos, caves, and structural elements for specific places) [4,5,16,18,32,33]. However, this article assesses only geomorphological and geological elements, with additional values defined for rock ages based of the specificity of Western Samoa's geology. Moreover, the coastal areas and eruptive centres were also added into the assessment, where volcanic features influence the geological values (Table 1).

Table 1. Evaluation system for the Western Samoa region, based on the conceptual framework of geodiversity estimates developed in Coromandel Peninsula, New Zealand [18].

<table>
<tr><th colspan="5">Main Values of Geodiversity</th><th colspan="3">Additional Values of Geodiversity</th></tr>
<tr><th rowspan="3">Values (5-point system)</th><th colspan="7">Elements of Geodiversity</th></tr>
<tr><th>Morphology</th><th colspan="2">Geology</th><th rowspan="7">Additional features for assessment</th><th>Volcano</th><th colspan="2">Hydrology</th></tr>
<tr><th>Slope degree</th><th colspan="2">Rock type and ages (Right column for Samoa)</th><th>Eruptive centres</th><th colspan="2">Coastal sections</th></tr>
<tr><td>1 (the lowest)</td><td>0–7.5</td><td rowspan="5">The rock type values are no applicable for the Western Samoa region: all are Extrusive rocks, the the highest value—5</td><td>Alluvium (Holocene)</td><td rowspan="5">The mark is applicable for the areas of spreading, with the lowest value—1</td><td colspan="2">Quality system</td></tr>
<tr><td>2 (low)</td><td>7.5–22.5</td><td>Mulifanua</td><td>0.5</td><td>Sand beaches</td></tr>
<tr><td>3 (middle)</td><td>22.5–45</td><td>Lefaga</td><td>0.75</td><td>Shallow water sand with rocks</td></tr>
<tr><td>4 (high)</td><td>45–67.5</td><td>Puapua and Fagaloa</td><td>1</td><td>Hard rock cliffs and reefs</td></tr>
<tr><td>5 (the highest)</td><td>67.5–90</td><td>Aopo and Vini Tuff</td><td></td><td></td></tr>
</table>

The table shows the summary of grades values of four elements of core of geodiversity. Morphology can be assessed according to the steepness of the slope, geology—rock types with connection to their ages which depend on their amount exposed on the surface.

Core elements of geodiversity, geology and geomorphology, were utilized for this study. The value system was created according to the rareness and uniqueness of assessed units. The geomorphological 5-point value system is based on the slope steepness, e.g., the higher degree the higher value (Table 1). According to "geographical cycle" [34–36], uplift creates a new geomorphological formation, ageing at geological timescales with weathering processes weakening the rock and becoming a trigger for collapse to obtain equilibrium and reducing elevation closer to sea level. Additionally, steeper slopes identify the rock formations, which are the core elements behind elevation changes in the area. This may indicate a relatively young rock formation (from geological time perspective) created by volcanic activity, or an older one, where erosion has exposed core sequences of volcanic geoforms on the surface (e.g., older and eroded volcanic edifices can be dissected by erosion exposing geological rock units valuable to understand the eruptive processes responsible for their formation) [34,35].

Geological values are based on the rareness of outcropping rock types and their defined ages (Table 2) [37]. From the Devi's formation, Sedimentary-Cenozoic rock is the most common rock on the surface, so it has been assigned as the lowest value, while Extrusive and Intrusive rocks received the highest value due to relative rareness. This has been tested earlier in the Coromandel Peninsula, New Zealand, which has a higher diversity of rock types, formed over a broader time scale [18]. This approach established a methodology globally accessible as it uses very general rock classifications as found exposed on the surface. Meanwhile, it can be more useful for local applications to develop a more precise evaluation system, but within the framework of geological units and time scales recognized globally. For example, according to the global evaluation system, the young Western Samoan Islands (<2 my) are composed of one major volcanic rock type, basalts [30]. As this is the rarest type of rock exposed on the surface, therefore, they receive the highest value (5) for geodiversity. To further refine the assessment, the local uniqueness rock formations was studied more precisely with attention given to the ages of volcanic rocks. Aopo and Vini Tuff are the youngest volcanic formation, so they fall within the parameters of the most primal forms and get the highest (5) values in the assessment. Puapua and Fagaloa receive a high value (4) through this method even though their ages are different. Then, Fagalo receives the same value (4) as it is exposed at a completely weathered area, displaying the oldest rocks known on the surface of Samoa after complete transformation of their original volcanic geoforms (e.g., some sort of complex, polygenetic volcanos). Lefaga and Mulifanua are assigned middle (3) and low (2) values, respectively, following the previous principles outlined above, as they are older than Aopo and Puapua and covered with thick soils and other weathered material. The lowest value (1) was given to Alluvium (Holocene) (Sedimentary-Cenozoic rock), which fits to the main geological value system outlined in previous study [18].

Table 2. Percentage of rock types exposed on Earth's surface as function of geological age [37]. According to the table, extrusive and intrusive rocks are the rarest type, hence they have the highest value from geological perspective.

Eras	Crystalline				Sedimentary	No. of Usable Data Points
	Extrusive	Intrusive	Metamorphic and "Precambrian"	Total		
Cenozoic	4	0	0	4	33	290
Mesozoic	2	1	1	4	18	177
Palaeozoic	1	1	<1	2	13	117
Precambrian	0	6	15	21	1	173
Age unknown	1	1	1	3	1	26
Total	8	9	17	34	66	783

To make the assessment more complex and diverse, eruptive centres and coastal areas were added into the calculation as an additional value for Western Samoa, expanding and refining the general methodology. For eruptive centres, the values are 1 as they were put here to increase the values of the final mark of geodiversity as an additional value to the geological assessment. Meanwhile, coastal areas are also presented here with the same point as eruptive centres. The evaluation system for coastal areas is still based on the exposure of clear rock formation on surface, so sand beaches −0.5, which is the lowest value because it is a sediment of weathered material, shallow water is mixture of sand and rocks, which raise the value up to 0.75, and riffs and cliffs which are represented by solid rock masses receive a value of 1. Although this is not suggested as a final deviation and evaluation systems for coastal areas, these elements are visible on the Google Hybrid map. These areas are located out from the territory of geological and geomorphological assessment, so they were added to improve the final mark of the regions (grid cells) and associated coastal areas.

Our methodology and associated database require a free QGIS software (https://qgis.org/en/site/ (accessed on 3 September 2021)), access to the Internet, and geological maps. QGIS (https://qgis.org/en/site/ (accessed on 3 September 2021)) provides sufficient tools to download the SRTM model and Hybrid Google map (these are not essential, other DEM and Satellite Images can be used as well), which will be utilized for geomorphological (slope degree) assessment [38,39], while a Hybrid Google map contains enough visible information to select eruptive centres and coastal areas.

