Geodiversity Estimation of the Coromandel Peninsula through a Digital Model Analysis under special Consideration of the Geology and Geomorphology of this Region

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Abstract

This thesis has drawn on a wide range of published research in understanding the term geodiversity in a philosophical and scientific context. Geodiversity description is one of the first steps in the establishment of geoparks, as it recognizes and describes the surface evolution of the physical research area. Subsequently it can lead to development of tools for geodiversity assessment and geosite recognition. The Coromandel Peninsula, New Zealand, has been selected as the research area for testing geodiversity description and assessment, because of its variety of geological and geomorphological compositions, formed through volcanic processes shaped by and interacting with a coastal environment. To provide a general scientific context, a literature review has been undertaken, supported by direct field observations. For estimation of geodiversity of the region, a qualitative-quantitative assessment of geodiversity (QQG) has been developed for areas with limited available data. Development of this framework was initiated by an in-depth systematic literature review of terminology relating to geodiversity.

In developing this methodology, the abiotic environment has been divided into main and additional values (elements), according to their roles in shaping of geodiversity. This becomes the philosophical foundation for the new qualitative-quantitative methodology for geodiversity assessment. It is not only describing density of geosites in the studied area but also introduces a ranking system for assessing geodiversity. The ranking system applied to geological and geomorphological elements combined, can be used to describe any area globally, making it useful for comparative for assessment of different regions. Meanwhile, additional values are recognized for their impact in shaping and altering surface features. This approach is a completely new way to assess and describe geodiversity and its contribution to geoconservation, geotourism, and geoeducation. The foundation of QQG has been tested, corrected, and improved with several applications utilizing Geographical Information Systems (GIS), and supported by research. The result of this process is a geodiversity model for the whole Coromandel Peninsula, providing a deep description of potential geosites on the northern region of the peninsula. Therefore, the QQG methodology is now fully developed for assessment of territories and highlighting potential geosites, especially in cases where only low amounts of data are available. Our methodology does allow for addition of further data as it comes available, thereby expanding and improving results. Therefore, with enough elements included in the assessment, the methodology can be transformed from a geosite recognition tool to overall geodiversity description and modelling. In developing the methodology, it was also applied to regions outside of the Coromandel Peninsula for comparative testing on a range of differing geological and geomorphological compositions.

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Whiritoa Beach, Coromandel Peninsula, North Island, New Zealand

Table of content

List of Figures

Each figure contains its name code: the first refers to the Chapter of the manuscript; the second refers to the Section; and the third refers to the figure's number in (round brackets).

List of Tables

Each figure contains its name code: the first refers to the Chapter of the manuscript; the second refers to the Section; and the third refers to the figure's number in [square brackets].

Chapter 1 – Introduction

1.1 Terminology of Geodiversity

Geodiversity as a term has been used to describe abiotic aspects of the environment as analogous to biodiversity, and a necessary layer in providing a full holistic description of the environment (Brilha et al., 2018, Burnelli et al., 2023, dos Santos et al., 2020). Environment refers to a defined location and includes all biotic and abiotic elements, existing in a balance of material and energy exchange. Therefore, the biological sphere is represented by flora and fauna in the environment, while the abiotic sphere includes all other elements which provide the foundation of sustainability for living organisms and ecological processes. Therefore, the term geodiversity is applied to all elements of abiotic nature, including geology; geomorphology; hydrology; exogenic (solar energy and climate) and endogenic (tectonics, Earth's gravitation) processes; and footprints of the anthroposphere and biosphere (Burnelli et al., 2023, Kozłowski, 2004). A more specific description of geodiversity is: "the variety of nature elements, such as minerals, rocks, fossils, landforms and their landscapes, soils, and active geological/geomorphological processes" (ProGEO, 2017). Therefore, geodiversity can be described as a multidisciplinary field focused on understanding the connection, exchange, and collaboration of all elements forming the environment (Ruban, 2017). Currently, UNESCO, IUGS and other programs are concentrated on applying measures of geodiversity for conservation planning, education, and protection of values. These factors are also the main focus of current geodiversity research (Ruban, 2017, da Silva et al., 2022). In addition, geodiversity tools can be used to increase awareness of the environment and improve levels of economic and cultural well-being (Henriques and Brilha, 2017).

On the other hand, geodiversity as a term is subject to contrasting perceptions and understanding between researchers. For example, the understanding of geodiversity can be outlined in two ontological modes of existence introduced by Sarter: being-in-itself and being-for-itself. The first mode is referring to the actual nature of the studied object, while the second is the meaning of the studied object for the subject (observer). Geodiversity applied as "being-in-itself" is referring toward the objects of abiotic nature, which exist in a constant exchange of energy and matter. In contrast, seen through the lens of human perception as "being-for-itself", geodiversity becomes the experience of places and landscapes manifested in the lived order from a phenomenological point of view. Subsequently, geology as a scientific concept can be transformed into that of meaningful places, like those we call "home" or "work". This phenomenon is always updating our perception of the objects of the nature, transforming them into something more than they really are (Karjalainen, 1983, Ollier, 2012). This raises a shortcoming in purely quantitative assessments of geodiversity, where only a number of geodiversity elements present in the region are given importance without reflecting a deeper meaning inherent in landscapes and geosites which may not be immediately apparent (Burnelli et al., 2023). Therefore, other types of assessment must be applied to locations in question, giving weight to cultural, historical, and sociological factors. We describe this aspect of assessment as qualitative (Necheş, 2016, Fernández et al., 2020). This has been demonstrated to provide more meaningful results related to the human perception of geodiversity as shown by Gonçalves, J (2022) research on Miguel Pereira Municipality, Rio de Janeiro, Brazil where quantitative and qualitative methodologies were applied (Gonçalves et al., 2022). A further issue is the relationship between geodiversity and biodiversity, described as the concept of "omnidiversity". This term has been introduced to combine geodiversity and biodiversity to describe their influences on each other, and to provide relevant conservation criteria for vulnerable environments and ecosystems (Crisp et al., 2022). Biodiversity is still often the fundamental focus point of conservation, while geodiversity may be given more consideration in the studies of their combined assessments (Gordon et al., 2021, Crofts, 2018).

Geodiversity assessments can be used to describe the value of abiotic objects in the environment, but its ranking methodologies depend on the type of assessment and main goals of the researcher. For example, the basin of the Manawatu River, in the North Island of New Zealand, contains 32 different rock groups (Lo Re et al., 2018), which can be considered as a high geodiversity rate. However, all rock groups are represented by sedimentary rocks, demonstrating a high value for explanation of geological evolution of the region but losing other aspects of Geodiversity. This issue has been explored by Gray (2008) in his research "*Geoheritage 1. Geodiversity: a new paradigm for valuing and conserving geoheritage*". He proposed 15 different values of geodiversity such as: scientific, cultural, economic, spiritual, aesthetic, and others (Gray, 2008). This has resulted in geodiversity assessments unable to be compared between each other as researchers consider varying purposes for their research and associated parameters of investigation.

In developing methodologies for geodiversity research, we define two important terms in this field of research: geosite and geoheritage. Geosite is a label given to a location of high importance, usually due to values contributing to the overall geodiversity of that location and the general area. A geosite contains a range of specific information describing the uniqueness of the environment of the studying area. The recognition of a geosite is based on application of an evaluation system measuring a variety of different aspects like conservation, tourism, education etc. Meanwhile, geoheritage is a quality represented by a specific geosite and its value in recording and demonstrating historical aspects of the Earth's evolution (Brilha, 2018). Hence, the establishment of an objectively correct and useful evaluation system with an effective methodology to be applied to an assessed region has been one of the main drivers behind geosite recognition. Currently geodiversity researchers are still working on development of an effective methodology for assessment of geodiversity, and recognition of potential geological locations with high values, based on an objective evaluation system. However, the specific evaluation system is still the main point of argument as each researcher will inevitably display a bias towards those locations or subject areas where their knowledge and history of past research may give greater weight to some values, while missing out others all-together.

Geodiversity research is a new and relatively undeveloped field of study in the scientific community of New Zealand, which mostly refers to specific areas focusing on geological aspects (Cody, 2007, NZGI, n.d.). This new area of study shows a high potential for the development of more reliable approaches, leading to better and more sustainable outcomes for environmental management and planning. The Coromandel Peninsula has been considered as a case study because of it famously known as one of New Zealand's touristic, historical of conservation areas (Fairweather and Swaffield, 1999, Holzapfel, 2003, Matthews et al., 2018). It is located in the north-east part of Waikato district in the North Island of New Zealand between Hauraki Gulf and Bay of Plenty (Hayward, 2017, Homer and Moor, 1992). The Peninsula is approximately 40 km wide, and 100 km long formed by Miocene-Pliocene volcanism with marine–sedimentary environments from the Jurassic period featuring a complex geological and geomorphological history with potentially high geodiversity values (Hayward, 2017). Recently the region has been highly considered highly attractive by Māori tribes as a place with rich biodiversity and access to the ocean, which make it important for gathering-hunting ground and strategically important location (Davidson, 2018, Maxwell et al., 2018, Moore, 2013, Wellman, 1962). Their settlements and cultural heritage mostly became concentrated in the coastal regions. Europeans came to the Coromandel Peninsula in the early 1800's primarily for gold/silver mining because of geological richness of the region and access to epithermal deposits formed by alteration processes. The main mining areas used to be in the central-west and south part of the Peninsula, while now it is only occurring in the south (Barker et al., 2006, Legget, 2012, Spörli and Cargill, 2011). Therefore, the Coromandel Peninsula has been chosen as the main area of research for this thesis, but due to time and resource limitations, the research was concentrated more on the scientific values of the region with a focus on the geological and geomorphological elements of the peninsula.

1.2 Geodiversity assessment

Geospatial analysis uses a range of tools and analytical frameworks developed for assessing the Earth's surface, utilizing mathematical models for its description (De Smith et al., 2007). Analysis is used by geoscientists to recognize records of the Earth's surface evolution, enabling a holistic description and supporting forecasting, modelling, and predictions of future processes and events. For example, geospatial analysis of current volcanic activity can be used to describe parameters of lava flows (speed, mass, volume, orientation, etc.,) which in turn can be used to model potentially hazardous areas in future events. Geospatial assessments can be applied at a multidisciplinary level, combining different elements at a range of scales for a holistic description of some specific event or its influence. For example: influences of morphology on prolonged droughts (Dubinin et al., 2021, Yizhaq et al., 2017); relationships between soils and biodiversity and geodiversity (Thwaites, 2000, Ibanez and Brevik, 2019, Ibáñez and Brevik, 2022, Ibáñez and Brevik, 2023); and geomorphological diversity of coastal environments (Ferrer-Valero, 2018). Therefore, holistic geospatial analysis of the Earth's surface evolution and associated energy and mass exchanges have become a fundamental pillar of geodiversity assessment (Stavi et al., 2018).

The results of geospatial analysis can be represented by models, maps, 3D surface visualisations, sub-surface profiles, and animations. These provide engaging, meaningful, and useful ways of representation and combination of the data (Pérez-Gómez et al., 2014). Geographical Information Systems (GIS) are the most popular tool for geospatial analysis, which are regularly utilized in conducting geodiversity assessments. Software like ArcGIS, QGIS, Grass GIS, R statistics, and others, can be utilized by researchers to assess geological, morphological, archaeological, and other mapping data for a range of different goals. However, the methodology, goal, and data range will differ according to aims of the research and the location of study.

Three main types of methodologies have been described by Zwoliński at al. (2018) in their research "*Methods for assessing geodiversity*", broadly described as qualitative, quantitative, and qualitative-quantitative methods (Zwoliński et al., 2018). The quantitative methodology of geodiversity assessment is the most frequently used by researchers. Its accuracy depends on the amount of data available for each point or area defined in the studied region (Pellitero et al., 2011, Serrano and Ruiz-Flaño, 2007, da Silva et al., 2019a, da Silva et al., 2019b, Micić Ponjiger et al., 2021). This scientific information can be presented as geological, topographical, hydrological, anthropological, and archaeological maps, which can increase the accuracy of geodiversity description and information recorded and presented. Therefore, the quantitative assessment shows the best results for describing local geodiversity when applied to regions with a long-standing history of research. However, it is not suitable for comparative analysis of geographically diverse regions because of differences in available data and scale of research.

The second methodology is qualitative. It is based on an expert's knowledge applied to the studied region and is most suitable for recognition of geosites as this methodology is not practical for large territories and does not require a complicated assessment process. The term geosite describes those sites representing geological heritage of the region which contain features contributing to the understanding of geological and/or geomorphological evolution with application to conservation and land management (García-Cortés et al., 2013, García-Cortés et al., 2000, Henriques et al., 2011). Expert-based methodology is the fastest and most subjective methodology, where geosites are defined based on existing knowledge and interest of the researcher, however this does leave them open to challenge by other scientists and stakeholders (Gray, 2013, Gordon and Barron, 2013). For example, in the previously mentioned Manawatu basin, an initial assessment of general geology may define it as an area with low values based on geology, however that value can be rated higher when assessed by sedimentological and hydrological experts (Zakharovskyi and Nemeth, 2023).

The last methodology is the qualitative-quantitative, which unites the previous two methods. The expert knowledge (qualitative part) is utilized to create an evaluation system for each element introduced into calculation, while the quantitative aspect is represented by the number of elements. The most positive aspect of qualitative-quantitative methodology is its suitability for application to territories with a low amount of readily accessible scientific information or historical research. For example, we utilized a qualitative-quantitative assessment of geodiversity (QQG) for the western islands of Samoa, represented by only one broad map of volcanological groups throughout the whole region (Zakharovskyi and Németh, 2021a). Additionally, QQG provides globally comparable results, allowing for introduction of globally recognised evaluation systems for each element included into the assessment. However, as the evaluation system is the foundation of the QQG method, it is crucial and objectively correct. In the context of our research, we have applied, tested, and refined the qualitative-quantitative method, as our areas of interest were mostly those with low amounts of available scientific data for the studied regions.

1.3 Aims and Objectives

Geodiversity research is a new and relatively undeveloped field of study in the scientific community of New Zealand. It shows high potential for development of more reliable approaches, leading to better and more sustainable outcomes for environmental management and planning. The Coromandel Peninsula is considered an iconic destination in New Zealand's North Island for tourism and has a strong and highly visible history of conservation initiatives. The landscape is shaped by the interaction of Miocene-Pliocene volcanism with marine–sedimentary environments, resulting in a complex geological history with potentially high geodiversity values. The main goal of this thesis is to create a geodiversity model of the Coromandel Peninsula, thereby fulfilling three aims: to explore the terminology of geodiversity through describing its main elements and the underlying conceptual philosophy; to analyze the current state of scientific knowledge of the Coromandel Peninsula; and to develop a new methodology for geodiversity assessment of the Coromandel Peninsula. A literature review focusses on conceptual philosophy underlying geodiversity, and the current scientific knowledge of the Coromandel Peninsula. This provides the theoretical foundation required for the development of a qualitative-quantitative methodology for geodiversity assessment. Development of the methodology underpins the practical aspect of this research, resulting in fulfillment of the main goal. Each aim was fulfilled by completing main and additional objectives. The main objectives are required to fulfill the principal goal of the research, while additional objectives are used to facilitate deeper exploration and development.

The aims of the thesis:

1) Geodiversity is a relatively new concept with different meanings and a variable range of elements applied by researchers. The first aim is to explore the terminology applied to geodiversity, and to describe its elements and philosophical background. The recognition of the terms related to geodiversity has been achieved by undertaking a systematic literature review of the published scientific research.

   Main objectives:

   a) Determine the concept of geodiversity and its associated terminology through systematic literature reviews of previous research on this topic to recognize the development of the concept and its variabilities.

   b) Define the ontology of geodiversity and establish its philosophical foundation.

   Additional objectives:

   c) Analyze the comparison of geodiversity and biodiversity as applied by researchers and describe the amalgamation of these two terms into “omnidiversity”.

2) After defining the concept of geodiversity and its relationship to other commonly applied terms, detailed analysis of scientific data about the Coromandel Peninsula is required. The second aim is describing historic and current research applied to the Coromandel Peninsula, providing a summary of available data and research on the abiotic environment of the

peninsula. The systematic literature review was achieved by utilizing the main scientific databases for search, analysis, and classification.

Main objectives:

a) Utilize Web of Science, JSTOR, and Scopus databases to extract and analyze all scientifically recognizable research applied to the Coromandel Peninsula historically and continuing into the present.

b) Recognize the most common areas of study in the region and describe the existing knowledge connected to geodiversity and its elements.

3) The literature review on terminology about geodiversity and scientific knowledge about the Coromandel Peninsula forms the theoretical basis of this thesis. Development of a new geodiversity model for the Coromandel Peninsula is the last aim and comprises the practical aspect of this research. Subsequent results are applied in fulfillment of the main goal. For development of the methodology, the qualitative-quantitative method has been utilized with a newly developed evaluation system; based on the standard geological map; DEM; and GIS software to emphasize its global utility and accessibility for other researchers.

Main objectives:

a) Develop a qualitative-quantitative assessment of geodiversity (QQG) based on the main geodiversity elements recognized from literature reviews.

b) Create a globally applicable evaluation system, based on objectively measured parameters common throughout the Earth and applied to general elements of geodiversity.

c) Utilize the basic qualitative-quantitative assessment on the northern part of the Coromandel Peninsula for initial testing of the methodology.

d) Test the QQG methodology on other territories presenting different challenges, to highlight potential shortcomings, and define directions for further research and application to further refine and improve the results.

e) Compare and contrast different geomorphological models within the QQG assessment to recognize the most useful.

f) Apply QQG assessment to the whole territory of the Coromandel Peninsula to create a complete and holistic geodiversity model.

Additional objectives:

g) Create a model with detailed description of geosites in the north part of the Coromandel Peninsula for touristic and educational use. Utilize acquired knowledge about the Coromandel Peninsula for affirming the results of the QQG assessment.

h) Include the hydrological element into an amended evaluation system as part of the overall QQG assessment.

i) Compare the QQG model of the Coromandel Peninsula with a QQG model of the Carpathian Mountains due to the similarities in geological history of the regions.

j) Compare the QQG methodology with a strictly quantitative methodology of geodiversity assessment to recognize their differences and drawbacks.

1.4 Thesis structure

This thesis is structured as Chapters 2-7, which are based on original papers that have been peer-reviewed and published over the time undertaken to complete this PhD. Each chapter is represented by paper(s) based on research into geodiversity and development of a qualitative-quantitative assessment of geodiversity to meet the objectives and aims of this thesis.

The theoretical foundation of this work is presented in Chapter 2 and Chapter 3, as general literature reviews on philosophical concepts of geodiversity and description of scientific knowledge about the Coromandel Peninsula.

- Chapter 2 presents a study examining terminology of geodiversity, exploration of its elements, and reviewing the work of other researchers on this concept (Zakharovskyi et al., 2022). This research has become the basis for the conceptual foundation of geodiversity, recognizing it as a complex and multilayered view of the landscape represented by geological and geomorphological components as the core surface parameters, while all other elements relate to type of changes applied to the main elements, and the rate at which they occur.

- Chapter 3 describes the body of scientific knowledge of the Coromandel Peninsula, which can be used to support and refine the geodiversity assessment. The Coromandel Peninsula is well recognized as a bioconservation region with an aim of protection of significant flora and fauna, and related biodiversity. However, it also has a well-documented historical silver and gold mining industry, which has played an important role in the past. A systematic literature review on the Coromandel Peninsula was undertaken based on Scopus, Web of Science, and JSTOR databases (Zakharovskyi and Németh, 2021c).

The practical aspect of our research is presented in Chapters 4-6, demonstrating the development and testing of our qualitative-quantitative assessment of geodiversity, to fulfil the objectives of the third aim of this research. Chapter 7 includes the discussion and conclusion sections.

- Chapter 4 describes development of the core aspects of our qualitative-quantitative methodology for geodiversity assessment. This utilized the standard geological map of the region; and low resolution, 30 m per pixel, SRTM in comparison with 8-m DEM. This shaped the methodology utilizing a 5-point evaluation system based on the definition of geodiversity in this thesis. QGIS software has been utilized for the assessment, thereby laying the foundation of our qualitative-quantitative assessment of geodiversity (Zakharovskyi and Németh, 2021b).

- Chapter 5 presents a refined methodology, developed by testing with different evaluation systems and adding additional elements. This was applied to the western islands of Samoa. The model was adapted to recognize the volcanic composition of the islands and included values for volcanic geoheritage specifically tailored for this region (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022b). This model of volcanic geoheritage was then applied to Mayor Island, North Island of New Zealand (Zakharovskyi et al., 2023). Then, we comparatively analysed six different models of geomorphological elements for qualitative-quantitative assessment of geodiversity for the Coromandel Peninsula. Additionally, an 8-points evaluation system for the main elements of geodiversity is introduced (Zakharovskyi and Németh, 2022a). Results from this evaluation are the basis for a geodiversity model for the Coromandel Peninsula. In addition, the transformability of the methodology for the Manawatu Basin hydrological element on the river system is tested. Subsequently a hydrological element is introduced into the assessment based on the Strahler Order (Zakharovskyi and Nemeth, 2023).

- Chapter 6 demonstrates utilization of our methodology for recognition of geosites in the northern part of the Coromandel Peninsula, based on the results of previous research (Chapter 5). The result of our assessment demonstrates that this methodology is a useful approach for geosite recognition, thereby minimizing the area required for direct observation. However, to acquire a full model of the Coromandel Peninsula with all potential geosites, requires further research, survey, and assessment.

- Chapter 7 includes discussion and conclusions of the thesis, demonstrating the knowledge acquired through the process of PhD research. It discusses the issues with terminology of geodiversity and its elements; development and application of qualitative-quantitative assessment of geodiversity; results of our assessment of geodiversity of the Coromandel Peninsula; unfulfilled objectives; and possibility for further development of the model. Finally, conclusions with respect to the aims of the thesis are presented with future recommendations.

1.5 Scope of the study and Model limitations

The qualitative-quantitative geodiversity (QQG) model contains limitations which need to be acknowledged. The first issue is the evaluation system which is the one of the main contributing attributes of this type of assessment. One of the benefits of the evaluation system is to avoid the reliance on a high amount of data and expert knowledge. The QQG should be based on a low amount of robust data, but the reliance on qualitative data and ranking of data can make the model subjective effectively producing different results with the same data. This could then lead to the inability of the model to demonstrate accurate geodiversity due to lack of details or included elements. Therefore, the model has potential “for the recognition of potential geosites”, as the model highlights areas of the potential interest (at a coarse resolution) reflected in the evaluation system. However, with inclusion of more additional elements and refinement in the processing, the model will become a method to define geodiversity. In this research, the scope was focused on geological and geomorphological elements of geodiversity. These two elements have been used as the main core parameters, which can be found ubiquitously across the Earth creating a core focus for geodiversity.

The second limitation of the model is the lack of inclusion of additional elements such as hydrology, climate, biological and human footprint. Concentration on geological and geomorphological elements has been chosen to build the core of a geodiversity model which again makes any model produced more applicable for implementation and comparison of the regions across the globe. For now, additional elements have been excluded from assessment due to their datasets having limited coherence across the globe or lack of global coverage e.g. only local or regional models created in isolation. Another important aspect that is difficult to address are archaeological and anthropological sites located in the area of study. Effectively and ethically including anthropomorphic factors can take vast amount of time and is beyond this current stage of methodology development.

The main elements of geology and geomorphology at times can lack local detail but is underpin by globally unifying parameters. The parameters are usable for comparison of geological and geomorphological values across the Globe demonstrating the core of geodiversity value. Currently, geological elements are represented through such parameters as rock rareness calculated from areas. This also creates two main issues with the use of geological elements: bedrock and local uniqueness. Bedrock refers to rock formations hidden under the surface which are not included into the model as they are not easily studied and verifiable. Then, the local uniqueness connected to the vast number of details and information inscribed in the rock formation, which reflects geoheritage aspect of the region can be hard to determine. This issue can be solved with a qualitative methodology, where experts will collect information from the field and literature reviews and attribute some additional values, which will be difficult to compare at a global scale. The clearest example of local limitations are sedimentary rocks, which is the most common type of rock found on the Earth’s surface, but local these rocks can contain a lot of information, which can describe the geological and climate history of the chosen region. However, this kind of information on a global scale requires each parameter of sedimentary rock to be studied and evaluated separately. This can be done in future research and for all types of rocks, but it requires considerable time and resources.

Geomorphological elements presented as a core parameter of geodiversity also have issues connected to global generalization of the QQG model. In the model geomorphological elements presented with slope angle show a higher value for higher angles. The first drawback is a limited description of the surface not truly representing the geomorphological uniqueness of the region. Geomorphological descriptions require a recognition of different features referring to the form of relief, which are plains, hills, mountains, valleys, ranges and others. However, the main problem with the recognition of these features are differences in school of thoughts from around the globe that are based on their own unique representations of these features, which leads to difficulties with the creation of a single valid evaluation system. Slope angle is the only globally applicable parameter which can be calculated from and Digital Elevation

Models utilizing GIS software making it efficient for assessment. Geomorphological elements can be emphasized with a greater number of parameters, but slope angle is more globally applicable and accessible.

From the start of the research, the QQG model contained all predisposition to evolve into two different directions for geodiversity descriptions: natural and anthropogenic. The natural aspect was chosen for prioritization in this study because of the concept to establish an assessment model for the core values of geodiversity. Even though, geodiversity is described of abiotic in nature it also contains human perceptions projected on the environment. Additional values can be included at a later date to represent anthropogenic elements and aimed toward some other values except scientific. Hence, the aim towards the establishment of core parameters focused this research into a scientific lens to a new global model that to demonstrate for other researchers to test and provide relevant feedback, and suggestions for its improvement. This leads on to confuse models with conservation and tourism values and aspects of geodiversity. The development of QQG assessment is focused on natural scientific principles for its demonstration and testing, while geographical aspects will be included through the inclusion of anthropogenic values into the assessment. Touristic and conservation can be added and be focused on after recognition of sites with unique fundamental geodiversity.

1.6 Additional methodologies

The literature review is the first step for any research, which here has been focused on specifically understanding of the main terminologies surrounding the topics of geodiversity with a focus on the recognition of the mainstream terminology and philosophical views of geodiversity within published literature. The literature search was aiming to objectively collect different viewpoints on the terms of geodiversity to identify its foundational elements. Then, the research scope moved toward identifying different methodologies of geodiversity assessments and a deeper understanding of the elements of those assessments. With respect to the study of the Coromandel Peninsula a systematic literature review was applied focusing on only known online databases accessing only published information. The aim of this review was to demonstrate the volume of published knowledge about the Coromandel Peninsula presented in scientifically recognizable databases. However, for field investigations and geodiversity assessments, New Zealand scientific literature has been utilized, which contains significant unpublished research resources, which are not recognized in online data sources. Hence, the literature review of the thesis can be divided on two parts. The first part is aimed toward exploration of philosophy and terminology about geodiversity. The second part is focused on the Coromandel Peninsula where information required for field investigations and geodiversity analysis was sourced from wider scientific databases.

The qualitative-quantitative method of assessment has been chosen for analysis and application. The methodology utilizes a range of elements arranged within evaluation system. Elements, required for the calculation of geodiversity are presented with geological and geomorphological models determined through GIS analyses such as cutting, reclassification (according to evaluation system), raster calculations (slope angle, assessment itself) and vector-raster transformations. All GIS analyses and their outputs have been undertaken within the

QGIS software, because of its user-friendly interface and free access. Therefore, qualitative-quantitative methodology and QGIS software have been utilized for the main geodiversity assessment.

With respect to field investigations of the Coromandel Peninsula in the first and second year of the research there were two main aims: to become familiar with the region and collect images of the region and then collect samples and basic descriptions of geological and geomorphological features. To recognize the places for visiting a sketch of the Coromandel Peninsula was compiled (Appendix A), which is based on topographical and geological maps of this area. Additionally, on the sketch I added 26 locations mentioned by Lloyd H. and Phil M. (1992) described in their book "Vanishing Volcanoes A Guide to the Landforms and Rock Formations of the Coromandel Peninsula", then locations of hydrothermal mineral deposits mentioned by Bruce W. Hayward (2017) in "Out of the Ocean, Into the Fire: History in the rocks, fossils and landforms of Auckland, Northland and Coromandel". Some, waterfall locations have been extracted from "The Coromandel" web page (HAURAKI n.d.), and finally location of the gemstones have been extracted from the map of Rei Hamon (1968) "Gem locations on the Coromandel Peninsula". The sketch was the result of preparation for field trips to the Coromandel Peninsula. Each site has been recorded with the coordinates, name, rock type, description of some specific process if presented (Appendix A). Then, at least one picture has been made for each location. However, during this research only pictures and coordinates of locations themselves have been utilized, while description and samples have been left for future research.

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Chapter 2 – Philosophical views on concept of geodiversity

Description: Our first step in studying the geodiversity of the Coromandel Peninsula is defining terminology. Hence, in this chapter I describe a literature review on the topic of geodiversity, where I concentrate on exploring previous studies with respect to philosophical views and understanding of the common terms used. Common elements used like geology, hydrology, and geomorphology are mostly presented in similar ways by all researchers, other elements used in very different ways as some researchers add cosmic influences (solar and space radiation), climate and/or anthropological applications. Meanwhile, the element of soil becomes a point of discussion as the element can belong to mineral and biological foci. In this study elements have been divided on two categories: main and additional. This deviation was based on the representation of geological and geomorphological parts of the abiotic nature as parameters, which describe the core of geodiversity showing its qualitative composition (geological value) and form (geomorphological value). Meanwhile, the rest of elements of geodiversity have been arranged as additional values of geodiversity. In this research we present a possible evaluation system for each element of geodiversity. This research then becomes a first step for a more ubiquitous view of geodiversity and its assessment possibilities.

The published article can be accessed: https://gcr.isfahan.iau.ir/article_688931.html accessed 5th of May 2023

Reference: Zakharovskyi, V., Nemeth, K., Gravis, I. and Twemlow, C., 2022. Geoheritage and geodiversity assessment framework for practical application to geoconservation of the Coromandel Peninsula, New Zealand. Geoconservation Research, 5(1), pp.59-88.

In this research: the article has been slightly changed to meet the style of the thesis from editing perspective.

2.1 Title: Geoheritage and Geodiversity Assessment Framework for Practical Application to Geoconservation of the Coromandel Peninsula, New Zealand

Abstract: We provide a globally applicable method, using the Coromandel Peninsula as a case study. The Coromandel Peninsula is in the north part of the North Island of New Zealand. This environmentally diverse and ecologically rich region is shaped by interactions between volcanic activities and terrestrial/shallow marine sedimentation, potentially providing a rich geodiversity. A systematic table defining the elements of geodiversity is the main product of our research, and we demonstrate how these elements can be assessed in a simple way to define values of facets of abiotic nature, ultimately resulting in a holistic, integrated, and complete view of our unliving environment. This study is an initial step in building a common system for assessment of geodiversity of any part of our world using the most available data and records as a foundational database.

Keywords: Geodiversity, Mapping assessment, Abiotic nature, Geology, Geomorphology, Coromandel Peninsula.

2.1.1 Introduction

Here we present a qualitive-quantitative conceptual framework for assessment of geodiversity and apply it to a geoconservation and geotourism “hot spot” of New Zealand’s the Coromandel Peninsula (Figure 2.1.(1)). The method is specifically tailored to estimate geodiversity values within the geological context of an eroded Miocene to Pliocene bimodal volcanic arc formed on a Mesozoic greywacke basement and evolved within a typical siliciclastic shallow marine sedimentary basin. In addition, the complicated volcanic geoforms in combination with their non-uniform erosion provide a perfect geoenvironment where the terrestrial and marine geological settings interface, creating complex coastal areas and near sea level – in many aspects Alpine style – geomorphology. We demonstrate our proposed method is easy to apply to anywhere on Earth and ready to be adapted to local geological and geomorphological assets.

The method is based on an arithmetic average value of key geodiversity elements of the studied area, where the range of the units is based on 5-point system. The identified geodiversity elements represent geological and geomorphological aspects of settings, and we demonstrate how our method can be applied to other geoenvironments. The system utilizes the scientific knowledge relating to the subject and includes aspects of geodiversity: geology, geomorphology, soil science, hydrology, and others. In terms of conceptualization, we explore the terms of geodiversity and established methods for assessment to gain a deeper understanding of the current scientific view.

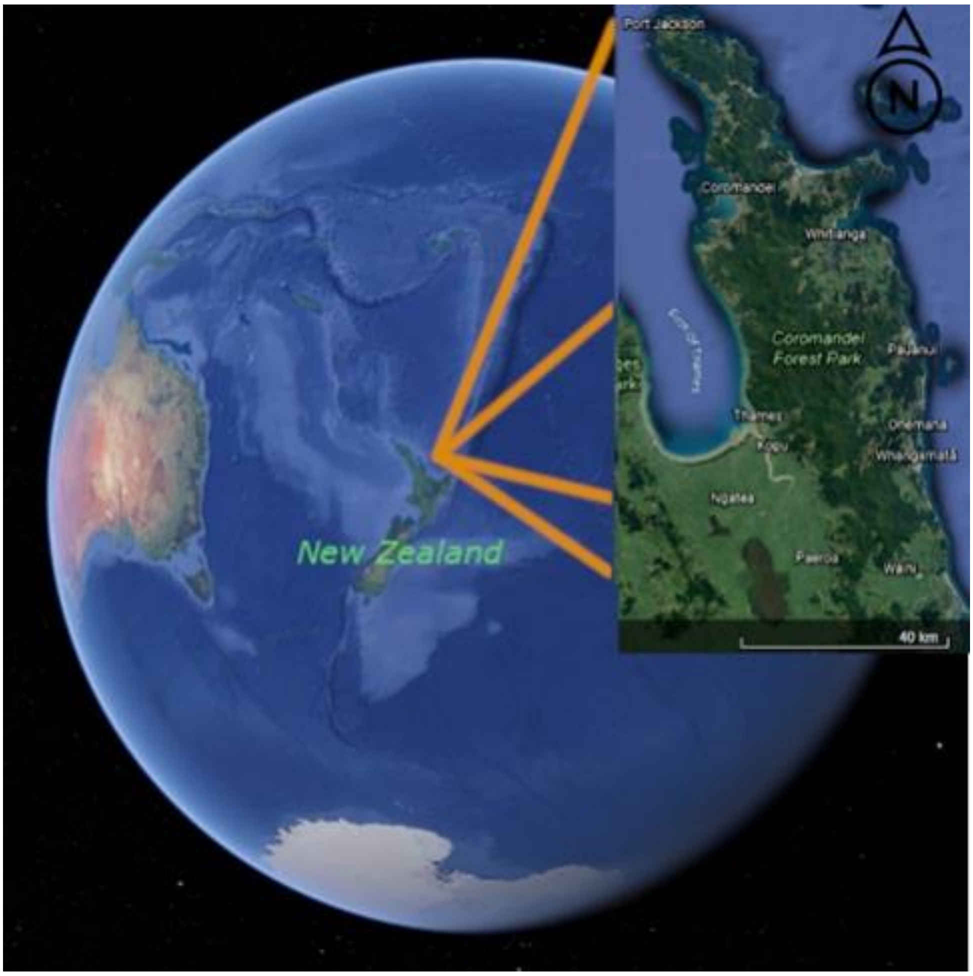

Figure 2.1.(1): The location of Coromandel Peninsula in the North Island of New Zealand (image is from Google Earth). It is a narrow (~40-km) NW-SE-trending, about 100km-long peninsula separating the Bay of Plenty from the Hauraki Gulf.

The Coromandel Peninsula was selected as a focus for our research due to its iconic position in conservation initiatives and tourism (mostly eco and niche tourism) ventures in New Zealand with strong international recognition (Matthews et al., 2018). While the region is recognized for significant conservation developments both in a New Zealand and global context, to date conservation initiatives have been heavily biased towards flora, fauna, and ecology, the biotic environment (Gardner-Gee and Beggs, 2010, Gesing, 2019, Hare and Cree, 2005, Hitchmough et al., 2020, Stevens et al., 2007, Bell, 1994, Bell et al., 2004). Systematic assessment of its geological heritage associated with establishment of a basic inventory has just started recently in New Zealand (Hayward, 2017). Conservation research and initiatives based on coastal regions of the Coromandel Peninsula provide useful case studies for assessing global and planetary changes (Schneider et al., 2017).

The Coromandel Peninsula is a narrow (~40-km) NW-SE-trending peninsula, about 100 km long, separating the Bay of Plenty from the Hauraki Gulf in the North Island of New Zealand (Figure 2.1.(1)). Its Mesozoic greywacke-dominated basement (Mortimer et al., 2017, Mortimer et al., 2014) hosts Miocene-to-Pliocene andesitic-to-dacitic stratovolcanoes in the western and central parts and Pliocene silicic calderas in its eastern locations (Hayward, 2017, Briggs and Fulton, 1990, Adams et al., 1994, Malengreau et al., 2000, Nicholson et al., 2004, Smith et al., 2006, Booden et al., 2012). Pliocene basaltic volcanoes are significant geo-cultural sites in the NW of the peninsula and the Mercury Islands group, forming dense coastal settlement sites used by pre-European indigenous inhabitants. The region has a rich Māori cultural heritage (Moore, 2013, Maxwell et al., 2018, McIvor and Ladefoged, 2016, Lyver et al., 2008, Wellman, 1962, Davidson, 2018) as well as mining heritage from the early European settlement time, with mining for epithermal mineral deposits still active (Legget, 2012, Barker et al., 2006, Spörli and Cargill, 2011). The region's geology is strongly influenced by the effect of immediate and prolonged post-volcanic activity, creating a great variety of rock alteration features, mineralization, and landforms (Malengreau et al., 2000, Mauk et al., 2011, Sheppard et al., 2009, Simpson et al., 2019). The Coromandel Peninsula is one of New Zealand's iconic tourism destinations, especially Cathedral Cove, Hot Water Beach and nearby areas (PNZ, n.d.). Meanwhile, research in this region is concentrated on biosphere and cultural studies (Betty et al., 2020).

The peninsula also consists of extensive rural areas and is strongly impacted by local and regional tourism developments The region has been the subject of some advanced research on tourism perceptions, useful for an expanded understanding of the geoheritage framework of the region (Fairweather and Swaffield, 1999, Holzapfel, 2003). The post-pandemic economic downfall has impacted the region heavily, but it still stands as a top New Zealand tourism destination (Rowland, 2020, Thames-Coromandel District Council, 2021, Tantau, 2020). Meanwhile, tourism research, biotic nature research, and a few core geological researches have been undertaken relating to the region, there has been no geoheritage or geodiversity research conducted yet in the area. However, the Coromandel Peninsula is a prime location to explore and develop geodiversity studies from multiple directions. Here we present a preliminary conceptual framework to highlight the geodiversity of the region. Geodiversity is a complex definition with several meanings (Brilha et al., 2018). In the next sections we explore the current state of our understanding of geodiversity and provide a locally suitable conceptual framework to apply to the Coromandel Peninsula.

2.1.2 The Definition of Geodiversity

Geodiversity as a scientific discipline is relatively young, with consensus of a complete meaning still to be reached. Its definition often depends on the type of research and environment of the region. Some researchers define geodiversity as a value based on the number of geological features (Gray, 2008a), while others claim that processes and climate must be included in this paradigm, as well as evidence of human and biological activities (Kozłowski, 2004). This demonstrates contemporaneous development of the term that could include geological sites, abiotic processes, geomorphic processes, and cultural connections and influences. Therefore, clarification of the definition will assist us in creating a simple method to calculate the rate of geodiversity throughout the world, with an embedded ability to compare the results and establish regionally appropriate systems for geoconservation and geotourism.

According to Serrano & Ruiz-Flaño (2007), the first recorded use of the term geodiversity was by Federico Alberto Daus, an Argentinian geographer, in the 1940s, but it was used to describe the landscape of human habitation and cultural diversity on geographical territory (geographical diversity), with only a light connection to geological values. In contrast, Gray (2008a) described geodiversity as the sum of the Earth's history, tectonics, minerals, rocks, sediments, fossils, landforms, geomorphological processes, and soils. In other words, it is an aggregation of all geo-objects and processes that have an influence on geodiversity of the Earth. Kozłowski (2004) collated definitions of geodiversity as used by other researchers and concluded that geodiversity is information about the Earth's surface objects such as: geological aspects, geomorphological aspects, soils, and water resources. Systems, as the result of natural processes and human activity, were also added to his paradigm.

Polish scientists are working on the Geodiversity Atlas of Poland (Kozłowski, 2001) which defines categories of geodiversity such as geological structures, the Earth's surface relief, soils, surface water, groundwater, mineral and therapeutic waters, thermal waters, and landscape structures. However, only a few Polish maps of geodiversity are currently available for specific territories such as the Polish Carpathian Mountains (Zwoliński, 2009; Zwoliński 2008), Tatra National Park (Zwoliński and Stachowiak, 2012) in the south of Poland and Karkanowski Park Narodowe (Knapik et al., 2013) in the south-west part of Poland on the border with the Czech Republic. Kozlowski also referred to Postgate (1994), who claimed that "Geodiversity should be dealt with as a determinant of life which can evolve on planets with an appropriate humidity and temperature, and when metastability is present". This quotation shows that climate has a high influence on the composition of geodiversity through the changes in weather condition which can be easily seen in the tropical areas of Africa and Australia (Milnes et al., 1987), where the high temperature and wet climate forming laterite which is considering as a rock and soil type (Tardy, 1997). González Trueba (2007) considers seas and oceans and the physical elements and processes within them as an important part of geodiversity, which led to an expansion of this definition from the lithosphere to hydrosphere and atmosphere of the planet. Then, Gray (2018) claimed that geodiversity is the natural range (diversity) of geological (rock, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. Additionally, it includes their assemblages, structures, systems, and contributions to landscapes (Gray, 2013). Brilha et al. (2018), demonstrated the importance of nature diversity, as biotic and abiotic nature are the main elements for sustainability of human society. He showed how to identify geodiversity based on quantitative and qualitative approaches, scale, and potential use, while the main issue is to highlight the connection of geodiversity with ecosystem services such as: water, minerals, fuel, number of services from supporting and regulation to cultural.

Our method is one step towards placing geodiversity within a framework of sustainability against the backdrop of current environmental issues faced by humanity, much as biodiversity has become a marker for our continued impact on the Earth and its biotic systems. Brox & Semeniuk (2019) identified the "8G's" for protection, management, and education in the field of geology: geology (1), geoheritage (2), geoconservation (3), geosites/geoparks (4), geomanagement (5), geo-education (6), geotourism (7), and geodiversity (8). They concentrated on the questions of geoheritage, geoconservation, geosites/geoparks, geomanagement and, only lightly touched on geoeducation aspects. However, the 8G's are a complex paradigm in understanding management of geological data and can in fact complicate the application of geological knowledge for geoconservation, geoeducation, and geotourism. However, Gray & Gordon (2020) criticized Brox and Semeniuk's work on the 8G's, especially on the aspect of geodiversity. They questioned the separation of geodiversity from the other 7 G's and presented it as one stand-alone geological aspect, which is contrary to Gray's (2018) previous work, where geodiversity is the backbone of geoconservation and geoheritage. This demonstrates that defining aspects of geodiversity, geoheritage and all other subjects related to them are still subject to debate. This can be justified by the complexity represented by the term geodiversity where abiotic nature is not only landforms and geology shaping our environment, but also the many other aspects, which interact with them.

2.1.3 Geodiversity as a Concept in Mainstream

2.1.3.1 Global Scientific Outlets

Our main aim is to assess the current global understanding of geodiversity and define the most measured and utilized aspects in any geoheritage valorisation work. We aim to create a method for the geodiversity assessment of the Coromandel Peninsula using research outputs based on numerous globally recognized databases such as Thomson Reuters and Web of Science (WOS. n.d.). We followed this logical path to ensure the global relevance and acceptance of our results, so they can be compared immediately to other locations. The most significant concept this study addresses is geodiversity, and we have used the Web of Science (WoS database) to identify internationally significant and peer-reviewed research outputs from 1900 to 2021. The results of our search demonstrate the influences of various researchers on the field of geodiversity and define the number of studies accessible to scientists throughout the world. A further issue is that a significant proportion of the knowledge base (articles, reports, and research) may only be accessible for local use. The search word "Geodiversity" was chosen as a topic through all databases (WOS, BIOABS, CABI, CCC, FSTA, KJD, MEDLINE, RSCI, SCIELO). Our search identified 813 articles from 1995 (Sharples, 1995), which we consider a very good number for such a young science topic. The highest number of papers have been published in the last five years (390 results) 2017 – 84 articles, 2018 – 98 articles, 2019 – 120 articles, 2020 – 119 articles and 2021 – 26 articles (Figure 2.1.(2)). Hence, search through the WoS shows that geodiversity is a developing term. Moreover, these actions encourage others to further refine the definition of geodiversity and extend the research framework for abiotic nature.