2.4. Equation

The equation for the value of the object compares its area of extension against the area of the whole studied region:

$$D = \frac{\sum (\boldsymbol{p} * \boldsymbol{s})}{\boldsymbol{S}}$$

where ($\boldsymbol{p}$)—number of points of element (geology or geomorphology (Table 1 [-]; ($\boldsymbol{s}$)—area of element ($\boldsymbol{p}$) [L]; and ($\boldsymbol{S}$)—area of research [L].

This equation is used to calculate all geodiversity elements (Table 1) applied to a grid with intervals of 2.5 km per side. The equation is applied to each cell separately to obtain the mean value (arithmetic average) for every element of geodiversity assessment. The scale was chosen with the previously described parameters (2.5 km side) as they align with the human ability to observe the territory on the field, which is the distance of half of human vision range. Studies in visibility range showing that a person facing no obstacles can recognize an object at a 6 km distance in dry and bright weather conditions [40]. These studies show that a standard camera would be sufficient to take a picture of a cell of observation to cover the whole area of research. Moreover, standard methodology for geological mapping at a 1 to 250,000 scale requires data collection at least every 250 m, hence, from 10 observation points. Hence, the grid scale at 2.5 × 2.5 km scale, allows a useful fit with the geological data of the studied area, as well as simplifying observation of the territory during the field justification.

2.5. Example of Calculation and Creation

The example of quantitative-qualitative geodiversity's assessment is presented below through the 8 steps applied for each region (one grid cell 2.5 km × 2.5 km) of the studied territory with scheme (Figure 5).

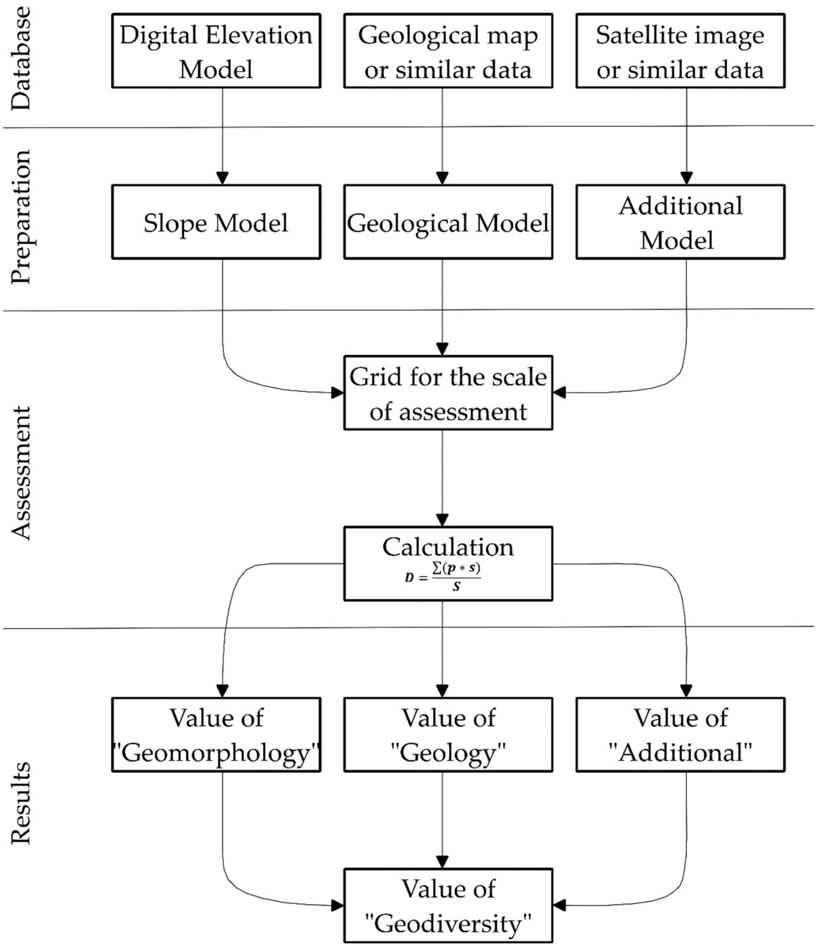

Figure 5. Scheme of assessment of geodiversity.

(1) Required data:
   (a) DEM (Digital Elevation Model) needed for geomorphological assessment. In this project, SRTM 1-Arc-Second Global model [31] was downloaded through SRTM downloader (QGIS plugin).
   (b) Geological map of the territory and some additional information (if they are acceptable such as thematic maps).

(2) A Google Hybrid model was utilized for background, georeferencing [41,42], and selection of additional elements (Eruptive centres and Coastal areas in this research).

(3) The grid (module in QGIS) was created with parameters 2.5 km horizontal spacing and 2.5 km vertical spacing according to the scale mentioned in previous section [31]. Then, the grid was cut according to the territory of research (clip tool in QGIS).

(4) A slope model was created from SRTM to provide information about steepness measured in degrees, utilized to calculate geomorphological values (Table 1):

  (a) Gaussian filter is SAGA (System for Automated Geoscientific Analyses) (http://www.saga-gis.org/en/index.html (accessed on 29 September 2021)) [43] tool acceptable in QGIS, which can be utilized for smoothing the SRTM model.
  (b) A slope model was created utilizing Slope, Aspect, Curvature tool from SAGA terrain analysis—Morphometry 9 parameter second-order polynom [44,45] based on the filtered SRTM. However, other modules: (slope (GDAL), slope (QGIS), r.slope.aspect (GRASS GIS)) [46,47] can be used as well.
  (c) The slope model was reclassified by table in Raster analysis (QGIS tool) [42] according to parameters of geomorphological values (Table 1).

(5) The geological map [30] was transferred into QGIS and polygonised into a geological model:

  (a) The geological map was georeferenced into QGIS project for raster analyses [41,42].
  (b) Transformation created polygonal files with associated values (Table 1).
  (c) The polygonal vector model of geology was transformed into a raster file. For this operation, v.to.rst (GRASS) [46,47] was utilized, where geological values were used as attributes for the raster model.

(6) The equation of arithmetic average (Section 2.4) is acceptable in Zonal Statistic Tool of QGIS [42,48]. Hence, it was applied to the created grid vector file as impute layer and raster of geology (Step 5 (c)) and geomorphology (Step 4 (c)) for calculation of mean value of each region (grid cell). The result is presented in the next section (Figures 6 and 7).
(7) The results (Figures 7 and 8) were calculated together to get the result of geodiversity.
(8) Additional information about coastal areas and eruptive centres were extracted from the satellite Google Hybrid map (parameters for value were used from the Table 1) (Figure 6). Then, results from both models were combined with the previous geodiversity results (Figure 9).