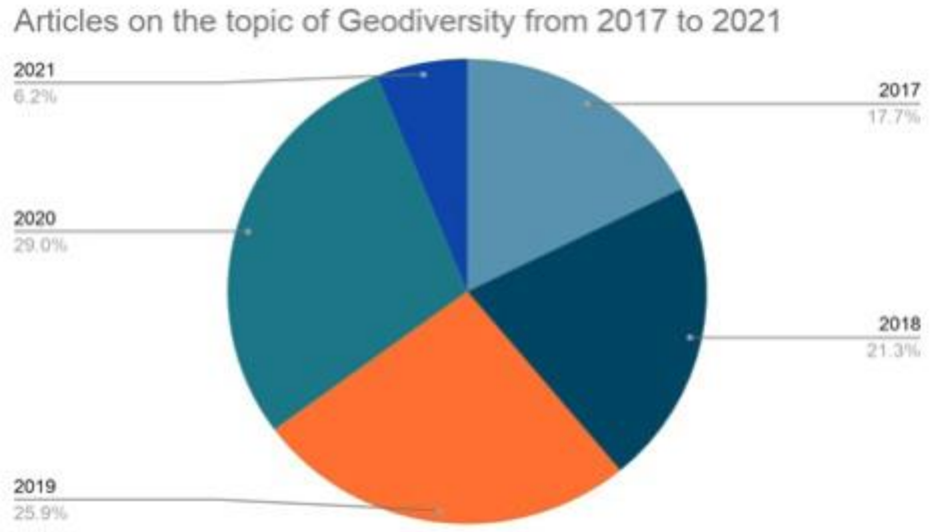

Figure 2.1.(2): The number of articles on the topic of Geodiversity from 2017 to 2021 was based on a search through Web of Science database. Where 2019 and 2020 are the most productive years for geodiversity.

In their publication, Serrano & Ruiz-Flaño (2007) summarized all geodiversity's parameters in one table to display elements of existing definitions (Table 2.1.[1]). However, they claimed that components of geodiversity are not as important as their scale of research. The scale shows the level of organization which scientists should use for assessment, and they created four levels of geodiversity: particles (atoms and molecules, minerals, sediment particles, energy processes), elements (topography, geology, geomorphology, hydrology, and soils), places (geotope and geosystem etc.), and landscape geodiversity (includes biotic and abiotic factors (natural diversity) and human influence). The final scale level is open relationships to geographical diversity through the connection of geology and other scientific fields of study.

Geodiversity values are given to factors of abiotic nature such as lithology, tectonic processes and features, geomorphology, soil, hydrology, topographic elements, and physical processes on the land surface and in the seas and oceans. Further, geodiversity can be seen in all systems generated by natural and human processes, which cover the diversity of particles, elements, and places. A significant study of geodiversity was made by Gray (2008b), where he added to the geological and geomorphological objects also their assemblages, relationships, properties, interpretations, and systems, thereby widening the definition. Earlier, Gray (2005) also presented the table of values for study of geodiversity and geoconservation (Table 2.1.[1]).

Currently, geodiversity research occurs predominantly in Europe, Asia, and America, with a particular geoconservation perspective to protect the heritage of abiotic nature and human culture, as well as providing geotourism and geoeducation in these places. Zwolinski et al. (2018) described a framework for assessment of geodiversity by two methods. First, the direct method is based on field work observation with collecting and measuring elements of the natural environments such as rocks, soils, types of landforms, etc. Analytical methods are then used to establish an accurate view of the geodiversity of the region. However, this method is expensive and time-consuming as well as being limited. In contrast, the indirect method is much cheaper as it is based on calculation of raster and vector data using Geographical

Information System (GIS) software, which though accessible and widely applicable can have low accuracy. Additionally, Zwoliński et al. (2018) distinguish three groups of methods: qualitative, quantitative, and qualitative-quantitative. The qualitative method uses the experience of experts to create a value system for features or sites to be assessed. The quantitative method is the simplest as it applies instrumental measurements, calculations, and analysis of the raw data. Qualitative-quantitative methods is a combination of the previous two, hence it is probably the most advanced and technically one of the best solutions in the assessment of geodiversity.

Table 2.1.[1]: Elements of geodiversity on the Earth (Serrano and Ruiz-Flaño, 2007). This table shows that the basic parts of geodiversity are topography, geomorphology, hydrology, and soils. The right column shows elements, which are subcategories of the basic parts.

<table>
<tr><td rowspan="8">Topography</td><td colspan="2">Energy</td></tr>
<tr><td colspan="2">Roughness</td></tr>
<tr><td rowspan="4">Earth materials</td><td>Minerals</td></tr>
<tr><td>Lithology (Rocks)</td></tr>
<tr><td>Superficial deposits</td></tr>
<tr><td>Fossils</td></tr>
<tr><td colspan="2">Tectonic</td></tr>
<tr><td colspan="2">Structures</td></tr>
<tr><td rowspan="5">Geomorphology</td><td colspan="2">Morpho-structures</td></tr>
<tr><td colspan="2">Morphogenetic structures</td></tr>
<tr><td colspan="2">Processes</td></tr>
<tr><td colspan="2">Erosion landforms</td></tr>
<tr><td colspan="2">Accumulation landforms</td></tr>
</table>

	Micro-landforms	
Hydrology	Water states	Water
		Snow
		Ice
		Glaciers
	Hydrologic elements	Oceans
		Seas
		Rivers
		Springs
		Wetlands
		Lakes
Soil	Orders	
	Suborders	

Table 2.1[2]: Summary of geodiversity values (Gray, 2005). Gray presented this table to show how the term geodiversity can relate to different science subjects through values. For example: intrinsic value shows things as they are rather than how they can be used.

Intrinsic value	Intrinsic
Cultural value	Folklore
	Archaeological/historical

	Spiritual
	Sense of place
Aesthetic value	Local landscape
	Geotourism
	Leisure activities
	Remote appreciation
	Voluntary activities
	Artistic inspiration
Economic value	Energy
	Industrial minerals
	Metallic minerals
	Construction minerals
	Gemstones
	Fossils
	Soils
Functional value	Platform
	Storage & Recycling
	Health

	Burial
	Pollution Control
	Water chemistry
	Soil functions
	Geosystem functions
	Ecosystem functions
Scientific value	Geoscience’s research
	History of research
	Environmental monitoring
	Education & training

Today, quantitative assessment of geodiversity is the most popular among researchers. One method (Pellitero et al., 2011, Serrano and Ruiz-Flaño, 2007) uses an equation based on the number of elements in the study area, thus creating an index of geodiversity as well as a roughness index. Da Silva et al. (2019) applied this equation in their assessment of the Seridó Geopark Project, north-east Brazil, using a 2 x 2 km grid to divide the area into 824 polygons, and then calculating a value for each polygon. To obtain a result for geodiversity, they calculated and combined five subindex maps: hydrology, geomorphology, lithology, pedology, and mineral occurrences.

Bétard and Peulvast (2019) used the same method to identify geodiversity hotspots in the Ceará State, in north-eastern Brazil, using the geodiversity and threat indexes to highlight places with high geodiversity and subject to a high threat as the main sites which would most benefit from protection. To create a geodiversity index, they applied a calculation to the geological diversity index, the geomorphodiversity index, the pedodiversity index, and the hydrodiversity index. All these indexes were presented as models created from maps and readily available online resources such as SRTM. Meanwhile, the threat index was calculated using the protection level sub-index, the land degradation sub-index, and the land use sub-index.

Russian researchers used their own variant of this methodology to highlight places with high geodiversity. For example, Loskutova (2020) researched geodiversity of the Kosh-Agachskij district of SE Altai, Russia, aiming to establish geotrails and excursion-education programs that would be easily accessible to tourism operators and planners. She uses earlier definitions of geodiversity, such as Eberhard's (2002) claim that "Geodiversity includes evidence of the Earth's history, previous life, ecosystems, environment, and range of current processes (biological, hydrological and atmosphere), which emerge in rocks, surface relief and soils" and Stanley's (2004) definition that "Geodiversity is the link between people, landscapes, and their culture through the interaction of biodiversity, soils, minerals, rocks, fossils, active processes, and the built environment". Loskutova (2020) concluded that geodiversity is a range (or diversity) of geological formations, surface formations and soil specialties with collaboration of all systems and processes. According to Chernyh (2008), "*Local systems of specially protected natural territories: reality and perspective*" describe geodiversity as abiotic natural objects such as water source ecosystems, natural facies with high radioactivity, caves, and others. He claimed "Often, the specialty of territory is determined through the complex of typical parameters, which together create a unique object. All processes are repeatable, but their complexes are always special". Then Korf (2020) in her PhD dissertation demonstrated a quantitative assessment of geodiversity of the territory of Verhnia Chui in Altai Geopark, Russia. The main goal of this project is to develop a methodology to assess the significance of elements of geodiversity for geotourism in the defined territory. Korf (2020) proposed a table defining types and subtypes of elements of geodiversity (Table 2.1.[3]) incorporating elements of geodiversity such as biogeological, stratigraphic, geomorphological, geoarcheological, geological, water resources, and complexes. These elements were chosen according to sites with a high level of tourism attraction.

2.1.4 Components of Geodiversity in our Evaluation

2.1.4.1 Method

To sum up, geodiversity from a global perspective is a relatively new area in the scientific arena, which has not been completely defined (Nemeth et al., 2021). To date, it has been developing towards a definition mainly based on geological factors shaping the diversity of abiotic nature around us (Serrano and Ruiz-Flaño, 2007, Gray, 2008a). Hence, we have arrived at a picture of geodiversity as a systems-based definition containing information about all abiotic elements and processes, and the subsequent impact on geological objects and landscapes, including human and biological footprints (Kozłowski, 2004). Reflecting on this definition, any data collected from the natural environment can be considered a facet of geodiversity or an influence on geodiversity values. For example, soil evolution demonstrates abiotic processes (weather condition, epithermal activity) working in parallel with biologically driven processes to alter solid rock into soil through chemical, mechanical, and biological weathering resulting in a nutritionally complex soil profile (Van Breemen and Buurman, 2002). This demonstrates that soil should be considered an element of geodiversity, while associated abiotic and biological processes as weathering triggers can be considered side effects rather than main elements. In this case, any point on a landscape surface contains many natural abiotic elements, which may lead scientists to modify the scale of their research to simplify their study.

It is also apparent that there are two pathways towards estimating geoheritage; one that follows a globally calibrated theoretical and practical method, and another that is specifically tailored to the study area following its special geological and geomorphological values. Intuitively, the first approach can be used for comparative studies across a great variety of geological and geomorphological scenarios. However, this may provide low resolution results with limited use for local authorities and organizations in regional assessment and local planning.

Table 2.1.[3]: Table of the proposed conceptual framework of geodiversity of the Coromandel Peninsula. The table contains two main objects: geology and geomorphology, while additional objects are hydrology, climate, human and biological footprint. Every object contains the number of elements which describe it in more details.

Objects	Elements	Subject
Main Values **Geology and Geomorphology**	***Morphology and Valley Network*** General topography of region	Definition of landform categories, valley network and slope angle categories
	Rock and Fossil Types Definition of the rocks, fossils, and their ages	Spatial representation and weight value assignments of specific rock/fossil types
	Volcano types Definition of the volcano types recorded in the field	Application of volcano geology model to calderas, intermediate stratovolcanoes, and small monogenetic volcanoes (assignment of values)
	Caves Identification of caves	Measuring numbers and types of caves as well as their spatial distribution pattern
	Alteration, Weathering and Mineralization Definition of alteration and weathering types	Application of weathering index to surface areas, assignment of number density of altered and weathers surfaces and mineralization types
	Structural elements Definition of faults and folds in the context of the region structural geology	Spatial measurement of the types and abundances of the structural elements
	Soil – Mass movement Identifying type, distribution, and mass movement	Categorization and valorisation of soil types and mass movements with spatial representation

Additional Values **Hydrology - Hydrosphere**	***Drainage network*** Identifying the drainage pattern and types (links to the "Valley network" but measuring the current runoff pattern)	Measuring of drainage pattern, assigning values of water production
	Lakes - Swamps - Marshland Identifying their locations	Spatially assigning values of swamp in respect of their geological entity
	Coastal Hydrosphere Identifying coast types, tidal zones, and shallow marine environment	Defining the values associated with specific coastal environment
	Geothermal and Hot Spring Region Location and definition of their types	Associating values of their significance in geological context
Climate	***Weather Pattern, Wind Pattern Sunny Hours*** Identification of weather pattern, seasonality, and paleoclimate	Categorization of weather patterns in geological context with special reference to orogenic rain fall data, temperature variation and sun exposure data
Biological Footprint	***Modern Biological Impact on Rocks and Soils*** Identifying biological footprint types	Categorization of biological footprint types (marine, domestic/wild animals, and humans)
Human Footprint	***Human Occupation Sites and Archaeology*** Identification of type of archaeological sites, human activities, cultural horizons and geological tool mastering and trading	Categorization of archaeological values and spatial representation of them.
	Mining and Natural Resource Utilization Identification of ore types, distribution, and exploitation through history	Categorization of ore and economic geology sites of the region

To overcome the above-mentioned issue, we provide a geodiversity measuring system specifically tailored to the Coromandel Peninsula in New Zealand (Table 2.1.[4]). While our framework is site-specific, the proposed method is not. Our research methodology can be applied to visible factors (no deeper than mineral level) within landscapes to create an overall inventory of geodiversity values at a practical and useful scale for further research, land management, tourism ventures, and community development.

Our method (Table 2.1.[4]) builds on previous definitions of geodiversity (Serrano and Ruiz-Flaño, 2007, Gray, 2005, Gray, 2008a, Kozłowski, 2004). The Coromandel region has high values for volcanic geology together with coastal processes (Adams et al., 1994, Malengreau et al., 2000), mineralization and alteration genesis (Adams et al., 1994). All these themes have made this area attractive for human settlement and development (Harding and Boothroyd, 2004). Definitions of geodiversity, geology and geomorphology have been considered as core factors, so we weigh these more than other processes and influences, as these relate to the physical body of the Earth. On the other hand, climate, hydrology, human and biological footprints are considered processes that shape geodiversity and trigger changes in the core geology and geomorphology (Fookes et al., 1988). We separated core geodiversity values based on geological and geomorphological processes shaping the region from those we define as additional values. We include streams and rivers in the SW and Central sector which have had a considerable influence on landscape morphology (West et al., 2005), namely geomorphology and valley networks. An additional main value is rock and fossil types, which is strongly connected to the third main value of volcano types. This is reinforced by the geological definition of the wider region as the Coromandel Volcanic Zone, which includes andesite, rhyolite, and basalt rock formations (Booden et al., 2012). Subsequently, we included weathering, mineralization and alteration, even though previously we described them as an additional value. However, here we refer to weathered rock masses as geosites (McPhie, 1993; Hack, 2020). Alteration and mineralization have provided ideal conditions for forming epithermal gold and silver ore deposits, resulting in a significant history of extraction from quartz, and associated social and economic development (Hayward, 2017). Structural elements are significant, as faults and folds provide visual evidence of tectonic movements (Fossen, 2016). Cave formation may also be influenced by geological processes but are ultimately shaped by weathering and erosion (Davies and Morgan, 1986). The last element of geodiversity we consider are soil forming processes and soil types, as rocks become highly altered by biological, chemical, and physical weathering over long periods (Nazarenko et al., 2006).

Table 2.1.[4]: The scale of the main values of geodiversity. 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; weathering showing the rate of rock erosion; structural elements are folds and faults, where their values depend on their complexity.

Main Values of Geodiversity				
Morphology	Geology	Weathering	Structural el.	
Slope degree	Rock type and ages	Rock mass	Folds	Faults

1) 0-7.5	1) Sedimentary-Cenozoic	1) Slightly weathered	1) Symmetric	1) Normal
2) 7.5-22.5	2) Sedimentary-Mesozoic	2) Moderately weathered	2) Asymmetric	2) Reverse
3) 22.5-45	3) Metamorphic-Precambrian	3) Highly weathered	3) Recumbent	3) Strike-slip
4) 45-67.5	4) Sedimentary- Palaeozoic	4) Completely weathered	4) Overthrust	4) Horst
5) 67.5-90	5) Extrusive and Intrusive	5) Residual soil.	5) Nappe	5) Graben

As an additional value, we chose hydrology as rivers, streams, lakes have a considerable influence on rock formation in the south part of the peninsula, while oceanic activities in the north and east strongly shape coastal geomorphology (Hayward, 2017, West et al., 2005). Climate is included as an important factor shaping geodiversity through its influence on weathering and erosion of rock masses (Tukiainen et al., 2017). Biological activity has influences on rock in transforming it into soils, especially through metabolic processes in the micro-biome (Nazarenko et al., 2006). As previously mentioned, human activities have had a significant impact on the Coromandel ecosystem with weathering, mineralization, and alteration processes leading to mining activities in the region (McPhie, 1993, Hack, 2020). Our approach fulfils criteria outlined by other researchers and uses approaches to understand and characterize geodiversity. Geographical Information Systems (GIS) will help scientists make a simple calculation of general geodiversity of the studied territory resulting in a precise plan of geoconservation for protection, or to provide a foundation for the most economical and highly educational tracks for geotourism and geoeducation ventures (Bétard and Peulvast, 2019, Gravis et al., 2020).

2.1.4.2 Assessment Methodology

In this section, we concentrate on the main geodiversity values as previously defined, to create a general systematic framework applied specifically to the Coromandel Peninsula. Assessment of the main values can be achieved relatively simply by selecting mapped locations with the highest concentration of different types of geomorphologic and geological features and marking them for comparison with other points. However, this type of assessment could be improved through accurate assessment of the whole territory. A similar approach has been followed by Betard & Peulvast (2019) in Ceará State (Brazil) by creating a range of maps in ArcGIS to calculate the geodiversity hotspots through the index of geodiversity and index of threats. Their research demonstrates this type of methodology as effective in visualizing geodiversity at a landscape scale, thereby facilitating protection of the most valuable, vulnerable, or high-risk locations. However, their research was driven by a different goal than ours, and they used maps at a relatively low 1:500,000 scale, providing a low-resolution overview of the geodiversity. Our project may be a first step towards establishing a foundational database for higher scale thematic geodiversity maps that could be deployed for local, regional, and national planning and land-use mapping. Higher scale geological maps at 1:100,000 and 1:50,000 scale exist for the Coromandel Peninsula, but some were published in the 1970s and are nearly fifty years old, leading to challenges in creating detailed thematic geodiversity maps without substantial on-ground field-surveys. Therefore, for this project our target is only the region of the Coromandel Peninsula where we can realistically use existing data and create new data to provide a realistic and effective map of geodiversity values.

To create a geodiversity map, we calculate the main elements of abiotic nature of the region (Table 2.1.[4]) as a sum of 7 marks, with 35 the highest achievable. These 7 marks are representative of main values (Table 2.1.[3]), and each is rated from 1 to 5, where 1 is the most common object and 5 is the rarest and the highest mark possible for one element of geodiversity (Table 2.1.[4]). The area of research will be assessed (Dias et al., 2021) according to information from the morphological (elevation and slope), geological, soil and other maps. For the first time, the assessment will be done through GIS software which allows us to divide the whole area into polygons with a specific mark from 1 to 5. Chosen maps are divided into a grid, with each square assigned elements of geodiversity to provide enough information to calculate a mean value for the square for every element of geodiversity. In conclusion, each square has 7 maps with marks that sum up in a single number a representation of the geodiversity value.

2.1.4.3 Observation of Main Values

The main values in the conceptual framework of geodiversity (Table 2.1.[3]) include 7 elements: morphology, rocks, volcanoes, caves, weathering, structural elements, and soils. Morphology is one of the main elements of geodiversity, describing the shape of the landscape, and including all aspects of the rocks and history of a region. We begin assessment with mapped and surveyed landscapes, where basins, plains, hills, cliffs, and mountains can be used as an analogue for the scale from 1 to 5, where plains are the lowest mark of geodiversity and mountains the highest (Figure 2.1.(3)). While this may prove useful, one shortcoming is the difficulty in defining strict boundaries between landscape forms. For example, a plain displaying a slope of 7 degrees could be a stand-alone plain, or a plain transitioning to a region of foothills. Therefore, wider landscape and geological context is important. Hence, we decided to concentrate not on the forms of the relief but on their parameters. Sloping areas can easily be divided into small polygons based on degree of slope, using the program Grass GIS (GRASS, n.d.). This software has a function that can create a slope raster map based on a horizontal vector map. Slope steepness was chosen, as steep slopes are most likely to contain rock outcrops because orogenic activity can create higher elevations. On the other hand, steeper slopes can also result from weathering and erosion, which transfer particles downhill and expose new outcrops where rocks were covered by weathered material. However, even with this concept, we still encounter problems relating to gradation.

Some researchers have explored dividing slopes into categories according to steepness; Zhuchkova & Rakovskaja (2004), created two scales of slopes for steppe and mountain areas (Table 2.1.[5]). The Barcelona Field Studies Centre (BFSC, 2024) proposed their own grade, and unlike the previous one, it can be used to assess any kind of territory. Despite the differences, all have similarities for steep slopes from 45 degrees and higher. Based on their work, we chose these five levels: 1) 0–7.5, 2) 7.5–22.5, 3) 22.5–45, 4) 45–67.5 and 5) 67.5–90 degrees (Table 2.1.[5]).

Table 2.1.[5]: The scale of slopes made by Zhuchkova and Rakovskaja (2004) for two morphological types of territory plains and mountains. The difference in the rate of slope's degrees according to the erosion threat for soils layers.

Plains		Mountains	
Less than 1 degree	Flat	Less than 4 degrees	Flat
1-3 degree	Slight slope	4-10 degree	Gentle slope
3-5 degree	Gentle slope	10-20 degree	Light slope
5-7 degree	Light slope	20-30 degree	Middle slope
7-10 degree	Middle slope	30-45 degree	Steep slope
10-15 degree	High slope	45-60 degree	High-steep slope
15-20 degree	Steep slope	60 and more degree	Cliffs
20-40 degree	High-steep slope		
40 and more degree	Cliffs		

Steeper slopes have more value for geodiversity due to the unrelenting nature of erosional processes, we suggest that all types of landforms evolve in the direction of equalizing towards the sea-level surface according to the geographical cycle (Davis, 1899). We describe this as a form of "geomorphological entropy" and suggest this justifies placing a higher value on cliffs and mountains. Moreover, steep slopes can be seen to form more dramatic landscapes with defined lookout points; specific elevation-dependent ecological sites with their unique communities; diverse stream networks; common landmass movement sites with open cliffs and outcrops; and more intense processes due to climate, weathering, and steepness and elevation. Additionally, we note here that mountains hold significant cultural and aesthetic value for many societies through history (Fearnley and Hersey, 2018, Gossage, 2008), as well as providing an important backdrop to the historical development of geological research and theory (Schaer, 2010). We suggest elevation as a useful factor for assessment as well as correction of the slope mark. However, this is not within the scope of this initial study but should be included in further modifications of the method.

Rocks and geology are considered the next most valuable facet of geodiversity as they are the actual material forming the Earth's crust (Guéguen and Palciauskas, 1994), continuously changing through volcanic, tectonic, and weathering processes. In the Earth's crust, sedimentary rocks are the most common, forming around 66 % of the Earth's surface, while igneous rocks are only 17% (consisting of 8 % extrusive and 9 % intrusive). Metamorphic and Precambrian rocks form 17% of the surface (Blatt and Jones, 1975), with metamorphic evolution only taking place through temperature and pressure driven processes taking place deep below the Earth's surface (Yardley and Warren, 2021). Based on this knowledge, we suggest a higher value for igneous and metamorphic rocks than sedimentary, but age should be included in the assessment framework. (Table 2.1.[6]).

The age of rock is another way to weigh the final mark of geodiversity in the rock type value. Here the oldest rocks are often the lowest, according to Steno's laws of superposition and original horizontality (Kelly and Thomas, 2013) that make them the most unlikely to be exposed at the surface (Blatt and Jones, 1975). While this gives the oldest rock the highest value, we can also use the table of abundance of rock types exposed on Earth's surface according to their geologic ages (Table 2.1.[6]). Therefore, according to our arbitrary values, sedimentary rocks from the Cenozoic have a value of 1; sedimentary rocks from the Mesozoic a value of 2; metamorphic rocks from the Precambrian a value of 3; Paleozoic sedimentary rocks a value of 4; and all extrusive and intrusive rocks of any age a value of 5 (Table 2.1.[4]).

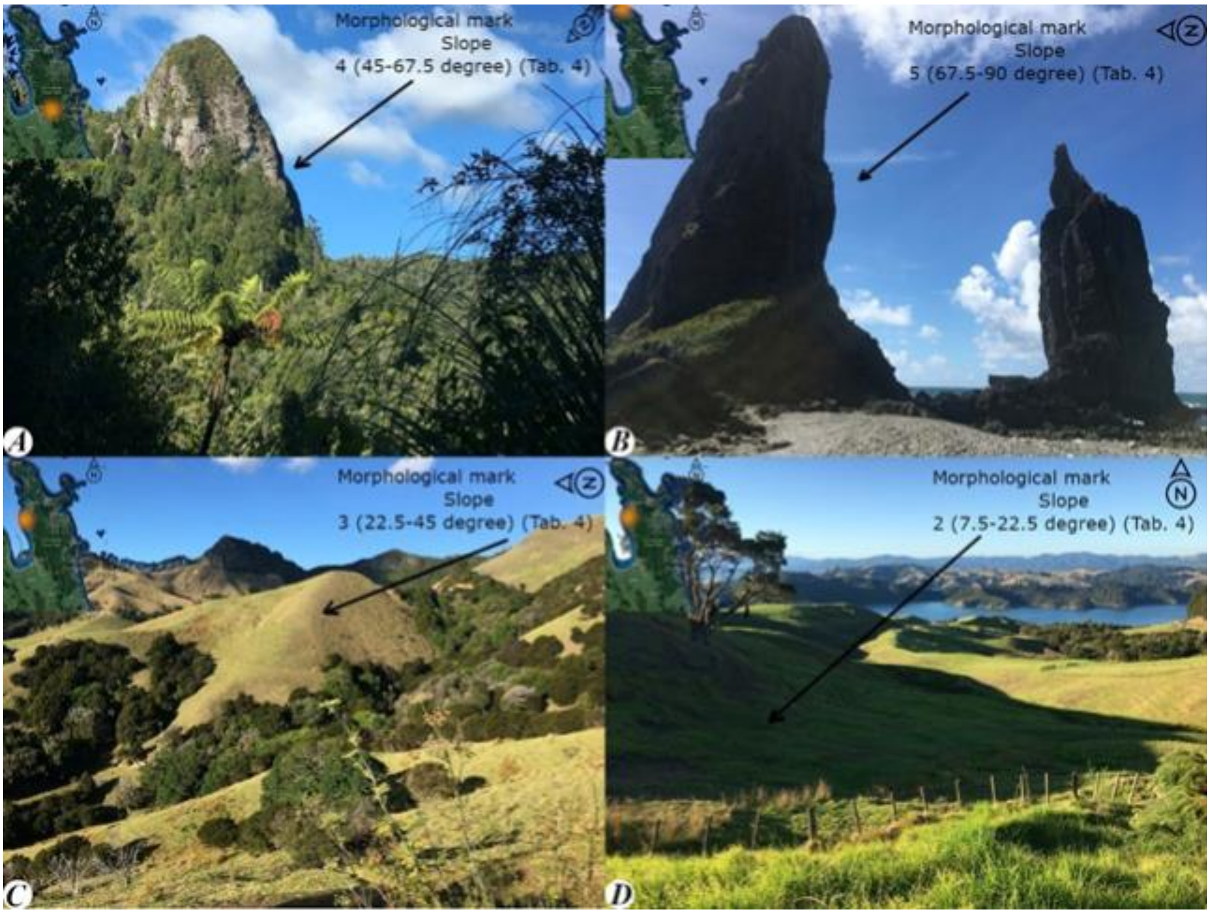

Figure 2.1.(3): The variety of morphology of the Coromandel Peninsula. A – one of Camel's humps is a volcanic conduit of rhyolite is demonstrate the high value of morphology, as a steep weathered cliff (Neavesville (Nevesville), Coromandel Peninsula, New Zealand) (WGS 84: 175.659117; -37.188237), B - Sugar Loaf are two pillars of andesite rock, with nearly 90 degree slope (Fletcher Bay, Coromandel Peninsula, New Zealand) (WGS 84: 175.412924; -36.470640), C - Hilly area formed on the Mesozoic greywacke with different types of nearly 45 degree slopes (Kirita Hill, Coromandel Peninsula, New Zealand) (WGS 84: 175.436965; -36.876089), D – the another part of hills of the same greywacke, where slopes are more gradual (The road from Kereta to Manaia, Coromandel Peninsula, New Zealand) (WGS 84: 175.438123; -36.871195)

Volcanic diversity has a particularly high value for the Coromandel Peninsula, and we suggest it should be calculated separately from rocks and relief as a more precise combination of geological and geomorphological features (Németh and Palmer, 2019, Martí et al., 2018, Casadevall et al., 2019, White and Houghton, 2006, Suthren, 1985, Cas and Wright, 1988). Moreover, volcanic landforms can be studied separately, focusing on type of volcano (Figure 2.1.(4)), rock material, (Figure 2.1.(5)), and/or type of erosion (Figure 2.1.(6)), and their age together with influence of historic and recent tectonic activities. In this way, a volcano can be seen not as an isolated facet in the collective assessment of territory, but the aggregate sum of all objects and evidence of processes. They can be mapped according to their stratigraphic units and facies distribution (Martí et al., 2018, Németh and Palmer, 2019). Here we choose to concentrate on the dominant rock material distributed around the source of eruption, which can additionally be classified as a transporting agent and forming the environment of deposition and composition (Martí et al., 2018). Therefore, the main outcome is to clearly identify the eruptive unit and facies within the ring plain of stratovolcanoes and on outflow ignimbrite sheet for caldera-dominated systems (Martí et al., 2018, Németh and Palmer, 2019).

Table 2.1.[6]: Percentage of rock types exposed on Earth's surface as function of geological age (Blatt and Jones, 1975). According to the table extrusive and intrusive rocks are the rarest, while sedimentary rocks especially Cenozoic are the most common.

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
Paleozoic	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

Figure 2.1.(4): Cliff of the volcanic caldera. Rhyolite eroded mostly by oceanic activities (physical and chemical weathering) (Hahei, Coromandel Peninsula, New Zealand) (WGS 84: 175.81513; -36.84298). The height of the person is 188 cm.

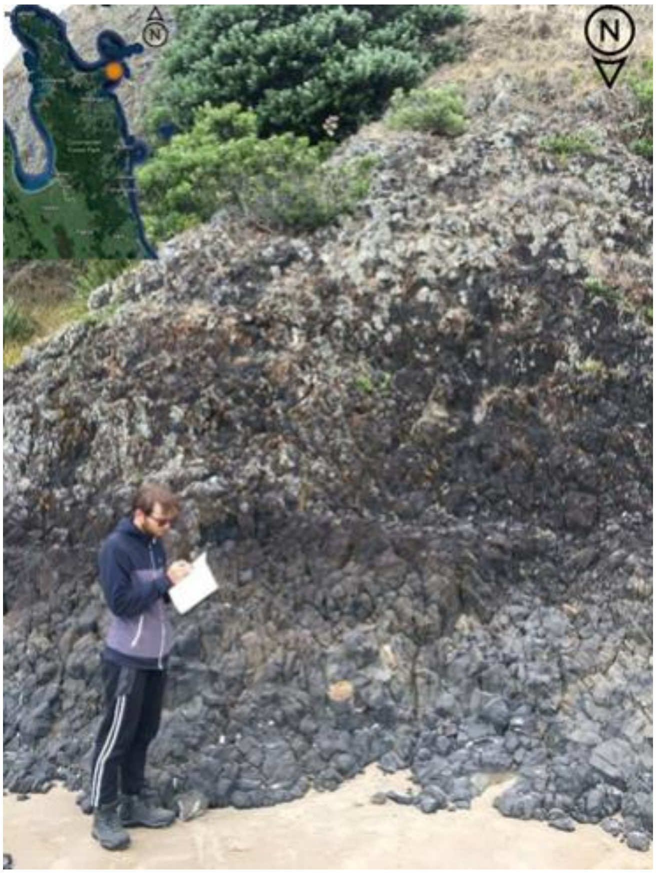

Figure 2.1.(5): Outcrop on the beach. Columnar jointed basalt was influenced by oceanic and biological activities (physical, chemical, and biological weathering) (Opito bay, Coromandel Peninsula, New Zealand) (WGS 84: 175.811136; -36.722004). The height of the person is 168 cm.

For volcanic landforms in the Coromandel region, we use the description of volcano facies types (Wohletz and Heiken, 1992). Remnants of Miocene-to-Pliocene andesitic-to-dacitic stratovolcanoes in the western and central parts are assigned a range of values for facies depending on composition and proximity to eruption centers: the Central Facies (0.5 to 2 km from central vents), which is close to volcano vents, is assigned the highest value of 5, as the source of lava flow and ash ejection and likely to contain nearly all original rock types. The scale is divided into increments of 1.5, with the next assigned value 3.5 for proximal facies (5 to 10 km from central vents); medial facies (10 to 15 km from central vents) a value of 2; and distal facies 0.5 (>10 to 15 km from central vents) (Table 2.1.[7]). Rhyolitic caldera complexes can be used for assessment of the eastern locations of the Coromandel Peninsula with Pliocene silicic calderas featuring dominantly in the landscape (Hayward, 2017, Briggs and Fulton, 1990, Adams et al., 1994, Malengreau et al., 2000, Nicholson et al., 2004, Smith et al., 2006, Booden et al., 2012). Rhyolitic caldera complexes have also been assigned a range of values based on facies: intra-caldera dome facies a value of 5 (with caldera diameter up to 20 km); intra-caldera fill facies a value of 3.5 (with caldera diameter up to 10–20 km); extra-caldera proximal facies a value of 2 (with caldera diameter up to 10–20 km); and extra-caldera distal facies a value of 0.5 (with caldera diameter 10–100 km) (Table 2.1.[8]). Additionally, general information about volcanoes will be calculated through the standard calculation of geological and geomorphological diversity and other main values, with facies recognizable through geological maps and photographs of the surface and supported by field surveys.

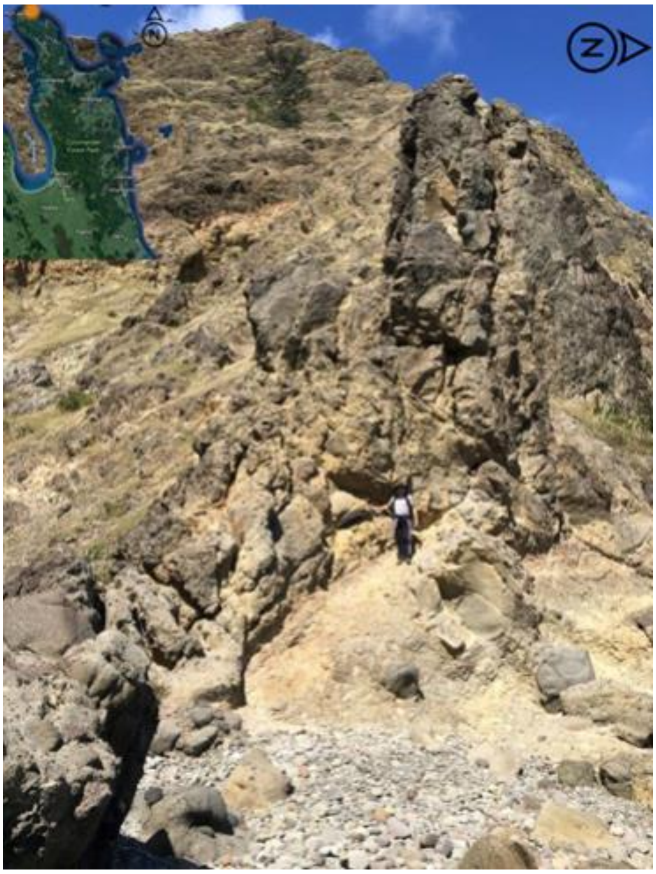

Figure 2.1.(6): Erosional remnants of andesite volcano dome eroded by the power of gravity (an example of physical weathering) (Fletcher Bay, Coromandel Peninsula, New Zealand) (WGS 84: 175.40256; -36.47189). The high of the person is 168 cm.

Caves are included in the main values of geodiversity as they provide access to underground features and processes highlighting continual lithological diversity. Though caves are poorly studied in the Coromandel Peninsula, we can include them in this assessment as they can be located using topographical maps. Ideal information would relate to volume, type, and more detailed descriptions obtained through field surveys. As in previously described frameworks for assessments, we base this on a mix of geological, geomorphological and volcanological descriptions. Assigned values follow the same format as for rocks and slope, with the rarest type assigned the highest value. Types of caves were described by Davies & Morgan (1986) in their report about cave geology, created as an educational resource for earth science students. Provisionally, we assign a simple value system for caves as: lava tubes - 4, wind caves - 3, sea caves - 2 and solution caves - 1. We also note that some caves may hold significant cultural values for the indigenous population, with caves often used as burial sites by Māori (Gravis et al., 2017). Because of their tapu (sacred) nature we acknowledge that there may be undisclosed caves in our study area, and these would not be included in our assessment unless in partnership with local tangata whenua (indigenous people of the land).

Table 2.1.[7]: Scale of volcanic facies of subaerial andesitic stratovolcanoes. This is a useable scale for the assessment of young (active) volcanos.

Value	Subaerial Andesitic Stratovolcanoes	
5	Central Facies	• consanguineous dykes, especially those that are radial or randomly oriented. • consanguineous sills that are concordant with moderate to steep initial dips. • breccia pipes and stocks • hydrothermal alteration with steep lateral gradients. • coarse agglomerates. • thick, steeply banded siliceous lavas. • coarsely stratified but poorly sorted tephra. • steep initial dips. • thin lava flows that are volumetrically subordinate to fragmental ejecta. • ponded crater - and vent-fillings with sharply divergent cooling joints.
3.5	Proximal Facies	• dominated by broad, thick lavas. • intercalated coarse grained pyroclastic, poorly sorted pyroclastic breccias may be cut by consanguineous dykes • moderate to step initial dip
2	Medial Facies	• pyroclastic dominate over lavas. • lahars with angular or subangular blocks up to 10 m or so in diameter. • tephra layers with good sorting and grain sizes mainly in the lapilli to coarse ash range. • zones of weathering and soil development (paleosols) between lava flows. • clastic debris reworked by water. • moderate to shallow dips.
0.5	Distal Facies	• fine layered tephra with grain sizes in the range of coarse-to-fine ash, and with an outward increasing ratio of glass to crystals • lahars with blocks that rarely exceed a meter in diameter and have rounded or subrounded particles in their matrix. • Interlayered shallow-water sediments, soils, and organic debris. • lava flows restricted mainly to isolated vents, basaltic sheets, and intra-canyon flows.

Table 2.1.[8]: Scale of volcanic facies of rhyolitic caldera complexes. This type of graduation is especially important for the Coromandel Peninsula as it has 5 calderas in the central-east part of peninsula.

Value	Rhyolitic Caldera Complexes	
5	Intracaldera Dome Facies	• rhyolitic lava domes and short flows • autobreccia carapaces and aprons • near-vent pyroclastic falls • minor basalt scoria cones may be present
3.5	Intracaldera Fill Facies	• collapse breccias interbedded with ignimbrite • very thick crystal rich ignimbrites • co-ignimbrite lag fall breccias and interbedded epiclastics • lacustrine deposits
2	Extracaldera Proximal Facies	• interbedded, mainly thick, ignimbrite and airfall rhyolitic tuffs • minor rhyolitic domes • basalt scoria cones • welded centers • coarse lithic clasts
0.5	Extracaldera Distal Facies	• mainly un-welded ignimbrites with fine clasts • volcanogenic epiclastics

In our study area, we can calculate the arithmetic average of the sum of marks of all caves. To meet the criteria of 5 as the highest mark, we include a coefficient of 1.25 in cases where the area being assessed has three or more caves. In addition, caves may have internal features such as stalactites, stalagmites, columns, drapery, cave pearls, and others that can only be assessed by a ground survey, with this being the case for volume as well. Presently we include them in the assessment of geodiversity according to their types, with future research proposed for a higher resolution assessment of caves and their contribution to geodiversity of the area.

Weathering, alteration, and mineralization of rock formations are assessed collectively as they all reflect different facets of erosional processes (McPhie, 1993; Hack, 2020). The three main types of weathering are biological, chemical (disintegration), and physical (decomposition). All these processes may act independently of each other, or in a complementary manner (Arıkan et al., 2007, Ng et al., 2001, Cabria, 2015). In the Coromandel Peninsula, most volcanic landforms have been subject to intensive weathering from proximity to the seashore, where biological, atmospheric, and hydrological weathering are more intensive compared to continental areas. Additionally, underground hot springs influence overlying rock formations, which can lead to irreversible damage to their textural connection, making them unstable and fragile (McPhie, 1993, Gifkins et al., 2005). Therefore, we consider this assessment valuable for our study area because of the large number of hydrothermally alteration processes (Hayward, 2017). In our study we concentrate on two types of assessments of weathering as described by Cabria (2015) and Hack (2020), one of which is simple according to ISO 14689-1:2017 and the other more complex (Table 2.1.[9]). We applied the simplest method as we consider it adequate for our initial assessment. Applying a scale of 1–3 we assign the following values: intact or fresh rock (0), discolored rock (1), disintegrated rock (2), and decomposed (3). For rock mass we assign a scale of 1–5 as follows: fresh (0), slightly weathered (1), moderately weathered (2), highly weathered (3), completely weathered (4) and residual soil (5). Alteration and mineralization have a high influence on weathering processes and the condition and appearance of rock. Alteration is a change in mineralogy and texture created by cold or hot aquatic solutions or gases, while mineralization is a process that changes the concentration of some chemical elements. Both processes can be driven by underground thermal activity heating up overlying rock formations, which can lead to irreversible damage to their textural and structural integrity, making them unstable and fragile (McPhie, 1993, Gifkins et al., 2005). In volcanic areas, diagenetic and hydrothermal alteration can occur together, for example dissolution, replacement, and precipitation of minerals along the path of drainage. Assessment of these factors is valuable for the Coromandel Peninsula region (Figure 2.1.(7)) because of the large number of hydrothermal processes that have taken place and resulting in hydrothermal alteration and mineralization (Hayward, 2017). Epithermal mineral deposits have resulted in a significant history of mineral exploitation, with exploration and mining still taking place (Christie et al., 2001, Moore and Ritchie, 1996, Piddock, 2019). The next step in our assessment is to divide the areas influenced by mineralization and alteration from those only subject to weathering through surface processes such as weather, gravitation, and biological influences. We note an initial impression of the number of hot springs under rock formations as additional evidence of volcanic activities with a high impact on the geology and geodiversity values of our study area.

Structural elements such as faults and folds are widespread in areas subject to tectonic processes, where they may influence landforms and weathering (Fossen, 2016). Faults and folds in geological maps can show types and areas of influence. However, we consider it more useful to concentrate on the assessment of folds, as they can be more readily recognized in the field, while most faults may be missed on a map, due to small displacements at a scale of mm–cm (Barnes and Lisle, 2013). The value of folds and faults can be calculated using the same numerical approach as for caves, calculating an arithmetical average for all types of faulting, and folding. According to “description of folds” (Fleuty, 1964), we may observe features such as shape, altitude, and size, which may be measured in a field survey, but we consider this beyond the scope of this initial assessment. Therefore, we will use a map for calculating fold values, while additional photographs will be used to support the result.

Table 2.1.[9]: Weathering rate of intact rock and rock mass (ISO 14689-1:2017). The rate of changes can be easily recognizable during field observation utilizing this table as it connects to the color, hardness, and stability of the rock mass.

Grade	Intact rock		Rock mass	
0	Fresh	No visible sign of weathering/alteration of the rock material	Fresh	No visible sign of rock material weathering perhaps slightly discoloration on major

				discontinuity surfaces.
1	Discoloured	The colour of the original fresh rock material is changed and is evidence of weathering/alteration. The degree of change from the original colour should be indicated. If the colour change is confined to particular material constituents, this should be mentioned.	Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces
2			Moderately weathered	Less than half of the rock material is decomposed or disintegrated. Fresh or discoloured rock is present either as a continuous framework or as core stones.
3	Disintegrated	The rock material is broken up by physical weathering, so that bonding between grains is lost and the rock is weathered/altered towards the condition of a soil in which the original material fabric is still intact. The rock material is friable, but the mineral grains are not decomposed.	Highly weathered	More than half of the rock material is decomposed or disintegrated. Fresh or discoloured rock is present either as a discontinuous framework or as core stones.
4			Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.
5	Decomposed	The rock material is weathered by the chemical alteration of the mineral grains to the condition of a soil in which the original material fabric is still intact, some or all the mineral grains are decomposed.	Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.

Figure 2.1.(7): Hydrothermal alteration of andesite (Coromandel, Coromandel Peninsula, New Zealand) (WGS 84: 175.491980; -36.761419). A) Exit in the typical mine near Coromandel Wharf. B) Intense hydrothermal alteration of andesite rock near Coromandel Wharf. The height of the person is 168 cm.

The typology of folds and faults can be scaled according to accepted sequences from simple to complex types (Table 2.1.[4]). For folds, the scale is: symmetric (1), asymmetric (2), recumbent (3), overthrust (4), and nappe (5). We apply a similar scale for faults: normal (1), reverse (2), strike-slip (3), horst (4), and graben (5). Meanwhile, the length of the structural element will improve the accuracy of the final mark through its multiplication with the value for type. However, due to vegetative covering in the Coromandel Peninsula region, it is difficult to conduct on-ground surveys, leading us to concentrate on information from geological maps and indirect evidence. However future research could explore utility and practicality of LIDAR and other remote sensing methods for landscape scale investigation and assessment (Lo et al. 2021).