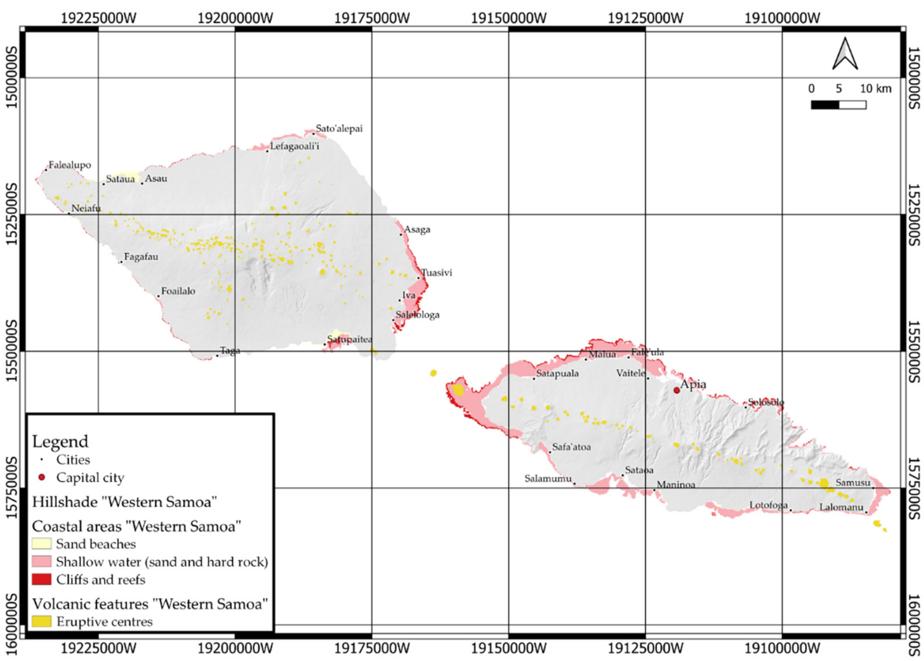

Figure 6. Additional elements of geodiversity such as type of coastal areas and eruptive centres extracted from Google Hybrid Map in combination with Hillshade map. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

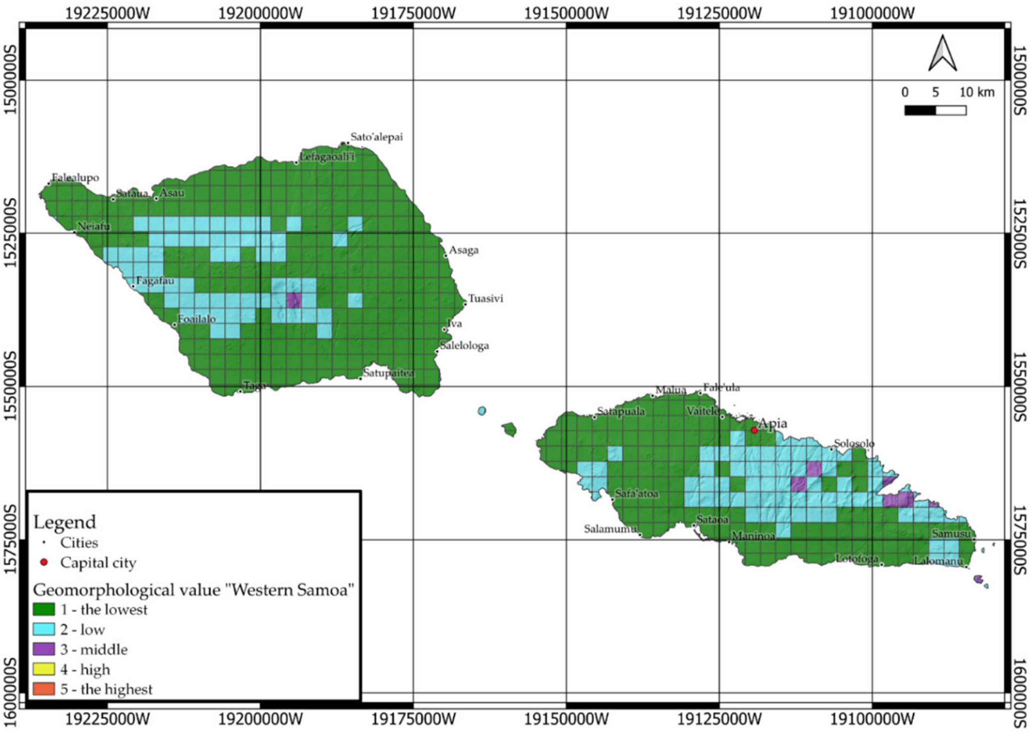

Figure 7. Geomorphological value of Western Samoa. The map based on SRTM 1 Arc-Second Global (Figure 4) utilized scheme (Figure 5). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

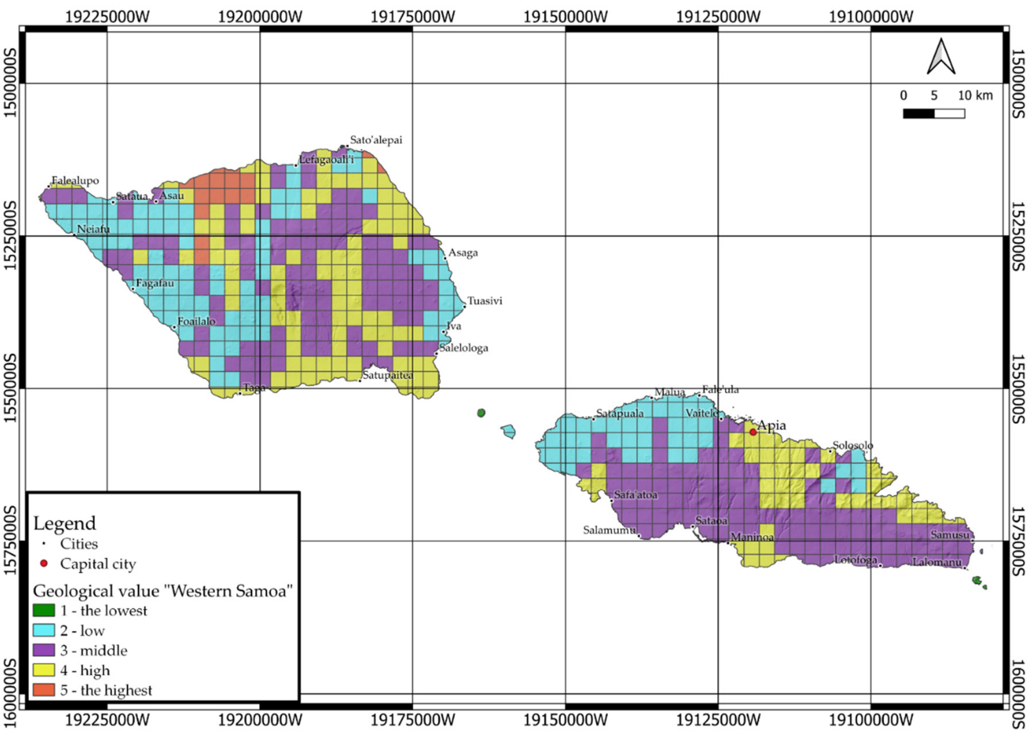

Figure 8. Geological value of Western Samoa. The map based on geological model of Western Samoa (Figure 3) utilized scheme (Figure 5). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

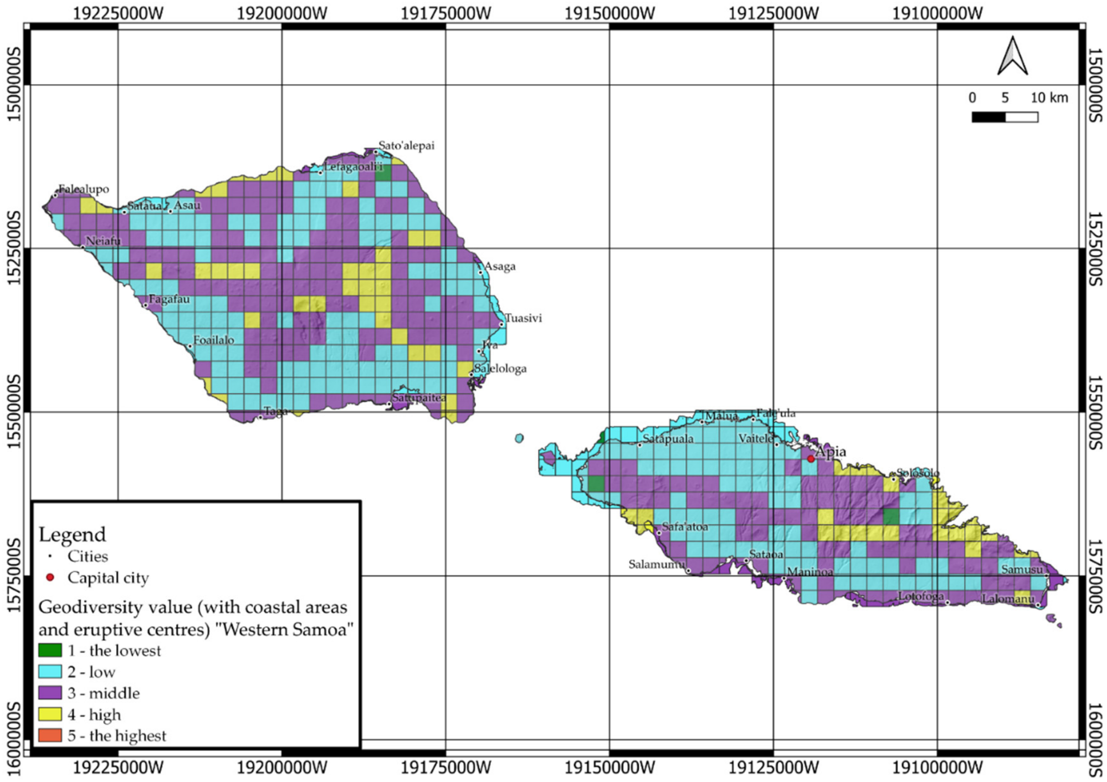

Figure 9. Calculated geodiversity values of Western Samoa. The map based on the models of the combination of geomorphological value (Figure 7), geological value (Figure 8), and additional value (Figure 6) of Western Samoa utilized scheme (Figure 5). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

3. Results

Our results define the finalized values used for the geomorphological (Figure 7) and geological (Figure 8) assessment of Western Samoa based on the methodology and required data described in the sections above. Then, these models were calculated together to obtain the final values for geodiversity, subject to some additional data about eruptive centres and coastal areas.

Geomorphology values of the Savai'i Island are lowest (less than 7.5 degrees) mostly through the whole territory, while the western part to the centre of the island displays growing steepness compared to the rest of this territory. The only exception is the centre of the island given a middle value due to a slope steepness of up to 45 degrees. Therefore, within this whole territory, geomorphologically, only the one region displays potential as a high value geosite with strong geomorphological values. Upolu Island is subject to a similar situation, except for the territory from the centre to the east, which displays higher values in comparison to the rest of the island. Additionally, this territory contains five regions with middle values, two near to the centre of the island, and three near the coastal area of the northeast sector.

The geological statistics show a completely different picture; there is no region with the lowest values, while the central part of the Savai'i Island lengthening to the east contains many regions with middle and high values. However, the sites with the highest values are located in the northwestern part, the site of the years 1905–1911 lava flow field of Matavanu and its source scoria and spatter cones. The two islands have a middle value for geology through the whole length in the south. Meanwhile, the northwestern part has many regions with high values.

Even though the quality of geological values shows that these islands should be unique places, the final compilation data of geological and geomorphological data, together with additional parameters, showed that the region's geodiversity is in fact moderate. Coastal areas and eruptive centres were included into the calculation to highlight some important places. Finally, the geodiversity of the Savai'i Island of Western-Samoa contains middle-high values of the central regions of the island thanks to the eruptive centres in those regions. Additionally, the regions adjacent to coastal areas also had been raised to middle values in the south and high values in the north. Upolu Island has increased to middle values from the west to the east part of the island, especially in the central-east region with increasing geodiversity contributing to high values. However, the situation here is the same as in the Savai'i Island, and the eruptive field with craters can be seen through the whole length of the island. Additionally, the coastal regions contain middle values in the southern region, while the high values fall in the northeastern part. Hence, the territories that have been presented on the set of field site images (Figure 10) demonstrate the typical appearance of various geodiversity value elements to help to select the most valuable and protentional places for geosites. Geosite selection is envisioned as the next step that can directly emerge from the study that requires more accurate mapping (increased scale) with additional material and field surveys.