Soil type is one of the most complicated elements of geodiversity as it is formed by a combination of abiotic and biotic processes and closely linked to biodiversity and ecological environment (Bétard and Peulvast, 2019, Lausch et al., 2019, Rangel et al., 2019, Stavi et al., 2019, Fossey et al., 2020, Reverte et al., 2020, Santos et al., 2020, Zaady et al., 2021). Here we use a similar framework as for rock assessment; to assign a scale allowing assessment of soil-types according to uniqueness and rareness. However, this does require a precise analysis of New Zealand soils, especially on the Coromandel Peninsula. We suggest the main issue in soil categorization is the range of classification systems that may differ from country to country. For example, the United States uses three different systems with variations in levels of assessment. The United States Department of Agriculture (USDA) uses a system based on particle size distribution and is the most used method. The American Association of State Highway and Transportation Officials (AASHTO) uses a more accurate and complex system focusing on soil plasticity factors making it most useful for state and county highway departments. Finally, the Unified Soil Classification System (USCS) uses aspects of the previous systems, and includes liquid limit and organic matter concentrations, and is generally only used by geotechnical engineers (García-Gaines and Frankenstein, 2015).

New Zealand uses its own classification system, initially based on aspects of the USA systems, and then improved by scientists due to the uniqueness of our territory and genesis processes (Lausch et al., 2019, Hewitt, 2010). Additionally, the Food and Agriculture World reference base for soil resources (FAOWRB) is a globally recognized soil classification system that can be used for assessment and gradation of all soils as it is common for all countries. FAOWRB is based on three general principles: diagnosis of horizons, properties, and materials. It is considered the more acceptable system as it includes all soil types found throughout the world. Soils can also be assessed according to their age. Moreover, New Zealand soils have a specific genesis resulting from volcanic activities, which can create soils as a sequence of young soils buried under tephras (Gibbs, 1980). A difficult decision is whether to concentrate on the topsoil profile or the sub-surface horizons as well. Considering all the previously discussed issues, we have simplified our assessment for this initial stage of our research. Each assessment grid territory will be assigned a value based on the number of soils on the chosen area with the highest mark of 5 assigned to the highest diversity of soil types in the assessed territory. We suggest for further research the FAOWRB would be considered the most useful resource.

2.1.5 Example of the Assessment

According to a study of human visual abilities (Krisciunas and Carona, 2015), human eyes can distinguish a candle flame from 2.6 km at night. Therefore, we will divide the study area into 6.25 km^2 which will be adequate for our purposes as all objects of observation can be distinguished in the field without the aid of additional devices. However, the distance and scale of geodiversity assessment can be changed because of the relief of the territory. Our principal goal for this initial research is to create a practical and useful framework providing significant results able to be confirmed by ground truthing. To assist our assessment, we use the free software GRASS GIS (GRASS, n.d.) and QGIS (QGIS, n.d.), while mapping data is used as a general source of information. However, we acknowledge this will be adequate only for assessing the main values of geodiversity as previously described. The detailed sequences of calculation are presented below step by step to demonstrate the process in a manual environment using computer tools and electronic maps.

1. For a database, we use a horizontal vector map (in .shp format). This map provides enough information for morphological assessment (Cherlinka et al., 2017). GRASS GIS has sufficient tools to create a slope map and divide it into segments according to the degrees scale (Table 2.1.[4]; Figure 2.1.(8)) presented in the previous section.

2. For rock assessment, we need a geological map (in .shp format) of the territory together with information about rock ages. This information can be used to calculate the area of rock using QGIS or GRASS GIS. Additionally, QGIS can be used to create a vector file with polygonal lines with different rock types according to the scale in case we have only a raster (.tiff format) map (Table 2.1.[4]; Figure 2.1.(8)).

3. Caves are visible on the topographic map; therefore, these sites can be added with QGIS into our model as points associated with information on cave type. This information is sufficient for this initial broad stage of assessment until we can obtain more detailed information.

4. Soil maps are used to assess soil diversity by counting the number of discrete soil types (Cherlinka et al., 2017). We acknowledge this as a very broad assessment, and future work may develop a higher resolution scale according to types, thereby laying the foundation for a high-resolution framework for assessment of soil diversity in the context of the overall assessment of geodiversity.

The methodology we have outlined is proposed as an initial baseline for geodiversity assessment, with further research suggested that will highlight areas of improvement. By describing our system and demonstrating our methodology, we hope to have opened a door towards future research, observations, and improvements in the assessment system and its associated scales.

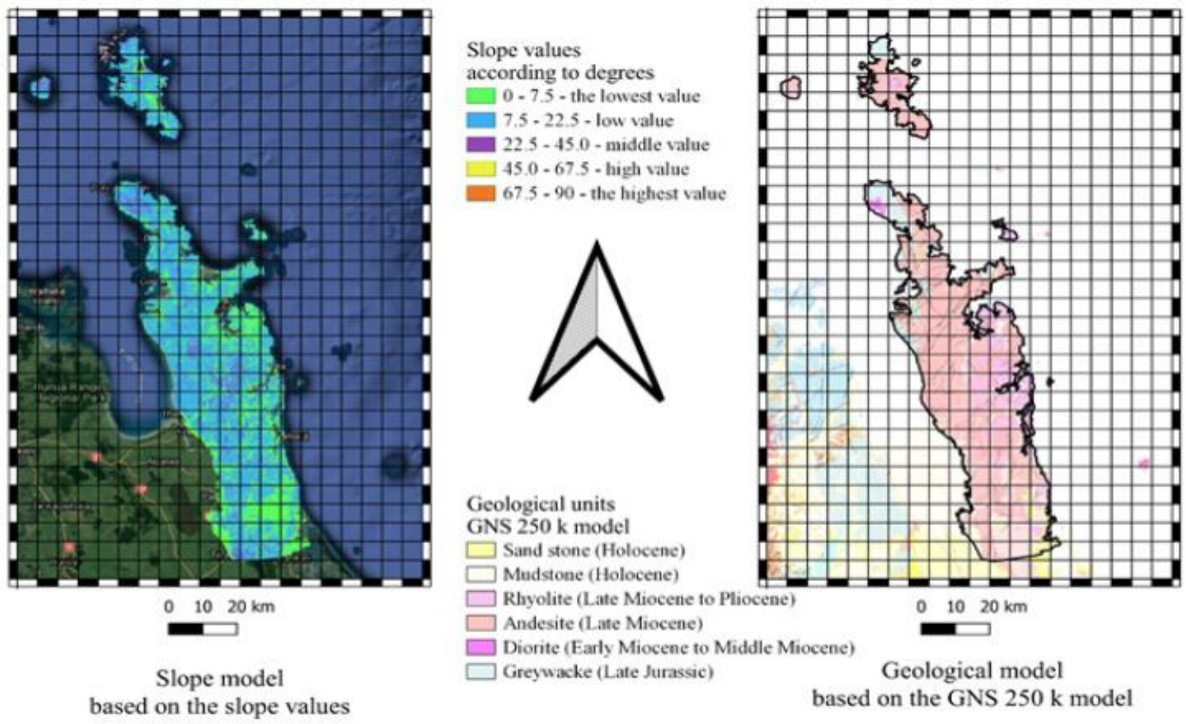

Figure 2.1.(8): Example of slope and geological models for geodiversity assessment. slope was created from SRTM 1-Arc-Second Global and Geological model from GNS 1:250,000 Geological Map of New Zealand (Q-Map).

2.1.6 Conclusions

Geodiversity is a relatively recently established field of study, now growing and subject to additions allowing a holistic and systematic description of the whole of abiotic nature. In our discussion we demonstrated how the current paradigm can be broadly divided into two parts. The first contains major elements of geodiversity, described as the general body of abiotic nature such as rock formations and surface morphology, while the second part is more process based and includes elements such as climate, hydrology, biology, and humanity that influence and alter the former elements. We also demonstrated a basic methodology of geodiversity assessment, based on a 5-point system, where 1 is the lowest rate and 5 is the highest.

We suggest further research to refine this methodology for assessing geodiversity of the Coromandel Peninsula based on the previously described system. This will highlight potential improvements for our methodology; refine accuracy of the grading system; and allow application to other territories in New Zealand, and ultimately globally. This will facilitate the development of a system applicable to any type of region and its associated landscapes and abiotic environment. Subsequently, this will provide information for a readily accessible database able to be applied to geoeducation, geotourism, and geoconservation projects.

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Chapter 3 – Scientific knowledge about the Coromandel Peninsula

Description: The second step of this research is to quantitatively assess the scientific knowledge of the Coromandel Peninsula from a pure geodiversity perspective. During this stage of the research, I explored three main scientific databases: Scopus, Web of Science and JSTOR. In these databases I explore all articles connected with "Coromandel Peninsula, North Island, New Zealand". The investigation includes examining statistical data such as topics presented in the manuscripts, year of publication, and the main locations of interest for the scientific community. The results of this research outline a description of scientific data which demonstrates the current published knowledge about the Coromandel Peninsula in the subjects of geology, biology, conservation, and archaeology, which influence our understanding of geodiversity.

The published article can be accessed: https://www.mdpi.com/2673-7159/1/4/21 accessed 5th of May 2023

Reference: Zakharovskyi, V. and Németh, K., 2021. Systematic Literature Review of the Natural Environment of the Coromandel Peninsula, New Zealand, from a Conservation Perspective. Conservation, 1(4), pp.270-284.

In this research: the article has been changed to meet the style of the thesis.

3.1 Title: Systematic Literature Review of the Natural Environment of the Coromandel Peninsula, New Zealand, from a Conservation Perspective

Abstract: This research presents a literature review of published scientific literature on the Coromandel Peninsula, a well-known region of the northern part of the North Island of New Zealand. It contains many biological, geological, and historical features and is well known for beautiful scenery, resulting from a volcanic rock-dominated terrestrial environment influenced by oceanic factors at the coast. All these factors have combined to make the Coromandel a popular tourism destination for New Zealanders and offshore visitors. In researching the current state of knowledge of the region, we searched three scientific databases to define the main ways of studying the region. The results demonstrated a high interest in biological and environmental factors, reflected in the type and scale of conservation measures applied to flora and fauna of the region. Additionally, specificity of geological evolution was a highly examined subject, in the context of hydrothermal alteration as related to gold and silver mineralization resulting in extensive exploration and mining. Meanwhile, indigenous cultural aspects of the land were not recognizable as expected within Western scientific literature, even though the region contains sites recognized as some of the earliest Māori habitations. Therefore, we suggest future studies to expand our understanding of scientific, cultural, and social aspects of the region as applied to the field of conservation in the region.

Keywords: geodiversity; geoheritage; geomorphology; geology; conservation; culture; Miocene; New Zealand.

3.1.1 Introduction

The Coromandel Peninsula is located on the northeast side of New Zealand's North Island. This territory is widely known as a tourist hotspot (Wiltshier, 2019, Holzapfel, 2003, Hall, 1993, Matthews et al., 2018, Dudding and Ryan, 2000, Adams, 2010), with a reputation for beautiful landscapes and a high diversity of biological and geological natural features (Hayward, 2017, Adams et al., 1994, Bell, 1994, Homer and Moore, 1992, Morley and Hayward, 2016). Coastal areas of the Coromandel Peninsula have magnificent geological features resulting from interaction between volcanic and sedimentary (terrestrial and marine) processes (Figure 3.1.(1)). In addition, the land is covered with lush subtropical bush featuring a range of rare and not-so-rare native tree species, providing habitats for birds, mammals, and insects (WRC, 2020). Moreover, this place was and still is important for the mining industry (Clement et al., 2017, Legget, 2010, Rudzitis and Bird, 2011, Craw and Chappell, 2000), with gold and silver epithermal deposits concentrated in areas of hydrothermal alteration due to past volcanic activities (Christie et al., 2007, John, 2011, Rabone et al., 1989, de Ronde and Blattner, 1988). Today, we can find evidence of mining throughout the whole length of the peninsula, as a footprint of European culture together with architecture reflecting European colonization and settlement of the area. In addition, the area contains many Māori archeological sites, as it was one of the first areas settled on a semi-permanent basis by Pacific colonists (Walter et al., 2017, Ladefoged et al., 2019). Hence, this area can be the subject of research in a wide range of disciplines, with a vast amount of information for different areas of research such as biology, geology, archeology, hydrology, social science, and others.

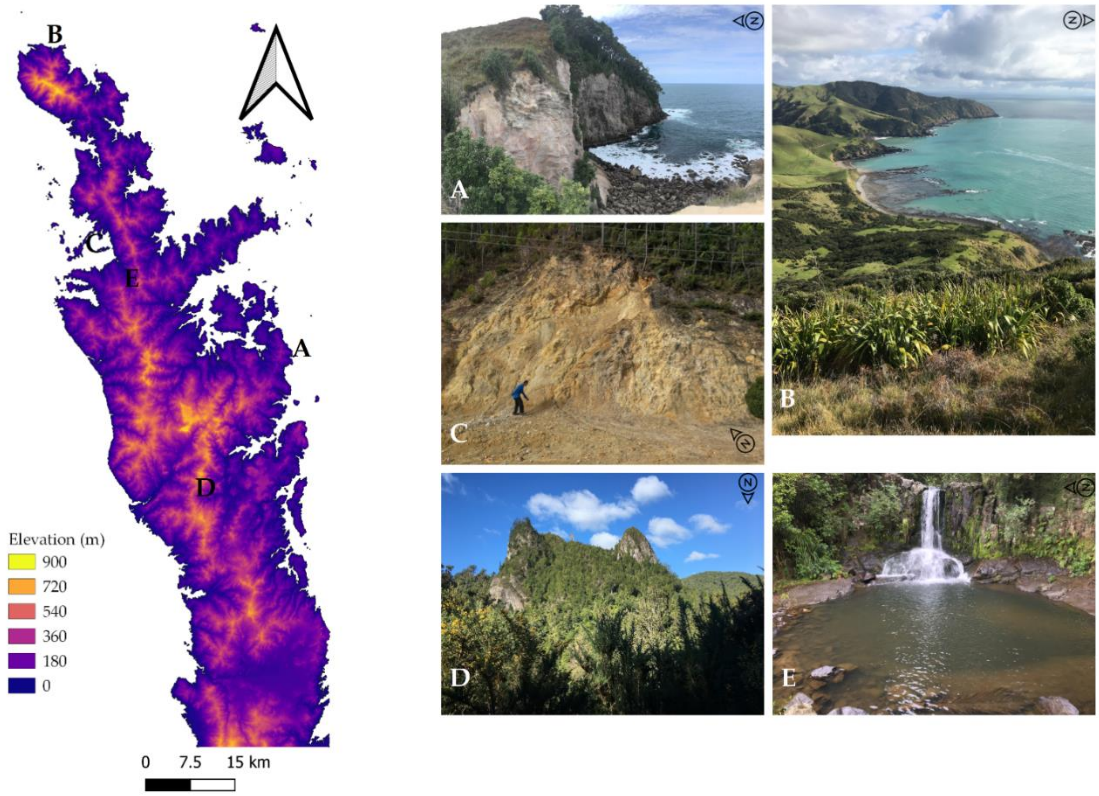


Figure 3.1.(1): The elevation overview model of the Coromandel Peninsula. The model was created based on the LINZ Topo50 20 m contours (LINZ, 2022) of topographic map (Moehau NZTopo-AZ34) (1:50,000 scale). (A)—Hehai (East cliff; altered rhyolite lava dome). (B)—Fletcher Bay (greywacke rolling hills with remnants of andesite volcano). (C)—Coromandel wharf (altered intermediate volcanic rock). (D)—Nevesville (rhyolite "Camel humps"). E—Waiau Falls (andesite).

The method of our research was based on searching and analyzing the available information, accessible through the internet using scientific sites to collect manuscript databases. Hence, authors, topics, keywords, and abstracts were studied, thereby defining those scientific fields in which researchers have made significant contributions. Our research demonstrates a need for the abiotic nature (geology, climate, hydrology, geomorphology, and others) of this area to be developed and understood in an integrated manner with processes (human and biological influences), leading to a holistic approach to geodiversity and geoheritage as keys for planning geoeducation, geotourism, and geoconservation projects in the future. Our study defines the general trends in current research within geoconservation, using published scientific outputs as the basis of knowledge of abiotic aspects of the natural environment of the region (Brilha and Reynard, 2018, Brilha, 2018, Brilha, 2016, Tavares et al., 2020, Reverte et al., 2020, dos Santos et al., 2019, Reynard and Brilha, 2018, Prosser et al., 2018, Gray, 2018). We acknowledge some limitations in this approach as it does not include traditional, oral, or indigenous knowledge directly. This problem is acknowledged in discussion on this subject recently, as we remain far from a consensus for a systematic methodology to integrate total scientific knowledge with other factors, thereby forming the basis of effective conservation strategies. Others argue that regardless of the lack of an integrated and holistic view, the scientific knowledge that is accepted through peer review and publication in global academic platforms reflects the current knowledge base of the environment. Hence, it can be used as the first proxy to identify the studied environment's scientific significance. In other words, we follow the idea that the current scientific value identified within the global net of scientific literature and research platforms forms an absolute and main value framework while oral traditions, indigenous knowledge, and other culturally driven aspects that may be difficult to identify in written databases are key additional elements. Therefore, they will form a vital part of the total environment that we can aim for in the future characterization.

The main goal of this research was to define the type of scientific work undertaken and subjects studied in the Coromandel Peninsula region, through the history of recorded science in New Zealand. This research provides an objective and clear view on the types of study reaching a global scientific audience through publications within Western scientific media. Subject areas and research aims were defined and a threshold value quantified for the science to be visible within traditional and widely accepted global science media. We observed the contrast within published research outputs accessible globally for general popularity and common "wisdom" about the status and standing of the Coromandel Peninsula within the conservation context. This work supports identification of key trends, knowledge, and/or information gaps in the network of conservation strategies, especially in its abiotic aspects.

3.1.2 Materials and Methods

3.1.2.1 Methodology

The object of this research was to screen the accessible literature from scientific databases, which are the most popular and accepted among researchers and which allow simple data mining within their resources. Our methodology was based on a standard collection of accessible scientific data for the studied region (the Coromandel Peninsula, New Zealand). For our search, we used three databases of peer-reviewed scientific publications (Table 3.1.[1]). We used the Scopus database and search platform, the Web of Science "All Databases", and the JSTOR database to define the scientific visibility of the Coromandel Peninsula. Our selection of these three databases was based on the level of access to keywords, subjects, and author searches within given time periods and easy, non-restricted downloads of the identified materials. Accessibility of the identified scientific outputs may be subscription dependent, but most major academic libraries have access to these databases. Most importantly, we used these databases as they are considered major scientific data repositories with a high number of globally scaled and tested entries. While it was tempting to explore Google Scholar as it is a truly open data source that is globally accessible for viewing and downloading data, it has numerous obstacles such as non-reliable bulk download methods associated with it. To explore Google Scholar would involve significant manual modifications that would increase the subjectivity of results. We used Google Scholar in our research for random cross-checks only. However, we were able to establish that Google Scholar follows similar trends of identified research outputs as Scopus or Web of Sciences with a broader sampling of the "gray literature" and lower accuracy of captured research outputs (e.g., multiple appearances of the same outputs) (Falagas et al., 2008, Henzinger and Lawrence, 2004, Banks, 2005, Denyer and Tranfield, 2009).

Scopus was used as the main source, as it contains enough available data about research (authors, titles, keywords, and abstracts) together with units' popularity, while Web of Science (WoS) was used as comparable and containing data about field of research despite a lack of keyword functionality. JSTOR, as a third comparable database, was used to highlight additional literature, commonly referred to as "gray" (e.g., papers that appeared in local, regional, or non-mainstream publishers as well as books, chapters, or reports), because they have less relevance to the global science community, unlike WoS and Scopus. For calculating the number of keywords, author's impact, abstract, and titles, we utilized Microsoft Office Excel.

In our analysis of the Scopus database, we utilized the words (phrases) "Coromandel Peninsula" and "New Zealand" as additional search words (Table 3.1.[1]). The search was through the article title, abstract, and keywords. For WoS, we used the same phrases applied for "All Databases" within our searches to cover any entry captured by the site since the platform has been operating. Then, we searched through the JSTOR database, which offers more than 12 million academic journal articles, 85,000 books, and 2 million primary source documents in 75 disciplines (JSTOR, n.d.) as well as access to electronic resources in a far broader range than Scopus or WoS by providing publications not listed in other databases (e.g., commonly papers published in local or regional scientific magazines). The JSTOR book collection covers scientific reports of local and regional sources, which may not be published by the more mainstream publishers.

Table 3.1.[1]: The list of results of the search.

Sources	Scopus	Web of Science	JSTOR
Search types	Article, Title, Abstract, Keyword	Topic	Author, Item title, Abstract, Caption
The word/phrase of search	"Coromandel Peninsula" (As an additional "New Zealand")	"Coromandel Peninsula" (As an additional "New Zealand")	("Coromandel Peninsula") AND ("New Zealand")
Date of search	14/09/2021	14/09/2021	14/09/2021
Results	150 documents	180 documents	357 documents 2 pictures
Exported information	Citation information (Full) and Abstract, Keywords (Full)	Author, Title, Source, and Abstract	Author, Title, Source, and Abstract
Additional data	The areas of research	The areas of research	The areas of research

In this study we aimed to present the scientific knowledge about the Coromandel Peninsula, New Zealand utilizing popular scientific databases: Scopus, Web Of Science and JSTORE. Methods of systematic literature review have been used to gather data about literature commonly used and applied in published literature with respect to geodiversity. The target of this research is to demonstrate the amount of scientific literature accessible for researchers throughout the globe about the Coromandel Peninsula. However, this process misses knowledge presented about the region from unpublished works, termed as “grey” literature, which may be found in university theses, reports and other unpublished works. Examining all literature about the Coromandel Peninsula is a challenge as works in libraries archives and private companies’ reports are inaccessible and could possibly lack rigor in their accuracy. However, standard searches through geological databases in universities, limited liability companies resulted in 204 pieces of work (Appendix B). From them 159 articles (some have been deleted because of duplication) have been found in New Zealand Journal of Geology and Geophysics (TAF. n.d.); 17 reports belong to mining Ltd.s’; 7 documents from Institute of Geological & Nuclear Sciences; 10 reports from NZ Geological Survey; 8 reports/thesis from University of Auckland; 3 reports/thesis from University of Waikato. However, all this literature only captures some knowledge about the Coromandel Peninsula on topic of geology which needs to be examined in an international context. Grey literature is important for the in depth understanding of a local area however when forming methods that should be globally transferrable analytical techniques need to be based on open source and easily accessible information and data.

3.1.3 Results

3.1.3.1 Scopus Database and Results of Assessment

As a result of our Scopus search, we received 150 documents from 1965 to 2020, where the most productive years were 2004 (12 articles), 2007 (eight articles), 2012, 2005, and 2003 (six articles each) (Figure 3.1(2)). Meanwhile, Mauk J.L. wrote 13 articles about the Coromandel Peninsula, followed by Nelson C.S. and Moore P.R. (eight articles each), then Bryan K.R. (seven), Simpson M.P., Rowan D., and Christie A.B. (six each), with this list being only those scientists who made the highest value on the study of this area. Hence, this territory seems to have become visible to the global science community through globally relevant research outputs since 1965, which is a reasonably long time. However, its database has only 150 documents from the different fields of importance through the region, while similar random tests for other geologically and geographically similar locations gave higher results. For example, the Carpathian Mountains in Eastern Europe (Miocene–Pliocene subduction-related bimodal volcanism [andesitic to dacitic/rhyolitic], greywacke basement, and thick flysch successions but colder, temperate climate, and more alpine morphology) consistently yielded research outputs nearly two orders larger than the number of research outputs for our studied area (the Coromandel Peninsula) (Rădulescu and Săndulescu, 1973, Fielitz and Seghedi, 2005, Melinte-Dobrinescu et al., 2017b, Melinte-Dobrinescu et al., 2017a).

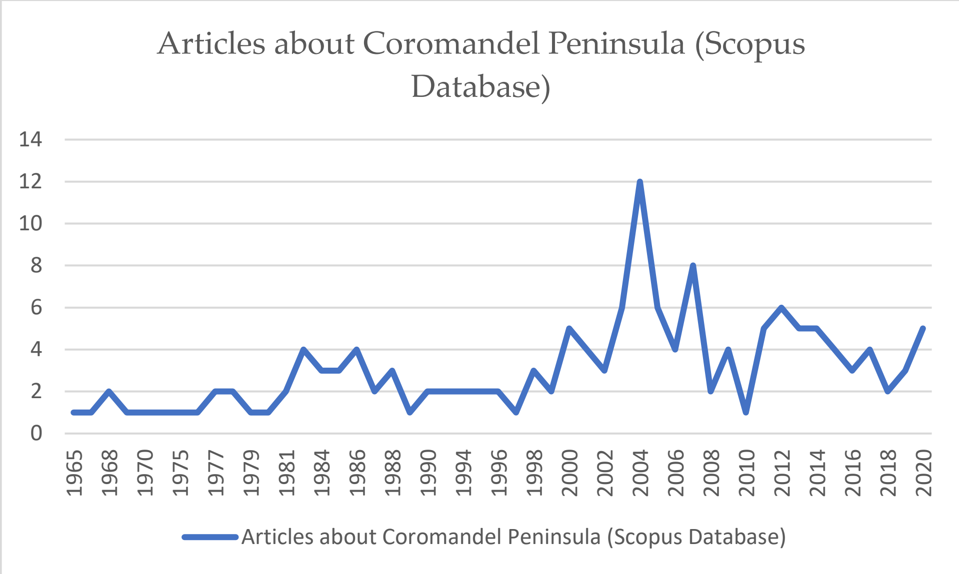


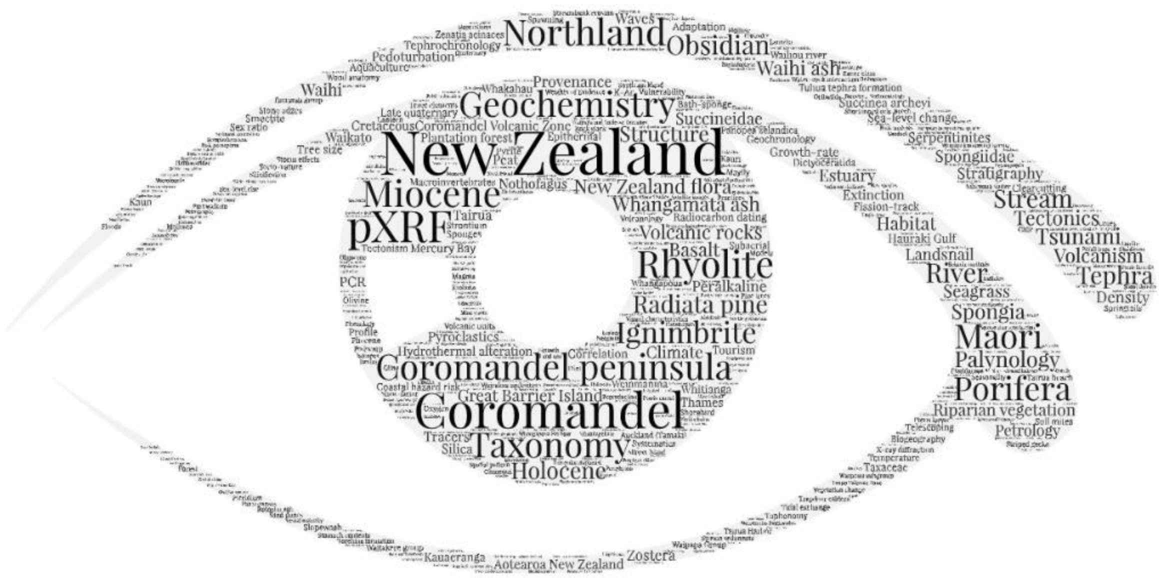
Figure 3.1.(2): The number of articles written about the Coromandel Peninsula each year from 1965 to 2020 (Scopus database).

For the studied areas, we directed our attention towards the authors' keywords mentioned in information about every manuscript. According to the result from authors' keywords (total number of 702 words or phrases) (Table 3.1.[2]), "geochemistry" was the most popular and was mentioned five times, (except "New Zealand", 34; "Coromandel Peninsula", 14; and "Coromandel", seven times), then "taxonomy", "Northland", "New Zealand Flora", "Miocene", "ignimbrite", and "Great Barrier Island" were mentioned four times each. Meanwhile, index keywords compounded by Scopus (1985 words or phrases) contain "North Island" (59 keywords), Waikato (47), and Australasia (33) were the highest number of words (except "New Zealand" (107) and "Coromandel Peninsula" (54), which have not been included as they are search words), which are connected mostly to the location of the place without any connection to a specific scientific field. Then, "*Asystasia gangetica*" was mentioned for 20 articles, "hydrothermal alteration" (11), and "gold deposits" and "forestry" (10 times each). More precise information is outlined in the table below, where author keywords are presented together with Index 1.

From Microsoft Office Excel calculations (Table 3.1.[2]), author keywords and index keywords were justified as the most relevant by researchers' topics around the Coromandel Peninsula region; however, the table contains the number of words, which can be used in any kind of research, such as names of locations. Hence, we used a color code for the table (Table 3.1.[2]) to highlight different fields of studies such as geology (red color), biology (green color), locations (light-green color), and periods (gray color).

Table 3.1.[2]: The comparison of author and index keywords. The information was taken from Scopus database on the search words "Coromandel Peninsula" and "New Zealand".

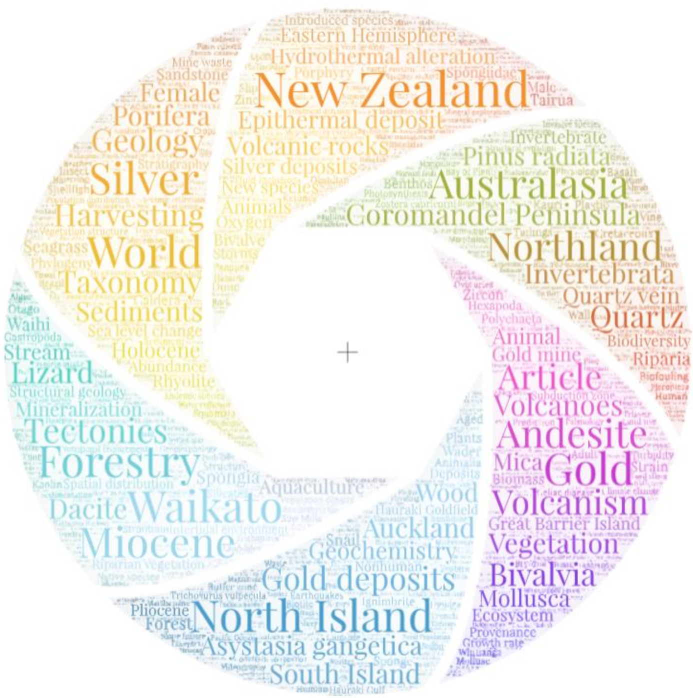
Author keywords



34 New Zealand	3 Māori
14 Coromandel Peninsula	3 Hydrothermal alterations
7 Coromandel	3 Holocene
5 Geochemistry	3 Coromandel Volcanic Zone
4 Taxonomy	3 Aotearoa New Zealand
4 Northland	2 Waihi ash
4 New Zealand flora	2 Volcanism
4 Miocene	2 Tuhua tephra formation
4 Ignimbrite	2 Tsunami
4 Great Barrier Island	2 Tephrochronology
3 Whangamata ash	2 Tephra
3 Volcanic rocks	2 Tectonics
3 Riparian vegetation	2 Succineidae
3 Rhyolite	2 Succinea archeyi
3 Radiata pine	2 Structure
3 pXRF	2 Stream

3 Porifera	2 Stratigraphy
3 Palynology	2 Spongiidae
3 Obsidian	2 Spongia

Index keywords



107 New Zealand	6 Volcanism
59 North Island	6 Tectonics
54 Coromandel Peninsula	6 Taxonomy
47 Waikato	6 South Island
33 Australasia	6 Silver
20 Asystasia gangetica	6 Pinus radiata
11 Hydrothermal alterations	6 Invertebrata
10 Gold deposits	6 Great Barrier Island
10 Forestry	5 Volcanoes
9 Gold	5 Vegetation
9 Epithermal deposits	5 Silver deposits
8 World	5 Sediments

8 Northland	5 Quartz vein
8 Miocene	5 Mineralization
8 Harvesting	5 Geology
8 Eastern Hemisphere	5 Bivalvia
8 Andesite	5 Auckland
7 Volcanic rocks	5 Article
7 Geochemistry	5 Aquaculture

Except for keywords, the Scopus database contained statistics about articles connected to different fields of research (Table 3.1.[3]). Hence, 71 articles were written about “Earth and planetary sciences”, then 54 for “agriculture and biological sciences”, and 43 for “environmental science”. After this, the number of articles dropped to 15 manuscripts in “social science” and eight and seven in “arts and humanities” and “multidisciplinary”, respectively, while other areas of studying were low in the Coromandel Peninsula.

Table 3.1.[3]: The number of articles according to the area of research (Scopus database).

Number of Articles	The area of research
71	Earth and Planetary Sciences
54	Agricultural and Biological Sciences
43	Environmental Science
15	Social Sciences
8	Arts and Humanities
7	Multidisciplinary
4	Engineering
3	Chemical Engineering
3	Medicine
2	Biochemistry, Genetics and Molecular Biology
2	Energy
1	Business, Management and Accounting
1	Chemistry
1	Computer Science

1	Mathematics
1	Nursing
1	Pharmacology, Toxicology and Pharmaceutics

In conclusion, the general information shown in Table 3.1.[1] demonstrates that the Scopus database contained 150 articles about the Coromandel Peninsula, and keywords (Table 3.1.[2]) show most of them were about geology and more specifically about volcanic activities, justified by keywords such as "obsidian", "volcanism", "tephra", "geochemistry", "epithermal deposits" and others. Meanwhile, biological spheres were also studied in this region and words like "vegetation", "*Radiata Pine*", "*Asystasia gangetica*", "New Zealand flora" and "forestry" showed the interest in the Coromandel flora. Additionally, words like "*Spongiidae*", "*Spongia*", "invertebrate", and "porifera" demonstrated the fauna part of the study of marine life, especially sponges, "*Succineidae*", and "*Succinea archeyi*" snails. Other keywords such as "taxonomy", "structure", and periods "Miocene" and "Pleistocene" were not related to any kind of specialization as they can be used in multiple fields, which have not been checked as they have no significant influence. The same trends for science priorities can be seen in areas of studying databases shown in Table 3.1.[3], where geological, biological, and environmental research were dominant in comparison to other fields. Additionally, the number of research areas in the table of studying areas was higher than the number of documents, 180 and 150, respectively. Hence, some documents were included in two or more areas. This pattern, mostly visible between environmental science and agriculture and biological science, 21 documents, showed a strong connection in these areas. It was followed by collaboration between Earth and Planetary Sciences and Environmental science—12 documents. Meanwhile, seven documents mentioned multidisciplinary areas of studying related to geological, biological, and environmental subjects and related collaboration. In the next sections we demonstrate how information taken from other sources can further refine the overall picture based only on the Scopus data.

3.1.3.2 Web of Science Database and Results of Assessment

The Web of Science search through topics with the words "Coromandel Peninsula" and "New Zealand" in the results found 180 documents in the period from 1946 to 2020 (Figure 3.1.(3)). From the figure, the most productive years were 2003–2004, 2007, and 2020 as they included publication of eight or more manuscripts about the Coromandel Peninsula. According to the authors' influences, Mauk J.L. was mentioned in eight articles, then Simpson M.P. (seven documents), Christie A.B (six), Quinn J.M. (five), and Bryan K.R. (four).

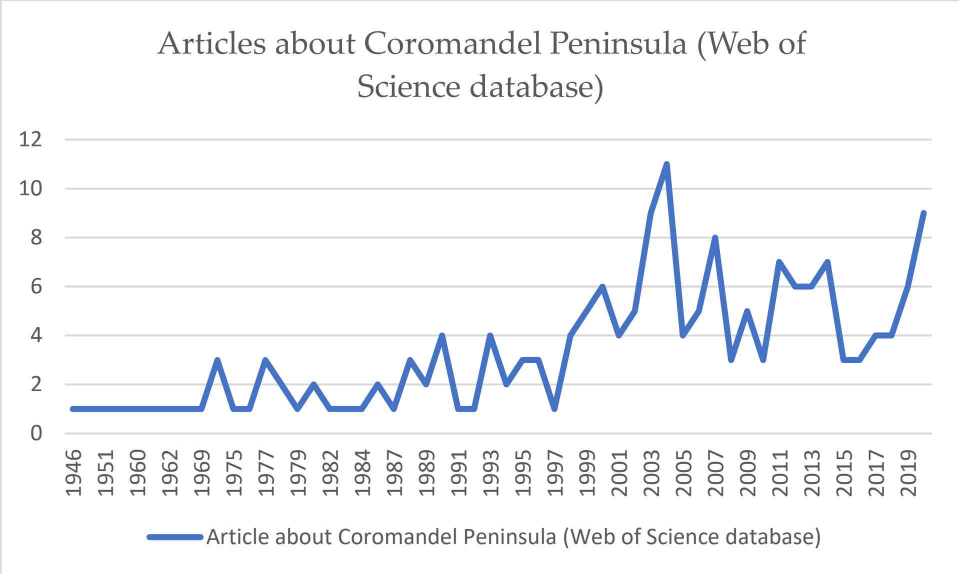


Figure 3.1.(3): The number of articles written about the Coromandel Peninsula each year from 1946 to 2020 (WoS database).

As previously mentioned, WoS does not provide a dedicated database about keywords like Scopus does, but it does include information about science fields (Table 3.1.[4]), where "environmental science ecology" shows the highest number of articles (96), followed by "zoology" (68), "life sciences biomedicine other topics" (44), then "Biodiversity conservation" and "geology" (39 each).

Table 3.1.[4]: The number of articles according to the area of research (WoS database).

Number of Articles	The area of research
96	Environmental Sciences Ecology
68	Zoology
44	Life Sciences Biomedicine Other Topics
39	Biodiversity Conservation
39	Geology
35	Physical Sciences Other Topics
34	Plant Sciences
32	Marine Freshwater Biology
27	Forestry
23	Agriculture
20	Palaeontology
19	Geochemistry Geophysics

18	Anatomy Morphology
18	Meteorology Atmospheric Sciences
15	Oceanography
14	Geography
13	Nutrition Dietetics
12	Developmental Biology
12	Fisheries
12	Physiology
12	Science Technology Other Topics
11	Anthropology
11	Biochemistry Molecular Biology
10	Evolutionary Biology

In conclusion, we can state that analysis of our searches within WoS and Scopus yielded similar results for number of peaks of annual productivity for articles about the ed similar results for number of peaks of annual productivity for articles about the Coromandel Peninsula (Figures 3.1.(2) and 3.1.(3)). For influence of authors, we saw that most of the manuscripts in both databases contained the same names, such as Mauk J.L., Simpson M.P., Christie A.B., Bryan K.R., and others. However, keyword analysis of Scopus results (Table 3.1.[2]) showed that the most significant field of research in the Coromandel was geology (specifically, volcanology and hydrothermal deposits), then flora and botany, and fauna presented by studies about marine sponges and snails, as shown in research areas outlined in Table 3.1.[3]. The WoS database about areas of research (Table 3.1.[4]) showed that topics like biology, biodiversity, environmental conservation, and zoology showed a higher ranking than geology, which did remain at a relatively high position.

3.1.3.3 JSTOR Database and Results of Assessment

Results for JSTOR showed 784 documents and three pictures, with half of them showing no connection to the Coromandel Peninsula and New Zealand at all. Therefore, we chose to concentrate specifically on the mentioned phrases. Using this option, our search showed 357 documents and two pictures (Table 3.1.[1]), which were published in the period from 1883 to 2019. From the period (Figure 3.1.(4)), 1980 was the most productive year on the topic connected to the Coromandel Peninsula (18 documents), then the next peak was in 1998 with 11 articles. For influence of authors, Hayward B.W. wrote 10 articles, then Morley M.S. (nine articles), Davidson J. (eight), Thrush S.F. (seven), and Healy T.R., Golson J., Furey L., Eagle M.K., and Bryan K.R. were mentioned in six different manuscripts.

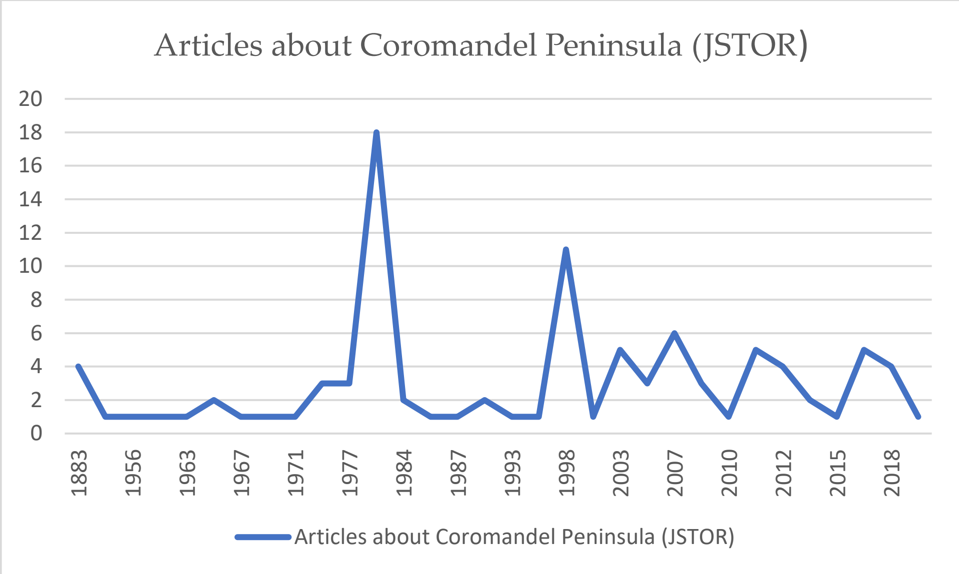


Figure 3.1.(4): The number of articles written about the Coromandel Peninsula each year from 1983 to 2019 (JSTOR database).

The JSTOR database is like WoS, in that it does not provide information about keywords, but it does contain a table, with different areas of research (Table 3.1.[5]). According to our search, 183 manuscripts were written on the subject of "ecology and evolutionary biology", then 77 on "biological science", and 75 on Asian studies. Continuing, 58 and 48 articles were related to "anthropology" and "archeology", respectively. Meanwhile, on geological studies, only five were written for each "geology" and "paleontology". Other areas of study were shown to have much less impact on the Coromandel Peninsula.

Table 3.1.[5]: The number of articles according to the area of research (JSTOR database).

Number of Articles	The area of research
183	Ecology & Evolutionary Biology
77	Biological Sciences
75	Asian Studies
58	Anthropology
48	Archaeology
42	Aquatic Sciences
20	Botany & Plant Sciences
13	Geography
13	History
13	History of Science & Technology
12	Environmental Science

10	Zoology
5	Geology
5	Palaeontology
4	Education
3	Art & Art History
3	Business
3	Language & Literature
3	Political Science
2	Economics
2	Linguistics
2	Sociology

In conclusion, the JSTOR database showed different information compared to Scopus and WoS. Firstly, it provided two times more results than the other two studied databases. Additionally, within JSTOR searches, new authors tended to appear such as "Hayward B.W.", who also had the highest number of articles on the topic of "Coromandel Peninsula" according to the JSTOR database. This was despite his research outputs being barely noticed in Scopus and WoS. This might be a result of any of the following: The science media his publications appear in have not been captured properly; his publications date back to a time not captured by other databases; or research outputs were not specifically associated with the Coromandel Peninsula at a level that would have been captured by Scopus or WoS.

On the other hand, JSTOR's fields of study (Table 3.1.[5]) provided similar outcomes to those found by searching through WoS (Table 3.1.[4]) in environmental and biological studies. In both cases, the highest amount of research occurred in geology in WoS, and completely opposite results were found in JSTOR compared to Scopus keywords (Table 3.1.[2]) and areas of research (Table 3.1.[3]) results, where most of them were around geological areas of science.

3.1.4 Discussion

This research demonstrated that using similar search terms about the location of study the "Coromandel Peninsula" through three databases yielded different results. The JSTOR database had the highest numbers for scientific literature, which were two times higher than others (WoS and Scopus). This can be justified by the time range presented in this system from the 19th century and older, as well as the wider types of documents based on regional and local studies with no interest or influence on world science. Moreover, the JSTOR database showed a low number for literature connected to geological spheres, unlike WoS and Scopus data searches, where these topics were the most common. However, biological, and ecological studies were in the first place in all databases, which showed a high interest in the living nature of this region. In conclusion, Scopus and WoS showed similar results, with domination of geological studies in the former and biological–ecological in the searches of the latter, and high interest to the Coromandel Peninsula especially in 2007. Meanwhile, JSTOR results showed the highest number of articles in the 1980s, with dominance of biology, ecology, anthropology, and history, unlike the previous databases where social science was in the low position.

Additionally, we created a map (Figure 3.1.(5)) to show the number of articles that had a connection to some specific locations in the Coromandel Peninsula. (The information is based on the 150 documents found through the Scopus search.) It shows that the highest number of articles were written about the south part of the peninsula: 12 articles about Hauraki Goldfield and Whangamata each; on the east part, seven articles were about the Whitianga area and nine about east coast of the Coromandel Peninsula more generally. Meanwhile, the west coast was poorly studied (only three manuscripts), and the North coast was slightly better, with four articles. Such differences in the numbers of articles are connected to the most significant places of the region, where the south and southeast areas of the Peninsula are mining areas, while the central and eastern areas are considered the main tourist destinations. Meanwhile, the western part is a historic mining area and no longer subject to active mining. The northern part is the subject of some articles, also connected to the study of epithermal deposits; however, these places are remote and take considerable effort to reach. Hence, the Coromandel Peninsula has a lack of data about the north and the west part, which shows that these places should be subject to further research, thereby contributing to a fuller picture of the region.