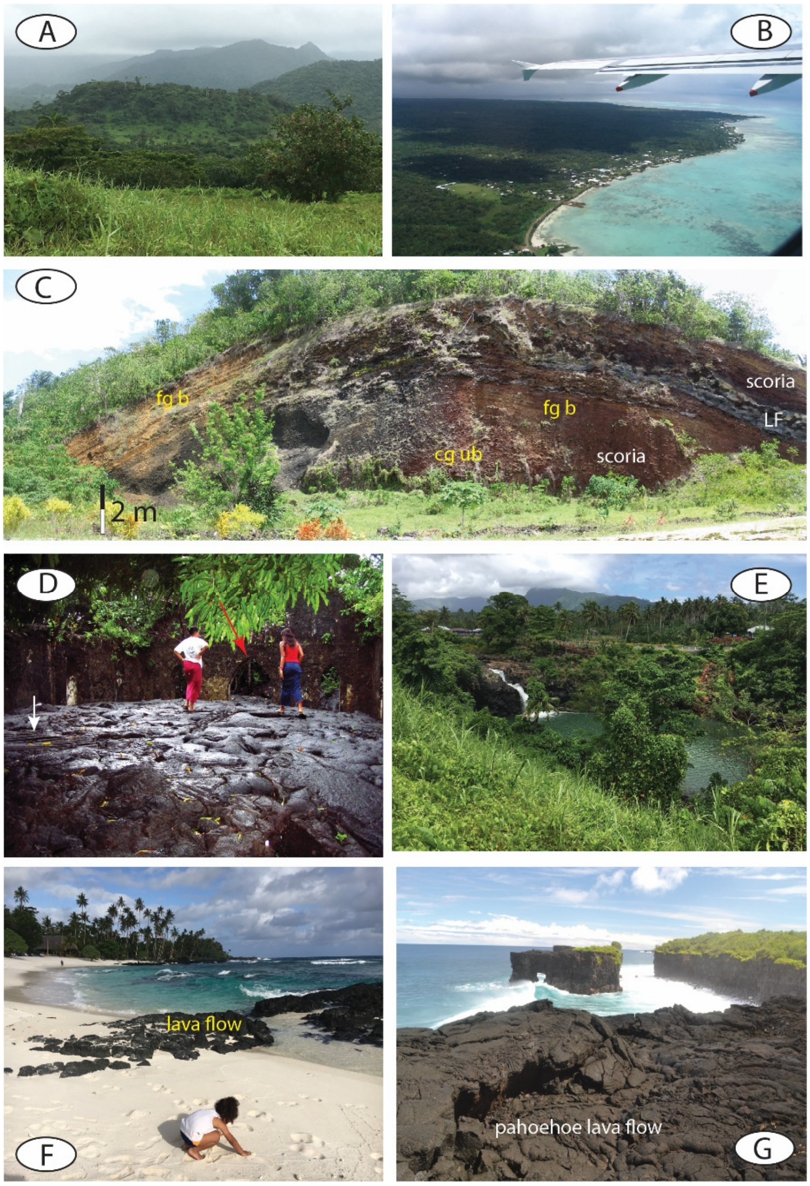

Figure 10. (**A**) Middle to high geodiversity value volcanic cone regions along the eastern section of the dorsal ridge of Upolu. While they yielded high geodiversity values, their access is difficult due to

its tropical jungle coverage and lack of access roads. (**B**) Low geodiversity value regions along the coastal plains in NW Upolu. They are flat areas with intensive agriculture and high population values. The coastal areas are lagoon fringed shallow water environment with low geodiversity values. (**C**) Additional geodiversity values were given to the eruptive centres (mostly scoria cones and small lava shields) along the dorsal ridges of Upolu and Savaii. Among these eruptive centres, the young ones still retain their original cone morphology, but they are normally forested and hard to access. In rare occasions, along the coastal regions such as in this NW Savaii scoria cone in the Seuseu area, local demand for building materials quarried and half sectioned few cones, allowing us to see the internal architecture of a typical scoria cone. In this example, a lower coarse-grained unbedded (cg ub) scoria cone section gradually turns into a fine grained bedded (fg b) section reflecting the eruption explosivity changes over time during the eruption formed the cone. The cone emitted small lava flows that are captured within the growing scoria cone section. Such half-sections of scoria cones are high in geodiversity values, but they do not show up well in the geodiversity calculations due to their small size. In addition, these sites quickly change due to the stopping of quarrying and tropical vegetation overgrowth. (**D**) Pahoehoe lava flow of the 1905–1911. Matavanu eruption in northern Savaii entered to the LMS Church in the Saleaula, filling the church interior halfway up. White arrow points to a roof corrugated iron roof fall on the hot lava and created an imprint on the solidified lava surface while yellow arrow shows one of the main entrances of the church. (**E**) High geodiversity region in the northern section of Upolu with common spectacular waterfalls such as the Falefa Falls formed in older Salani and Falagaloa weathered olivine basalts and basaltic andesite lava flows and pyroclastic rocks. (**F**) White coral sand beach at Matareva Beach in south Upolu with pahoehoe hummocky lava surfaces made additional value to the region geodiversity. (**G**) Coastal lava flows of one of the youngest lava flow fields in Upolu (post-mid Holocene O le Pupu lava field) forming a spectacular pahoehoe lava flow region and high energy coastal region elevating the geodiversity of the area.

4. Discussion

The results of the geodiversity assessments show that in the Western Samoa Islands, the most valuable places from a geodiversity perspective are found near the centre part of the islands, where the elevation may reach over 1000 m above sea level. Meanwhile, the sites featuring eruptive centres and coastal areas influenced the final mark of the regions, resulting in higher values for geodiversity. These results demonstrate that a detailed study of those areas will improve the ability to highlight points with high to highest values for geodiversity. This is especially important and applicable to sites subject to limitations in accessibility such as no roads or tracks and covered by dense tropical vegetation.

In the research, additional values have been included into assessment of geodiversity to change the values for assessment of geology. These steps increased the variability for geological assessment for the regions featuring the same rock types as in the Western Samoa Islands. Additionally, eruptive centres were selected from the satellite image of Hybrid Google Earth, utilize the values shown in Table 1 to increase geodiversity values for places where they are present. Then, coastal areas around Samoa Islands were selected from satellite image (as with eruptive centres) and divided into three categories: sand beaches, shallow waters, and riffs with cliffs. Values range from the lowest (-0.5) to the highest (1). The evaluation system for coastal areas was used as an example that can be applied to readily accessible satellite images. These parameters complete the final picture and provide a holistic view based on in situ geological and geomorphological observations. However, this is a still incomplete methodology, especially for the evaluation systems. Hence, the further research should improve and refine the methodology and consider any other recommendations related to the evaluation system and possible changes/improvements in assessing geology and geomorphology as well as other elements contributing to geodiversity.

This assessment of geodiversity is simple to utilize as it requires a standard type of geological map and QGIS software with a connection to the Internet, while DEM and additional data derived from the satellite images can be downloaded directly from the software. Additionally, this assessment is based on a standard arithmetic average equation, which is already included in QGIS software and can be easily used. However, this is not a complete assessment method, as this article demonstrates the calculation of core parameters for the assessment of geodiversity, geology, and geomorphology, while other factors such as soils, volcanos, caves, and weathered and altered rocks, together with processes such as climate, hydrology, and human and biological footprints, are still in development. Nonetheless, some improvements were demonstrated through the research to develop the methodology of the assessment of geodiversity, acknowledge additional work required to refine the assessment, and allow for greater complexity.

This methodology can be compared with other commonly used quantitative models demonstrating advantages and disadvantages between methods. However, the main difference is the amount of data required for the assessment of both models. To achieve global utility, the quantitative-qualitative method described earlier in this paper requires simple data on geology and geomorphology. However, the evaluation system becomes problematic as it may be subjective depending on the researcher's specialty and background. Meanwhile, the quantitative methodology requires a large database and ample time for assessment, hence, the result is more objective and accurate. However, this method would only be applicable to a region with sufficient high-resolution information. Subsequently, the Western Samoa Islands cannot be subjected to comparisons between the two methodologies due to the limited database for the geology of this region. However, this question can be answered through future research, when the quantitative-qualitative model will include all geodiversity elements of the area, already assessed through a quantitative methodology or a sufficient database. Moreover, both models could be used together (Figure 11), where quantitative-qualitative methods could identify high values of geodiversity, and a qualitative assessment could highlight specific geosites in the context of an overall geoheritage description.

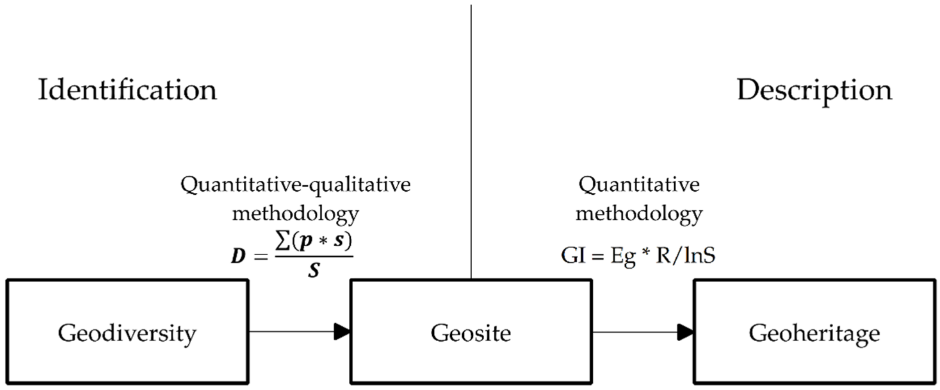

Figure 11. The conceptual scheme of potentional connection between quantitative-qualitative (Section 2.4 Equation) [18] and quantitative [5] methodologies in geodiversity estimates.

$\boldsymbol{D} = \frac{\sum (\boldsymbol{p}*\boldsymbol{s})}{\boldsymbol{S}}$, where ($\boldsymbol{D}$)—diversity; ($\boldsymbol{p}$)-number of points of element (geology or geomorphology (Table 1) [-]; ($\boldsymbol{s}$)—area of element ($\boldsymbol{p}$) [L]; and ($\boldsymbol{S}$)—area of research [L] [18].

$\boldsymbol{GI} = \frac{\boldsymbol{Eg}*\boldsymbol{R}}{\boldsymbol{InS}}$, where ($\boldsymbol{GI}$)—geodiversity index; ($\boldsymbol{Eg}$)—number of different physical elements in a unit of surface; ($\boldsymbol{R}$)—roughness coefficient; and ($\boldsymbol{InS}$)—natural logarithm of the surface unit [5,22].

The Samoa Islands are suggested as a suitable location for geotourism and geoeducation because of the significant history of volcanic activity throughout the region. This place has broadly only one type of rock (basalt) but formed in different periods and subject to different rates of weathering. This could depend on the place of rock formation, where some of them may become mantled by forest or be subject to human impacts. Furthermore, coastal areas are constantly subject to oceanic weathering processes (e.g., wave action), biogeological activity (e.g., coral reef development), or coastal sedimentation (e.g., marsh land, mangrove lagoons, etc.). The accessibility of the sites with the highest values needs to be considered, which can be demonstrated by plotting access roads, taken from the Google

Maps (Figure 12). Savai'i roads that circle around the island and its coastal areas provide ready access to coastal areas, which have middle values of geodiversity, as well as some places in the south and the north with high values. Meanwhile, Upolu has the longest road system, which covers the whole island running near the south coasts, so access is available to a number of places with middle values of geodiversity. Moreover, three additional branches of the road lead to the northern part of the island, with the first western branch leading to Apia city and not providing access to any high value sites. The second road to the east also leads to the city of Apia but crosses near several middle value sites. The last road on the East has a fork deviation to the north, and to the northeast. The north road crosses several highly valuable regions, while the northeast road only crosses some middle value regions. In conclusion, the road accessibility on both islands is relatively low as most of them lead to coastal areas, while most of the high value sites are closer to the central regions. Nonetheless, Upolu Island has one north–south road, which is directed straight to the most concentrated sites from a geodiversity perspective.