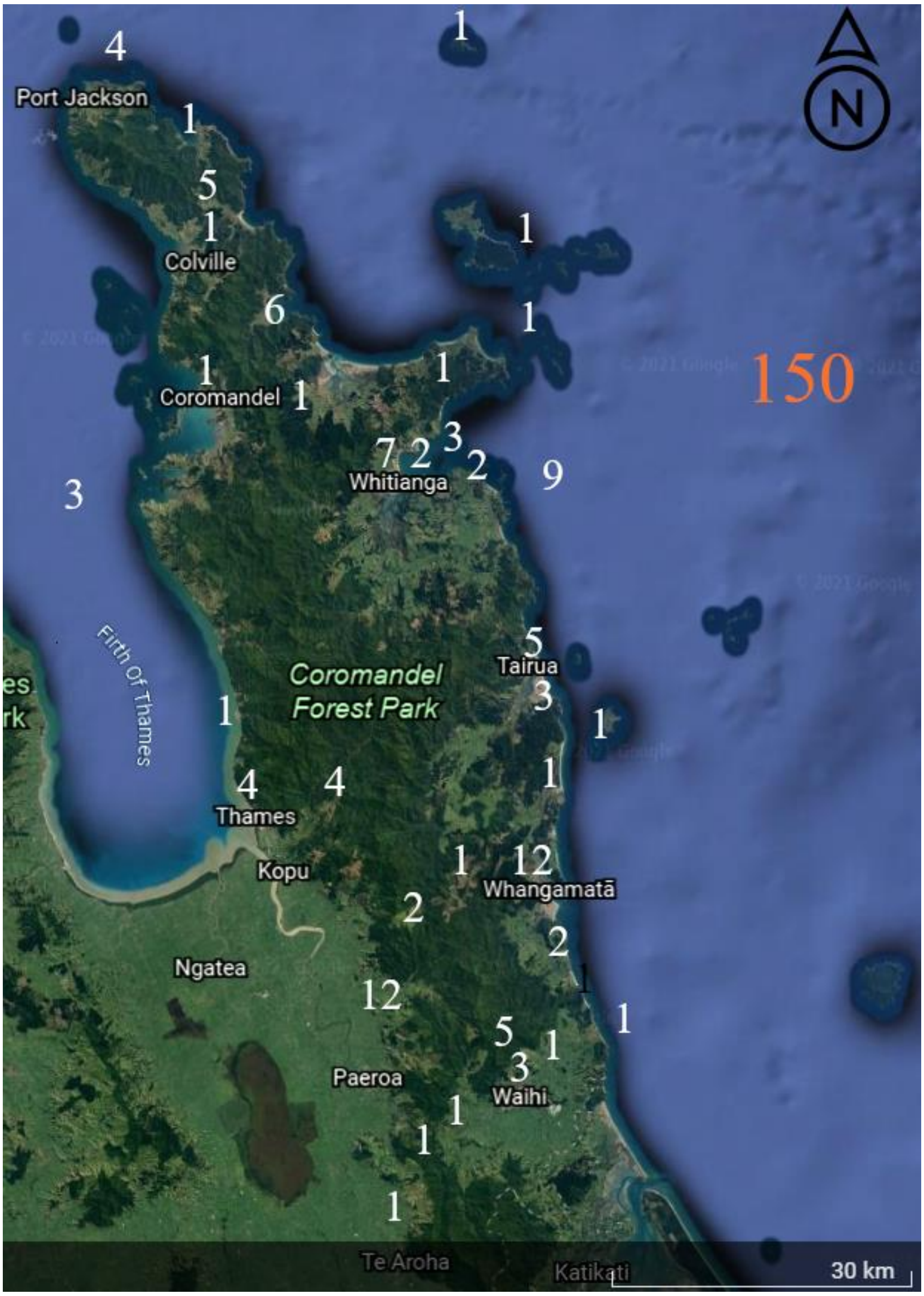


Figure 3.1.(5): The number of articles written according to the specific location in the Coromandel Peninsula. The orange number showing the total number of manuscripts was taken from Scopus database. For the complete list of papers, please refer to the Supplementary Material associated with this article.

As our study was in the context of conservation of the region, we added “conservation” to our Scopus search, thereby magnifying results towards our subject of interest. In conclusion, we completed a table, showing 10 documents related to conservation of the Coromandel Peninsula (Table 3.1.[6]). From their titles, we saw most of them were related to fauna and flora protection as an important subject of study in the Coromandel Peninsula. Hence, it is apparent that the subject of geoconservation remains undeveloped in this area and a potential area of considerable research based on the knowledge of the region's geological, geomorphological, and environmental aspects.

Table 3.1.[6]: The number of articles according to the conservation aspect of the Coromandel Peninsula (Scopus database).

Authors	Title	Year
Hitchmough R.A., Nielsen S.V., Bauer A.M.	Earning your stripes: A second species of striped gecko in the New Zealand gecko genus Toropuku (Gekkota: Diplodactylidae)	2020
Dowding J.E.	Changes in the number and distribution of northern New Zealand dotterels (Charadrius obscurus aquilonius): results of four censuses undertaken between 1989 and 2011	2020
Gesing F.	The politics of artificial dunes: Sustainable coastal protection measures and contested socio-natural objects	2019
Feltrin L., Motta J.G., Al-Obeidat F., Marir F., Bertelli M.	Combining Weights of Evidence Analysis with Feature Extraction - A Case Study from the Hauraki Goldfield, New Zealand	2016
Ogden J., Dowding J.E.	Population estimates and conservation of the New Zealand dotterel (Charadrius obscurus) on Great Barrier Island, New Zealand	2013
Gardner-Gee R., Beggs J.R.	Challenges in Food-Web Restoration: An Assessment of the Restoration Requirements of a Honeydew-Gecko Trophic Interaction in the Auckland Region, New Zealand	2010
Steens M.I., Winter D.J., Morris R., McCartney J., Greenslade P.	New Zealand's giant Collembola: New information on distribution and morphology for Holacanthella Börner, 1906 (Neanuridae: Uchidanurinae)	2007
Schwarz A.-M., Morrison M., Hawes I., Halliday J.	Physical and biological characteristics of a rare marine habitat: Sub-tidal seagrass beds of offshore islands	2006
Neumann D.R., Orams M.B.	Behaviour and ecology of common dolphins (Delphinus delphis) and the impact of tourism in Mercury Bay, North Island, New Zealand	2005
Brook F.J.	Distribution and conservation status of the dune snail Succinea archeyi Powell (Stylommatophora: Succineidae) in northern New Zealand	1999

In a previous section we mentioned similarities between the Coromandel Peninsula and the Carpathian Mountains in the context of geological evolution, which directed us to compare these territories in analysis of differences in scientific development. For example, Scopus data contained 1132 results for the search "Carpathian Mountains". This raised new questions highlighted by differences between studies of the Coromandel Peninsula and the Carpathian Mountains. However, we acknowledge the Carpathian Mountains as being larger in area (1700 km long) than the Coromandel Peninsula (85 km long). Additionally, the Carpathian Mountains extend over the territory of 11 European countries, while the Coromandel Peninsula is in the North Island of New Zealand, thereby being subject to only one national identity. Hence, scientific interest in the Carpathian Mountains has been more influential through history. In contrast, the first Europeans came to New Zealand in the 18th century. "Modern" scientific data began from the 20th century (Brocx and Semeniuk, 2015, Brush, 1989); therefore, old literature is rare in both regions. Moreover, in both cases, articles in Scopus displayed peaks in the 21st century. We recommend future study of the two territories in comparison to highlight currently unrecognized scientific values in the Coromandel Peninsula. While the Coromandel Peninsula is recognized as a valuable conservation asset in a broad sense, we note that, in contrast, the Carpathian Mountains have 10 national parks (four of them recognized by UNESCO) located in Slovakia and six national parks (two of them recognized by UNESCO) in Poland. In addition, other countries also have several reserves, but with significant differences in levels of nature protection and conservation (Oszlányi et al., 2004).

Our studies may be utilized by other researchers to understand the level of interest in the Coromandel Peninsula in a range of disciplines, which should uplift the more neglected fields of interest applied to the territory. For example, social sciences could be applied to this region to a higher degree. Initial investigations showed this area contains many sites of importance to indigenous traditions (Wahi tapu). Facilitating and supporting recording and exploration of traditional knowledge in the context of *te ao Māori* (a worldview that acknowledges the interconnectedness and interrelationship of all living and non-living things) are suggested as ways of supporting recovery and protection in a framework shaped by geoheritage and geoconservation concepts (Cunningham, 2000, Harmsworth and Awatere, 2013). Moreover, the high values placed on this area by Europeans provides a context in which to study the relationship between different types of societies and their influences on each other (Salmond, 1992, Schaniel, 2001). In our Scopus search, from 150 documents only six of them were related to Māori culture and they were found under the arts and humanities disciplines. Meanwhile, results also showed the Coromandel Peninsula is an area of high interest to researchers in geology, biology, ecology, and anthropology. All these fields can be studied through their links to and the influence of geodiversity, making explicit connections between the scientific fields. The connection between abiotic and biotic elements of nature and the human societies that shape their environments, and are also shaped by those environments, provides a clear path for understanding and maintaining a healthy balance between society and the environment.

3.1.5 Conclusions

Scientific databases contain a limited amount of data about the Coromandel Peninsula, where biological, ecological, and geological spheres were represented the most. Meanwhile, the Peninsula has a low number of studies in the Sociological disciplines. More consideration needs to be given to these aspects, in the light of its high value as a well-known tourist destination, and the widely acknowledged heritage of human settlements dating from the earliest human arrivals through to thriving Māori settlements and, in time, important centers of European colonial settlement.

Even though nature-related data are extensive for the area, the available information is mostly connected to specific places. This does not allow for a clear region-wide holistic assessment and description, with a notable lack of information pertaining to the west and the north part of the region. Future geodiversity studies of the region must endeavor to collect more data through field observations and historic literature searches about different aspects of the Peninsula from geology and geomorphology to climate and social science.

The future study of this region can be compared alongside similar regions elsewhere in the world, which have higher amounts of data. For example, the Carpathian Mountains, which have the same geological evolution, can be used as a case study to demonstrate the kind of transdisciplinary studies that could be undertaken here to allow for a higher level of planning for geotourism, geoeducation, and geoconservation.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/conservation1040021/s1. Supplementary Material [Scopus search results for the search words: Coromandel Peninsula AND New Zealand].

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Chapter 4 – Qualitative-quantitative assessment of geodiversity

Description: After understanding of the term geodiversity and scientific knowledge about the Coromandel Peninsula, I decided to calculate a geodiversity measure. Due to the low amount of information and accessible maps/models of the Coromandel Peninsula, Q-Map – 1:250 000 geological model of New Zealand, SRTM model, and Topographical model were used as data for a geodiversity assessment through the qualitative-quantitative methodology. This methodology itself based on expert evaluation of the assessed elements for places of interests matches with the view on geodiversity assessment described in the Chapter 2.1. Here, I utilized only main elements of geodiversity: geology and geomorphology, which are also core parameters for the abiotic environment. For assessment, geological elements have been represented through the rock type and their age according to their rareness throughout the surface of the Earth, while geomorphological elements were presented as 4 different types based on slope models. Both elements have been utilized for the northern parts of the Coromandel Peninsula to recognize hotspots, which can be considered as potential geosites for further examination. This manuscript is the starting point for the development of qualitative-quantitative assessment of geodiversity for the recognition of potential geosites, which will be improved with additional data and tested in different places in further studies.

The published article can be accessed: https://www.mdpi.com/2073-445X/10/9/946 accessed 5th of May 2023

Reference: Zakharovskyi, V. and Németh, K., 2021. Quantitative-qualitative method for quick assessment of geodiversity. Land, 10 (9), 1–21.

In this research: the article has been changed to meet the style of the thesis.

4.1 Title: Quantitative-Qualitative Method for Quick Assessment of Geodiversity

Abstract: This article demonstrates a method for qualitative-quantitative geodiversity assessment based on core elements of abiotic nature (geology and geomorphology) according to a proposed weight multiplied by the area of spread through the studied region. The territory of the Coromandel Peninsula was selected as a case study due to its diverse geology and geomorphology. The north part of the Peninsula (Port Jackson, Fletcher Bay, and Port Charles districts) was chosen because of the variety of rock types (sedimentary and volcanic groups) covering the region, while historical stratovolcano remnants and old sediments provide a good variety of meadow hills and weathered coastal cliffs. Meanwhile, the method utilizes easily accessible data (topographical and geological map) to assess slope angle (morphometry) and rock groups, including their age (geology) to identify areas in the sample region with significant geodiversity values. Moreover, the aim of this research is to make the assessment of geodiversity simpler and more accessible for various parts of the world with minimal required information. In this paper, we provide access to improve and utilize this method in geologically diverse territories to select the best areas for geotourism, geoeducation and geoconservation planning.

Keywords: geodiversity; GIS-assessment; geoheritage; geomorphology; morphometry; geology; slope; volcanics; greywacke; New Zealand.

4.1.1 Introduction

The assessment of geodiversity is developing as a research field whereby studying abiotic nature can be used as an analogue for biodiversity as the living part of the environment. Some researchers seek the best solution to objectively determine the geodiversity of a territory (Dias et al., 2021, Pereira et al., 2013, Reverte et al., 2020). Researchers such as Gray, Kozłovskyi, Serrano and others (Gray, 2008, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007) have established a core definition of geodiversity as the sum of the Earth's history, tectonics, minerals, rocks, sediments, fossils, landforms, geomorphological processes and soils, geological structures, surface water, groundwater, mineral and therapeutic waters, and thermal waters. Meanwhile, Gray's table of value (Gray, 2005) shows that geodiversity has a connection to a variety of aspects of human endeavor, our place in the environment, other scientific fields, socioeconomics, cultural traditions, spirituality, and art. Geodiversity is intuitively looked at as a mirror term of biodiversity. However, biodiversity, in short, is an expression of the health of an ecosystem, which is not directly applicable to the diversity of the geological and geomorphological features of Earth, as the value of the geological and geomorphic sites does not depend on diversity. Related to this, Ollier (Ollier, 2012) pointed out that "geodiversity might be useful as a way of recording diverse features within a given area, but it should not be treated as a value-judgement on the significance of individual sites" a philosophical view we agree with. Ollier also pointed out that "geoheritage is under threat from the redefinition of geotourism, and the potential misapplication of the concept of geodiversity" (Ollier, 2012).

However, the recognition and studying of geosites demand a general assessment of geodiversity. Such works are commonly driven by the need to find objective measures of values of geosites to identify those areas that need more attention for geoconservation purposes. A better understanding of the geodiversity of a region can also be utilized as core information geopark programs can embrace along various levels of geoeducation. The main streams of research have focused on calculating all recognizable and/or recorded lithological types within a defined field and providing a value according to the number of geological units identified within that area. In 2007, Serrano and Ruiz-Flaño presented an equation to calculate an index of geodiversity based on the number of existing elements and their roughness index presented on the studied region. This method was well utilized by de Silva, do Nascimento, and Mansur in their assessment of geodiversity in the Seridó Geopark Project in northeast Brazil. Bétard and Peulvast also used geodiversity and threat indexes to identify geodiversity hotspots in the Ceará State (northeastern Brazil) (da Silva et al., 2019, Bétard and Peulvast, 2019). The geodiversity index can be seen as the sum of geological diversity, geomorphodiversity, pedodiversity and hydrodiversity. To sum up, this provides a useful quantitative method of assessment widely used by researchers (Bétard and Peulvast, 2019, Pereira et al., 2013, Silva et al., 2013).

In this article, we propose an alternative and simplified method to assess geodiversity based on a pre-defined table outlining a proposed conceptual framework of geodiversity. The framework is based on the general definition of geodiversity and tested through our research in the Coromandel Peninsula. For a geodiversity assessment, geology and geomorphology are considered the most important elements as they provide the foundation underlying all aspects of abiotic nature, hence they are the first step in establishing our qualitative-quantitative methodology. Therefore, this research provides a method to grade general elements, based on five-point system from 1 to 5, and calculate their weight on the sample area of research. The key point of the method is its simplicity and utility for other researchers throughout the world, using available GIS (Geographical Information System) software (preferably free and open-source) and readily accessible data about the area of research, based on topographic maps, socio-geographic data, geological maps, and satellite images.

The scale of research was specifically tailored to the available data, and to be confirmable through direct on-ground observation during field visits to the studied area. Hence, the results contain the final grade of our assessment and field photographs of the landscape demonstrating the visual appearance of the region in comparison to geodiversity values of the assessed territory.

4.1.2 Materials and Methods

4.1.2.1 Aim

The main goal of this research is to present an easy replicable qualitative–quantitative analytical method to assess geodiversity. The method is expected to provide enough information to separate the most unique and rare types of territories quickly based on the easy-to-access geological and geomorphological data accompanied with field validation. This method is the basis of the assessment of geodiversity in selecting the most suitable places for further research and data collection to establish systematic plan for geoeducation and geotourism. Recognition of high geodiversity values within a given area is based on scientific data, which helps to define zones for next promotion and preservation based on geodiversity spectrum. A further aim of this research is to make this method as simple as possible, yet objective and practical enough to assess geodiversity throughout the field by readily utilizing accessible data and tools.

4.1.2.2 General Geographical Presentation

To develop our method, we chose the territory of the Coromandel Peninsula, which is in the North Island of New Zealand between Hauraki Gulf and Bay of Plenty districts (Figures 4.1.(1) and 4.1.(2)) (Hayward, 2017, Homer and Moore, 1992). The western part of the selected area consists of low-land plains with crop fields, while the north and the east are hilly meadows, used as pastures (Marden and Rowan, 2015). Within the central parts of the peninsula, there are known tourist hotspots such as Hot Water beach, Cathedral Cove, Coromandel town and other distinct locations, while the north and south of the region are recognized as nationally significant biology conservation areas especially for endemic species of birds such as Brown Kiwi (Apteryx mantelli) or trees like Kauri (Agathis australis). However, for this assessment we chose only the northern part of the peninsula including the settlements of Port Jackson, Fletcher Bay, and Port Charles (Figures 4.1.(1) and 4.1.(2)) (Schneider et al., 2017) as this provides a relatively small area of diverse geological and geomorphological elements (around 20.5 km^2), which will be described in the next sub-sections.

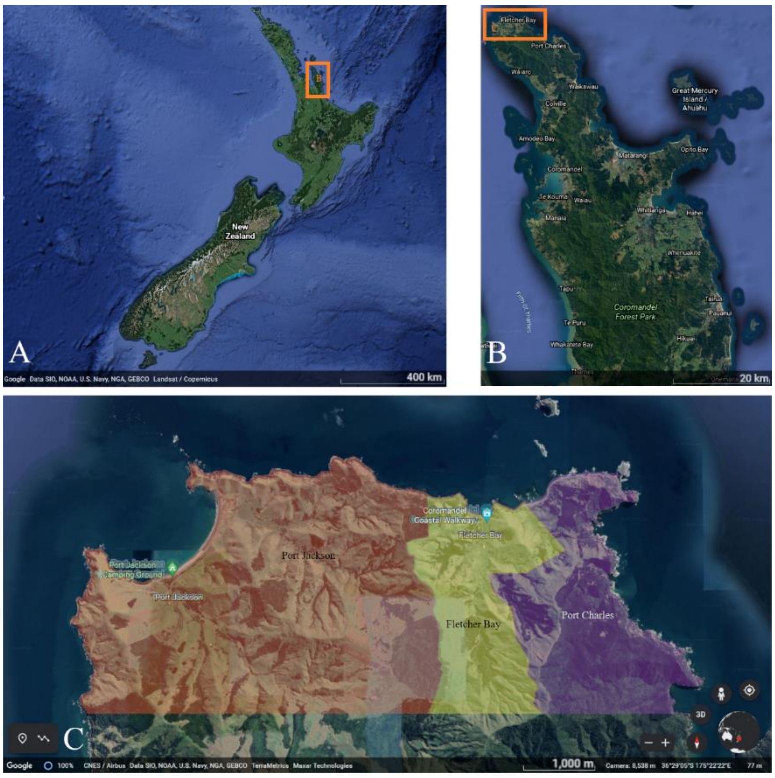


Figure 4.1.(1): The location of the studied territory. (A) New Zealand. (B) the Coromandel Peninsula. (C) The north part of the Coromandel Peninsula: Port Jackson district (orange on the left), Fletcher Bay

district (yellow on the center), and Port Charles district (purple on the right) show area of the research. The pictures were taken from Google Earth and the districts from Google maps.

4.1.2.3 Geomorphology

From a geomorphological perspective, the northern Coromandel Peninsula is also highly diverse, with a range of topographic relief (Booden et al., 2012). The geological basement of the studied territory is sedimentary rocks (Late Jurassic greywacke—Manaia Hill Group sediments) forming a variety of rolling hilly meadows, with the highest elevation in the south 476 m. Coastal areas feature Miocene to Pliocene andesitic remnants of volcanic eruptions (Coromandel Group andesites and dacites) (Hayward, 2017). From the Port Jackson coastal area hydrological features include two main streams: Pahi in the south part of the shore and Muriwal in the north (Figure 4.1.(2)) draining the inland catchment, while Holland creek drains a catchment formed by the Fletcher Bay district. In conclusion, the territory contains a variety of hills with different slope angles climbing from the shore towards the inland hills, andesitic rock cliff sites) and five different rock types underlying the visible landscape, making it an ideal area and testing ground for our first geodiversity assessment.

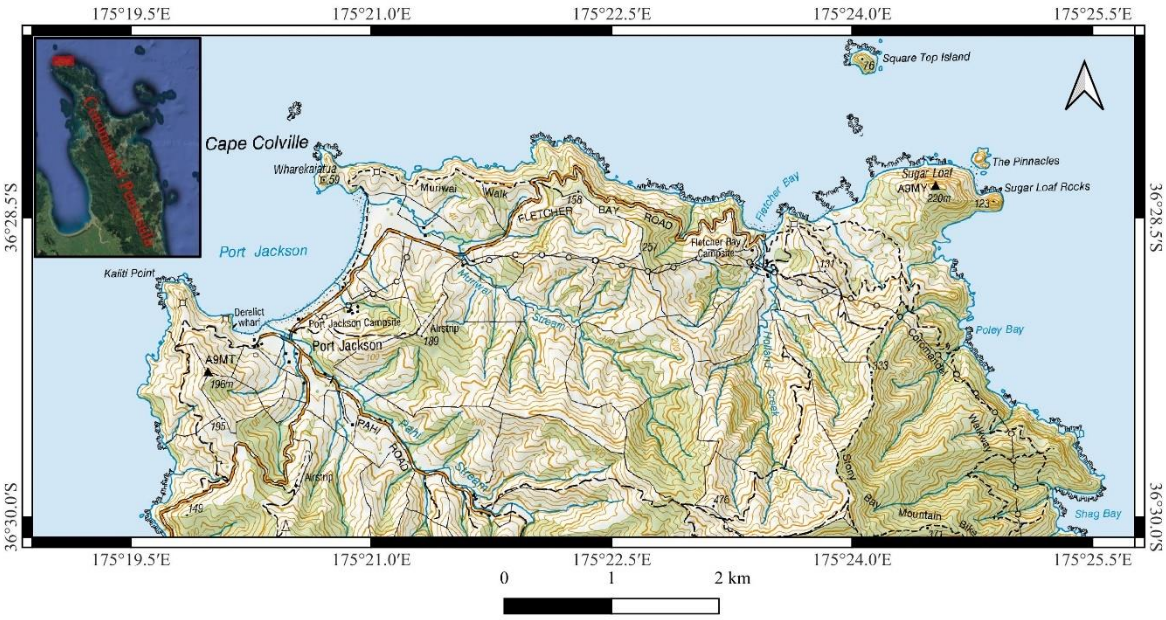


Figure 4.1.(2): Detail from the topographic map of New Zealand (Moehau NZTopo-AZ34) 1:50,000 scale showing the territory of the northern part of the Coromandel Peninsula: Port Jackson, Fletcher Bay, and Port Charles. The small satellite image (on the top left side) shows the whole territory of the Coromandel Peninsula.

4.1.2.4 Geology

The peninsula has a diverse geology, which is related to the remnant of rhyolite and ignimbrite volcanism (Whitianga Group) with four identified calderas spreading from the center to through the SW of the Peninsula. Meanwhile, the basement is Jurassic greywacke, which can be found in the NW part of the field (Mortimer et al., 2017, Mortimer et al., 2014), while andesite and dacite groups are the most common rock formations throughout the whole territory from Miocene to Pliocene volcanic activity (Hayward, 2017, Briggs and Fulton, 1990, Adams et al., 1994, Malengreau et al., 2000, Nicholson et al., 2004, Smith et al., 2006, Booden et al., 2012, Homer and Moore, 1992). Additionally, plutonic rocks such as granite–granodiorite commonly referred to as "Coromandel Granite" in the far north of the peninsula at Paritu Bay have been widely used as decorative building stones across New Zealand between 1900–1970s, for example in New Zealand's Parliament Buildings, the Auckland Chief Post Office, and the Auckland War Memorial Museum (Hayward, 2017, Homer and Moore, 1992, Black, 1972, Skinner, 1975, Garmson et al., 2014). While today the trip from Paritu Bay to Auckland takes around 4–5 hours by motor vehicle, during the mining period, the journey could take two days by land. However, large blocks of Coromandel Granite could be transported from the mining area to Auckland by boat using a direct route across the Firth of Thames "as the crow flies". Similar plutonic rocks cannot be found elsewhere at the surface in the North Island; hence it is a single building and decorative stone source with high geocultural values as part of New Zealand heritage (Garmson et al., 2014). Additionally, Quaternary deposits and some Early Miocene sandstone/siltstones and mudstones crop out mostly on the eastern part nearby Miocene andesites (Figures 4.1.(2) and 4.1.(3)).

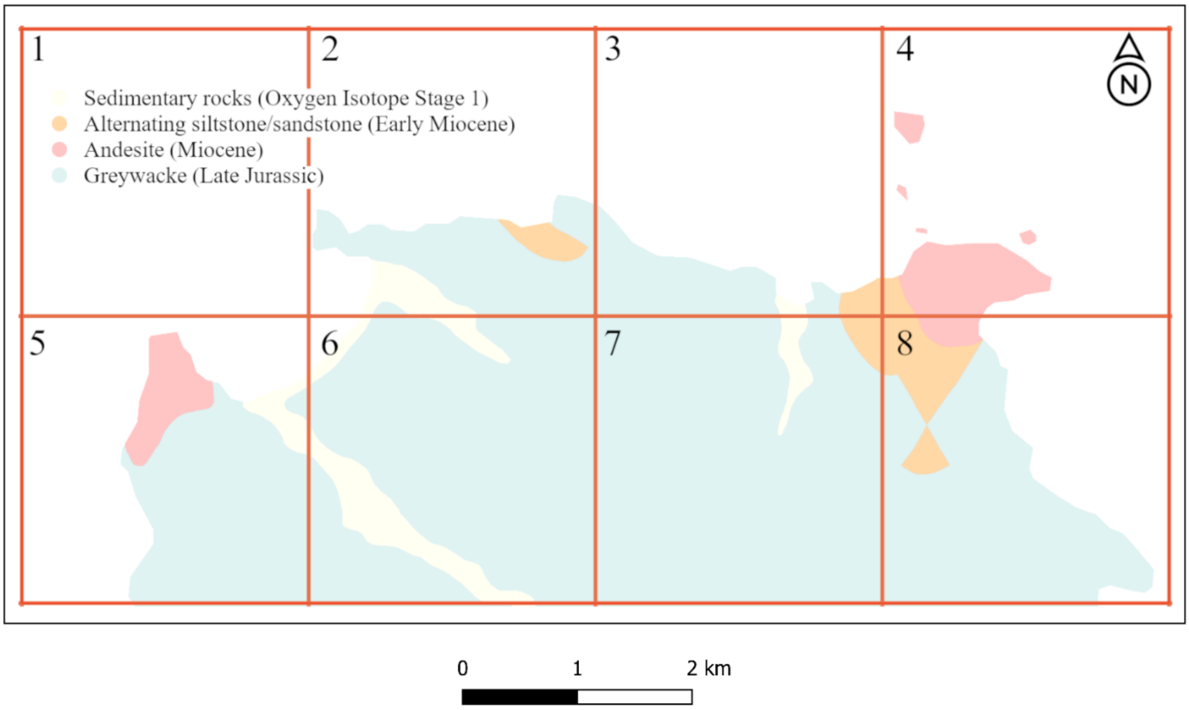


Figure 4.1.(3): Detail from the Geological Q-Map of Auckland area 1:250,000 (Edbrooks, 2001) including the territory of Port Jackson, Fletcher Bay, and Port Charles, the north part of the Coromandel Peninsula. The area of research contains 4 rock types: Quaternary sedimentary rocks (Oxygen Isotope Stage 1), alternating siltstone/sandstone (Early Miocene), andesite (Miocene), and greywacke (Late Jurassic).

4.1.2.5 Method

The introduction and testing of the methodology are the major subject of this paper outlining the conceptual foundation and theory behind our research. The definition of geodiversity was the main source information used to create and populate the table of elements of geodiversity presented here (Table 4.1.[1]) (Brilha et al., 2018). In this table (Table 4.1.[1]), the main value shows the current geodiversity of the territory, then additional values are defined as weighted by different processes (climate, hydrology, human and biological footprint) that bring about changes to the original geology and geomorphology as well as other elements of the main values. The main value includes seven elements such as geomorphology, geology, structural elements, caves, volcanoes, and soils (Gray, 2008a, Gray, 2008b, Brilha et al., 2018, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007). Additional values are given to the four parameters including hydrology, climate, biological and human footprint. However, in this methodology, we concentrated on the main values of geodiversity, more precisely on geomorphology and geology as the core elements of our table as descriptors of the abiotic environment. These elements describe the form and quality of the area, and they are common throughout the Earth, while other elements of main values (volcanos, caves, weathering mass, and structural elements) are connected to places with conditions that contribute to evolution of these processes. Additionally, soils were not mentioned above, as this element is considered to fall within the sphere of biological activity and will be studied in future research (Bétard and Peulvast, 2019, Lausch et al., 2019, Rangel et al., 2019, Stavi et al., 2019, Fossey et al., 2020, Reverte et al., 2020, Santos et al., 2020, Zaady et al., 2021). Notably, soils represent the interface between abiotic and biotic nature and processes, with soil formation and type impacting on the geocultural aspects of societal development, such as evolution of agricultural practices.

Table 4.1.[1]: Table of the proposed conceptual framework of the geodiversity of the Coromandel Peninsula. The table contains two main objects: geology and geomorphology, while additional objects are hydrology, climate, human and biological footprint. Every object contains several elements, which describe it in more details.

Main Values **Geology and Geomorphology**	***Morphology and Valley Network*** General topography of the region	Definition of landform categories, valley network and slope angle categories
	Rock and Fossil Types Definition of the rocks, fossils, and their ages	Spatial representation and weight value assignments of specific rock/fossil types
	Volcano types Definition of the volcano types recorded in the field	Application of volcano geology model to calderas, intermediate stratovolcanoes, and small monogenetic volcanoes (assignment of values)
	Caves Identification of caves	Measuring numbers and types of caves as well as their spatial distribution pattern
	Alteration, Weathering and	Application of weathering index to surface areas, assignment of number

	Mineralization Definition of alteration and weathering types	density of altered and weathered surfaces and mineralization types
	Structural elements Definition of faults and folds in the context of the region structural geology	Spatial measurement of the types and abundances of the structural elements
	Soil – Mass movement Identifying type, distribution, and mass movement	Categorization and valorisation of soil types and mass movements with spatial representation
Additional Values **Hydrology – Hydrosphere**	***Drainage network*** Identifying the drainage pattern and types (links to the "valley network" but measuring the current runoff pattern)	Measuring of drainage pattern, assigning values of water production
	Lakes – Swamps – Marshland Identifying their locations	Spatially assigning values of swamp in respect of their geological entity
	Coastal Hydrosphere Identifying coast types, tidal zones, and shallow marine environment	Defining the values associated with specific coastal environment
	Geothermal and Hot Spring Region Location and definition of their types	Associating values of their significance in geological context
Climate	***Weather Pattern, Wind Pattern and Sunny Hours*** Identification of weather pattern, seasonality, and paleoclimate	Categorization of weather patterns in geological context with special reference to orogenic rain fall data, temperature variation and sun exposure data
Biological Footprint	***Modern Biological Impact on Rocks and Soils*** Identifying biological footprint types	Categorization of biological footprint types (marine, domestic/wild animals, and humans)
Human Footprint	***Human Occupation Sites and Archaeology***	Categorization of archaeological values and spatial representation of them.

	Identification of type of archaeological sites, human activities, cultural horizons and geological tool mastering and trading	
	Mining and Natural Resource Utilization Identification of ore types, distribution, and exploitation through history	Categorization of ore and economic geology sites of the region

Geology and geomorphology were studied in detail to create the table of values (Table 4.1.[3]) that define the weight for each element, based on a five-point system. Geomorphology was divided based on the slope angle (steepness) of the landscape from 0 to 90 degrees, where 0–7.5 is 1 (the lowest value), 7.5–22.5 is 2 (low value), 22.5–45 is 3 (middle value), 45–67.5 is 4 (high value) and 67.5–90 is 5 (the highest value). We focused here on the morphometry of the landscape as slope angle is one of the simplest values we can extract from the landforms without complex analysis and justification allowing us to define geomorphology elements. Integrating the geodiversity elements of the region with the geomorphology feature, their description and development will be the next step we intend to explore. The grades were created according to previous studies about erosion processes, weathering, and geological outcrops (Zhuchkova and Rakovskaja, 2004, Davis, 1973). It shows that processes have a stronger influence on the steeper relief on the evolution of the “geographical cycle”. For example, uplift creates new geomorphological formations, and over time weathering processes become a trigger for landform collapse, leading to a state of equilibrium and being reduced closer to sea level (Davis, 1899, Davis, 1922). Meanwhile, “geomorphological entropy” has a connection with the second law of thermodynamical entropy; describing increase in entropy in every natural process providing all systems included in the process are considered (Leopold and Langbein, 1962, Davy and Davies, 1979, Ferrer-Valero, 2018, Phillips, 2010, Milaghardan et al., 2020). The increase in entropy drives losses in energy used for mechanical work. Therefore, it can be used to define the degree of short-term weathering (unlike “geomorphological cycle”), which in geomorphological research is mostly used for assessment of rock weathering provoked by hydrological processes (river flow, precipitations, oceanic activity) (Leopold and Langbein, 1962, Huggett, 2007, Zhao et al., 2017). Geomorphological entropy can be used for connection of core geodiversity (main value) with hydrology (additional value) (Table 4.1.[1]).

The assessment of “geological” elements is based on the research of proportion of rock types exposed on the surface of Earth (Blatt and Jones, 1975) (Table 4.1.[2]): sedimentary rocks cover more than half (around 66%) of the Earth’s surface, while igneous rocks are only 17% (consisting of 8% extrusive and 9% intrusive). Metamorphic and Precambrian rocks (grouped together) also comprise 17% of the surface, with metamorphic evolution only taking place through temperature- and pressure-driven processes occurring deep below the Earth’s surface (Yardley and Warren, 2021). Using the rareness of the rock types, we have established a five-point system as shown in Table 4.1.[3]. Sedimentary rocks from the Cenozoic period have the lowest value, which is 1 (as proxy for the most common rock types on the Earth surface), sedimentary–Mesozoic are 2 (low value), metamorphic and Precambrian are 3 (middle value), sedimentary–Paleozoic are 4 (high value), and extrusive and intrusive rocks from any period are 5 (the highest value) as they are the rarest type of rocks throughout the Earth's surface. While this survey was conducted some time ago, its resolution is sufficient to provide a good first order proxy to calibrate the weight we assign to each main rock type. Here, we keep the global rock abundance ratios as a key for our weighting system as the main aim of our study is to develop a first order proxy method to express geodiversity compared to a global reference frame.

Table 4.1.[2]: Percentage of rock types exposed on Earth's surface as function of geological age (Blatt and Jones, 1975). According to the table, extrusive and intrusive rocks are the rarest, while sedimentary rocks, especially Cenozoic, are the most common at the Earth's surface.

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
Paleozoic	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

Table 4.1.[3]: The evaluation system of the main values of geodiversity. The table shows the summary of grades and underlying values of four elements of core geodiversity. Morphology can be assessed according to the steepness of the slope, with geology and rock types and their ages also dependent on amount of surface exposure. Color codes are used as guide to better distinguish various rock types by their age.

Main Values of Geodiversity		
Quantities of each value (5-point system)	Elements of Geodiversity	
	Morphology	Geology
	Slope degree	Rock type and ages
1 (the lowest)	0–7.5	Sedimentary–Cenozoic
2 (low)	7.5–22.5	Sedimentary–Mesozoic

3 (middle)	22.5–45	Metamorphic–Precambrian
4 (high)	45–67.5	Sedimentary–Palaeozoic
5 (the highest)	67.5–90	Extrusive and Intrusive

After the initial calculations, we add up the final values of geology and geomorphology of the studied area, thereby defining discreet areas most likely to benefit from further investigation to confirm these rankings. Therefore, on a final scale of 1 to 10 points, 0–2 points are the lowest value, 3–4 points are low value, 5–6 points are middle value, 7–8 is high value and 9–10 points are the highest value. Ideally, the highest value can be seen only with extrusive or intrusive rock with the slope steepness from 45 to 90 degrees. Alternatively, a high value could also be assigned to an area featuring sedimentary rock from the Precambrian period with a steepness from 67.5 to 90 degrees. Furthermore, the areal extent of each element will be included in the equation (section 4.1.2.7 Equation), which will also influence the final mark. In conclusion, to obtain the highest value, the territory must be unique from both a geological and geomorphological perspective. However, we have aimed to define best sites for further investigation, i.e., those which have a middle and higher final mark according to the previously described ranking system. The scale of research is also important for our study as this will have a direct influence on these and subsequent results, to be discussed in the next sub-section.

4.1.2.6 Scale of Research

Scale may be considered one of the most important parameters in any kind of research and will often depend on the stated aims and applied methodology, extent of the studied area, and type of data available for the study. To select a suitable cell size for calculations and define parameters for further observations, we divided the proposed area of research using a grid with equal squares and calculated an arithmetic average of the specific geodiversity elements for each of the measured cells. The area of each square of the grid was selected to be an area of 6.25 km^2 formed by sides 2.5 km in length (regions can be seen in Figures 4.1.(3–6)). This cell size for geodiversity calculation fits well with our data material for assessment including the topographic map (Moehau NZTopo-AZ34) 1:50,000 and geological Q-Map of Auckland area 1:250,000 (Edbrooks, 2001). Additionally, the methodology for creating a geological map at 1 to 250,000 scale requires data collection at every 250 m, which allows for 10 observation points, while the distance of 2.5 km for each side of the cell can be readily matched to the meridian grid on a 1 to 50,000 scale topographic map (Figure 4.1.(7)).

Moreover, the scale must also be equivalent to the visibility range of an average person to allow for ground-truthing of results in the field through standard observation, and images recorded from the field (Figures 4.1.(8–10)). The scale of our research is based on 2.5 km interval for each region, as this distance is less than half of human vision range. Studies on the range of human vision show that a person can recognize an object at 6 km in dry and bright weather conditions without any kind of obstacles between the observer and the object (Kim, 2018), while another study showed that a candle flame at night can be recognizable for a human at a distance 2.6 km (Krisciunas and Carona, 2015). We note these studies to demonstrate this scale allows for on ground observations in a variety of field conditions to support the value given to a site. In the results section, we present images from the eastern zone of the studied area (Figures 4.1.(8–10)) demonstrating that an observer can see geological and geomorphological objects from one side of the applied grid to another.

4.1.2.7 Equation

In this research, we pay more attention to rock type according to its rareness throughout the world (quality), and slope angle for geomorphology (quality) (Table 4.1.[3]), then multiplied this by the area of their extent (quantity). The rarer type of rock and/or the higher slope angle combined with a wider area of spread will be assigned a higher value, as an indication of unique and specific values of the studied site (we provide further details in section 4.1.2.10 The Assessment of Geology).

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

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

where, ($\boldsymbol{p}$) is the number of points of element (geology or geomorphology (Table 4.1.[3]) [–], ($\boldsymbol{s}$) is the area of element ($\boldsymbol{p}$) [L], and ($\boldsymbol{S}$) is the area of research [L]. Measurements: “L” – length, “–“– the number of value not-defined.

The equation shows the weight of each studied element (geology and geomorphology) extrapolated to its area of spreading. Meanwhile, each grid section (cell) (described in section 4.1.2.10 The Assessment of Geology) shows the area of research (or region), which has geological formations according to the geological map (Figure 4.1.(3)) or a few different slope angles (Figure 4.1.(5)). For example, region 4 (the northeast part of the studied area) from the geological map (Figure 4.1.(3)) contains two types of rocks: Miocene andesite and alternating early Miocene siltstone/sandstone. The white area in the region has been not included in the calculation as it is ocean and has no surface geology. Subsequently, a value for each rock type will be calculated according to the equation presented above.

Region 4 has an andesite rock formation, with few islands; their value ($\boldsymbol{p}$) is defined as 5 (Table 4.1.[3]) with area of spreading ($\boldsymbol{s}$) 0.570 km^2, while alternating early Miocene siltstone/sandstone is given a value of 1 point ($\boldsymbol{p}$) and area ($\boldsymbol{s}$) 0.058 km^2 (scheme of assessment presented in Figure 4.1.(4)). Thus, the equation is as follows:

$$\boldsymbol{D} = \frac{(\mathbf{5} * \mathbf{0.57}) + (\mathbf{1} * \mathbf{0.058})}{\mathbf{0.628}} = \mathbf{4.63}$$

We obtain a result of 4.6 (or 4.63) out of five, which is at the very high end of the scale of points based on geological assessment. The geomorphological assessment is based on the same principal, but for points ($\boldsymbol{p}$) the range of slope angles will be used (Table 4.1.[3]) and their area ($\boldsymbol{s}$).

4.1.2.8 The Data for Assessment

The assessment of geology and geomorphology requires only two types of information and two types of software for preparation and calculation:

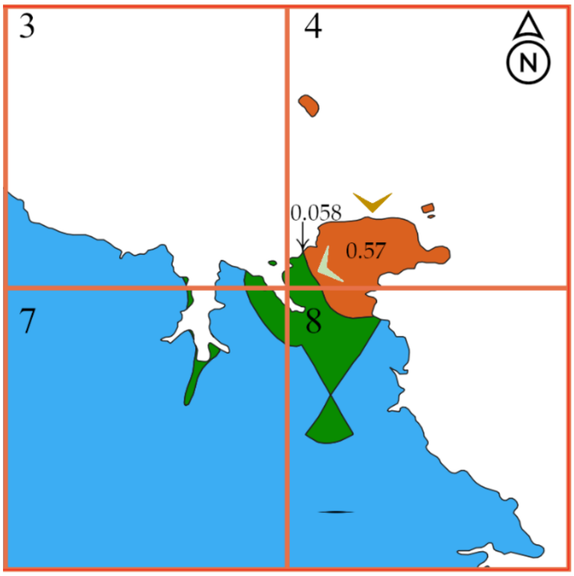
- Geological map model 1:250,000 (as vector polygons). We used Geological Q-Map of the Auckland area 1:250,000 (Edbrooks, 2001) to create a polygon file (SHP format) (Figure 4.1.(3)) using the drawing tool in QGIS freeware (QGIS, n.d.).

- DEM (or vector of elevation model). In our research, we used the vector (SHP format) of contour lines file of elevation of the territory based on the topographic map (Moehau NZTopo-AZ34) (1:50,000 scale) of studied territory (Albut, 2020) (Figure 4.1.(2)), 8m Digital Elevation Model (DEM) (LINZ, 2023), and SRTM 1-Arc-Second Global (Eros, 2015).

- As mentioned above, GIS software such as QGIS (QGIS, n.d.), Grass GIS (GRASS, n.d.), SAGA GIS, EASY trace can be used for preparation of vector files (SHP format) (Albut, 2020).

- Excel Office is a good, user-friendly, and popular software from Microsoft. This program contains many calculating algorithms, which can be used for any kind of assessment research.

- Data about geomorphology are needed to create a slope model in QGIS with Grass GIS plugin (QGIS, n.d.).



$$D = \frac{(5 * 0.57) + (1 * 0.058)}{0.628} = 4.63$$

Table 3: The evaluation system of the main values of geodiversity.

Main Values of Geodiversity		
Quantities of each values (5-point system)	Elements of Geodiversity[1]	
	Morphology	Geology
	Slope degree	Rock type and ages
1 (the lowest)	0–7.5	Sedimentary–Cenozoic
2 (low)	7.5–22.5	Sedimentary–Mesozoic
3 (middle)	22.5–45	Metamorphic–Precambrian
4 (high)	45–67.5	Sedimentary–Palaeozoic
5 (the highest)	67.5–90	Extrusive and Intrusive

Figure 4.1.(4): The visual scheme of equation. This scheme shows how to use an equation.

4.1.2.9 The Assessment of Geomorphology

Our methodology uses the slope model as a proxy for geomorphology of the selected territory (Dolan, 2012, Albut, 2020). As mentioned in a previous sub-section (section 4.1.2.8 The Data for Assessment), we used a contour line model, 8m Digital Elevation Model (DEM) both derived from Land Information New Zealand (LINZ, 2012), and SRTM 1-Arc-Second Global from the United States Geological Survey (Eros, 2015) to generate a slope steepness model, according to the geomorphological values (Table 4.1.[3]).