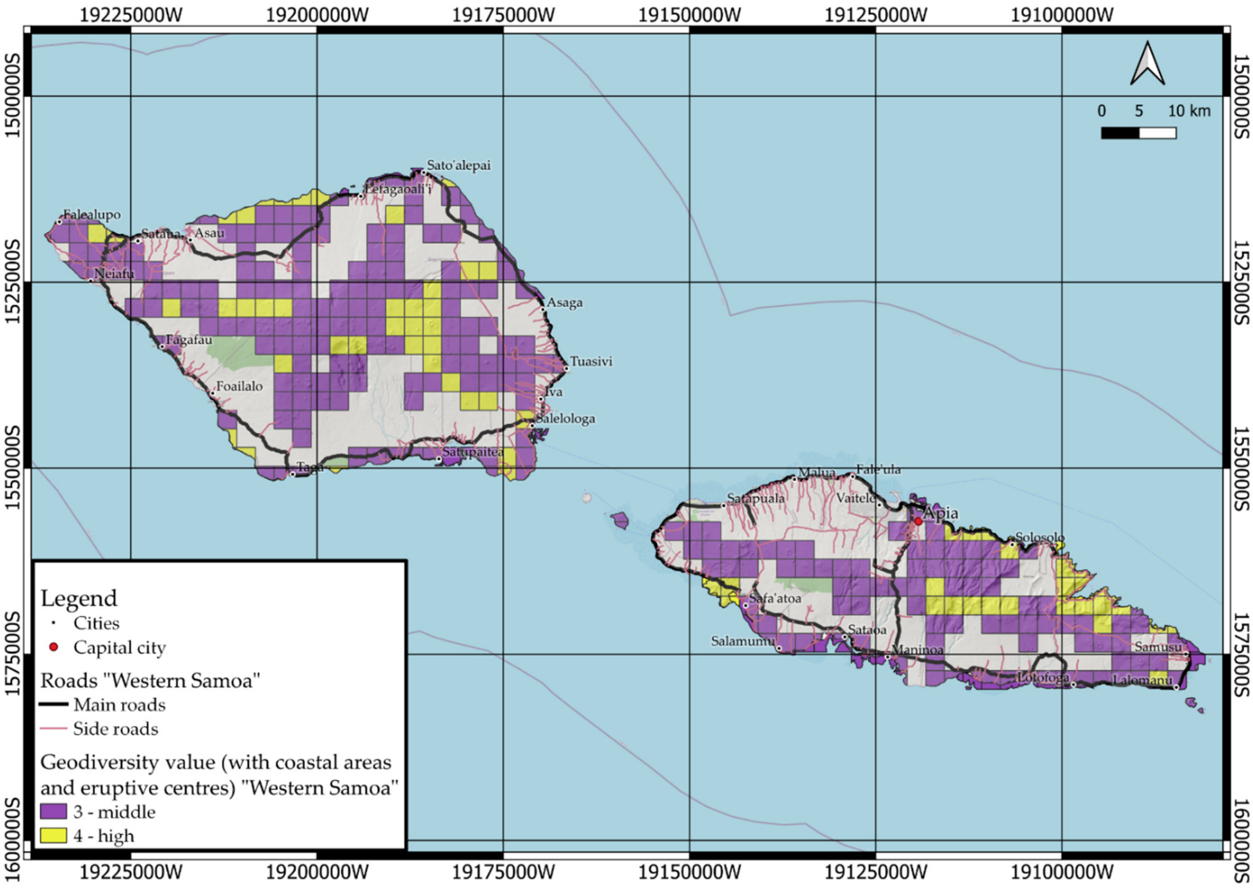

Figure 12. Road access to the most significant places on Savai'i and Upolu Islands. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

5. Conclusions

The study has demonstrated an interesting result for the assessment of the geodiversity of Western Samoa. Using a simple method to show the central parts of the islands, the highest elevations have the highest geodiversity values. In addition, coastal areas are defined as the most significant areas for further studies of geodiversity to facilitate planning and suggest recommendations for geotourism, geoeducation, and geoconservation planning in the future.

The initial methodology demonstrates the importance of the further study of the coastal areas and additional geological features to refine the methodology and provide a more accurate assessment of geodiversity. This will expand the utility of the methodology and increase the geographical range where it can be of the greatest effectiveness.

The assessment of Western Samoa shows a need for further research of the highlighted places, however, utilizing an online street map platform demonstrates that most of the valuable sites are in concentrated regions not accessible by car. Hence, the study of accessible but lower value regions and access to the higher value sites are issues for future studies.

Author Contributions: Conceptualization, K.N.; methodology, K.N. and V.Z.; validation, V.Z.; formal analysis, V.Z.; investigation, K.N. and V.Z.; resources, K.N.; data curation, K.N.; writing—original draft preparation, V.Z.; writing—review and editing, K.N.; visualization, V.Z.; supervision, K.N.; project administration, K.N.; funding acquisition, K.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research is part of VZ's PhD research on Coromandel Peninsula funded by the Massey University PhD Scholarship. We also acknowledge the support by The Geoconservation Trust, Ilmars Gravis and Chris Twemlow continuing support and in-depth discussions over geodiversity.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gray, M. Geodiversity: Developing the paradigm. *Proc. Geol. Assoc.* **2008**, *119*, 287–298. [CrossRef]
2. Gray, M. Geodiversity: The backbone of geoheritage and geoconservation. In *Geoheritage*; Elsevier: Amsterdam, The Netherland, 2018; pp. 13–25.
3. Kozłowski, S. Postępy prac nad ochroną georóżnorodności w Polsce. *Kosmos* **2001**, *50*, 151–165.
4. Kozłowski, S. Geodiversity. The concept and scope of geodiversity. *Przegląd Geol.* **2004**, *52*, 833–837.
5. Serrano, E.; Ruiz-Flaño, P. Geodiversity: A theoretical and applied concept. *Geogr. Helv.* **2007**, *62*, 140–147. [CrossRef]
6. Manosso, F.C.; de Nóbrega, M.T. Calculation of geodiversity from landscape units of the Cadeado range region in Paraná, Brazil. *Geoheritage* **2016**, *8*, 189–199. [CrossRef]
7. Brocx, M.; Semeniuk, V. Geoheritage and geoconservation-history, definition, scope and scale. *J. R. Soc. West. Aust.* **2007**, *90*, 53–87.
8. Cengiz, C.; Şahin, Ş.; Cengiz, B.; Başkır, M.B.; Keçecioğlu Dağlı, P. Evaluation of the Visitor Understanding of Coastal Geotourism and Geoheritage Potential Based on Sustainable Regional Development in Western Black Sea Region, Turkey. *Sustainability* **2021**, *13*, 11812. [CrossRef]
9. Williams, M.A.; McHenry, M.T.; Boothroyd, A. Geoconservation and geotourism: Challenges and unifying themes. *Geoheritage* **2020**, *12*, 1–14. [CrossRef]
10. Ólafsdóttir, R.; Dowling, R. Geotourism and geoparks—A tool for geoconservation and rural development in vulnerable environments: A case study from Iceland. *Geoheritage* **2014**, *6*, 71–87. [CrossRef]
11. Bentivenga, M.; Cavalcante, F.; Mastronuzzi, G.; Palladino, G.; Prosser, G. Geoheritage: The foundation for sustainable geotourism. *Geoheritage* **2019**, *11*, 1367–1369. [CrossRef]
12. Zwoliński, Z.; Najwer, A.; Giardino, M. Methods for assessing geodiversity. In *Geoheritage*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 27–52.
13. Gray, M. *Geodiversity: Valuing and Conserving Abiotic Nature*, 2nd ed.; Wiley-Blackwell: Chichester, UK, 2013.
14. Gordon, J.E.; Barron, H.F. The role of geodiversity in delivering ecosystem services and benefits in Scotland. *Scott. J. Geol.* **2013**, *49*, 41–58. [CrossRef]
15. Cañadas, E.S.; Flaño, P.R. Geodiversidad: Concepto, evaluación y aplicación territorial: El caso de Tiermes Caracena (Soria). *Boletín de la asociación de geógrafos españoles* **2007**, *45*, 79–98.
16. Brilha, J.; Gray, M.; Pereira, D.I.; Pereira, P. Geodiversity: An integrative review as a contribution to the sustainable management of the whole of nature. *Environ. Sci. Policy* **2018**, *86*, 19–28. [CrossRef]

17. Gray, M. Geodiversity and geoconservation: What, why, and how? In *The George Wright Forum*; George Wright Society: Houghton, MI, USA, 2005; Volume 22, pp. 4–12, ISSN1 0732-4715. Available online: http://www.georgewright.org/223.pdf (accessed on 5 September 2021)ISSN2 0732-4715.
18. Zakharovskyi, V.; Németh, K. Quantitative-Qualitative Method for Quick Assessment of Geodiversity. *Land* **2021**, *10*, 946. [CrossRef]
19. da Silva, M.L.N.; do Nascimento, M.A.L.; Mansur, K.L. Quantitative assessments of geodiversity in the area of the Seridó Geopark Project, Northeast Brazil: Grid and centroid analysis. *Geoheritage* **2019**, *11*, 1177–1186. [CrossRef]
20. Dias, M.C.S.S.; Domingos, J.O.; dos Santos Costa, S.S.; do Nascimento, M.A.L.; da Silva, M.L.N.; Granjeiro, L.P.; de Lima Miranda, R.F. Geodiversity Index Map of Rio Grande do Norte State, Northeast Brazil: Cartography and Quantitative Assessment. *Geoheritage* **2021**, *13*, 1–15. [CrossRef]
21. Pál, M.; Albert, G. Refinement Proposals for Geodiversity Assessment—A Case Study in the Bakony–Balaton UNESCO Global Geopark, Hungary. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 566. [CrossRef]
22. Ferrando, A.; Faccini, F.; Paliaga, G.; Coratza, P. A quantitative GIS and AHP based analysis for geodiversity assessment and mapping. *Sustainability* **2021**, *13*, 10376. [CrossRef]
23. Melelli, L. Geodiversity: A new quantitative index for natural protected areas enhancement. *Geoj. Tour. Geosites* **2014**, *1*, 27–37.
24. Filocamo, F.; Di Paola, G.; Mastrobuono, L.; Rosskopf, C.M. MoGeo, a Mobile Application to Promote Geotourism in Molise Region (Southern Italy). *Resources* **2020**, *9*, 31. [CrossRef]
25. Perotti, L.; Bollati, I.M.; Viani, C.; Zanoletti, E.; Caironi, V.; Pelfini, M.; Giardino, M. Fieldtrips and Virtual Tours as Geotourism Resources: Examples from the Sesia Val Grande UNESCO Global Geopark (NW Italy). *Resources* **2020**, *9*, 63. [CrossRef]
26. Piacentini, T.; Miccadei, E.; Berardini, G.; Aratari, L.; De Ioris, A.; Calista, M.; Carabella, C.; d'Arielli, R.; Mancinelli, V.; Paglia, G. Geological tourist mapping of the mount serrone fault geosite (Gioia dei Marsi, central Apennines, Italy). *J. Maps* **2019**, *15*, 298–309. [CrossRef]
27. Miccadei, E.; Piacentini, T.; Esposito, G. Geomorphosites and geotourism in the parks of the Abruzzo region (Central Italy). *Geoheritage* **2011**, *3*, 233–251. [CrossRef]
28. Bétard, F.; Peulvast, J.-P. Geodiversity hotspots: Concept, method and cartographic application for geoconservation purposes at a regional scale. *Environ. Manag.* **2019**, *63*, 822–834. [CrossRef] [PubMed]
29. McDougall, I. Age of volcanism and its migration in the Samoa Islands. *Geol. Mag.* **2010**, *147*, 705–717. [CrossRef]
30. Kear, D. Geological notes on western Samoa. *N. Z. J. Geol. Geophys.* **1967**, *10*, 1446–1451. [CrossRef]
31. Eros, U. USGS EROS Archive—Digital Elevation—Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. 2015. Available online: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1 (accessed on 5 September 2021).
32. Gray, M. *Geodiversity: Valuing and Conserving Abiotic Nature*; John Wiley & Sons: Hoboken, NJ, USA, 2004; pp. 1–433, ISBN 978-0-470-74215-0.
33. Gray, M. Geoheritage 1. Geodiversity: A new paradigm for valuing and conserving geoheritage. *Geosci. Can.* **2008**, *35*, 51–59.
34. Davis, W.M. The geomorphic cycle. *Geomorphic J.* **1899**, *14*, 481–504. [CrossRef]
35. Davis, W.M. Peneplains and the geographical cycle. *Bull. Geol. Soc. Am.* **1922**, *33*, 587–598. [CrossRef]
36. Davis, W.M. The geographical cycle. In *Climatic Geomorphology*; Springer: Heidelberg, Germany, 1973; pp. 19–50.
37. Blatt, H.; Jones, R.L. Proportions of exposed igneous, metamorphic, and sedimentary rocks. *Geol. Soc. Am. Bull.* **1975**, *86*, 1085–1088. [CrossRef]
38. Dolan, M.F. *Calculation of Slope Angle from Bathymetry Data Using GIS-Effects of Computation Algorithm, Data Resolution and Analysis Scale*; NGU Report 2012.041; Geologi for Samfunnet—Geology for Society (Norges geologiske undersøkelse—Geological Survey of Norway): Trondheim, Norway, 2012; p. 45.
39. Albut, S. Estimation of Slope Length (L) And Slope Steepness Factor (S) of RUSLE Equation by QGIS. *Int. J. Res. Eng. Sci.* **2020**, *8*, 43–48.
40. Kim, K.W. The comparison of visibility measurement between image-based visual range, human eye-based visual range, and meteorological optical range. *Atmos. Environ.* **2018**, *190*, 74–86. [CrossRef]
41. Tobias, M.M.; Mandel, A.I. Literature Mapper: A QGIS Plugin for Georeferencing Citations in Zotero. *Air Soil Water Res.* **2021**, *14*, 11786221211009209. [CrossRef]
42. Baghdadi, N.; Mallet, C.; Zribi, M. *QGIS and Generic Tools*; John Wiley & Sons hichester: West Sussex, UK, 2018; Volume 1.
43. Conrad, O.; Bechtel, B.; Bock, M.; Dietrich, H.; Fischer, E.; Gerlitz, L.; Wehberg, J.; Wichmann, V.; Böhner, J. System for automated geoscientific analyses (SAGA) v. 2.1. 4. *Geosci. Model Dev.* **2015**, *8*, 1991–2007. [CrossRef]
44. Schillaci, C.; Braun, A. *Terrain Analysis and Landform Recognition*; Geomorphological Techniques—Chapter 2, Section 4.2; British Society for Geomorphology: London, UK, 2015; pp. 1–18. ISSN 2047-0371.
45. Zevenbergen, L.W.; Thorne, C.R. Quantitative analysis of land surface topography. *Earth Surf. Process. Landf.* **1987**, *12*, 47–56. [CrossRef]
46. Reuter, H.; Nelson, A. Geomorphometry in ESRI packages. *Dev. Soil Sci.* **2009**, *33*, 269–291.

47. GRASS GIS 7.2.1svn Reference Manual. Available online: http://wgbis.ces.iisc.ernet.in/grass/grass72/manuals/ (accessed on 31 August 2021).
48. Jung, M. *LecoS-A QGIS Plugin for Automated Landscape Ecology Analysis*; PeerJ PrePrints: San Diego, CA, USA, 2013; p. 10. [CrossRef]