For the next step, we utilized QGIS and GRASS GIS software to create the slope model (Saxena et al., 2020). A researcher must choose a local projection of the studied area (in our case, the New Zealand Transverse Mercator 2000 projection) as they will be more accurate than standard world systems such as WGS 84. We set up 1:1 resolution for GRASS GIS region to create the required slope model, while attempting to create models based on the WGS 84 coordinate system, which provided a poor-quality result. For calculation in GRASS GIS, we propose the module v.surf.rst to create a slope model (steepness) based on vector lines (SHP format), or r.slope.aspect in GRASS GIS and the tool slope (algorithm “gdal:slope”) in QGIS for DEM (TIFF format).

For our research, we used v.surf.rst module in GRASS GIS, which performs spatial approximation based on z-value of input of point or isoline data given in a vector map; GRASS GIS manual (GRASS, 2017). The equation for this assessment was described by Mitasova and Mitas (Mitášová and Mitáš, 1993) in their research, which became the source for the named module in GRASS GIS. Subsequently Warrena and others in 2004 used different types of slope assessment (including GRASS GIS sprain) for comparison (Warren et al., 2004) to find out the number of errors during calculations. This module was utilized as we have ready access to elevation data for the Coromandel Peninsula, such as isolines with z-value (elevation), and contour interval 20 m. During the calculation, we used default parameters of tension 40 and smoothing (-) (Figure 4.1.(5)), then for comparison we decreased the tension parameter to 30 and increased the smoothing parameter to 3 (Figure 4.1.(5)) according to the manual recommendation for landscapes with a wide distance between the points.

Additionally, we utilized r.slope.aspect (GRASS GIS module) to create a slope model based on DEM represented by 8m Digital Elevation Model (Figure 4.1.(5)). The accuracy of the algorithm depends on the resolution of input elevation model as it determines 3 × 3 neighborhood for each cell. 8m DEM created from January 2012 LINZ Topo50 20m contours (LINZ, 2023) is the most accurate type of data for the Coromandel Peninsula available for free use. For calculation, we used default parameters of the mentioned algorithm according to the GRASS GIS manual (Reuter and Nelson, 2009, GRASS, 2017).

SRTM 1-Arc-Second Global coverage around 30 m resolution (Eros, 2015), which is available from USGS database (USGS, n.d.). This model is not accurate enough to utilize r.slope.aspect as it only produces a rough model. However, this issue can be resolved through a simple and fast mesh denoising (MDenoise) method (Sun et al., 2007), created to cut sharp edges and corners on any kind of 3-D model, available for download from Cardiff University site (CSIR, n.d.). We utilized this program to clean and smooth our SRTM model. However, the model still displayed a rough pattern, so the denoised SRTM model was transformed into a vector point model utilizing r.random module in GRASS GIS (GRASS, 2017) with a parameter of 33% for the number of allocated points. Then, based on the point-vector model, we generated the slope (Figure 4.1.(5)), utilizing the previously mentioned module v.surf.rst GRASS GIS, with parameters of 30 for tension, and 3 for smoothing as it was used for a smoother isoline model.

For the final step, all four slope models were reclassified and transformed into polygonal models (Van Westen et al., 2003, Albut, 2020) in QGIS (Figure 4.1.(5)) according to geomorphological values (Table 4.1.[3]). This step was performed as it allowed us to calculate the areas of each created polygon in every region 1–8.

- Slope “Isolines” default—source: contour lines vector model; generation module: v.surf.rst (GRASS GIS), with default parameters.
- Slope “Isolines” 30 intention, 3 smoothing—source: contour lines vector model; generation module: v.surf.rst module (GRASS GIS), with additional 30 intention parameter and 3 smoothing parameters.
- Slope “DEM” default—source: 8 m DEM (LINZ); generation module: r.slope.aspect module (GRASS GIS), with default parameters.
- Slope “SRTM” filtered—source: SRTM 1-Arc-Second Global; filtered by with MDenoise; transformation to point-vector module: r. random; generation module: v.surf.rst module (GRASS GIS), with additional 30 intention parameter and 3 smoothing parameters.

Then, oceanic areas were cut from the slope models (Figure 4.1.(5)), as this part of territory has no visible geological formations, though we note through diving observation and field work some coastal areas emerged during low tide (Figure 4.1.(6)). Meanwhile, we concentrated on the result of slope maps (Figure 4.1.(5)) and began with the first region (top left). This region was not included in the assessment as it is oceanic territory without any kind of rock formations on the surface. Visually, blue, and purple colors are the most dominant throughout the field, confirming that most of the territory has slopes with steepness of 7.5–45 degrees. The eastern zone (Region 4 and 8) contains some areas with steepness higher than 45 degrees, but they are limited in extent. In conclusion, from a strictly visual assessment of generated maps and models, we can see that the whole area will have a low–middle value with a slightly higher value on the east side.

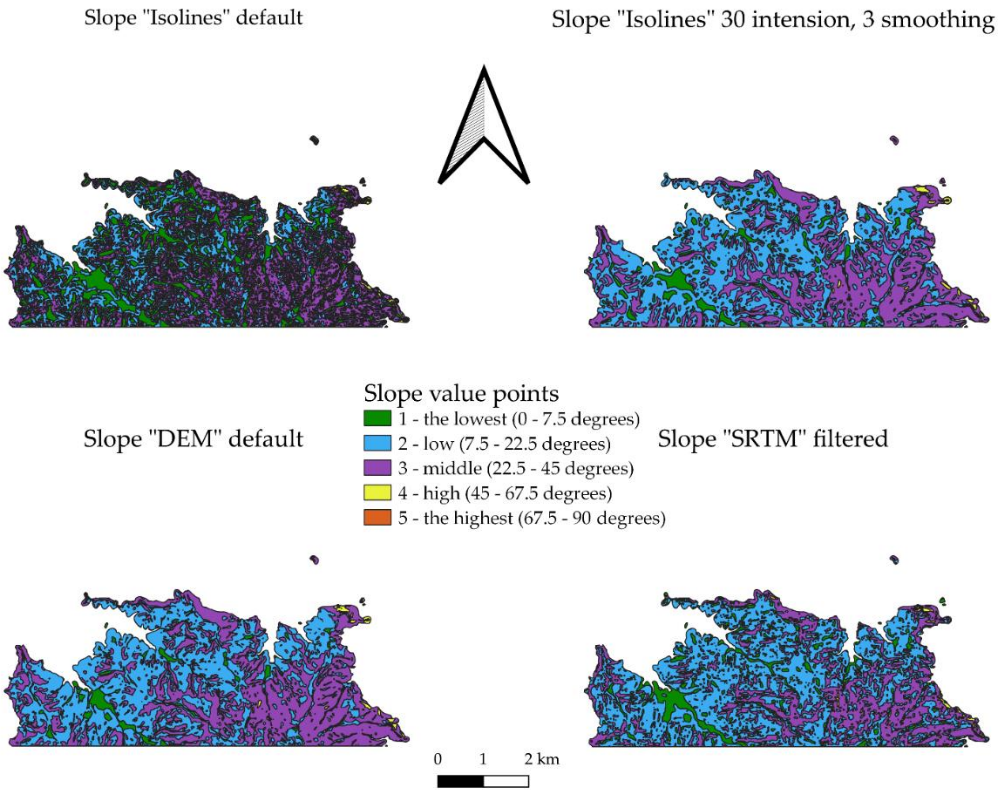


Figure 4.1.(5): Slope polygon vector models of the Port Jackson, Fletcher Bay, and Port Charles districts in the Coromandel Peninsula.

Using GIS, we obtained four slope models generated from different sources and parameters. However, all of them display the same pattern according to slope steepness, which we calculated for comparison utilizing the equation to calculate "geomorphologic" elements according to the values shown in Table 4.1.[3]. From this, we have compiled the geomorphological values (Table 4.1.[4]), showing a value for each region (from 1 to 5) of the studied area according to the different methodology of slope calculation. The results show that models may show minor variations of up to a value of 0.2; however, they will not influence the general index values overall. In comparing the variations in DEM models, we note that the highest values and variations are seen in the 2nd to 6th. For the purposes of this study, at our current scale we may consider these variations negligible, but for more precise calculations they will need to be considered.

Hence, the slope model shows variation dependent on the source (basial vector or raster data used for generation) and methodology, where SRTM is the most available source, resulting in a poor-quality outcome which will require additional changes to obtain a smooth and acceptable result in the slope model, but it does show similarities with Isolines models in contrast to DEM.

4.1.2.10 The Assessment of Geology

Assessment of geology may be considered simpler than for geomorphology, as this will only require vectorized data of rock types and their ages without application of any modeling operations. However, this does require knowledge of each geological formation known especially in the area selected for analysis. For our study, we used the 1:250,000 Geological Map of New Zealand (Q-Map) (GNS Science, 2012) of Auckland area (Edbrooks, 2001). While it is sufficient for this initial research as showing all required geological data, it may not be considered detailed enough for closer evaluation of geodiversity at a higher resolution. Using QGIS, we outlined the northern part of the Coromandel Peninsula (Port Jackson, Fletcher Bay, and Port Charles area) to present this data as vector (Figure 4.1.(3)). Colors on our model (Figure 4.1.(6)) reflect geological values (Table 4.1.[3]), based on the rareness of the rock types (explained previously in section 4.1.2.5 Method) (Albut, 2020).

Table 4.1.[4]: Geomorphological values generated by 4 different methods of slope generation. The blue color highlights similar values between models in our region. The orange color highlights models with a result considered too high in comparison to other models in that region. The green color highlights those models where we consider the results too low in comparison to others in that region. Color codes showing the calculated categories of each region applying various DEM input data.

Region	Isolines	Isolines (smoothed)	DEM LINZ	SRTM (Filtered) [1]
1	0.0000	0.0000	0.0000	0.0000
2	2.1478	1.9885	2.2772	2.0956
3	2.3856	2.4255	2.5258	2.3958
4	2.5654	2.5667	2.6422	2.4510
5	2.2145	2.2570	2.3244	2.1936
6	2.0383	2.1038	2.1706	2.0113
7	2.3418	2.3995	2.3995	2.2868
8	2.6122	2.6527	2.5301	2.7381

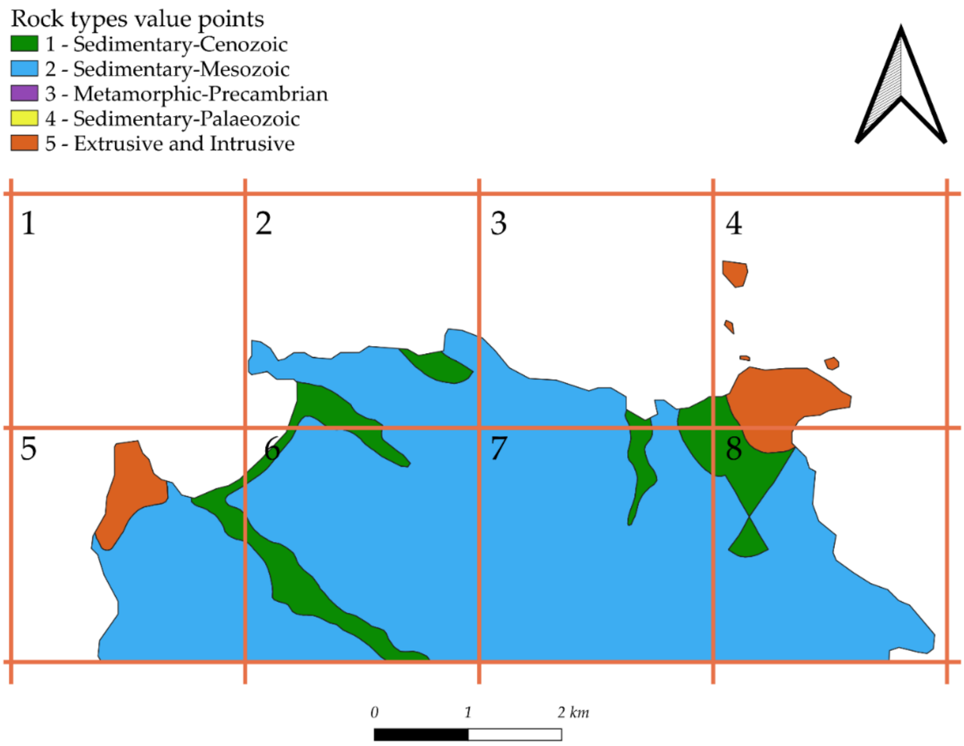


Figure 4.1.(6): Geological polygon vector model of the Port Jackson, Fletcher Bay, and Port Charles districts in the Coromandel Peninsula. According to geological values (Table 4.1.[3]). the green color represents 1 (the lowest value sedimentary–Cenozoic), blue color 2 (low value sedimentary–Mesozoic), purple 3 (middle value metamorphic–Precambrian), yellow 4 (high value sedimentary–Paleozoic), and orange is intrusive and extrusive). Additionally, the grid of 8 cells representing regions of 6.25 km^2 is shown.

Our results have given four different values represented by the colors, out of five rock types exposed on the surface of the studied territory. The number of geological units were decreased as sedimentary rocks (Oxygen Isotope Stage 1), and alternating siltstone/sandstone (Early Miocene) have the same value 1 (the lowest value sedimentary–Cenozoic). These geological units are locally accessible where the ocean has a high influence (especially Regions 6 and 8). The most widespread type of rock is Late Jurassic greywacke (the basement and the oldest rock in the Coromandel Peninsula), which visually takes up around 70% of assessed area and has been assigned a value of 2 (low value sedimentary–Mesozoic). Miocene andesite can be seen only in the southwest and the northeast parts of studied area (Regions 4 and 5). This is an extrusive volcanic rock; hence its assigned value of 5 (the highest value extrusive and intrusive). In conclusion, the chosen territory will have around 2 points in a geological context, because of widespread Late Jurassic greywacke, while Regions 4 and 5 will have higher values as they have Miocene andesite remnants of volcanic activities. The real marks will be discussed in the in the next section.

4.1.3 Results

For calculation, we used Excel Office software utilizing the equation for assessment from the previous section (section 4.1.2.7 Equation). Our results have given us values for eight regions of this area (they can be seen in Figures 4.1.(3–7)). The table of results (Table 4.1.[5]) shows the first region with no data about geology and geomorphology, as this region is oceanic area. Further calculation showed that nearly the whole area has an index value of 2 (low value); however, the geology of the 4th zone has the highest value, 5, suggesting that this zone is very important for further study. Furthermore, this zone and zone 8 have a moderate index value from the geomorphological perspective with a higher number of steep slopes than other areas. Zone 4 has high aesthetic values and is unique as the remnant of a Miocene andesitic volcano, containing several steep cliffs (geomorphology value is 3) and volcanic rocks (geology value is 5). We should remember that only intrusive and extrusive rocks have the highest value in this study, so the sites with present or past volcanic activity will have the highest point of interest. Even though zone 5 also has a Miocene andesite formation, this zone is mostly covered by Jurassic greywacke which has index 2 low, decreasing the uniqueness of the area.

Table 4.1.[5]: The results of assessment of geodiversity of Port Jackson, Fletcher Bay, and Port Charles territory. Eight regions were assessed to obtain the results. The table shows the results for geological and geomorphological assessment. Columns for geodiversity are sum of geology and geomorphology values. Numbers show regions 1–8 presented in article above (Figures 4.1.(3–7)). Value is the column showing the formulaic results after calculation. Final is the same value but presented as whole numbers (suggested by Excel Office). Color codes correspond to the same geodiversity class calculated.

Geology			Geomorphology			Geodiversity	
Number	*Value*	*Final*	*Number*	*Value*	*Final*	*Mark*	
Region 1	Ocean	0	***Region 1***	Ocean	0	0	0
Region 2	1.899626	2	***Region 2***	2.147842	2	4.047468	4
Region 3	1.963703	2	***Region 3***	2.385588	2	4.349291	4
Region 4	4.630127	5	***Region 4***	2.565447	3	7.195574	7
Region 5	2.349688	2	***Region 5***	2.214489	2	4.564177	5
Region 6	1.901862	2	***Region 6***	2.038269	2	3.940131	4
Region 7	1.975958	2	***Region 7***	2.341799	2	4.317757	4
Region 8	1.945017	2	***Region 8***	2.612180	3	4.557196	5

Additionally, we integrated geomorphology and geology to produce results of geodiversity for each region (graphically presented in Figure 4.1.(7)). Here, we can see that zone 4 displays the highest value from our geological assessment and moderate value from a geomorphological assessment, which make this zone more significant than the others. Zone 5 has a slightly higher value in the geological context which is not sufficient to provide an increase of low rank in geomorphology, which make it common to others. The reverse situation can be seen in the 8th zone; with a moderate steepness in geomorphologic context, but this zone is covered by early Miocene sand/silt stone, and which has an index value of 1 and Jurassic greywacke with a low geological index value of 2. In conclusion, the data we have analyzed show the importance of zones 4, 5, and 8, which confirms them as important areas for future study.

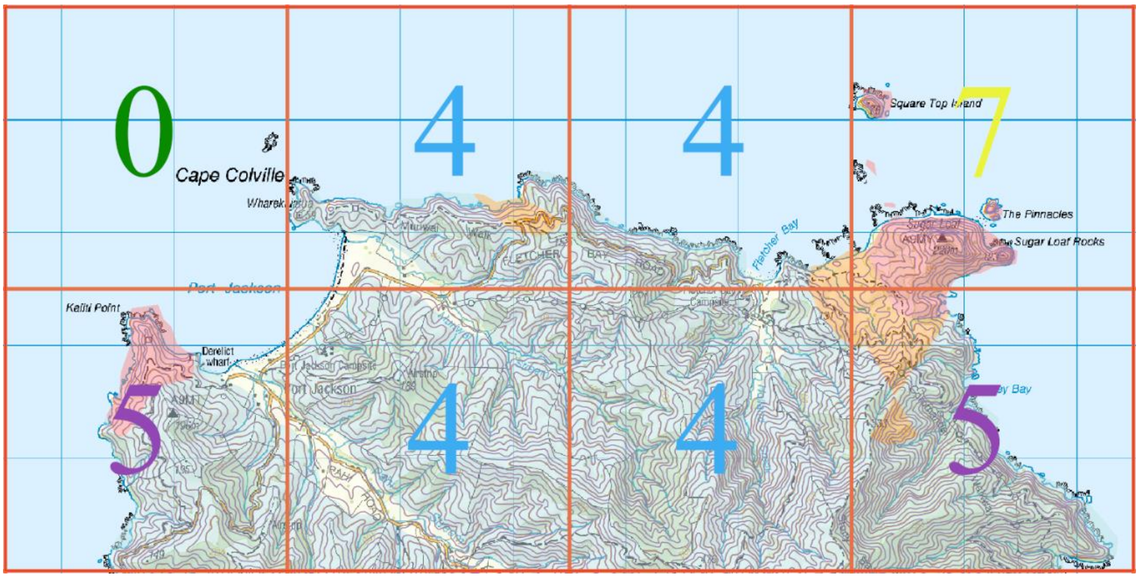


Figure 4.1.(7): The results of the assessment of geodiversity for every zone of the Port Jackson, Fletcher Bay, and Port Charles districts (Coromandel Peninsula). Geological polygon vector model, contour lines, and topographic map are presented as background.

Figure 4.1.(8): Landscape of Port Jackson, Fletcher Bay, and Port Charles districts (Coromandel Peninsula) according to scheme (Figure 4.1.(4)). which at an elevation of around 200 m allows viewing across to the neighboring zones 3, 7 and 8. Additionally, numbers are presented in colors according to their geodiversity final mark (Figure 4.1.(7)).

Figure 4.1.(9): Landscape of zone number 3 Fletcher Bay district (Coromandel Peninsula). This zone has a middle value of geodiversity. geology represented by Late Jurassic greywacke, and Quaternary sediments, while geomorphology is diverse with a distinctive number of green rolling hills. This picture is presented to visualize the scale of research (6.25 km^2 for each zone, 2.5 km the length of side of grid) and full territory of zone 3. Numbers show the places on the picture and topographic map of zones 3 and 4 (bottom left).

Figure 4.1.(10): Landscape of zone number 4 was taken by a drone, Port Charles district (Coromandel Peninsula). This zone has the highest value of geodiversity compared to others in the studied territory. Miocene andesite is representative of the highest geological value, while geomorphology has the middle rate as slope angles are mostly lower than 45 degrees. The circled tree approximately is 5 m in height and elevation parameters are marked to show the scale of the remnants of volcanic formation.

4.1.4 Discussion

In our research, we skipped the assessment of oceanic and coastal areas as this requires a knowledge of and the geology of the seafloor and that is rarely available for the scale of our assessments for geodiversity. However, the oceanic environment can contribute to additional values of geodiversity (Table 4.1.[1]), which we suggest for future research and testing to subsequently include in our methodology. Additionally, our method is in a development stage, which will aim to improve in further research utilizing internal calibration, where the relative weight of various rock types will be calculated against the measured rock abundances on the surface to the vicinity or the proximity of a studied area. Furthermore, the equation will be improved by inclusion of additional values such as soils, structural elements, caves, volcanoes, hydrology, climate, human footprint, and biological processes to provide more accurate and specific mark for the studied zones.

Meanwhile, the selected zones assigned a high value for geodiversity will be studied more precisely to emphasize their uniqueness, which will be the first step in establishing geoeducation, geotourism and geoconservation planning for these zones (For example, zones 4, 5 and 8 (Table 4.1.[5] and Figure 4.1.(7)).

Geological and geomorphological assessment are the core of abiotic nature, but they are not sufficient elements on their own to understand the uniqueness of any territory. The Coromandel Peninsula was settled as a hunting–fishing ground by the Māori society around 800 years ago, then in 19th century, the first Europeans in New Zealand used this place because of the epithermal gold and silver deposits widely spread in the Coromandel Peninsula. This area was initially appealing to human settlers for its biological, geographical, and geomorphological aspects, and over time also came to be valued because of its geological and economical richness. However, in many cases, high geodiversity may have no connection to human preferences, or diverse geology or geomorphology. For example, a territory with low geological and geomorphological values may be the scene of vast human activity. The central part of Ukraine in Eastern Europe described as the “Ukrainian Steppe”, is formed by a large plane territory with low parameters in the context of geomorphology and geology. However, this region is underlain by one of the most productive soils in the world “Chernozem” (Kravchenko et al., 2012, WRB, 2014), with good climactic conditions allowing for significant development of an agricultural society through human history. As a reflection of this, the region contains some of the richest evidence of early agricultural development in human history located on the south bank of the river Dnieper, while on the opposite north bank, hilly and forested areas facilitated development of a society more based on hunter–gathering (Potekhina, 2020, Kołodziejska-Degórska, 2016, Telegin et al., 2003, Telegin, 1987). Such geocultural situations are inferred to influence early urbanization and the same region contains evidence for some of the earliest large urban regions on Earth (Gaydarska, 2020, Chapman et al., 2020, Gaydarska et al., 2020). Therefore, we have included in our research the table (Table 4.1.[1]) containing several elements of main and additional values of geodiversity such as climate, hydrology, soils, and others. This provides the basis for looking forward to establishing a more accurate assessment of geodiversity through a more precise and higher resolution methodology.

As our geomorphological assessment of the studied area is fundamentally based on its morphometry, a question we pose is how new development of advanced geomorphological feature classifications could be utilized in quick geodiversity assessments in the future. Geomorphological classifications have been developed based on various data sourced DEMs or satellite image analysis applying a wide range of remote sensing techniques. Among these new methods, there are certainly promising features that could be used to refine our method. However, a barrier to ready utilization of these techniques is that each of them require data sources not readily available or free to access. Additionally, to generate more complex geomorphological classification requires significantly more resources. In the next stage of our research, we plan to test a variety of suitable geomorphological classification techniques and compare their results internally and with results obtained by application of pure morphometry as outlined in this report. Further research applied to geomorphological classification techniques will establish linkages and test sensitivity to geodiversity and uncover potential advantages over the pure application of morphometry such as slope characterization. All these together form a completely new subject of research we intend to explore in the next stage of our investigation.

4.1.5 Conclusions

In this research, we were able to utilize basic morphometric information and a conceptual framework of the geodiversity of the Coromandel Peninsula to successfully estimate geodiversity values. The method proposed here utilizes easy to access topography data to develop slope angle map as one of the key elements of the geodiversity value calculation. We provided a simple formula that operates through weighted geodiversity values of geological elements obtained from available geological maps and calculated slope angles from topography maps. Using publicly accessible software such as QGIS and GRASS GIS we were able to successfully create simple geodiversity map. We conclude that the generated map is simple and seemingly useful for a first order assessment of any area.

The results of our assessment could be predicted according to information obtained through maps and our slope models. From the whole area of research, three zones out of eight have a high enough value in geology and geomorphology to be selected for more in-depth research and study. Moreover, we have defined a methodology and equation, which can now be used for assessing other places in New Zealand and the world for comparison of results through further research. The selection of the territories relies on the accessibility of the required data and connection with some researchers or institutions, who will be able to check the assessed places. Moreover, the equation should be improved by other main values of geodiversity (weathering rock mass and soils) and additional values such as hydrology and climate. This will help us to assess geodiversity in a more complex way to highlight the unique aspects and values of the studied places.

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Chapter 5 – Further development of qualitative-quantitative assessment of geodiversity and its improvements

Description: In previous studies I established a fundament for development of qualitative-quantitative assessment of geodiversity for the recognition of potential geological locations (geosites), from a scientific perspective. In this study I challenged our methodology applying it to the western islands of Samoa as represented by homogeneous, two shield volcanoes formed with the same basalt rock in period from Pliocene to Historical time. In this study I focus on the search of geologically important locations known as "geosites", and apply terminology such as geodiversity, geosite, and geoheritage. To avoid homogeneity in the result, I include more local diversity of volcanic heritage into the assessment. Eruptive centres and hydrological elements of coastal areas also have been included into the calculation. The result demonstrates the volcanological uniqueness of the region throughout the Samoa western islands.

The published article can be accessed: https://www.mdpi.com/2673-7086/1/3/20 accessed 5th of May 2023

Reference: Zakharovskyi, V. and Németh, K., 2021. Qualitative-quantitative assessment of geodiversity of Western Samoa (SW Pacific) to identify places of interest for further geoconservation, geoeducation, and geotourism development. Geographies, 1(3), pp.362-380.

In this research: the article has been changed to meet the style of the thesis.

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

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 qualitative-quantitative 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.

5.1.1 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 (Gray, 2008a, Gray, 2018, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007). 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 (Manosso and de Nóbrega, 2016, Brocx and Semeniuk, 2007, Cengiz et al., 2021). Meanwhile, geoheritage refers to the values describing geosites with some uniqueness and significance in recording the Earth's history and demonstrating including humans and their society (Brocx and Semeniuk, 2007, Cengiz et al., 2021). 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 5.1.(1)).

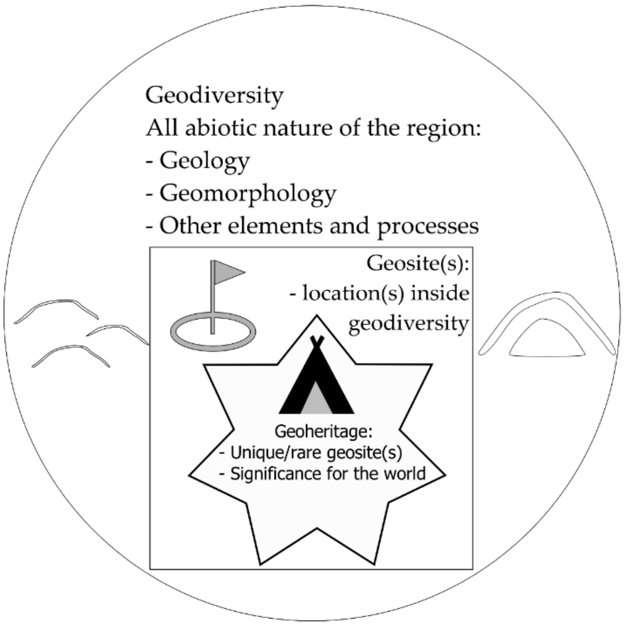

Figure 5.1.(1): Connection between geodiversity, geosite, and geoheritage. Geodiversity includes all elements of abiotic nature. Geosite is a specific location in geodiversity. Geoheritage is unique/rare geosite(s) with significance for the world as demonstrated in other works elsewhere (Williams et al., 2020, Ólafsdóttir and Dowling, 2014).

Utilizing systematic methodologies based on geoheritage databases, researchers may collaborate with government agencies and community organizations to develop strategies for geoeducation, planning for geoconservation, and facilitating niche tourism, including geotourism (Brocx and Semeniuk, 2007, Bentivenga et al., 2019, Cengiz et al., 2021). In the research, a methodology was established to recognize 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 (Zwoliński et al., 2018). Qualitative methodology is based on the expert knowledge and relies on a subjective view of the value system of geodiversity (Gray, 2013, Gordon and Barron, 2013). 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 (Pellitero et al., 2011, Serrano and Ruiz-Flaño, 2007) 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

(Brilha et al., 2018, Gray, 2005). 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 (Gray, 2008a, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007, Zakharovskyi and Németh, 2021, Zwoliński et al., 2018). This method is popular in studies of geodiversity and has been used in several assessments in Brazil (da Silva et al., 2019, Dias et al., 2021, Manosso and de Nóbrega, 2016), Hungary (Pál and Albert, 2021), Italy (Ferrando et al., 2021, Melelli, 2014, Filocamo et al., 2020, Perotti et al., 2020, Piacentini et al., 2019, Miccadei et al., 2011), and other countries. For example, da Silva and do Nascimento utilized quantitative assessment of geodiversity in Seridó Geopark Project, Northeast Brazil (da Silva et al., 2019), and Bétard and Peulvast used it to highlight the geodiversity hotspots in the Ceará State (Northeastern Brazil) (Bétard and Peulvast, 2019). 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 (Zakharovskyi and Németh, 2021). This methodology combines characteristics of qualitative and algorithmic quantitative models (Zwoliński et al., 2018). 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 centers) and coastal areas of the Western Samoa in the SW Pacific (Figure 5.1.(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.

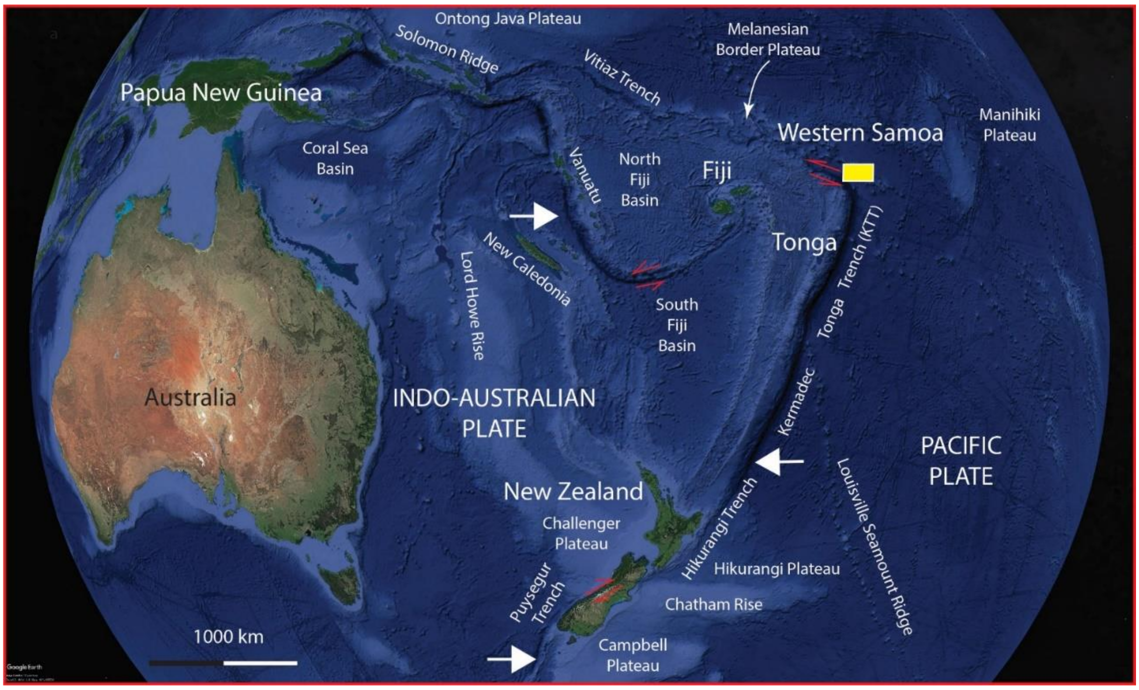

Figure 5.1.(2): Overview of the geotectonic situation in the SW Pacific and Western Samoa on Google Earth Pro satellite imagery. Study area of Western Samoa is highlighted by a yellow rectangle. Relative tectonic plate movements are marked by arrows. White arrows show the subducting plate move direction. 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 5.1.(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 (McDougall, 2010, Kear, 1967). Hence, to increase the variety of features and refine the assessment, the information about the islands' rock ages and identified eruptive centers 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 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 (Eros, 2015) 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") (QGIS, 2024), with its plugin "SRTM-Downloader" (Duester, 2024). 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.

5.1.2 Materials and Methods

5.1.2.1 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 centers have been included into calculations to expand the equation with parameters accessible from satellite images.

5.1.2.2 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 (McDougall, 2010, Kear, 1967) (Figure 5.1.(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 (McDougall, 2010, Kear, 1967) (Figure 5.1.(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 amphitheater-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 a 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.

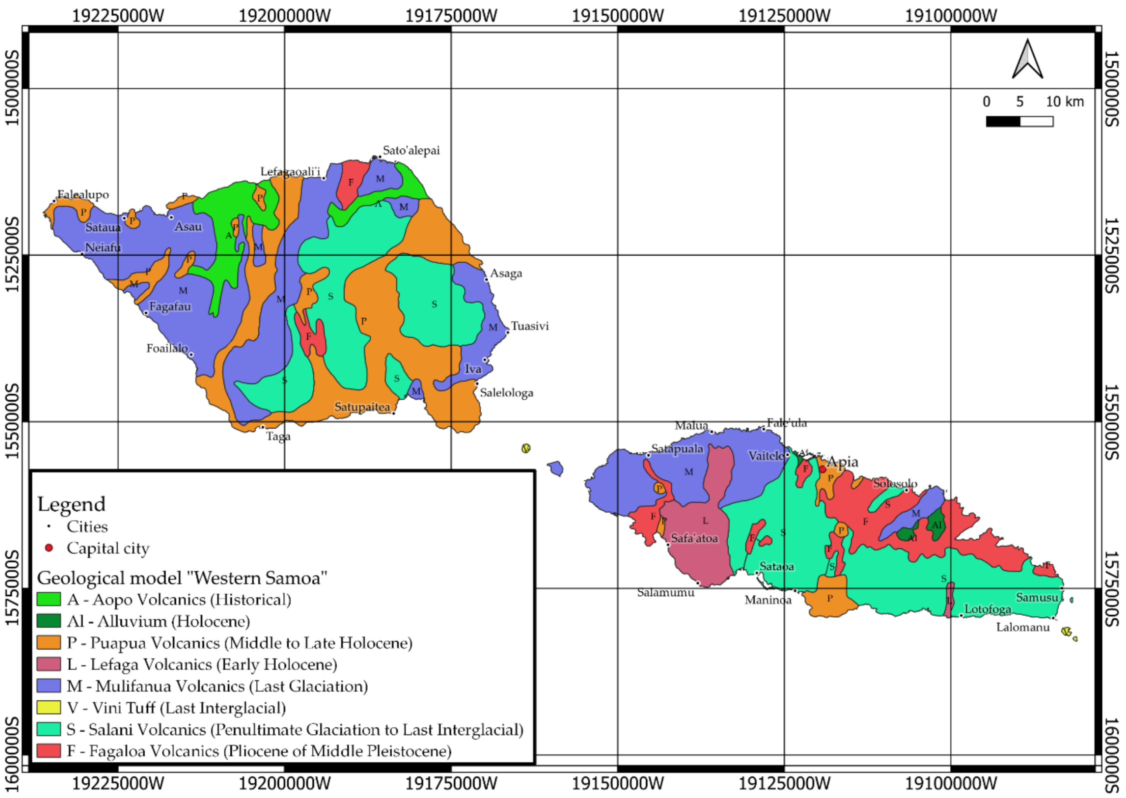

Figure 5.1.(3): Geological model of the Western Samoa adopted from the geological map of Western Samoa (Kear, 1967). Letters on the map are the first letter of geological units' names. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

From a geomorphological perspective (Figure 5.1.(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 center 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.

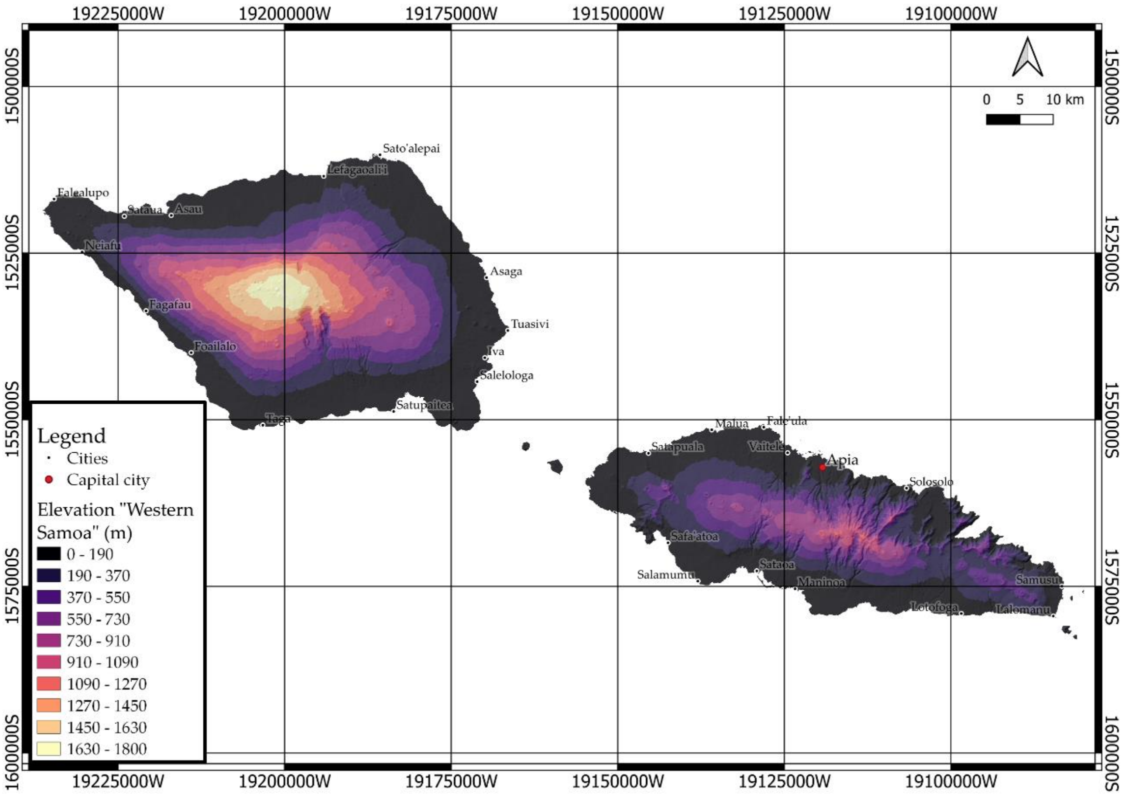

Figure 5.1.(4): Geomorphological model of Western Samoa based on SRTM data available for Western Samoa (Figure 5.1.(2)). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

5.1.2.3 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 5.1.[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) (Gray, 2008a Gray, 2008b, Brilha et al., 2018, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007, Zakharovskyi and Németh, 2021). However, this article assesses only geomorphological and geological elements, with additional values defined for rock ages based on the specificity of Western Samoa's geology. Moreover, the coastal areas and eruptive centers were also added into the assessment, where volcanic features influence the geological values (Table 5.1.[1]).

Table 5.1.[1]: Evaluation system for the Western Samoa region, based on the conceptual framework of geodiversity estimates developed in the Coromandel Peninsula, New Zealand (Zakharovskyi and Németh, 2021).

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

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 5.1.[1]). According to “geographical cycle” (Davis, 1899, Davis, 1922, Davis, 1973), uplift creates a new geomorphological formation, ageing at geological timescales with weathering processes weaken 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) (Davis, 1899, Davis, 1922).

Geological values are based on the rareness of outcropping rock types and their defined ages (Table 5.1.[2]) (Blatt and Jones, 1975). 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 (Zakharovskyi and Németh, 2021). 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 (Kear, 1967). 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 of 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 (Zakharovskyi and Németh, 2021).

Table 5.1.[2]: Percentage of rock types exposed on Earth's surface as function of geological age (Blatt and Jones, 1975). 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 centers and coastal areas were added into the calculation as an additional value for Western Samoa, expanding and refining the general methodology. For eruptive centers, 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 centers. 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 (QGIS, n.d.), access to the Internet, and geological maps. QGIS 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 (Dolan, 2012, Albut, 2020), while a hybrid Google map contains enough visible information to select eruptive centers and coastal areas.

5.1.2.4 Equation

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

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

where (p)—number of points of element (geology or geomorphology (Table 5.1.[1] [-]; (s)—area of element (p) [L]; and (S)—area of research [L]. Measurements: “L” – length, “–“– the number of value not-defined.

This equation is used to calculate all geodiversity elements (Table 5.1.[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 (Kim, 2018). 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.

5.1.2.5 Example of Calculation and Creation

The example of qualitative- quantitative 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 5.1.(5)).

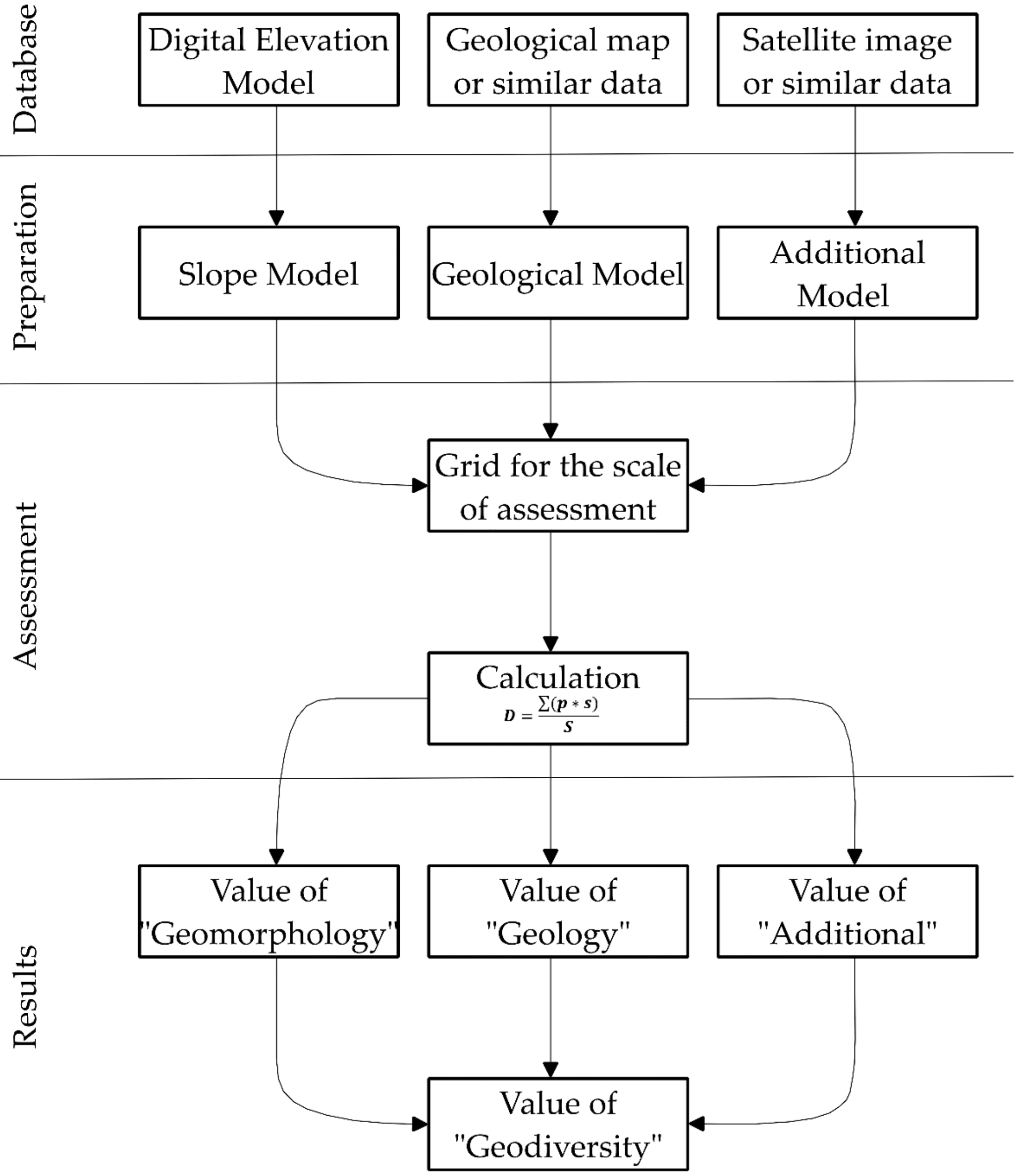

Figure 5.1.(5): Scheme of assessment of geodiversity.

1. The assessment requires geomorphological and geological data.

   (a) DEM (Digital Elevation Model) needed for geomorphological assessment. In this project, SRTM 1-Arc-Second Global model (Eros, 2015) 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 (Tobias and Mandel, 2021, Baghdadi et al., 2018), and selection of additional elements (eruptive centers 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 (Eros, 2015). 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 5.1.[1]).

    (a) Gaussian filter is SAGA (System for Automated Geoscientific Analyses) (Conrad et al., 2015, SAGA, n.d.) 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 polynomial (Schillaci and Braun, 2015, Zevenbergen and Thorne, 1987) based on the filtered SRTM. However, other modules: (slope (GDAL), slope (QGIS), r.slope.aspect (GRASS GIS)) (Reuter and Nelson, 2009, GRASS, 2017) can be used as well.

    (c) The slope model was reclassified by table in Raster analysis (QGIS tool) (Baghdadi et al., 2018) according to parameters of geomorphological values (Table 5.1.[1]).

5. The geological map (Kear, 1967) was transferred into QGIS and polygonised into a geological model.

    (a) The geological map was georeferenced into QGIS project for raster analyses (Tobias and Mandel, 2021, Baghdadi et al., 2018).

    (b) Transformation created polygonal files with associated values (Table 5.1.[1]).

    (c) The polygonal vector model of geology was transformed into a raster file. For this operation, v.to.rst (GRASS) (Reuter and Nelson, 2009, GRASS, 2017) was utilized, where geological values were used as attributes for the raster model.

6. The equation of arithmetic average (section 5.1.2.4 Equation) is acceptable in Zonal Statistic Tool of QGIS (Baghdadi et al., 2018, Jung, 2013). 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 5.1.(6) and

5.1.(7)).

7. The results (Figures 5.1.(7) and 5.1.(8)) were calculated together to get the result of geodiversity.

8. Additional information about coastal areas and eruptive centers were extracted from the satellite Google Hybrid map (parameters for value were used from the Table 5.1.[1]) (Figure 5.1.(6)). Then, results from both models were combined with the previous geodiversity results (Figure 5.1.(9)).

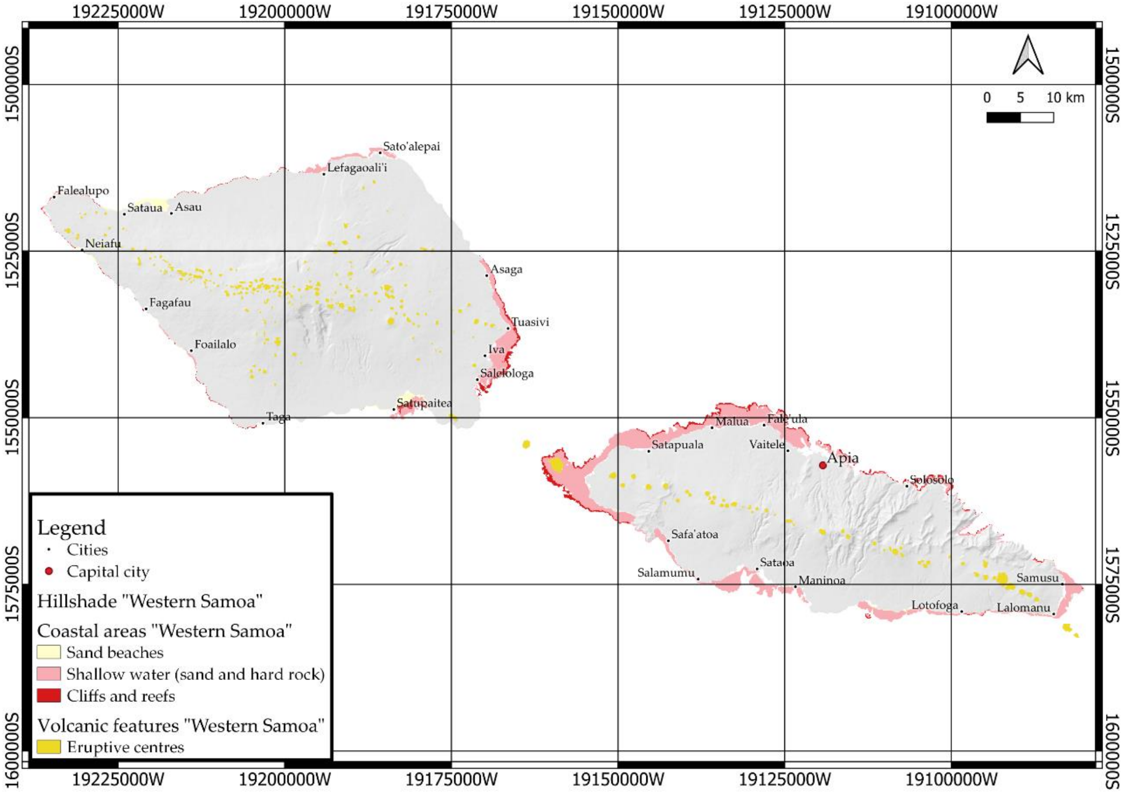

Figure 5.1.(6): Additional elements of geodiversity such as type of coastal areas and eruptive centers extracted from Google hybrid Map in combination with hillshade map. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

5.1.3 Results

Our results define the finalized values used for the geomorphological (Figure 5.1.(7)) and geological (Figure 5.1.(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 centers and coastal areas.

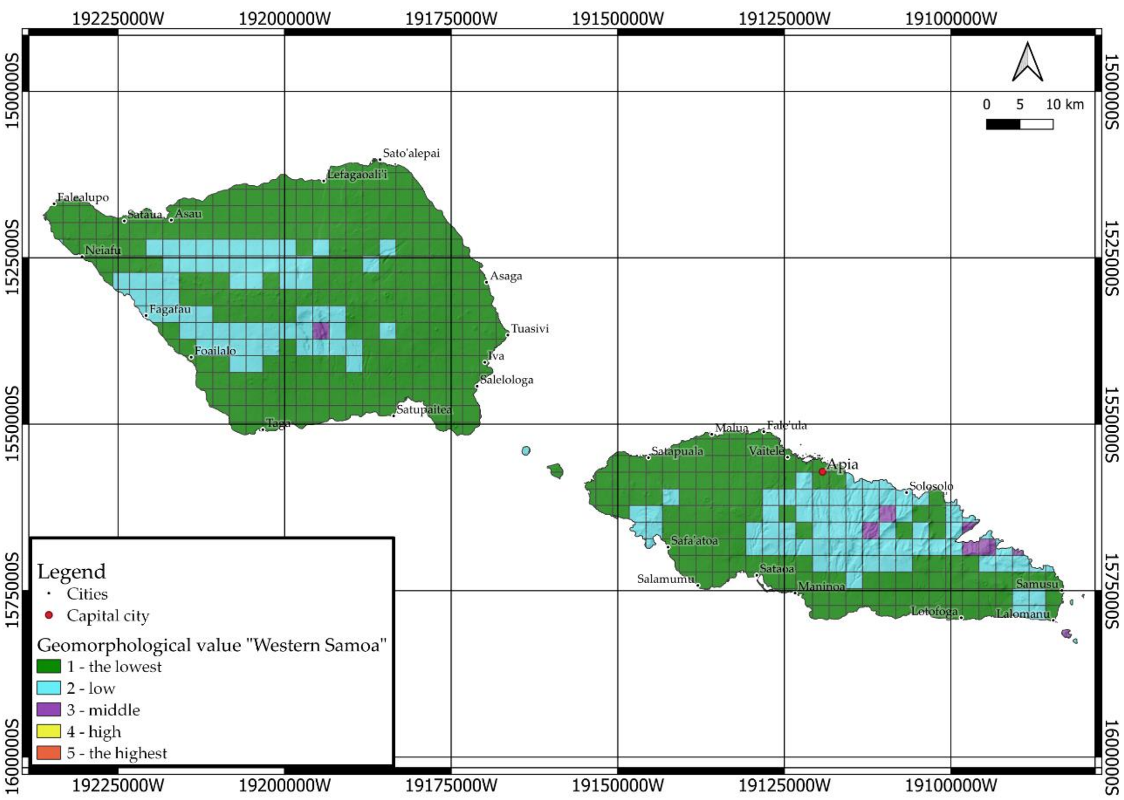

Figure 5.1.(7): Geomorphological value of Western Samoa. The map based on SRTM 1 Arc-Second Global (Figure 5.1.(4)) utilized scheme (Figure 5.1.(5)). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

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 center of the island displays growing steepness compared to the rest of this territory. The only exception is the center 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 center 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 center of the island, and three near the coastal area of the northeast sector.

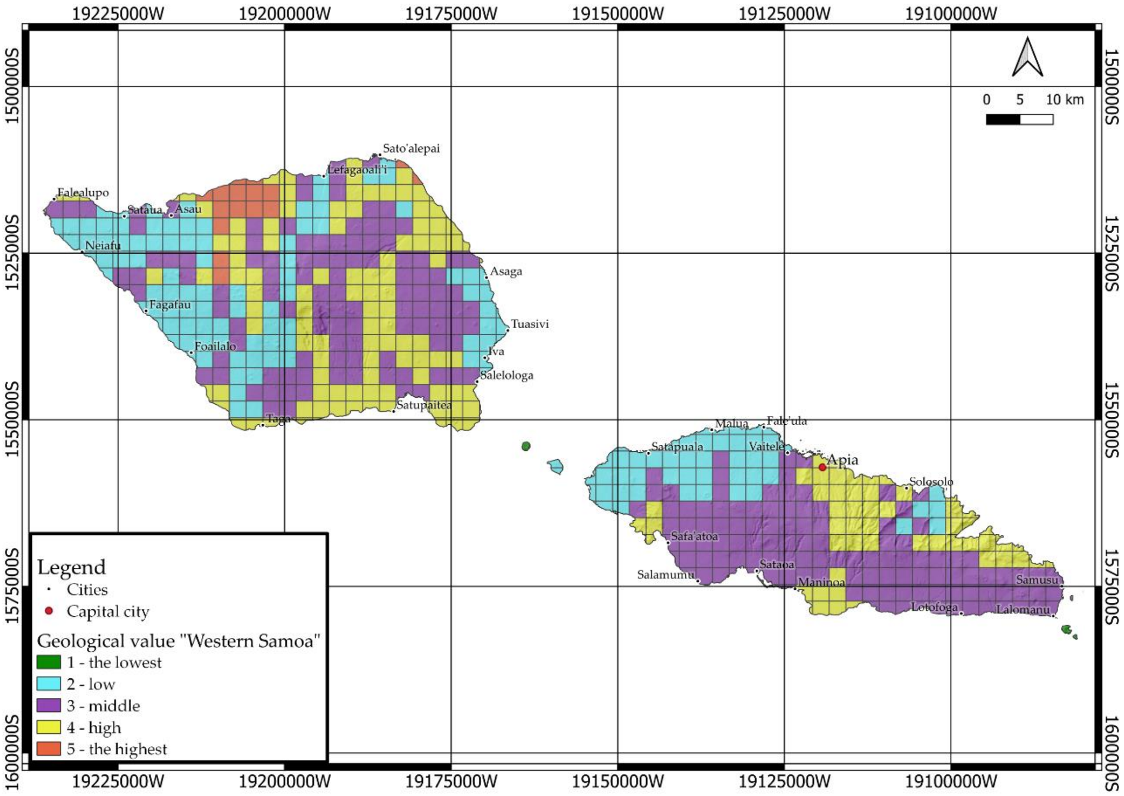

Figure 5.1.(8): Geological value of Western Samoa. The map based on geological model of Western Samoa (Figure 5.1.(3)) utilized scheme (Figure 5.1.(5)). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

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 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.

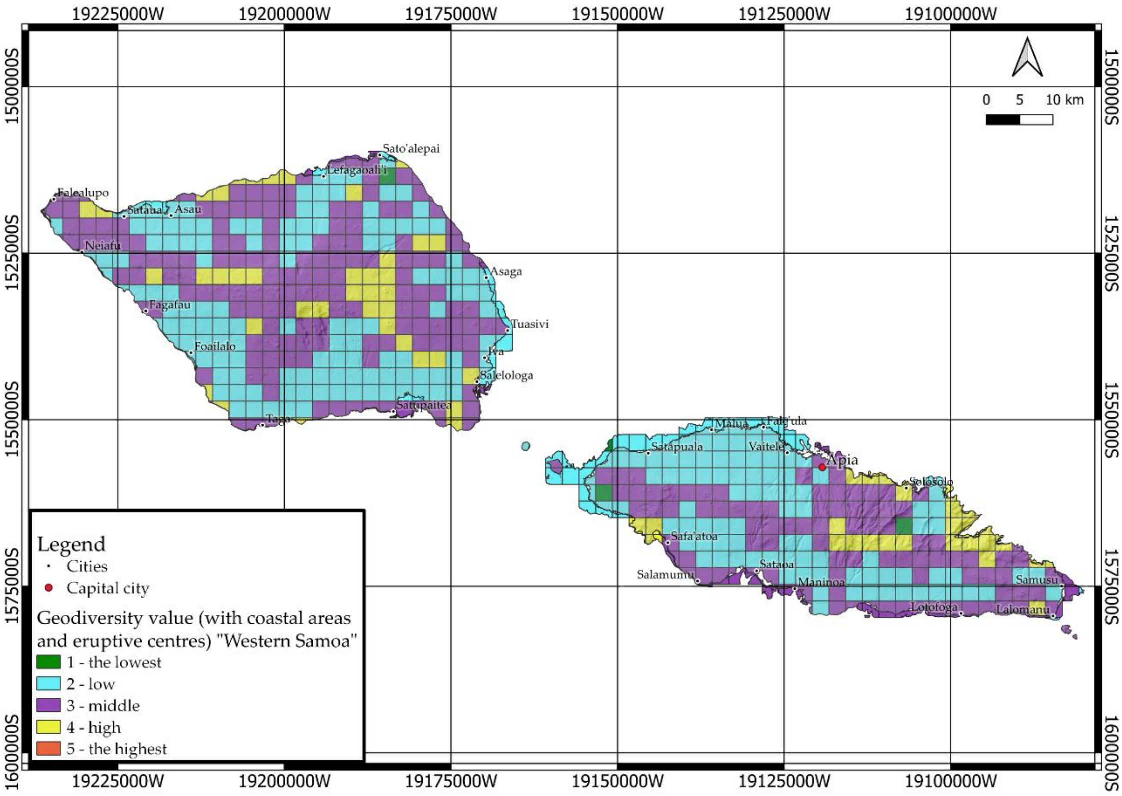

Figure 5.1.(9): Calculated geodiversity values of Western Samoa. The map based on the models of the combination of geomorphological value (Figure 5.1.(7)), geological value (Figure 5.1.(8)), and additional value (Figure 5.1.(6)) of Western Samoa utilized scheme (Figure 5). Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

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 centers 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 centers 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 5.1.(10)) demonstrate the typical appearance of various geodiversity value elements to help to select the most valuable and potential 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.

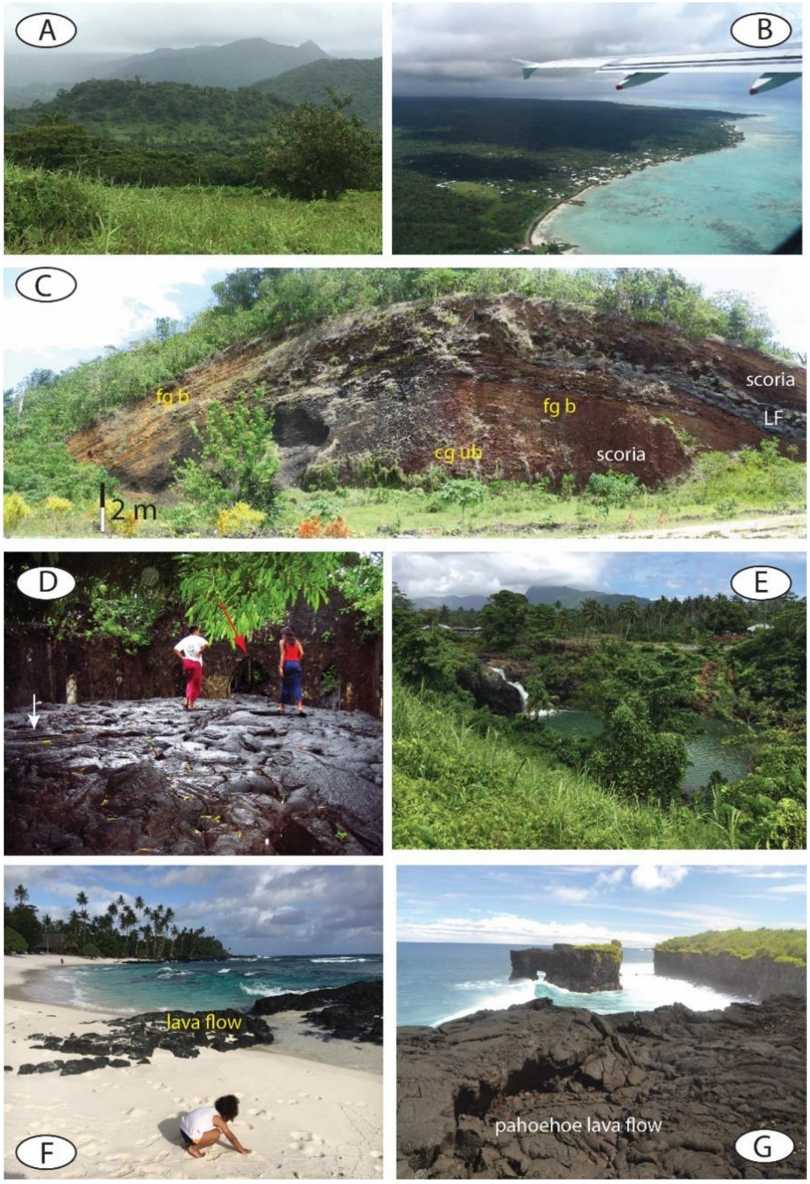

Figure 5.1.(10): (A) Middle to high geodiversity value volcanic cone regions along the eastern section of the dorsal ridge of Upolu. While they yielded high geodiversity values, their access is difficult due to its tropical jungle coverage and lack of access roads. (B) Low geodiversity value regions 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 centers (mostly scoria cones and small lava shields) along the dorsal ridges of Upolu and Savaii. Among these eruptive centers, 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 that 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 the LMS Church in the Saleaula, filling the church interior halfway up. White arrow points to a corrugated iron roof fell on the hot lava and created an imprint on the solidified lava

surface while red 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 lavas 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.

5.1.4 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 center part of the islands, where the elevation may reach over 1000 m above sea level. Meanwhile, the sites featuring eruptive centers 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 centers were selected from the satellite image of Hybrid Google Earth, utilize the values shown in Table 5.1.[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 centers) 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 qualitative-quantitative 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 qualitative-quantitative 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 5.1.(11)), where qualitative-quantitative methods could identify high values of geodiversity, and a qualitative assessment could highlight specific geosites in the context of an overall geoheritage description.

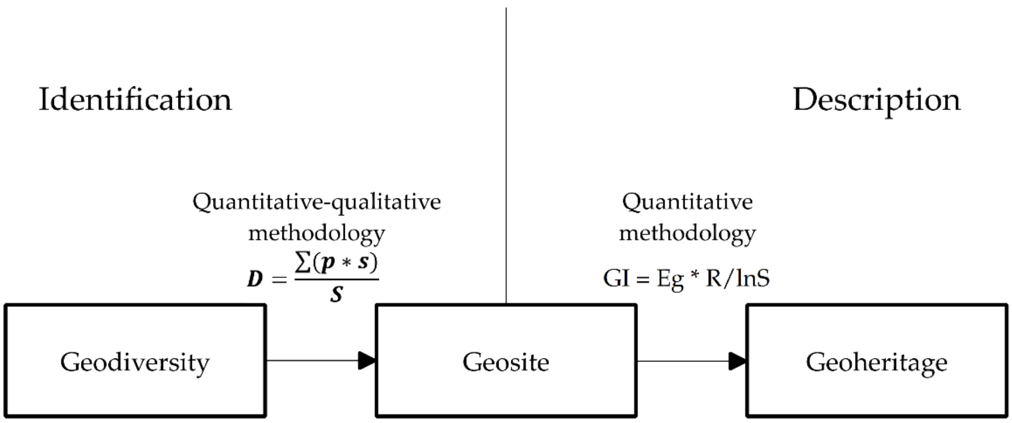

Figure 5.1.(11): The conceptual scheme of potential connection between qualitative-quantitative (section 5.1.2.4 Equation) (Zakharovskyi and Németh, 2021) and quantitative (Serrano and Ruiz-Flaño, 2007) methodologies in geodiversity estimates.

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

where (D)—diversity; (p)-number of points of element (geology or geomorphology (Table 5.1.[1]) [-]; (s)—area of element (p) [L]; and (S)—area of research [L] (Zakharovskyi and Németh, 2021). Measurements: “L” – length, “–“– the number of value not-defined.

$$Gl = Eg * R/InS,$$

where (Gl)—geodiversity index; (Eg)—number of different physical elements in a unit of surface; (R)—roughness coefficient; and (InS)—natural logarithm of the surface unit (Serrano and Ruiz-Flaño, 2007, Ferrando et al., 2021).

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 5.1.(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 few 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.

5.1.5 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.

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Description: This investigation focuses on a second assessment of Samoa but here I examine a non-scale representation of the final model compared to grid system. Here I utilized the same data as for "*Qualitative-Quantitative Assessment of Geodiversity of Western Samoa (SW Pacific) to Identify Places of Interest for Further Geoconservation, Geoeducation, and Geotourism Development*" avoiding hydrological elements of geodiversity. The result of this assessment shows that the non-grid system is more accurate in identifying the exact locations of interest (high and the highest values), which more efficiently targets future ground truthing. This work also encourages me to keep applying a 6.25 km^2 grid system for regional assessments with the application of a maximum value for each cell instead of mean.

The published article can be accessed: https://www.mdpi.com/2673-7086/2/3/29 accessed 5th of May 2023

Reference: Zakharovskyi, V. and Németh, K., 2022. Scale influence on qualitative–quantitative geodiversity assessments for the geosite recognition of Western Samoa. Geographies, 2(3), pp.476-490.

In this research: the article has been changed to meet the style of the thesis.

5.2 Title: Scale Influence on Qualitative–Quantitative Geodiversity Assessments for the Geosite Recognition of Western Samoa

Abstract: Spatial scale in modelling is one of the most important aspects of any kind of assessment. This study utilized previously studied assessments of geodiversity through a qualitative–quantitative methodology for geosite recognition. Our methodology was developed based on geodiversity as a complex description of all elements of abiotic nature and processes, influencing it. Based on this definition, geodiversity can be divided into main elements: geology and geomorphology, creating a core of abiotic nature; and additional elements including hydrology, climate, and human influences. We include this description of geodiversity here to emphasize the data which were used in the assessment. The methodology was based on an evaluation system, subject to improvements informed by previous research, and map-based models showing the area of spreading of calculated elements. Except for additional changes in the assessment, this article primarily addresses the problem of scale, by comparing two different methods of scale in the research: grid and non-grid. Grid types of assessment are considered a widely useable method, requiring definitions of areas of research with a potential variety of polygons, and calculating elements inside the cell and applying values to each cell. In contrast, non-grid assessment utilizes the natural borders of all elements (e.g., map view pattern of geological formations), and including them in calculations. The union of layers from different elements creates shapes which highlight regions with the highest values. Hence, the goal of this article is to demonstrate differences between grid and non-grid assessments of geodiversity in Western Samoa. In our results, we compare the methods and emphasize specific tasks most suitable for each method.

Keywords: rectangular grid; Cenozoic volcanism; geoheritage; geoconservation; geotourism

5.2.1 Introduction

Assessment of the values of abiotic nature is a widely pursued goal worldwide to provide an objectively determined spatial distribution of such elements (da Silva et al., 2019, Dias et al., 2021, Pereira et al., 2013, Zakharovskyi and Németh, 2021a, Silva et al., 2013, Serrano et al., 2009, Pál and Albert, 2021). Many researchers are concentrating on understanding and describing geodiversity of the environment, because this knowledge underlies biodiversity and humanity's connection to the Earth itself. Biodiversity is underlain by an abiotic foundation. This foundation is continuously evolving and shaped by human societies towards their convenience and needs. Meanwhile, humanity uses abiotic nature as it does flora and fauna, but with a higher rate of alteration and through the provision of needs. This significance of geodiversity for humanity has been accurately described by Grey who questions "*Geodiversity and geoconservation: what, why, and how?*" (Gray, 2005), stating unliving nature is not just a location providing needs for survival (economic and functional values), but also providing a range of "supernatural" (non-material) values such as cultural and aesthetic benefits. This demonstrates the significance of geodiversity for understanding the evolution of the environment.

The latest research in this topic shows that geodiversity includes a range of elements such as: geology, geomorphology, climate, hydrology, human and biological footprints, and tectonic processes. In addition, soils, as an element of abiotic nature, are also considered as transit zones where geodiversity adjoins biodiversity (Zakharovskyi et al., 2022). Geological and geomorphological elements should be viewed as two main parameters underlying geodiversity as foundational elements of the abiotic environment. Other elements are the results of weathering and/or erosion processes or altered rock material (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2021b). Even though hydrology is considered a process, it should be studied as another main parameter of geodiversity. However, this assessment of geodiversity concentrates on geosite recognition for the utilization of its role within the geosystem services (e.g., geotourism) rather than providing a complete geodiversity model. The methodology utilizes two core parameters, geology (quality) and geomorphology (form), which can be evaluated to identify the most valuable locations.

A geosite is defined as a location with significant information preserved within associated geological formations (Zakharovskyi and Németh, 2021a). The identification of such locations is a key goal of qualitative–quantitative geodiversity assessments because areas of research contain many different types of information, which may be mostly unreadable from the surface during observation. To find these places of significance, accurate observational research of the defined area must be undertaken on all levels, beginning with the literature, and mapping observations with direct on-site field observations of potential sites. However, significant technological innovations and developments can assist the assessment. For example, digital mapping provides tools to collect and calculate all available spatial data and highlight locations requiring further observation and research, reducing the areas of field observation to some specific places. Gathering and analyzing these data can thus demonstrate the significance of a site within the context of Earth's history and inform plans to preserve and manage sites to spread knowledge of geodiversity and provide opportunities for communities to engage with the geological stories of their land (Brocx and Semeniuk, 2007, Cengiz et al., 2021). In conclusion, in assessments of geodiversity, digital technology can be utilized to define, assess, and subsequently manage potential geosites in a more objective, efficient, and faster way.

The type of assessment of geodiversity is a significant consideration when utilizing GIS (geographical information systems) because digital calculations require data, being highly dependent on the methodology and aim of research. A qualitative–quantitative method of geodiversity assessment (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2021b, Zwoliński et al., 2018), requiring a relatively low amount of information, utilizing a standard geological map and SRTM (Shuttle Reader Topography Mission) model (Eros, 2015), can be used to highlight the most significant places of research. However, its accuracy depends on the quality of the data and evaluation system. Utilizing this methodology and data from previous research on Western Samoa (Southwest Pacific) (Zakharovskyi and Németh, 2021a), this assessment further applies improvements in evaluation systems and demonstrates an issue with previous grid scaling systems in comparison with a non-grid methodology (Dias et al., 2021, Pereira et al., 2013, Pál and Albert, 2021).

Scaling is one of the main issues in any kind of assessment (Serrano and Ruiz-Flaño, 2007). This article demonstrates qualitative–quantitative assessments, aiming to highlight the most valuable geosites on Western Samoa. Hence, the places of interest must be as accurate as possible, where a non-grid methodology can be utilized. Unlike a grid method, this does not divide the area of research on similar cell regions (rectangles or hexagons) but create more natural shapes based on elements and their value-input in modeling. Non-grid methodology utilizes the sum of values of two main elements of geodiversity (geology and geomorphology), which together creates a global value of studied region, but can also be improved with local elements (specific sites with cultural, archeological, volcanological, and/or other values). The accuracy of assessment using this scaling method depends only on the quality of data; grid deviation of the territory is not required. We chose Western Samoa, located in the Southwest Pacific (Figure 5.2.(1)) as a suitable region for comparisons of grid and non-grid types of assessments of geodiversity, as well as providing opportunities to build on previous research on this territory.

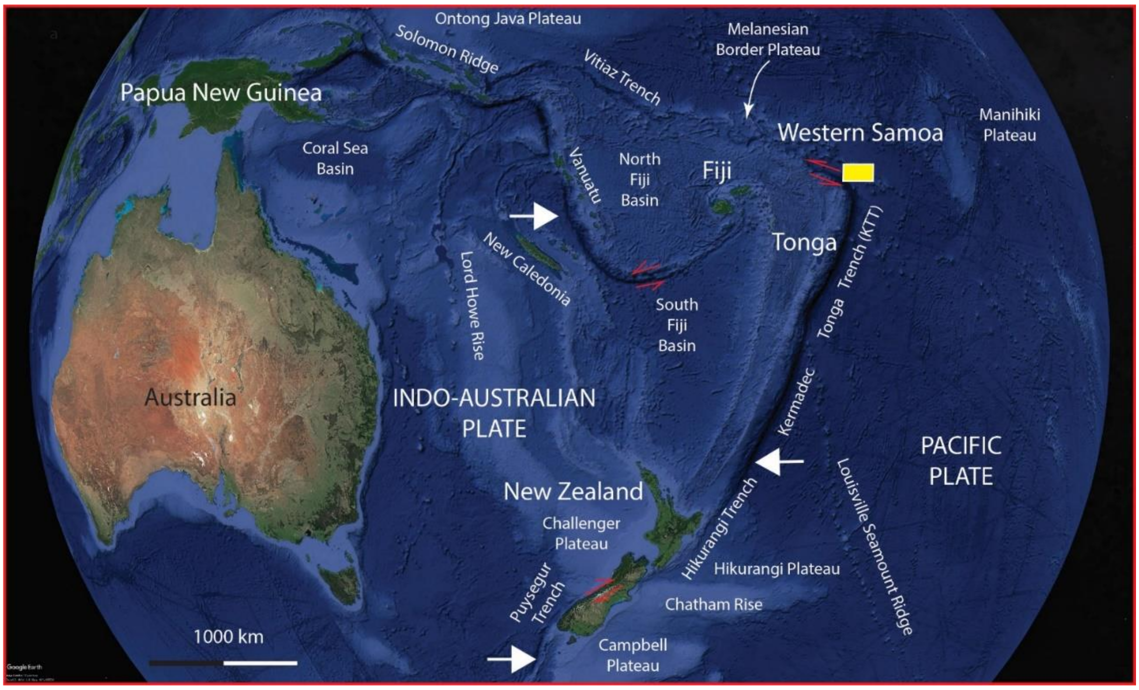

Figure 5.2.(1): Overview of the geotectonic situation in the Southwest Pacific and Western Samoa using Google Earth Pro satellite imagery. The study area of Western Samoa is highlighted by a yellow rectangle. Relative tectonic plate movements are marked by arrows. White arrows show the subducting plate direction of motion. 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.

Qualitative–quantitative assessment of geodiversity is an important methodology for highlighting abiotic aspects of sites with the potential for demonstrating information and processes relating to Earth’s evolution. However, the scale of assessment is one of the most significant parameters, directly influencing the accuracy of results. Therefore, we consider this an important area for further research; here, we demonstrate contrasting accuracy and the utility of grid and non-grid methods of scaling.

5.2.2 Materials and Methods

5.2.2.1 Aim

The main goal of our research was to study two different scale systems for qualitative–quantitative assessments of geodiversity, which include common grid type of calculation and non-grid. Then, we compared these methods, demonstrating differences in their accuracy, and highlighted benefits and drawbacks especially for searching geosites. Finally, we show that evaluation systems of geodiversity can be improved to provide more accurate results.

5.2.2.2 Sample

Two islands of Western Samoa were studied in our earlier research of assessment of geodiversity (Zakharovskyi and Németh, 2021a). Savaii and Upolu Islands are in the northeast sector relative to the Tonga trench in the Southwest Pacific. Islands have been formed by six periods of basaltic volcanism occurring from the Pliocene through to recent history, resulting in a group of shield volcanoes (McDougall, 2010, Kear, 1967). The volcanoes feature only one rock type represented by basalt from different periods, as shown on the geological map of Western Samoa (Kear, 1967) (Figure 5.2.(2)). The first is the Fagaloa lithostratigraphy unit (Pliocene to Mid-Pliocene) occasionally visible on the surface of the Island. Fagaloa volcanism created the landscape formed by shield volcanoes featuring gradual slopes rising from the sea floor to an estimated height 1800 m above sea level. This rock formation has been highly eroded, resulting in steep valleys and volcaniclastic debris aprons. The Salani Unit, located in the eastern part of Savai'i Island, and south-eastern and central parts of Upolu, can be observed mostly infilling the pattern of previously created valleys. Next, the Mulifanua event occurred during the last glacial period and is represented in the western and central parts of Savai'i, and the north-western area of the Upolu Island. After glaciation, the Lefaga unit was formed by small-volume volcanism, producing sporadic eruptive products in the south-western part of Savai'i Island. Subsequently, eruptive products of more recent volcanism have formed the Aopo lithostratigraphy unit. The final volcanic phase is represented by the Puapua rocks formed in the Middle to Late Holocene. These rocks can only be observed on Upolu Island in a small area in the south, whereas they cover the central to south, and eastern part of Savai'i Island. Additionally, the Holocene alluvium was formed in the western part of Upolu Island. The Vini Tuff, formed in the Last Interglacial period, can be seen in well-preserved tuff cones such as Apolima and Nu'utele islands, and in the western and eastern parts of Upolu Island. The information of Western Samoa is provided with its simple geological map which has been georeferenced with QGIS software (version 3.16 Hanover) and polygonised (Figure 5.2.(2)), whereas the elevation model (Figure 5.2.(3)) is based on Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global with a resolution of 30 m per pixel. This information shows that result of the assessment was not very accurate, although it was good enough for this type of assessment.

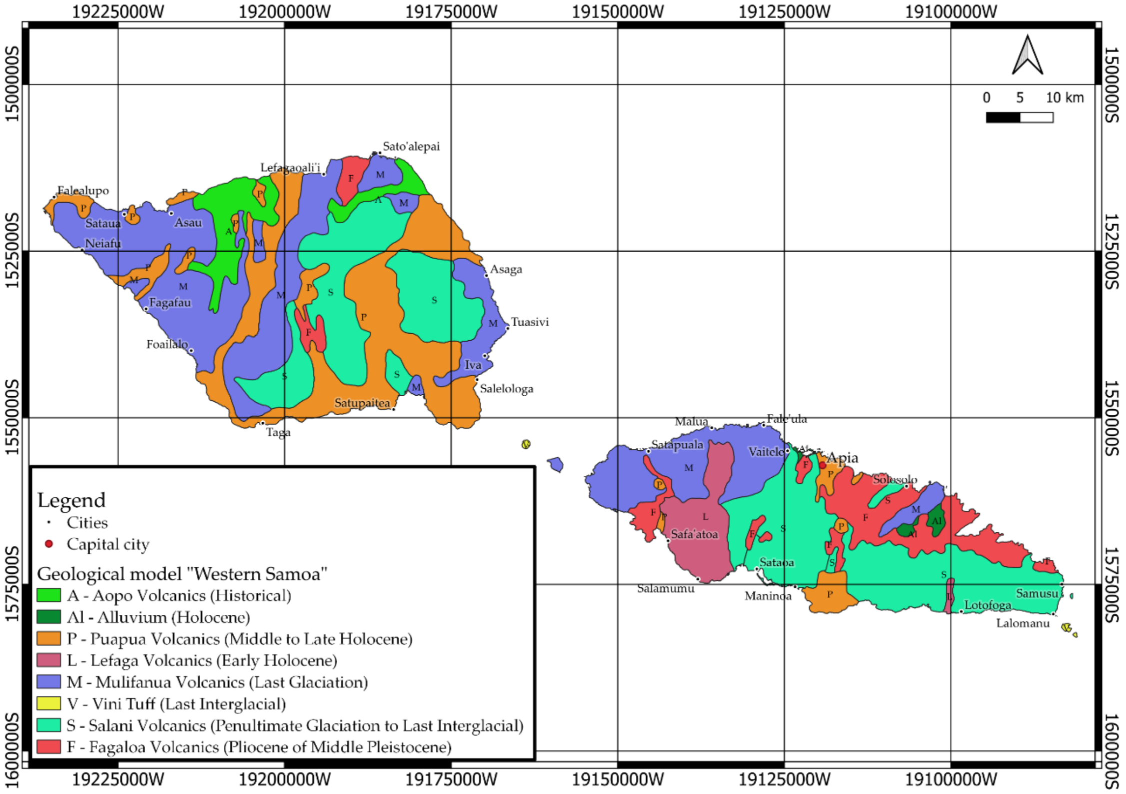

Figure 5.2.(2): Geological model of Western Samoa. Based on geological map of Western Samoa (Kear, 1967). Letters on the map are the first letter of geological units' names. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

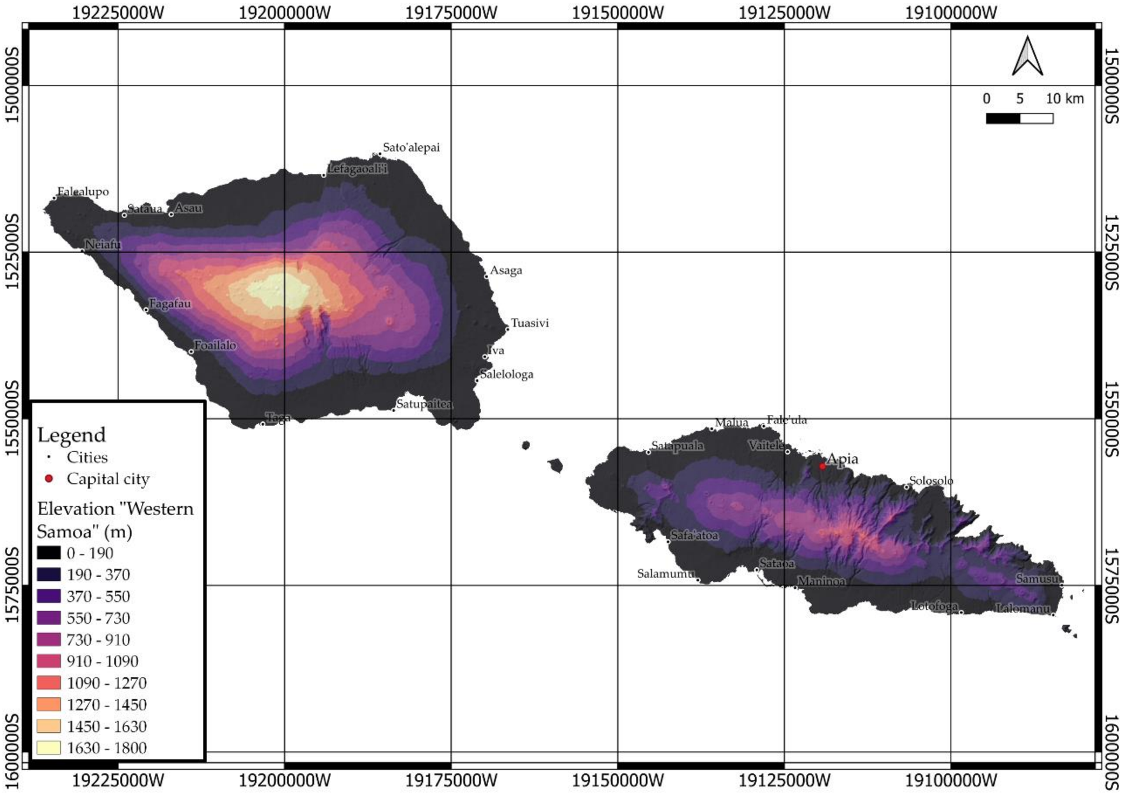

Figure 5.2.(3): Geological model of Western Samoa. Based on geological map of Western Samoa (Kear, 1967). Letters on the map are the first letter of geological units' names. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

5.2.2.3 Methodology

Qualitative–quantitative methodologies have been described in previous articles on geodiversity assessments of the northern part of the Coromandel Peninsula (Zakharovskyi and Németh, 2021b) and the Western Samoa Islands (Zakharovskyi and Németh, 2021a). This method requires basic territorial information (quantitative part) represented by geological maps and DEMs (digital elevation models). Then, evaluation systems (qualitative part) provide a rate for geological and geomorphological elements. This type of assessment was utilized as the most efficient way to create a model of geodiversity values for the purpose of geosite recognition (not full geodiversity description); however, we acknowledge the potential for further refinement of the method and resulting model. Data relating to the main elements (geology and geomorphology) can be calculated using a variety of GIS (geographical information systems) software; however, for our research we utilized QGIS (3.16 "Hannover") (QGIS, 2024), with its plugin "SRTM-Downloader" (Duester, 2024). We consider this software ideal because it is free, user-friendly, readily accessible to a wide range of users, and contains all the tools we consider necessary for qualitative–quantitative assessments of geodiversity.

5.2.2.4 Equation

Our equation for assessments of geodiversity can be applied to the grid method of assessment, which calculates the arithmetic average of all elements presented in each region. In contrast, non-grid assessments utilize the standard sum of all elements' values in the location chosen inside the regions of research.

The development of an evaluation system was introduced in the assessment to provide a qualitative part of the assessment and show the diversity between different types of geological and geomorphological formations presented on the territory of research. The first system was based on 5 points, from 1, the lowest, to 5, the highest part for the elements. However, our system was increased to 7 points plus rare for convenience and accuracy in assessments of geology (described in subsequent sections).

5.2.2.5 Evaluation System for Geomorphological Element

Geomorphological elements are based on elevation models (Figure 5.2.(3)), which contain information about the altitude of the surface in a specific coordinate system. Based on this information, GIS software can provide numbers of different models utilizing the information from DEM such as elevation model itself, slope angle, slope aspect, plan, and profile curvatures; then, more complex morphological models such as ruggedness and roughness, topographic position index (TPI), landform, geomorphon; and hydrological models such as watershed, channels, Strahler orders and others. From all these methods, we decided to concentrate on a more basic and simpler parameter, the slope angle, which is a core feature of most geomorphological assessments. This model can show basic differences in this research area and has already been used for general geological and topographical mapping; a steeper slope will likely contain exposed outcrops suitable for assessment and further observation. Therefore, landscape steepness can be indirectly associated with the evolution of the surface. Subsequently, any kind of formation undergoes the “Geographical cycle” (Davis, 1899, Davis, 1922, Davis, 1973), where the formation is influenced by processes of erosion and/or weathering, which reduce the slope angle and bring the surface to a state of equilibrium (closer to sea level), represented by the end point of a horizontal flat surface. Moreover, younger rock formations can be exposed by tectonic activities, which can uplift the surface and create a new formation with higher slope angle compared with the previous formation. Hence, geomorphological elements have been evaluated using slope steepness from 0 to 90 degrees, utilizing some data of previous researchers, where this parameter has been used for studying soil science, geology, and weathering (Zhuchkova and Rakovskaja, 2004). The evaluation of geomorphology in old and new systems is still very similar because places of 45 degrees and higher are important for considerations of possible geosites. In the old system, geosites had a value of 3–5 points, whereas in the new system, they had values of 5–7 points (Table 5.2.[1]). Meanwhile, other geomorphological models can be utilized for qualitative–quantitative assessments of geodiversity, but each of them has their own purpose and became more complex and problematic for their accurate evaluation to especially “assign” their link to geodiversity values. To consider them valuable for this assessment, they must be studied more precisely to understand their association with any geological evaluation system, or at least their support in geosite recognition, which must have direct dependence on the abiotic environment of the region (more information in section 5.2.2.6 Evaluation System for Geological Element).

Table 5.2.[1]: Geodiversity values of Western Samoa according to 7-point evaluation system.

Main Values of Geodiversity			
Values (7-Point System)	**Elements of Geodiversity**		
	Geomorphology	**Geology**	
	Slope Degree	**Rock Type and Ages**	**Western Samoa Volcano—Heritage**
1 (the lowest)	0–7.5	Sedimentary Cenozoic	Fagaloa volcanics
2 (low)	7.5–15	Sedimentary Mesozoic	Salani volcanics
3 (low to middle)	15–30	Sedimentary Palaeozoic	Vini Tuff
4 (middle)	30–45	Metamorphic Precambrian	Mulifanua volcanics
5 (middle to high)	45–67.5	Intrusive Precambrian	Lefaga volcanics

6 (high)	67.5–75	Extrusive Cenozoic	Puapua volcanics
7 (the highest)	75–90	Extrusive Mesozoic	Aopo volcanics
8 (the rarest) Only Rocks	Sedimentary (Precambrian), Metamorphic and Intrusive (Cenozoic, Mesozoic, Palaeozoic), Extrusive (Palaeozoic, Precambrian)		Additional 1 point for eruptive centres

5.2.2.6 Evaluation System for Geological Element

The evaluation system for geological value is more important than other elements of geodiversity because its formation is the main way the environment receives new material for the refreshment of the surface through volcanic–tectonic processes. Hence, the evaluation for this assessment is that older rock types must yield higher value than younger, and volcanic rocks must be more valuable than sediments because they have stronger link to the primary rock-forming processes. The older formations are remnants of past events inscribed in the rock as different types of environmental changes. Meanwhile, volcanic rock types show formations which emerged directly from the deep interior of the Earth, which are useful for helping geologists determine information about the hidden processes happening in the inner part of the Earth, whereas sedimentary and metamorphic rocks are already the result of processes which have "changed" the primary Earth material, providing additional information about the processes happening within or on the Earth's crust and on the surface. Thus, sedimentary, and metamorphic rocks lose pure information about the core, primary rock forming processes. However, this kind of evaluation does not strictly demonstrate the objective approach for geological evaluation, which is becoming a drawback to make the system globally accessible.

This issue turns the assessment to concentrate on the relative rarity of all rock types found on the Earth's surface. These values have been evaluated and applied to the assessment (Table 5.2.[2]) (Blatt and Jones, 1975): sedimentary Cenozoic are the most common formations (33%), then sedimentary Mesozoic (18%), followed by sedimentary Paleozoic (13%), next Precambrian metamorphic (15%). Together, volcanic rocks comprise 16% of the Earth's crust, and they are further divided between extrusive (8%) and intrusive (9%). Intrusive Precambrian (6%) formations have a lower value than extrusive Cenozoic (4%) and Mesozoic (2%) rocks. Additionally, sedimentary Precambrian, extrusive rocks of the Paleozoic and Precambrian ages, and metamorphic and intrusive formations from the Cenozoic, Mesozoic, and Precambrian periods are each found on 1% of the Earth's surface.

The relatively objective information about rock rareness has been used in evaluation systems because it can be easily applied for any part of the world. In previous research, we used a 5-point system, which presented problems in mixing different rock types under the same values (such as all extrusive and intrusive rocks—5 points; rare rock types were not included in the assessment). After its improvements, the contemporary 7-point evaluation system became more accurate because every point contained only one specific rock type and its age, except for the rarest rock types, which have been separated from the system because their existence on the Earth surface is less than 1%, which makes them more valuable, and are thus assigned a "symbolical" value of 8. Based on this evaluation system, the whole territory of Western Samoa (except for small spots of alluvial Holocene formations) is represented by Cenozoic volcanism, which we assigned a 6-point value for geological elements.

Table 5.2.[2]: Percentage of rock types exposed on Earth's surface as a function of geological age (Blatt and Jones, 1975).

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

[1] According to the table, extrusive and intrusive rocks are the rarest type; hence, they are having the highest value from geological perspective.

5.2.2.7 Evaluation System for Volcanological Element

The assessment of Western Samoa was selected specifically as a challenge for the qualitative–quantitative types of assessment of geodiversity. This assessment concentrated on the recognition of specific places (geosites) throughout the territory of research, where Western Samoa is viewed as a shield volcano with a gradual and relatively gentle sloping landmass mostly composed of effusive eruptive products (less than 45 degrees slope) with one type of rock represented by Holocene basaltic lava flows, which were assigned a value of 6 for all the islands. Hence, the standard assessments based on global parameters of geological rareness and slope steepness would have produced a relatively uniform result throughout the islands, covered in one or two colors on a geodiversity map. This result is unsuitable for proper geosite recognition in a scale normally expected for geotourism or geoconservation (e.g., few kilometers across regions). To solve this issue, the volcanological heritage of Western Samoa was treated with more emphasis and entered the assessment. The volcanic heritage of Western Samoa was evaluated in a 7-point system (Table 5.2.[1]) with eruptive centers as additional points. The table of volcanic heritage shows the local scale for the island, where the youngest rocks, the Aopo volcanics, received the highest value of 7 points. Values for all other volcanic formations decreased with age, i.e., Puapua—6, Lefaga—5, Mulifanua—4, Vini Tuff—3, Salani—2, and Fagaloa—1. This evaluation is based more on the expert (i.e., geologist) view.

Moreover, eruptive centers subject to previous research have been included in our assessment as an additional point. In previous research, the 5-point evaluation system was used as mentioned before for geology and geomorphology. However, the pattern of evaluation for volcano heritage is still the same. Hence, in this assessment, global geological and geomorphological values with additional parameters were used to create an overview of general geodiversity with a focus on local volcanological heritage, which is most important for the Western Samoa Islands. Additional values of volcanological heritage have been specifically tailored for the Samoa Island and cannot be used for other territories.

5.2.2.8 Grid and Non-Grid Scaling Methods

Grid methodology is a common type of assessment of geodiversity from the qualitative perspective. However, qualitative assessments require large amounts of data, which can be used together to identify places with the highest rate of different rock types, forming a spectacular surface. Moreover, this type of assessment also includes data on hydrology, soils, rate of degradation, etc. Meanwhile, qualitative–quantitative methods were developed with an orientation toward highlighting geosites in a more simplistic way. In the first assessment, square grids with a scale of 2.5 km each side were applied for calculation (Zakharovskyi and Németh, 2021a). This scale was used for assessment because it is arguably half of the distance of unobscured human visibility (Kim, 2018, Krisciunas and Carona, 2015). Moreover, this scale is appropriate for assessment because it aligns with the general scale of topographical and geological mapping and is well supported by field observations made in our previous research in the Coromandel Peninsula, New Zealand (Zakharovskyi and Németh, 2021b), where observers from the central point of the region can see the morphology of neighboring regions without visual improvement tools and/or surface obstacles. For calculation, QGIS software contains the “Grid” tool, which divides the area into sections. Then, the “Zonal statistic” tool was applied to calculate the territory of research with arithmetic average equation. However, after calculation, the researchers obtained a result (Figure 5.2.(4)) with large territories for field observation and still had to cover 6.25 km^2 to find the concrete geosites.

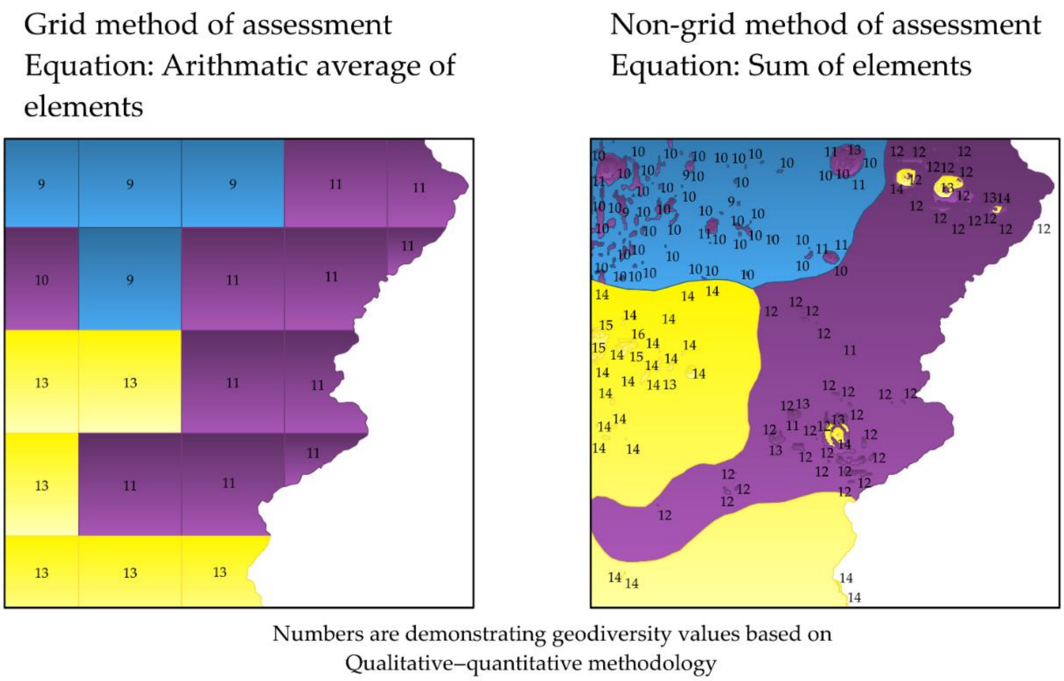

Figure 5.2.(4): Demonstration of results of two methods of scaling using the grid system with an arithmetic average equation and non-grid with the sum of input elements' values.

The geodiversity assessment based on grid methodology has a large drawback as it shows very large territory of observation, which must be covered to determine the locations of possible geosites. Hence, non-grid scales of assessment have been utilized with the "Union" tool (QGIS tool) (Figure 5.2.(5)), where geological and geomorphological models are divided by overlapping and creating sections with different shapes and values from all input elements. The description of the Union tool states that "this algorithm checks overlaps between features within the input layer and creates separate features for overlapping and non-overlapping parts. The area of overlap will create as many identical overlapping features as there are features that participate in that overlap" (QGIS, 2025). In this way, the results of calculations from all elements were totalled, providing the final mark specifically for each region (Figure 5.2.(4)). This method provides a much better result for geosite recognition because it shows some small specific features on the surface which should be observed in the field as possible locations of interest. For example, vents are good places for volcanological studies, and this system can highlight them specifically because they can be easily extracted from DEM. However, the accuracy of this assessment strongly depended on the quality of input data and evaluation systems.

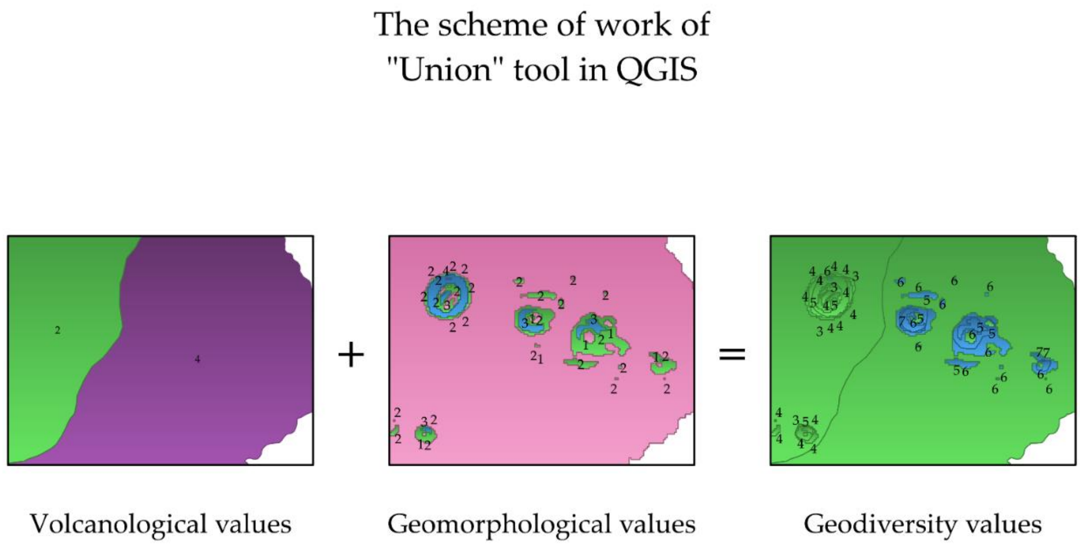

Figure 5.2.(5): Demonstration of the "Union" tool in QGIS. Geomorphological and geological values highlight the same locations, but with different values according to their elements. After applying the "Union" algorithm, geodiversity values show how models with different values have been overlain, creating a new model calculated with average values.

5.2.3 Results

The results of our assessment of geodiversity were the sum of all defined elements in Western Samoa, valued on a scale from 1 to 7 points for each element and 1 point assigned for eruptive centers. The calculation was applied to the same model, contrasting two different methodologies: grid and non-grid. The grid method (Figure 5.2.(6)) utilized cells with a size of 2.5 km per side, an appropriate distance for further observation of chosen sites, because this scale is acceptable for justification on the field. In contrast, the non-grid (Figure 5.2.(7)) methodology utilized borders of assessed elements as areas of deviation from some shapes, where each shape contained information from all layers (geomorphological, geological, volcanic heritage, and eruptive centers). To compare the methods, two models were created, with a sum of evaluated points (Table 5.2.[1]) (7 for each element, and 1 for eruptive centers), which were then divided into six categories with their point values ranging from 0 to 22. Additionally, all categories contained their area of spreading.

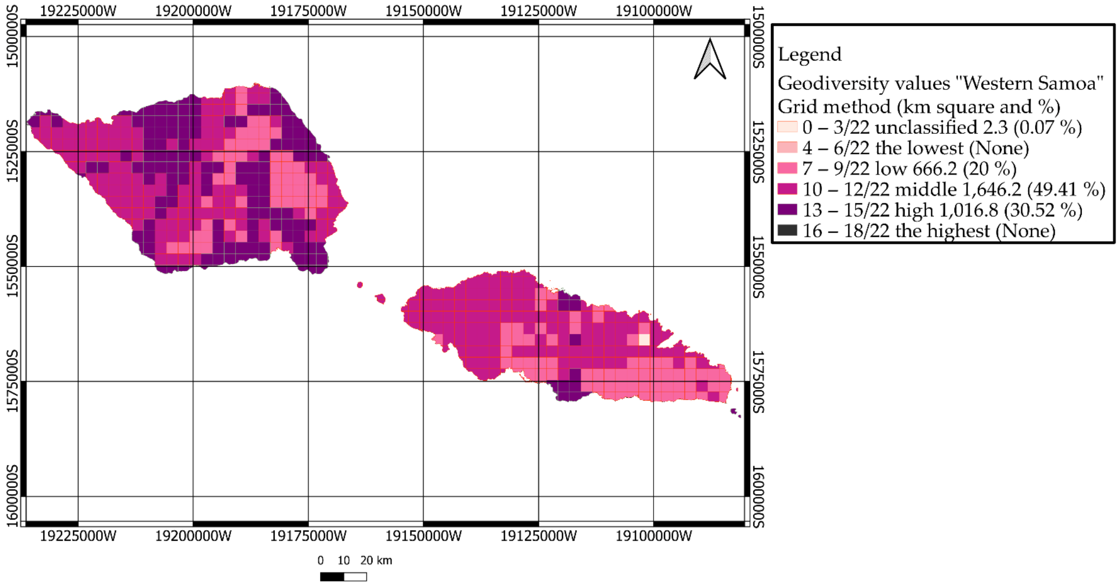

Figure 5.2.(6): Grid model of geodiversity values for "Western Samoa". Based on a geological map of Western Samoa (Kear, 1967) and an SRTM model. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

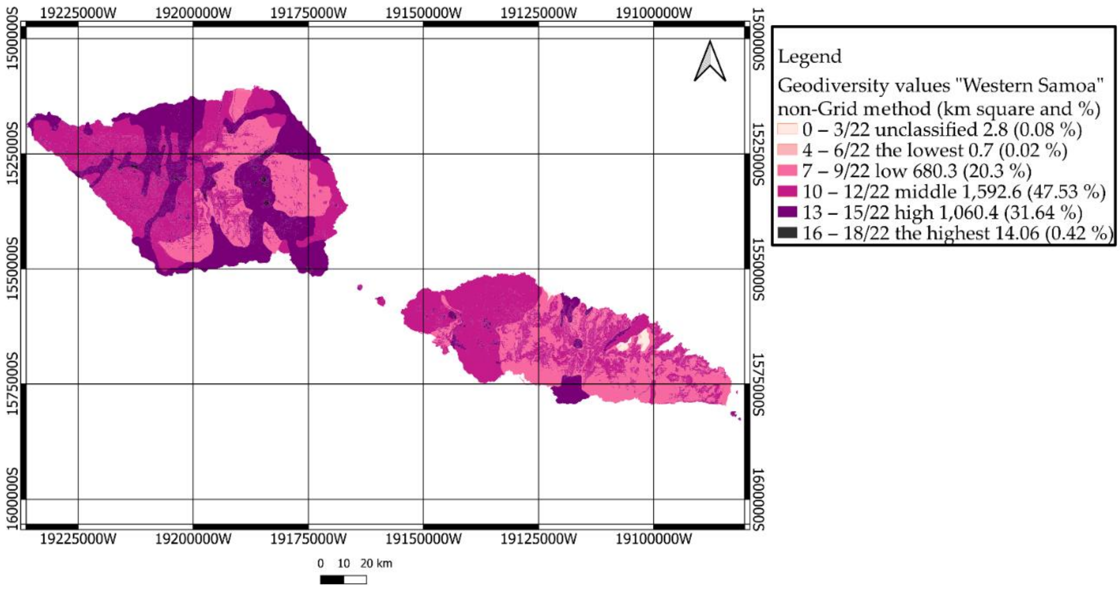

Figure 5.2.(7): Non-grid model of geodiversity values off "Western Samoa". Based on a geological map of Western Samoa (Kear, 1967) and an SRTM model. Map coordinate system: American Samoa 1962 UTM Zone 2S (in QGIS code: ESRI:102116).

5.2.3.1 Geodiversity Results Based on Grid Scaling Methods

The grid model (Figure 5.2.(6)) is presented for the whole area of research, except the ocean, and contained 586 cells, dividing the whole territory into regions containing cells with the same sum of arithmetic averages of all elements. In our results, 0–3/22 points were unclassified, because these geodiversity values are very low to be considered for further assessment; moreover, this was only 0.07% of the whole research territory. This area of the northeastern part of Upolu Island mainly contains alluvial sediments, which are also classified as the most common type of rock present on the Earth's surface. Thus, 4–6/22 is still considered a relatively low value for geodiversity, with no areas of this value present on our model. Salani volcanics represented 20% of our research territory with a value of 7–9/22, in the central–western part of Savai'i Island and mostly in the southeastern part of Upolu Island. The middle value of geodiversity, 10–12/22, mostly represented Mulifanua and Lefaga volcanics, and less so Salani and Fagaloa volcanics. These areas were considered to contain important additional information justifying further observation. Their area of spread was the largest (nearly 50%), mostly occurring in the western part of Savai'i Island and some areas closer to the east coast. On Upolu Island, they are situated in the western and central parts of the island. Finally, 13–15/22 was the highest value for geodiversity occurring in our study area. These were the areas that should be subject to further observation and assessment as potential geosites for Western Samoa. Areas with the highest values covered 30.52% of our total study area. These high-value areas were mostly found in the central, northern, and eastern regions of Savai'i Island, closer to coastal areas, and on Upolu in an area from the north to the south in the central part of the island. These areas were mostly formed by Puapua and Aopo volcanics. The places with the absolute highest values for geodiversity (16–18/22 and 19–22/22) were found in this model. Therefore, our grid method of assessment provided an area of 1016.8 km^2 with potential geosites, which should be observed for further assessment and inventory.

5.2.3.2 Geodiversity Results Based on Non-Grid Scaling Methods

Using the non-grid methodology, we obtained slightly different results compared with the grid model. The non-grid model (Figure 5.2.(7)) was based on areas with the same range of value points as the grid-based version; however, for scale we used a natural shape border, which resulted in 23,453 discreet regions. The regions were based on summarizing layers of geodiversity elements adapted specifically for the Western Samoa region. Layers and their associated range of points were geology (1–7 points); geomorphology (1–7 points); volcanic heritage (1–7 points); and eruptive centers (+1 point). Hence, the highest absolute value was 22, which was not present in this territory. In this model, the unclassified value range 0–3/22 (0.08%) was defined as a larger area compared with the grid model and is formed by alluvium (Holocene) in the northwestern part of Upolu Island, which we consider unnecessary for further research in a geoheritage context. The value 4–6/22 did not occur in the grid model, and in this non-grid model it was not considered influential because it occurred only in a small area (0.02%) contiguous with the lower unclassified values. Areas with the next value 7–9/22 of geodiversity (still considered low) are slightly higher in this model (20.3%) compared with the grid model. Both models include the same locations and rock formations in these areas, but some sites contain higher values influenced by geomorphology and eruptive centers. The middle value (10–12/22 points) of geodiversity is the most common range for Western Samoa for both models, but a slightly smaller area of spread (47.53%) on this non-grid model. The smaller area is described by more an accurate scale of regions with same value, especially in the western part of Upolu Island, where some locations with higher values are present, because of the presence of eruptive centers. The high value 13–15/22 is larger in area (31.64%) in this non-grid model and mostly includes the same locations as the grid model. This value also appears more specifically throughout the territory of Western Samoa in areas of middle value with eruptive centers and/or steeper slopes. These areas, together with regions with the highest present value of geodiversity (16–18/22), should be marked for further research, observations, and assessment. The highest range had a small area of spread (0.42%) and was mostly concentrated locally on areas with a high value occurring closer to eruptive centers and featuring steeper slopes. The absence of these areas in the grid model is notable.

5.2.4 Discussion

5.2.4.1 Grid and Non-Grid Methods of Scaling for Geodiversity Assessment

The main goal of our research was a comparison of two different scales applied to methods for assessments of geodiversity of Western Samoa. We observed slight differences in accuracy, but the overall locations and area of spread were similar. We considered the non-grid model to be better able to highlight locations with potential for classification as geosites. These locations often exhibited eruptive centers demonstrating geological and geomorphological processes. Additionally, they highlight an area most likely to feature surface outcrops of representative rock types which can be further described through detailed field observations. In contrast, we consider the grid assessment method to be more suitable for estimating the geodiversity of large territorial areas, rather than islands. Grid assessments can easily define larger areas (e.g., multiple cell size) to be considered for future geoconservation initiatives and potential geopark establishments. In contrast, non-grid assessments are more suited to estimating geodiversity values in small areas, with the goal of highlighting of potential geosites. Grid models can be used prior to non-grid models, especially in large territories, to identify optimum places for future studies. However, the drawback can be in the loss of some small geological objects such as vents that are hidden inside a grid cell, which are unlikely to have enough influence on the final mark of the grid.

5.2.4.2 Alternative Geomorphological Models and Their Issues for Geodiversity Assessment

Based on our research to date, we note the need for refinements in assessing the geomorphological factors in our overall assessment of geodiversity. Geodiversity estimates should be driven by geological, volcanological, and hydrological elements as a proxy for potential geodiversity values in the geomorphological context. Currently, we suggest using slope degree as the main factor informing assigned values, but also considering geomorphon, topographical position index (TPI), roughness, curvatures, slope aspect, and ruggedness as parameters sensitive to surface complexities. However, these parameters are still hard to evaluate because they do not show a direct association with geological formations, which makes them hard to include in assessments. Moreover, most of them are based on slope steepness and some additional parameters of calculation for specific purpose. For example, TPI utilizing slope angle and elevation dividing slopes on different parts and creating number of landforms such as valleys and ranges, which looks very good on a map but currently not showing any important information, which can lead us to see locations with possible geosites. In the current state, they are unlikely be used for qualitative–quantitative assessments of geodiversity. Naturally, this geomorphological layer of assessment is necessary for areas with no volcanism; however, we note that it can also be applied as an additional layer when assessing the value of geological and volcanological heritage, and other elements of geodiversity. Therefore, values assigned to geological elements can be considered important for distinguishing individual geosites compared with others, and this can be further emphasized by considering geomorphological elements.

5.2.4.3 Issues with the Territory of Western Samoa

Western Samoa Islands were chosen for this assessment as a challenge. This territory contains low value from a geomorphological perspective, and high value from a geological perspective, but this is evenly spread throughout the whole region, giving everything the same importance. Moreover, geological, and tectonic information of the islands is limited because it shows young volcanism without specific structural elements, but with a high number of vents diagonally spread throughout the islands of Western Samoa (Cronin et al., 2006, Fepuleai and Németh, 2019, Németh and Cronin, 2009). As a result, the assessment of Western Samoa with additional values of volcanic heritage specifically tailored to this territory shows that its geodiversity has fallen in value and is considered to be average. Even though Savaii Island has a large territory, which marks it as high value, it is unsuitable for study, because it is better to concentrate on the large number of small spots with the highest values. These locations are mostly concentrated on places with eruptive centers. Additionally, coastal areas must be considered as a good location, especially cliff sites. As a result, these conditions, with a relatively pure geodiversity, tropical climate, and a small human population are perfect for a high distribution of tropical forests, creating high biodiversity of the region (Whistler, 2002, Ibanez et al., 2021, Keppel et al., 2016, Neubert and Bouchet, 2015, Fall and Drezner, 2013, Keppel et al., 2010). Hydrology, one of the elements of geodiversity, was not included in this assessment because its evaluation remains unsolved; there are some possible ways of assessing the weathering power, accumulating alluvial sediments, and/or type of water (stream, lake, marshland, etc.). Additionally, hydrological information of Western Samoa is also limited, similarly to the geological data. However, from DEMs, the territory probably supports a large number of small streams with a short fluvial network, especially in the central part of Savaii Island and central–northern part of Upolu. Here, waterfalls are one of the most important hydrological features which can be included into assessments because they carry high geotouristic values, but they cannot be extracted directly from DEMs or other model, only input into assessments after observation or extracted from topographical maps. Meanwhile, in Western Samoa, waterfalls are commonly linked to the places of geological boundary (e.g., lava flow contacts), which decreases their importance for qualitative–quantitative type of assessment. In conclusion, Western Samoa is a place with opportunity to study geoeducation from a geodiversity perspective, but information is still limited and further observations are required.

5.2.4.4 Aims for Future Research

The non-grid type of assessment with four elements of geodiversity and subject to a 7-point evaluation system is currently our most developed qualitative–quantitative methodology. However, further research is proposed that would provide a more holistic overview by including elements such as archeological sites and soils. Additionally, biological factors and the human footprint must be considered in any overall assessment of geodiversity, enabling a comparison of geodiversity and biodiversity to inform and direct further research on omnidiversity (Crisp et al., 2022).

5.2.5 Conclusions

Both the grid and non-grid scaling methods presented in our study of geodiversity assessment methods display similar results on a global perspective. However, at a local scale, the non-grid methodology displays more complete and spatially refined results, providing exact locations with specific values based on the evaluation system. Hence, on a global perspective and/or for large territories, grid systems work well enough, whereas non-grid systems are more applicable for local scales. It is better to recommend grid systems for the assessment of geoparks, whereas non-grid systems should be used highlight specifical geosites.

To date, improvements in assessments of geodiversity demonstrate a need for further development of associated concepts. Results from our evaluation system demonstrate the high volcanic heritage value of eruptive centers as well as their influence on geodiversity values overall, applicable at a highly localized scale of assessment. Other values should be subject to the same studies and assessments as volcanic heritage, where geology and geomorphology situate the geodiversity in a global context, and additional elements such as archeology, cultural history, hydrology, and soils should be included and calculated for the local perspective and uniqueness, and to provide a more holistic overview of geoheritage.

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Description: The assessment of different geomorphological models currently used in comparison to the qualitative-quantitative methodology, became the focus of this topic. Previous research raised questions of the utilization of Slope angle as the geomorphological element for assessment. Hence, in this research I decided to compare 6 models, which represent geomorphological parameters. This was applied to the whole of the Coromandel Peninsula region. These models generate Slope, Ruggedness, Roughness, Total Curvature, Topographic Position Index, and Geomorphon. All models have been evaluated according to their default values based on an 8-point evaluation system, utilizing a local range of their values. Six models have been calculated according to qualitative-quantitative assessment of geodiversity (QQG) using the geological data QMAP 1:250 000 of New Zealand. The result of assessment demonstrates that slope, ruggedness, and roughness models result in similar location of interests, which slightly different than Topographical Position Index while total curvature and geomorphon outputs identified no overlapping sites. In general, this research has provided a good test for the QQG methodology, where TPI, Slope, Ruggedness, and Roughness geomorphological elements can be calculated interchangeable on the regional scale (through the whole Peninsula) for geosite recognition.

The published article can be accessed: https://www.mdpi.com/2673-7086/2/4/37 accessed 5th of May 2023

Reference: Zakharovskyi, V. and Németh, K., 2022. Geomorphological Model Comparison for Geosites, Utilizing Qualitative–Quantitative Assessment of Geodiversity, Coromandel Peninsula, New Zealand. Geographies, 2(4), pp.609-628.

In this research: the article has been changed to meet the style of the thesis.

5.3 Title: Geomorphological Model Comparison for Geosites, Utilizing Qualitative–Quantitative Assessment of Geodiversity, Coromandel Peninsula, New Zealand

Abstract: In qualitative–quantitative assessment of geodiversity, geomorphology describes landscape forms suggesting specific locations as geosites. However, all digital elevation models (DEM) contain information only about altitude and coordinate systems, which are not enough data for inclusion assessments. To overcome this, researchers may transform altitude parameters into a range of different models such as slope, aspect, plan, and profile curvature. More complex models such as Geomorphon or Topographic Position Index (TPI) may be used to build visualizations of landscapes. All these models are rarely used together, but rather separately for specific purposes—for example, aspect may be used in soil science and agriculture, while slope is considered useful for geology and topography. Therefore, a qualitative–quantitative assessment of geodiversity has been developed to recognize possible geosite locations and simplify their search through field observation and further description. The Coromandel Peninsula has been chosen as an area of study due to landscape diversity formed by Miocene–Pleistocene volcanism which evolved on a basement of Jurassic greywacke and has become surrounded and partially covered by Quaternary sediments. Hence, this research provides a comparison of six different models for geomorphological assessment. Models are based on DEM with surface irregularities in locations with distinct elevation differences, which can be considered geosites. These models have been separated according to their parameters of representations: numerical value and types of landscape. Numerical value (starting at 0, applied to the area of study) models are based on slope, ruggedness, roughness, and total curvature. Meanwhile, Geomorphon and TPI are landscape parameters, which define different types of relief ranging from stream valleys and hills to mountain ranges. However, using landscape parameters requires additional evaluation, unlike numerical value models. In conclusion, we describe six models used to calculate a range of values which can be used for geodiversity assessment, and to highlight potential geodiversity hotspots. Subsequently, all models are compared with each other to identify differences between them. Finally, we outline the advantages and shortcomings of the models for performing qualitative–quantitative assessments.

Keywords: GIS modeling; Geomorphon; Topographic Position Index; ruggedness; roughness; total curvature; slope; geoconservation; geotourism

5.3.1 Introduction

A variety of geodiversity assessment methods have been applied by geoscientists to areas of study to highlight locations which may contain high-value features based on abiotic factors. The range of abiotic elements (geology, geomorphology, hydrology, climate, cultural heritage, soils, and others) are compounded to provide a full description of the geodiversity of different studied areas throughout the Earth (da Silva et al., 2019, Dias et al., 2021, Pereira et al., 2013, Zakharovskyi and Németh, 2021a, Silva et al., 2013, Serrano et al., 2009, Pál and Albert, 2021). However, at a global scale, many areas do not display enough surface features or qualities to provide a useful reflection of historical and prehistorical events. Understanding landscape evolution is one of the most important research projects in geology, as it provides a range of possibilities for science development, especially for protection against hazard events, conservation, tourism, and education. Tectonic and erosion processes are the main drivers of surface and crustal evolution, creating new geological forms through the tilting and uplifting of old formations once buried underground; creation, transportation, and deposition of sedimentary particles; and creation of new outcrops. New formations and exposed surface areas provide information that describes the history of the Earth's evolution. Patterns and cycles of rock alteration are predominantly led by the geographical–geological cycle (Davis, 1899, Davis, 1922, Davis, 1973) of orogenetic uplift and volcanism, subsequently acted on by weathering and erosion (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2021b). The abiotic environment is shaped by two main elements: geology (parameter of quality or mineral (element) composition) and geomorphology (forms of rocks created after exogenic and endogenic processes). These processes are captured in the cycle of alterations which act over thousands of years. Hence, these elements are the most important part of geodiversity assessment, especially in research directed toward an understanding of the Earth's history. Moreover, geosites may contain this specific information, with their recognition a starting point for further field observations. Therefore, we define geosites as those sites which best represent the concepts of geosystems that we have outlined.

Geographical information systems (GIS) provide a range of tools, which can be utilized for geodiversity description and/or geosite recognition based on the stated aim of research and data availability. Our research aims to demonstrate geodiversity assessment, using six geomorphological models based on the same source for the data set. These models are slope angle, roughness, ruggedness, and total curvature, while the Topographic Position Index (TPI) and Geomorphon are more complex models applied to different types of landscape. All models have been generated from the Shuttle Reader Topography Mission (SRTM) data set (Eros, 2015) as it represents freely accessible data, which allow us to simplify calculations and describe methodologies easily reproduced by other researchers.

Qualitative–quantitative assessments of geodiversity are based on arithmetic average values between geological and geomorphological elements, described by a seven-point system (Zakharovskyi and Németh, 2022), which has been changed in this assessment to a better tailored system for our study area (more details in section 5.3.2 Material and Methods). Six geomorphological models have been assessed based on geological elements to create a general geodiversity model of the region. Geodiversity models are then compared in how they recognize geosites. Geological elements are evaluated by a seven-point range of values, based on global rarity of rock type found exposed on the surface. However, a detailed evaluation of numerical geomorphological models (slope, ruggedness, roughness, and total curvature) is beyond the scope of this paper, though they have been included for comparison through straight multiplication with geological values. Meanwhile, landscape models (TPI and Geomorphon) have been evaluated based on expert views.

The Coromandel Peninsula in the North Island of New Zealand is considered a good study area for the assessment of geosite recognition. This area contains several different rock types, creating unique geological and geomorphological formations, including mountain ranges, meadow hills, plains, and coastal cliffs (Hayward, 2017, Homer and Moore, 1992). It is significant that the area contains some of the earliest sites of Māori and then European settlements, geological resources, and is a globally recognized tourist destination (Moore, 2013, Maxwell et al., 2018, McIvor and Ladefoged, 2016, Lyver et al., 2008, Wellman, 1962, Davidson, 2018). Therefore, our research is relevant for the establishment of geoeducation, geoconservation, and/or geotouristic projects.

The main aim of our research is to compare TPI, Geomorphon, slope, roughness, ruggedness, and total curvature models as these are the most influential geomorphological elements for assessment of geodiversity. Moreover, the methodology must be simple and repeatable for other users and applicable for different territories throughout the world. Additionally, the results of our research will assist in demonstrating, understanding, and describing the differences and similarities between territories. This will be valuable for qualitative–quantitative assessments of geodiversity, which can be used to accurately locate potential geosites.

5.3.2 Materials and Methods

5.3.2.1 Sample

The Coromandel Peninsula is located on the northeast side of North Island, New Zealand. It comprises a territory approximately 40 km wide and 100 km long with a NW–SE orientation. The peninsula is contiguous with the Bay of Plenty on the southeast, Hauraki Gulf on the southwest, and the eastern shores open to the Pacific Ocean (Figure 5.3.(1)) (Hayward, 2017, Homer and Moore, 1992). We selected the peninsula as an area of research for this assessment as the region contains diverse biological and geological units and forms and contains significant conservation reserves and tourist destinations. Moreover, geological diversity of the territory is shaped by volcanic interaction with marine–sedimentary environments during the Miocene–Pleistocene. Evolution of features can be recognized throughout the research area, creating different types of relief, from mountain ranges and meadow hills to marshes and plains. We suggest that such a high amount of geological and geomorphological diversity provides potential opportunities for landscape evolution as a basis for education and community engagement. Additionally, it was the settlement region for the first Māori tribes, which leaves an important cultural footprint for anthropological studies, while Europeans used this region for mining based on the gold and silver epithermal deposits (Legget, 2012, Barker et al., 2006, Spörli and Cargill, 2011). Hence, our geomorphological assessment of the Coromandel Peninsula will provide a firm foundation for future research based on tourism, education, and conservation development.

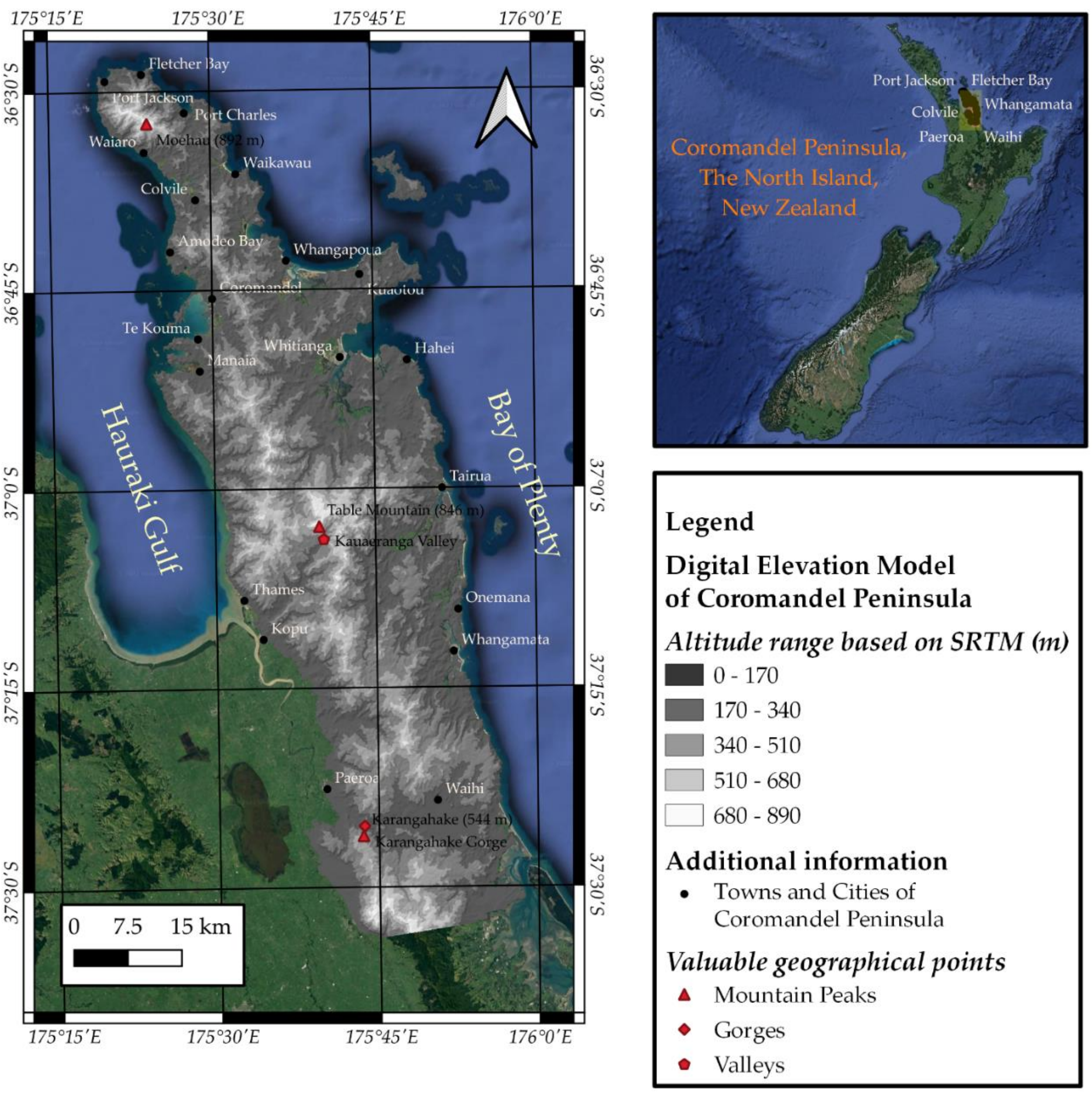

Figure 5.3.(1): Overview map and elevation model of Coromandel Peninsula created from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (EROS, 2015); background is Google terrain map. The coordinate system is WGS 84 (EPSG: 4327); the same applies for all other figures.

5.3.2.2 Geological Description

The geology of the Coromandel Peninsula has been formed by Miocene-Pleistocene land-based volcanic activities and some Holocene tephra derived from outside of the region. Basement lithologies are formed by the Jurassic siliciclastic rock greywacke (Figure 5.3.(2)) (Hayward, 2017, Briggs and Fulton, 1990, Adams et al., 1994, Malengreau et al., 2000, Nicholson et al., 2004, Smith et al., 2006, Booden et al., 2012, Homer and Moore, 1992). Younger clastic sediments can be found mostly on the boundaries of the Coromandel Peninsula, with greywacke forming the most frequently encountered and largest sediment formation presented in the west and north part (Mortimer et al., 2017, Mortimer et al., 2014). Lithologies encountered throughout the region in valleys, depressions, and hollows include mudstone, sandstone, conglomerates, and breccia from the Holocene and Pleistocene epochs. Felsic extrusive rocks from the Whitianga Group are represented by rhyolite and ignimbrite spread from the central to the eastern part of the peninsula. The most extensive lithostratigraphic formation on the peninsula is the Coromandel Group, which includes intermediate extrusive andesite and intrusive diorite (granite–granodiorite), also known as “Coromandel Granite” (Hayward, 2017, Homer and Moore, 1992, Black, 1972, Skinner, 1975, Garmson et al., 2014). Granodiorite is found at the far northwest part, while andesite mostly forms the whole peninsula and is widely spread from the south to the north. Basalt of the Neogene period is the rarest type of rock in the Coromandel Peninsula, which is exposed on the surface near coastal areas in the northeast part of the peninsula (closest to Great Mercury Island). Finally, a tuff formation can be observed in the transition zone between the far north and central parts of the Coromandel Peninsula. In conclusion, the geological variety of the Coromandel Peninsula is represented by a wide range of volcanic and sedimentary rocks spanning the time frame from the Jurassic to the Holocene periods.

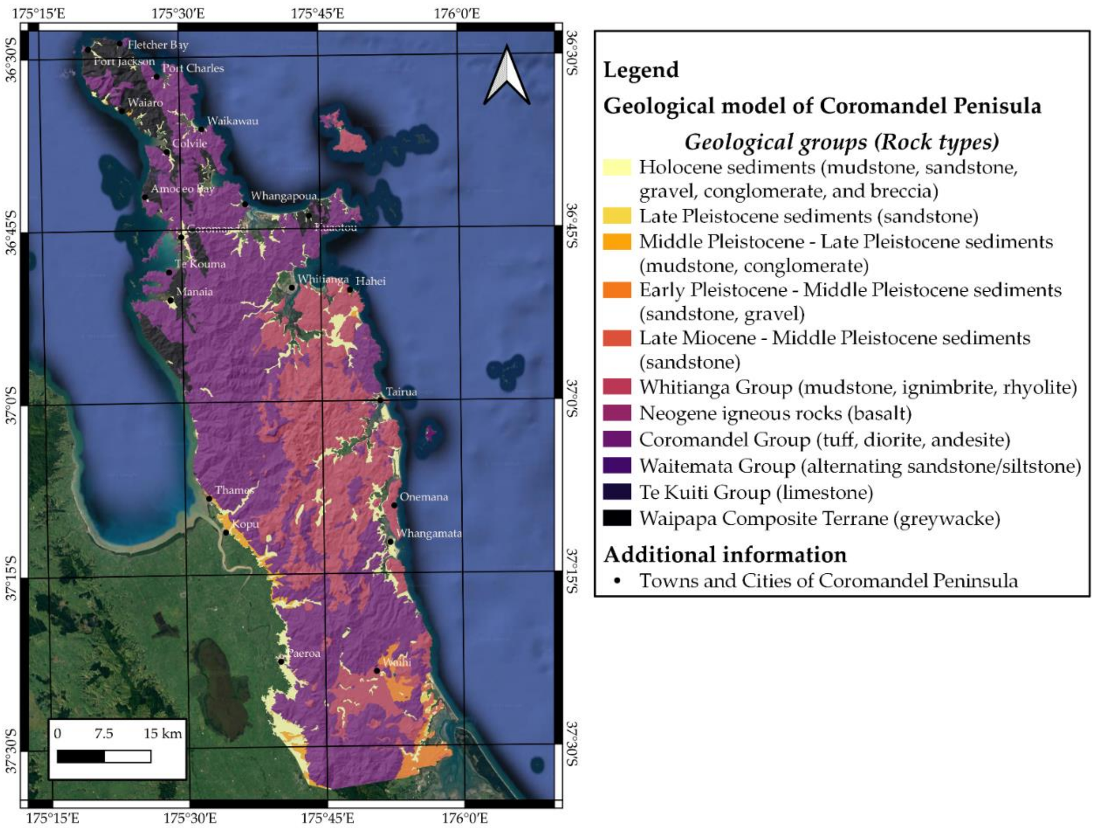

Figure 5.3.(2): Geological model of the Coromandel Peninsula based on the 1:250,000 scale New Zealand Geological Map (GNS Science, 2012); background is Google terrain map.

5.3.2.3 Geomorphological Description

The geomorphology of the studied area is variable based on the elevation model of the Coromandel Peninsula (Booden et al., 2012). The landscape of the south is mostly formed by mountain ranges with elevations between 700 and 900 m, mostly rising to the southwest from Karangahake Gorge (Figure 5.3.(1)). The relief is formed by remnants of the Waihi Caldera, with the area becoming flatter closer to sea level as one moves north. A long mountainous ridge at the center of the region commences at the Wharekawa Caldera (near to the settlement of

Whangamata) and extends to Colville in the far north, where elevation once more decreases closer to sea level. Moving west to east, a rise in elevation commences in the west, with the highest central point found at Upper Kauaeranga in the central region (Figure 5.3.(1)). Further east landscape features are formed by remnants of the Kapowai Caldera and the Whitianga Volcanic Center. The north part of the peninsula is mostly formed by rolling hills with lower elevations between 180 and 540 m above sea level. However, at Waiaro, elevation rapidly starts to rise from 180 to nearly 900 m, with the highest point being Mount Moehau at 892 m. In conclusion, the territory of the Coromandel Peninsula contains many uneven surfaces with rapid changes in elevation ranging from sea level to 900 m and above, resulting in a high diversity suitable for testing for geomorphological assessment.

5.3.2.4 Methodology

In this article, we compare six different methods using parameters based on the digital elevation model (DEM) of the Coromandel Peninsula. The methodology is originally based on slope steepness and evaluation of geological units (Zakharovskyi and Németh, 2021b, Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022). The main aim of our qualitative–quantitative assessments is to recognize geosites based on simple calculations of numeric averages; the qualitative aspect of our system is the evaluation system itself, while the quantitative aspect is based on the two main elements of geodiversity (geology and geomorphology) (Zakharovskyi and Németh, 2021a). Geology contains information about qualitative properties of the region, while geomorphology is a measure of its form. However, the main goal of this research is to compare six geomorphological models based on different parameters, with some featuring an axis displaying numerical values from 0 to positive only, while others display growth in the negative direction as well, to describe some specific morphological forms. Hence, the evaluation system cannot be easily applied to each model. Our suggested solution is calculation of parameters based on numerical models (slope, roughness, ruggedness, and total curvature) using multiplication with evaluated geological models (seven-point system as per sub-section 5.3.2.5 Geological Evaluation System). Meanwhile, Geomorphon and TPI as landscape models have been evaluated as demonstrated below (Table 5.3.[1]). The multiplication algorithm has been utilized to create a wider difference between results and does not require separate evaluation of each geomorphological model.

Table 5.3.[1]: The value systems for geodiversity assessment of the Coromandel Peninsula.

<table>
<tr><td colspan="5">Main Values of Geodiversity</td></tr>
<tr><td rowspan="3">Values
(7-point system)</td><td colspan="4">Elements of Geodiversity</td></tr>
<tr><td colspan="3">Geomorphology</td><td>Geology</td></tr>
<tr><td>Slope, Roughness, Ruggedness, Total curvature</td><td>Topographic Position Index</td><td>Geomorphon</td><td>Rock type and ages</td></tr>
</table>

<table>
<tr><td>1 (the lowest)</td><td rowspan="7">The numerical models have been included into assessment without direct evaluation.</td><td rowspan="7">Topographic Position Index model have been evaluated by 7-point system for positive and negative forms of landscape, where 0 is the lowest value</td><td>Flat and Slope</td><td>Sedimentary Cenozoic</td></tr>
<tr><td>2 (low)</td><td>Valley and Ridge</td><td>Sedimentary Mesozoic</td></tr>
<tr><td>3 (low to middle)</td><td>Footslope and Shoulder</td><td>Sedimentary Paleozoic</td></tr>
<tr><td>4 (middle)</td><td>Hollow and Spur</td><td>Metamorphic Precambrian</td></tr>
<tr><td>5 (middle to high)</td><td>Depression and Summit</td><td>Intrusive Precambrian</td></tr>
<tr><td>6 (high)</td><td rowspan="2">5 – point system</td><td>Extrusive Cenozoic</td></tr>
<tr><td>7 (the highest)</td><td>Extrusive Mesozoic</td></tr>
<tr><td>8 (the rarest)
Only Rocks</td><td colspan="4">Sedimentary (Precambrian), Metamorphic and Intrusive (Cenozoic, Mesozoic, Paleozoic), Extrusive (Paleozoic, Precambrian)</td></tr>
</table>

Next, our methodology utilizes a grid formed with 2.5 km length for each side of cells (6.25 km^2), applied to the whole Coromandel Peninsula for all six geomorphological models. As the territory of the Coromandel Peninsula is relatively large (~100 km long and 40 km wide), using a non-grid method of scaling will result in poor visibility of most features on the final map (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022). Therefore, the 6.25 km^2 area was selected as this length aligns with the range of human visibility, meaning that field observations can be applied to the whole cell together with its neighbors (Zakharovskyi and Németh, 2021b). Additionally, the same scale has been used for the creation of topographical and geological standard maps such as the 1:250,000 scale New Zealand Geological Map (GNS Science, 2012).

In the assessment, the maximum value of each region has been utilized for calculation of geology and geomorphology, in order not to miss potential geosite locations. This could occur when low values are seen in the surrounding assessed region, except in the case of the Geomorphon model. Therefore, every region shows potential for containing valuable sites, which can then be further defined through more precise observations, for example, on-ground field work. However, this methodology is of no use for describing geodiversity description as it avoids low-value locations. In contrast, the Geomorphon model based on default parameters will suggest small features throughout the cell, thereby resulting in an entirely homogeneous research area. Hence, Geomorphon is modeled on an arithmetic average calculated for each cell (Table 5.3.[1]).

In this research, we utilized Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (EROS, 2015) for DEM. Access is free and data are available for the entire surface of the Earth at a resolution of 30 m per pixel, which we consider suitable for large-scale geodiversity calculations. Then, QGIS (3.16 "Hannover") (QGIS, 2024), with its plugin "SRTM-Downloader" (Duester, 2024), was utilized for model calculation as it contains all the required tools for geomorphological modelling. Hence, six models for geomorphological description were created from SRTM data using QGIS software, based on two main classes, numerical values, and landscape types. Numerical classes are models that have parameters from 0 to the highest value found in research area based on qualities such as slope, ruggedness, roughness, and total curvature. Meanwhile, landscape types are represented by numbers, describing qualities of relief such as slope, plain, valley, or range. These models are the TPI and Geomorphon (Table 5.3.[1]).

5.3.2.5 Geological Evaluation System

Geological evaluation systems have been created in previous research on qualitative–quantitative assessment for geosite recognition (Zakharovskyi and Németh, 2022). Currently, the system is for global scale of assessment as it is based on the rareness of different rock types throughout the Earth's surface. Based on the research of Blatt, H. and Jones, R. L. *"Proportions of exposed igneous, metamorphic, and sedimentary rocks"* (Blatt and Jones, 1975), rock formations were divided into types such as intrusive, extrusive, metamorphic, and sedimentary; and their ages, i.e., Cenozoic, Mesozoic, Paleozoic, and Precambrian (Table 5.3.[2]). All types of rocks and their ages were considered and given values from 1 to 7, with value 8 reserved for only the rarest types, which are less than 1% throughout the global surface (Table 5.3.[1]). The lower values are as follows: 1 point for Cenozoic sedimentary, the most common type of formation at more than 60%; 2 points are assigned to Mesozoic sedimentary rocks, occurring at half the amount of the former type; 3 points are assigned to Paleozoic sedimentary; 4 points are assigned to Precambrian metamorphic which, although it has a slightly higher extent than the previous rock type (Paleozoic sedimentary), is given a higher value because metamorphic processes are more complex and may provide more information about geological processes; a value of 5 points is assigned to Precambrian Intrusive; and finally, Cenozoic and Mesozoic extrusive rocks are given 6 and 7 points, respectively. The remaining rock types were grouped under 8 points because of their rareness: Precambrian sedimentary; Cenozoic, Mesozoic, and Paleozoic metamorphic and intrusive; Paleozoic and Precambrian extrusive. Using this scale is apparent that the Coromandel Peninsula contains many formations that can be given a value of 6 for rareness, represented by extrusive rocks of Cenozoic time (andesite, rhyolite, ignimbrite, dacite); while greywacke is given a value of 2 points (Mesozoic sediments). Quaternary sediments found throughout the Peninsula are given 1 point. Finally, "Coromandel Granite" is one of the rarest types of Mesozoic intrusive rocks that can be found at the Earth's surface, so its value is 8.

Table 5.3.[2]: Percentage of rock types exposed on the Earth's surface as a function of geological age (Blatt and Jones, 1975).

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

5.3.2.6 Geomorphological Evaluation System

For geomorphological assessments, we considered two types of models: numerical (slope angle, ruggedness, roughness, and total curvature) and landforms (Geomorphon and Topographical Position Index (TPI)). Below, we present a short description of each model. In the Results section, they are compared with each other based on a qualitative–quantitative type of assessment of geodiversity. We utilize a 7-point scale for geological value multiplied by the value of each geomorphological model. A limitation of this assessment is that it is unable to utilize a global evaluation system as models are based on SRTM with a resolution of 30 m for pixel. At this resolution, we are unable to clearly define all high slope areas (especially coastal cliffs) throughout the peninsula; however, we consider it adequate to define the highest-value areas.

5.3.2.7 Slope Model Description

The slope model was calculated utilizing (Saga GIS module) in QGIS named "Slope, aspect, curvature". For assessment, we utilized the default method "9 parameter 2-nd order polynom" created by Zevenbergen and Thorne (1987), where they modified Evens' quadratic equation. The model has been used in different types of studies, ranging from geology and agriculture to trail and road plannings. Moreover, it has shown good results in wildfire and flood hazardous areas of research (Quesada-Román and Vargas-Sanabria, 2022, Quesada-Román, 2022). For our database, we utilized the SRTM model of the Coromandel Peninsula downloaded through the QGIS plugin "SRTM-downloader". This was modified with the "Gaussian filter" (Saga tool in QGIS) to smooth a surface and applied to every model described below. This resulted in a slope model of the Coromandel Peninsula containing values ranging from 0 to around 46 degrees, where the highest values are mainly found in the central and northern part of the Peninsula.

5.3.2.8 Roughness Model Description

Roughness is a parameter describing the degree of surface irregularity. Topography is the main factor influencing the parameter of roughness, which can also be influenced by altitude and surface features such as trees, buildings, relief, and terrain (Abbas et al., 2020). Its calculation is based on identifying differences between neighbouring cells and pixels describing features in those cells. This type of modelling is commonly used for river morphology, climatology, and geography (QGIS, 2025a). The roughness model was calculated from SRTM data utilizing QGIS software through the module GDAL “Roughness”. This results in a model that appears like a slope, but with different parameters ranging from 0 to 63 describing the surface irregularity. Hence, the highest points of the roughness model are mostly found in the central and northern part of the Coromandel Peninsula.

5.3.2.9 Ruggedness Model Description

Ruggedness calculation parameters have been described by Riley et al. (1999) as the quantitative measurement of the differences in terrain (heterogeneity) (Riley et al., 1999). Ruggedness has been used for in-habitat modelling to predict types of species habitats, their density, and variety. Then, ruggedness has demonstrated strong results in paleoglacier studies (Quesada-Román et al., 2020, Quesada-Roman et al., 2021). For our calculations, the main parameter was differences in elevation applied to a 3 × 3-pixel grid, whereby 8 surrounding cells are compared with the central one. A value of 0 describes a level and even surface, while a higher value describes higher heterogeneity (QGIS, 2025b). In QGIS, this parameter has been calculated utilizing the “Terrain Ruggedness Index (TRI)”, which is a Terrain Analysis tool (SAGA module). The results of this calculation can also be demonstrated visually, same as those of the roughness and slope models, but the values range from 0 to 72, with the highest points found in the same geographical areas as the former models.

5.3.2.10 Total Curvature Model Description

Total curvature or general curvature is a parameter which combines plan and profile curvatures and is used here for understanding the flow in our studied territory (Meten et al., 2015). Total curvature can range from a starting point of 0 and move in a positive or negative direction, describing different types of surfaces, such as flat, hilly, and dissected by valleys, respectively (Meten et al., 2015). For our calculation, we utilized the same tool as for slope calculation named “Slope, aspect, curvature” (Saga GIS module) in QGIS. For our assessment, we utilized the default method “9 parameter 2-nd order polynom” (Zevenbergen and Thorne, 1987). The results of our calculation have values ranging from 0 to $8.66252 \times 10{-}5$, where the highest values are mostly concentrated in the southern part of the center of the Coromandel Peninsula and reflecting the positive form of landscape represented by the mountain ranges of Coromandel Group formations (Figure 5.3.(2)).

5.3.2.11 TPI Model Description

The Topographical Position Index shows the differences between the parameter of elevation in a central cell and predetermined mean values of its surrounding cells. Mostly calculated to determine the position of the studied slope, it can also be used to classify standard landforms (QGIS, 2025c, Meten et al., 2015). The model was calculated utilizing the "Topographic Position Index (TPI)" tool as part of the Terrain Analysis (SAGA) module presented in QGIS software. Our calculations result in a model with parameters ranging from −2.8 to 2.9. These were then evaluated utilizing a 7-point system, where 0 is the starting point and values increase in both directions. The positive values represent hillslopes and mountainous terrain, while negative values describe valleys and hollows. As the aim of this research is geosite recognition, both negative and positive types of landforms have high values for this assessment; therefore, equal importance is given to negative and positive distance from the 0 point.

5.3.2.12 Geomorphon Model Description

Geomorphon is one of the newest methods of calculating divergence from a range of specific landscape forms. This model can be calculated using GRASS GIS "r. geomorphon", which is based on the relationship of the cell of assessment with its 8 closest neighboring cells. Neighboring cells can be placed in three different positions: on the same altitude as the studied cell, higher than the studied cell, or lower than the studied cell. The combination of all positions between the neighbors describes the exact type of the terrain. These types of terrain are divided into 10 forms, i.e., flat, slope, footslope, shoulder, valley, ridge, hollow, spur, pit, and peak (Stepinski and Jasiewicz, 2011, Jasiewicz and Stepinski, 2013). The 5-point evaluation system is presented according to difficulty in extracting the form from the territory, with values as follows: flat and slope are 1; ridge and valley are 2; footslope and shoulder are 3; hollow and spur are 4; pit and peak are 5. However, this system has some shortcomings as it is unable to describe the "geographical evolution" of slope and relief. In addition, at a global scale, this method for constructing a useful model requires changes in parameters for the chosen location to recognize all the significant places and decrease the amount of microrelief and noise to make the model readable. Hence, the Geomorphon model is highly dependent on the scale and type of evaluation.

5.3.3 Results

Qualitative–quantitative assessment of geodiversity was utilized based on a seven-point evaluation system for geological aspects and a free unspecified system for geomorphology, which resulted in 6 different models. Our aim is to recognize potential geosites in our study area, which can then be subject to further research for a more detailed description. The first four models share the same type of information, where the highest values are seen at high-value locations found in our study area. These models are slope angle, roughness, ruggedness, and total curvature (Figures 5.3.(3) and 5.3.(4)). Meanwhile, two other models express some specific landforms: TPI and Geomorphon (Figures 5.3.(5) and 5.3.(6)). All models were created utilizing QGIS (3.16 "Hannover") software, while additional calculations were made in Excel to contrast and compare results of evaluation modes: equal interval and natural breaks (Jenks) (Jenks, 1967). The results of the two modes are presented below, where each model has been compared with others based on the same mode.

In our results, model values were subject to equal interval mode calculations (Figures 5.3.(3) and 5.3.(5)), demonstrating that places with high and the highest values should be considered the most likely to contain potential geosites suitable for further assessment and evaluation.

Slope models express the most diverse results after equal interval mode calculations, as represented in Figure 5.3.(3). The results confirm that the northern region of the peninsula contains several regions with valuable geological formations such as “Coromandel Granite” (the highest value) and Miocene andesite from the Coromandel Group (high values). These areas also contain high slope degrees, based on the model. In addition, some areas with high values were also located in the north, closer to the central region of the peninsula, also formed by the same andesite. Meanwhile, Great Mercury Island contains only two areas of potential significance, as one of the few locations of Neogene basalts. Other areas with high and the highest values are found in the central region at the boundary between two extrusive Cenozoic groups, Coromandel (mostly andesite) and Whitianga (ignimbrite and rhyolite). The southern regions of the Coromandel Peninsula contain some areas of high value located near the Waihi and Karangahake regions. Moreover, the eastern region of the Coromandel Peninsula has some high-value areas close to coastal areas, which are most likely formed by near-vertical cliffs.

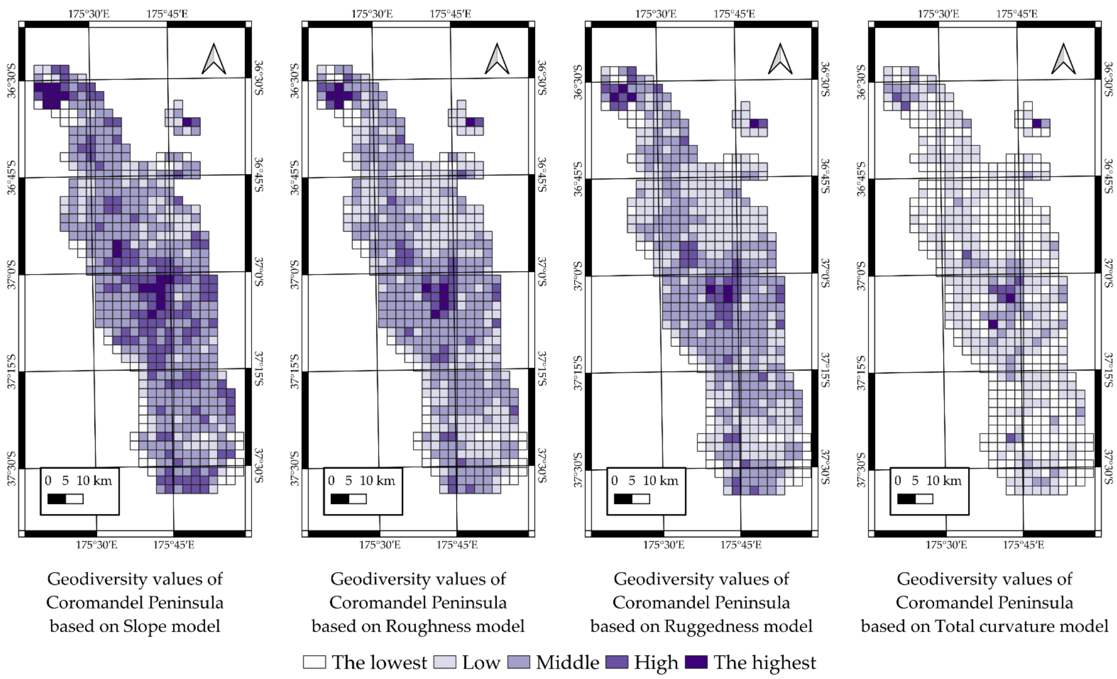

Figure 5.3.(3): Geodiversity values of the Coromandel Peninsula for geosite recognition, based on numerical geomorphological models: slope roughness, ruggedness, and total curvature. Equal interval mode of evaluation.

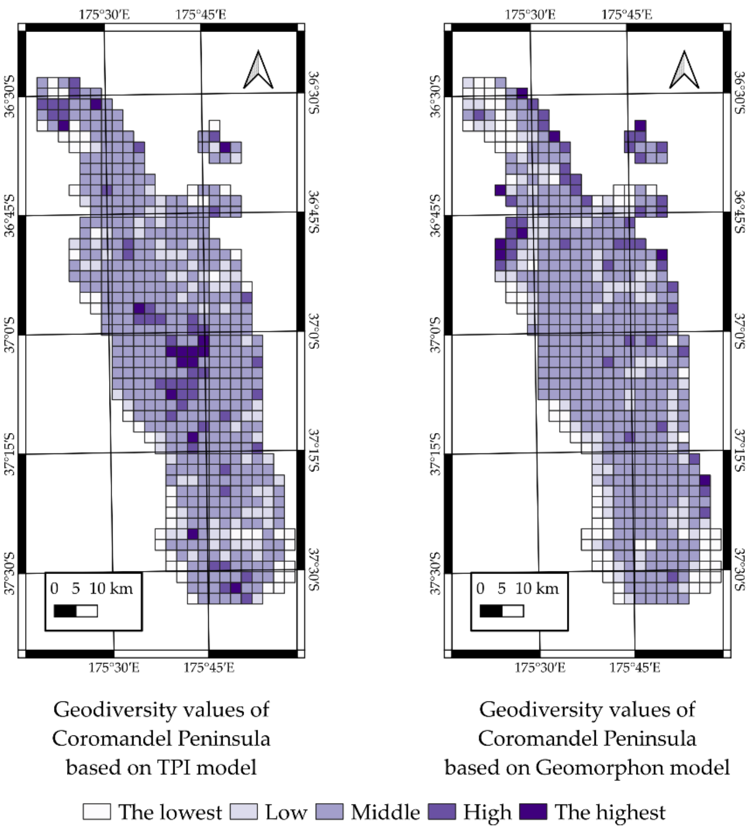

Figure 5.3.(4): Geodiversity values of the Coromandel Peninsula for geosite recognition, based on numerical geomorphological models: slope, roughness, ruggedness, and total curvature. Natural breaks (Jenks) mode of evaluation.

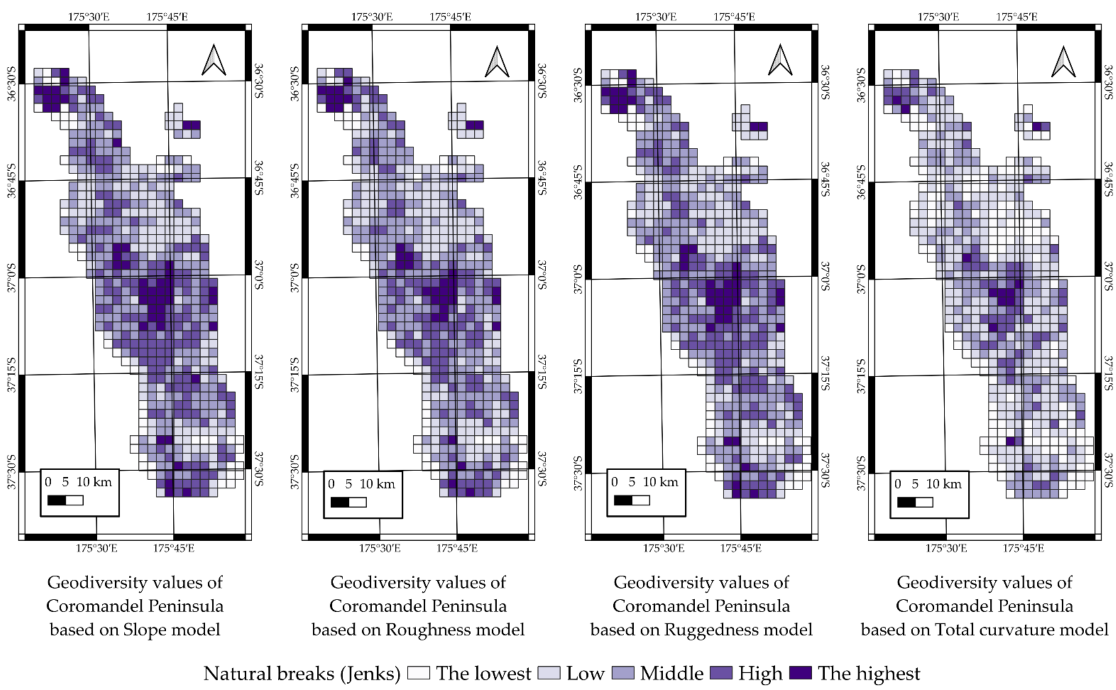

Figure 5.3.(5): Geodiversity values of the Coromandel Peninsula for geosite recognition, based on landform geomorphological models: TPI and Geomorphon. Equal interval mode of evaluation.

The results for the roughness assessment show similar patterns to the slope model, but with a lower number of areas for potential geosites. Meanwhile, nearly ~25% of the north–central region displays low values, while the slope model gives values in the middle range. Nonetheless, broadly speaking, both models assign the highest values to the same regions. Additionally, the ruggedness model shows very similar results to the roughness model, with differences mostly seen in the central and in the northern parts of the region, with some values lower compared to the former model in this sub-section. The last of the four numerical models is total curvature, which results in the low and the lowest values of geodiversity for geosite recognition throughout the whole region of research. Using this model, only a few areas as defined by previous models are suggested to be treated as areas containing potential geosites.

The Topographical Position Index (TPI) is one of the landform models we calculated in this research which, compared to previous numerical models, produces values that contain information on some specific form of the landscape. These could be valleys, cliffs, hills, or mountain ranges. This results in a homogeneous pattern throughout the Coromandel Peninsula assigned a middle value, except for the north and central regions, which can still be considered high- and the highest-value places. Meanwhile, the eastern part contains only five separated areas with high value. The Mercury Islands do show the same higher-value areas as other models.

The second landform model we evaluated is Geomorphon, which contrasts with the other models in the way it describes landscapes. We created this specific evaluation system to demonstrate which type of landform could be considered more valuable in the context of this exercise. The results derived from Geomorphon are displayed as homogeneous middle values throughout our study area, same as the results from the TPI. However, unlike TPI, which still defines high-value areas as in previous models (slope, roughness, ruggedness, and total curvature), Geomorphon defines completely different areas for potential geosites than other models. Most of these areas are in the eastern coastal areas and specific areas of the central–west region, which were not highlighted by any of the previous models.

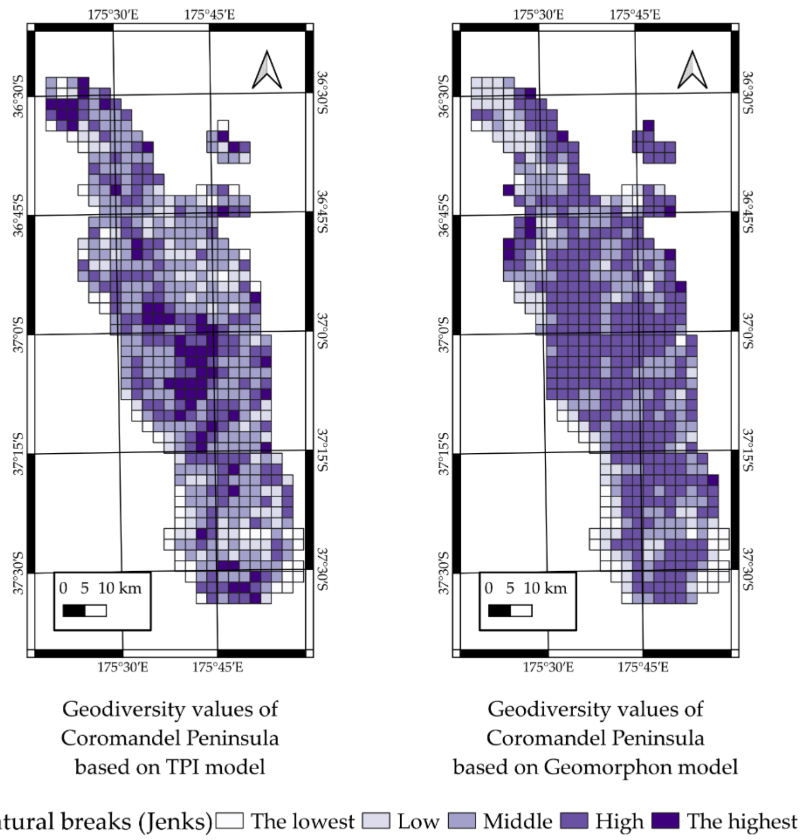

Figure 5.3.(6): Geodiversity values of the Coromandel Peninsula for geosite recognition, based on landform geomorphological models: TPI and Geomorphon. Natural breaks (Jenks) mode of evaluation.

For a more accurate representation of the differences in the models, we applied an equal interval value mode calculation and created a table showing the percentages of differences between models (Table 5.3.[3]). The slope and Geomorphon models are like each other and to roughness, with similarities at around ~50%. Meanwhile, the TPI model has around 60% similarities with other models. Then, ruggedness and roughness display the most similar results at 91.1%. Similarities between total curvature and other models are lower at 23%.

Table 5.3.[3]: Comparison of results of geodiversity assessment based on different geomorphological models evaluated with equal interval.

Similarities (%)	Roughness	Ruggedness	Total curvature	TPI	Geomorphon
Slope	58.2	54.2	8.6	65.7	49.5
Geomorphon	54.0	54.0	22.9	57.9	
TPI	62.4	61.4	11.7		
Total curvature	18.2	20.1			
Ruggedness	91.4				

Additionally, we applied natural breaks (Jenks) mode for comparison of results of the same models. This mode was considered as its divides the models' data based on common patterns. The slope model mostly defines the same areas, as we saw when applying the equal interval mode; however, clusters with high values are much wider, and more areas show the highest value for geodiversity (Figure 5.3.(4)). Clusters became more connected to each other when covering a large area of research with high values; however, significant locations are still found in the same areas with higher geodiversity values compared to equal interval mode. In this case, we see more convergence towards the slope (natural breaks) model. In locations with the highest values in the central region of the Coromandel Peninsula, we see differing values for ruggedness and roughness. Total curvature trends towards higher diversity compared to equal interval mode but still displays low values for geodiversity, especially in the central–east and southern regions of our study area.

For landform models, natural breaks mode significantly influences the resulting patterns (Figure 5.3.(6)). TPI shows similarities to previously described models with natural breaks mode of evaluation, in particular the northern region of the peninsula containing the highest value for "Coromandel Granite", and the highest values for andesite formations located at coastal areas. Additionally, some areas in the north- and central–western regions of the Coromandel Peninsula are represented by high values. Two main clusters with the highest values are recognizable with other models except Geomorphon, but with wider areas defined through application of natural breaks mode. Southern areas of the region show convergence with other models while maintaining the same patterns. Furthermore, the central–eastern region contains more areas with the highest values compared to previous models.

Geomorphon evaluated by natural breaks has a more diverse result compared to equal interval. However, around 60–70% of the region is showing high values, a significant difference from all previous models. In the northern region of the peninsula, the east coast contains high-value clusters spreading inland (Figure 5.3.(6)). Meanwhile, only a few places have been as assigned the highest values, two in the northeast region of the peninsula, one region in Mercury Islands (a different cell than other models), three more in the central–eastern region, and one in the southeast. Additionally, a few clusters have been highlighted in the central–western region, in contrast to other models.

For a more accurate representation of differences in the models divided by natural breaks mode, we created a table with percentages representing comparisons between models (Table 5.3.[4]). The slope, roughness, and ruggedness models are incredibly like each other at more than 84 %. Meanwhile, the TPI model has similarities to the former three at ~50%, and very low similarities with total curvature and Geomorphon. Furthermore, Geomorphon and total curvature display the lowest similarities with all other models, at less than 42%.

Table 5.3.[4]: Comparison of results of geodiversity assessment based on different geomorphological models evaluated with natural breaks.

Similarities (%)	Roughness	Ruggedness	Total curvature	TPI	Geomorphon
Slope	84.3	93.4	33.2	56.6	37.4
Geomorphon	34.6	34.6	24.1	38.6	
TPI	52.1	58.4	19.1		
Total curvature	41.3	36.4			
Ruggedness	87.1				

5.3.4 Discussion

The aim of this research is to compare six different geomorphological models based on geological data to highlight areas potentially containing geosites and areas for further observation. The Coromandel Peninsula was chosen for modeling and testing calculations. Our calculations show that slope, roughness, and ruggedness models evaluated using the equal interval mode define similar locations with high and the highest value of geodiversity. Slight differences are seen when we use the TPI and total curvature, while we demonstrated that the Geomorphon model shows mostly homogeneous results, so we consider it to be unsuitable for assessment of geodiversity. However, a more precise comparison shows that most of the models have similarities of more than 50%, except total curvature, which is 23% or less compared to the others. Additionally, natural breaks (Jenks) mode was utilized to examine the model's evaluation, where slope, roughness, and ruggedness have similarities in results that are higher than 84%. The TPI model shows ~55% similarities with slope and roughness models. Hence, results are dependent on which mode we used to evaluate the results of the models. Results show that models based on slope, roughness, or ruggedness are mostly exchangeable, giving similar results for geosite recognition and highlighting the same areas of interests. Meanwhile, the TPI model has fewer similarities to the slope, roughness, and ruggedness models but shows the same pattern of clusters of locations with the highest values. We demonstrated that total curvature and Geomorphon are not useful for geosite recognition, with the former showing some places with the highest values but missing others, while Geomorphon presents completely different and very homogeneous values throughout the study area. However, Geomorphon may provide higher accuracy at a lower scale of assessment without using the grid system. Slope, roughness, and ruggedness are more less exchangeable models and, together with TPI, recommended for qualitative–quantitative assessment of geodiversity for geosite recognition.

We identify the main issues with qualitative–quantitative assessment of geodiversity to be the scale of research, quality of accessible data, and the evaluation system. Our research utilized a grid of 6.25 km^2 cells grid to divide the Coromandel Peninsula into smaller and more convenient areas of focus. Previous research undertaken on the islands of Samoa demonstrates a more accurate non-grid system (Zakharovskyi and Németh, 2022); however, we do not consider this suitable for our large and diverse study area of the Coromandel Peninsula. Therefore, we instead used a grid system, which is suitable for field observation, and comparable with standard New Zealand topographical maps. This allowed us to define more precisely “geodiversity hotspots” calculated with more accurate data. The next issue is the accuracy of data. For this research, we utilized SRTM data as they cover the whole planet, are easily accessible, do not incur a cost, and provide enough resolution for our assessment. However, it is still possible to miss some important information. For example, slope, ruggedness, and roughness models are assigned low values in the central–eastern region of the peninsula, although these feature many valuable cliff sites, which are not recognizable by the SRTM model but visible in DEM based on a New Zealand topographic map. The last problem is the evaluation system. In previous research, we used a global evaluation system, which was based on slope degree values ranging from 0 to 90. However, it was not suitable for this assessment and comparison of geomorphological models, as all of them utilize different parameters, which cannot be evaluated equally. Therefore, we avoided separate evaluation of each model but calculated values by multiplying them with a global geological seven-point system for numerical models (slope, ruggedness, roughness, and total curvature). However, the evaluation system was applied to Geomorphon and TPI as they represent landforms rather than some specific parameter. Our research demonstrates the utility of this calculation for assessment, as this avoids strict evaluation systems and is suitable for numerically based models. SRTM data are adequate for qualitative–quantitative assessments for geosite recognition; however, the results should be cross-checked utilizing more accurate data if the ultimate purpose is geosite recognition. Finally, a grid system should be used for recognizing specific areas that may contain potential geosites, which than can be improved by assessing these regions with a non-grid system.

To demonstrate the accuracy of our qualitative–quantitative assessments of geodiversity more objectively, we utilized data from field observations carried out in the Coromandel Peninsula as well as sites extracted from the New Zealand Geopreservation Inventory (NZGI, n.d.) to check alignment between high and the highest values. To achieve this, all points of observation were overlapped on each model, utilizing natural breaks mode for evaluation (Tables 5.3.[5] and 5.3.[6]). However, not all these points should be considered as geosites as our field observations were based on checking the whole Coromandel Peninsula. Some points we observed may only be notable for views of offshore islands or distant mountains. In contrast, New Zealand Geopreservation Inventory research contains more points based only on specific geological or geomorphological information. Therefore, as shown in the table of our field observations, 56 locations were captured by our assessment, where slope model captures 8 locations of the highest values, then 6 locations are captured by ruggedness, and 4 locations by TPI. However, this model also has 23 locations as high values, while slope and ruggedness captured only 10 and 11, respectively (Table 5.3.[5]). Data about scenic points downloaded from New Zealand Geopreservation Inventory contain 76 locations of interest. All of them have been included in our assessment, giving similar results to data from field observations, or rather pattern (Table 5.3.[6]). Once more, slope and ruggedness captured 12 and 11, respectively, for the highest value. Meanwhile TPI has 11 for the highest and 22 for high values, which is higher than slope, roughness, and ruggedness, which captured 2 for each. Both tables demonstrate that the total curvature model is unfit for this assessment as most points falling into places with middle and low values. Additionally, Geomorphon is also demonstrated as being unsuitable for our purposes due to homogeneous results, as described in the Results section, despite capturing a high number of locations. We have visualized our results in Figure 5.3.(7), where geosite recognition based on TPI is presented with our field observation points and New Zealand Geopreservation Inventory sites.

Table 5.3.[5]: Comparison of results of geodiversity assessment based on different geomorphological models with location recognized through field observation.

Field observation sites	Slope	Roughness	Ruggedness	Total curvature	TPI	Geomorphon
1	1	1	1	8	0	0
2	9	16	13	20	7	7
3	28	24	25	22	22	21
4	10	14	11	5	23	28
5	8	1	6	1	4	0
Total	56	56	56	56	56	56

Table 5.3.[6]: Comparison of results of geodiversity assessment based on different geomorphological models evaluated with location from New Zealand Geopreservation Inventory.

Geopreservation sites	Slope	Roughness	Ruggedness	Total curvature	TPI	Geomorphon
1	3	3	3	12	2	5
2	17	23	19	34	11	11
3	25	23	24	14	30	24
4	19	19	19	10	22	36
5	12	8	11	6	11	0
Total	76	76	76	76	76	76

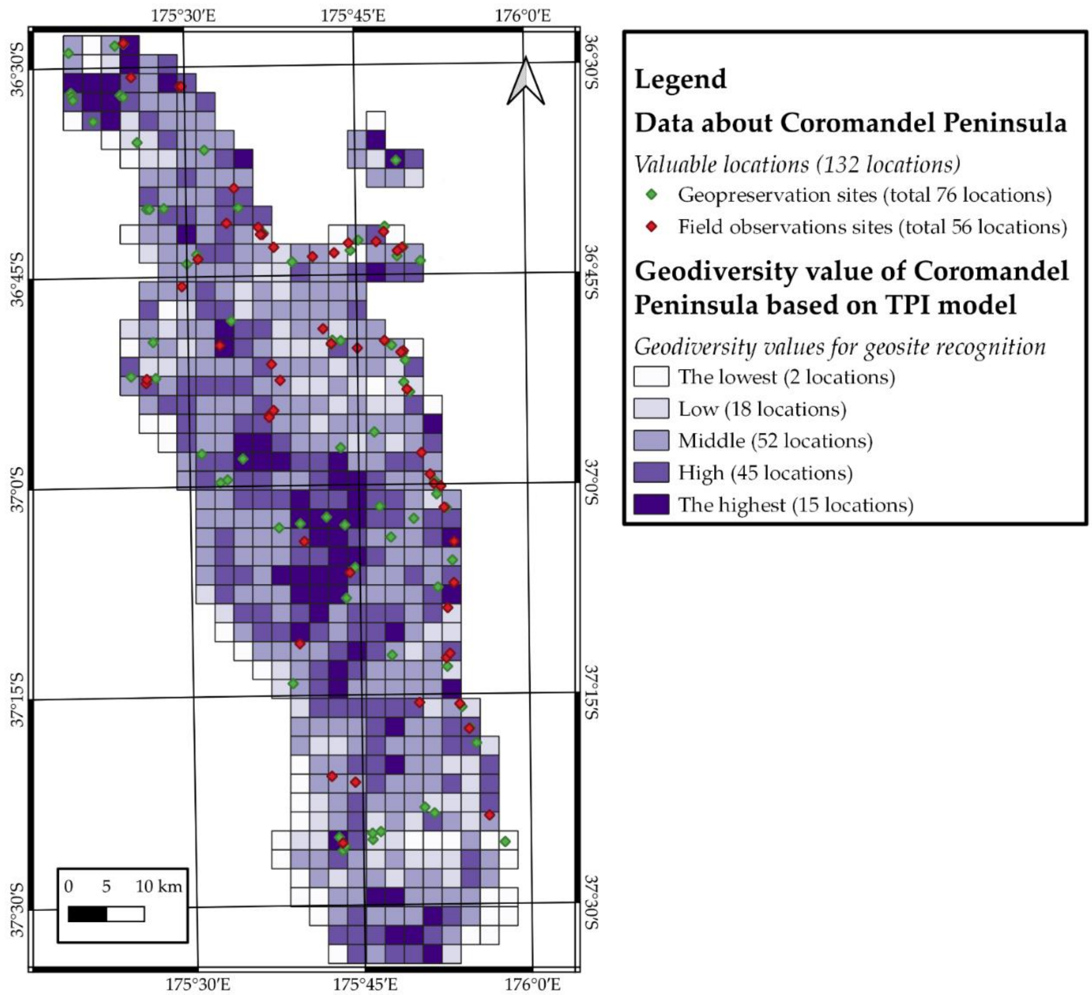

Figure 5.3.(7): Geodiversity values of the Coromandel Peninsula based on TPI model evaluated with natural breaks (Jenks) mode. Valuable locations throughout the Coromandel Peninsula gathered through field observation and New Zealand Geopreservation Inventory (NZGI, n.d.).

For future research, the results of slope, ruggedness, and/or TPI models will be utilized to select the most valuable locations in the Coromandel Peninsula. Subsequently, we will refine our results further using more accurate data from the digital elevation model based on the topographic map of the Coromandel Peninsula. Additionally, we will create further layers of information based on abiotic nature and cultural heritage. The geodiversity description will also include knowledge about hydrology, soils, fossils, archaeological sites, minerals, etc., which have not been included in this assessment. They will be described in more detail in future research. Photographic images recorded during field observation can be used to describe the most significant geosites in the Peninsula, with more detail for geotouristic and geoeducational perspectives (Figure 5.3.(8)).

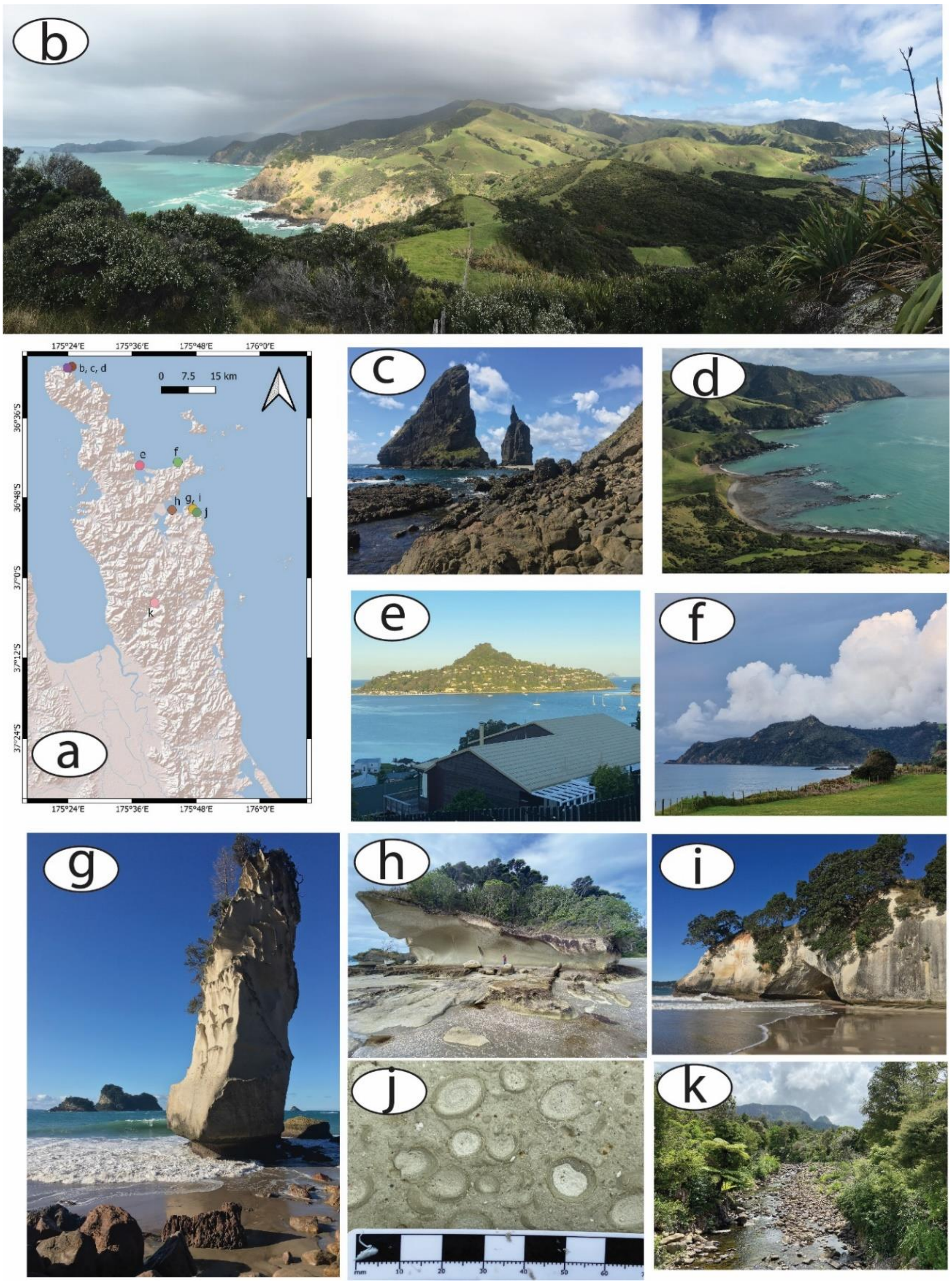

Figure 5.3.(8): Selected geologically important and interesting sites with high geoheritage values shown on an ESRI Shaded relief map (a). These selected sites are compared with the geodiversity values our calculation showed. (b) The Fletcher Bay area in the northern Coromandel area generally falls in the high geodiversity zones; however, inland areas are more in the middle level of geodiversity values, which is consistent with the relatively simple geology and low relief of the region; (c) our geodiversity estimate picked up well on the local high geodiversity area of the half-section of andesitic volcanoes; (d) coastal areas, especially shore platforms, are important as they commonly show well-exposed stratigraphy, such as in the Fletcher Bay; (e) the rhyolitic lava dome of Tairua is a key geosite that is part of a complex coastal

area, and our calculation yielded a high geodiversity value for this region; (f) similarly, the Black Jack area showed a high geodiversity value that is consistent with its complex hydrothermal-alteration-associated geological features; (g) in small areas, especially in coastal areas, important local geosites were commonly missed in our estimates, which is considered to be a scale problem of the method; (h) in some cases, however, coastal regions composed of geologically complex features such as the Shakespeare Bay, where ignimbrite outcrops form spectacular abrasion features and perfectly exposed rocks fall within high geodiversity zones, were calculated; (i) the major geotouristic hot spot of the Coromandel peninsula, the Cathedral Cove, also falls within the high geodiversity field of the calculations; (j) small-scale features such as spectacular accretionary lapilli beds within ignimbrite deposits can be missed by our calculation, and this highlights the fact that our method should be used for first-order identification of the geodiversity elements of the region that can later be followed by detailed site exploration to locate key, normally geometrically small features; (k) in regions where our method provided high geodiversity values, the vegetation cover and the rugged surface commonly hinder accessibility and restrict outcrops along stream valleys, such as in the Table Mountain region along the Kauaeranga River valley.

5.3.5 Conclusions

Based on our assessments of geodiversity for geosite recognition, the results demonstrate that using slope, ruggedness, and roughness models produces the most similar results, which is confirmed by natural break mode for evaluating similarities ~85%. TPI is also shown to be a useful model for geodiversity recognition as its results show a similarity of ~55–60% to the former models. However, the total curvature and Geomorphon models have been demonstrated to be unsuitable for our assessment purposes due to low diversity in their results. Hence, quantitative–quantitative assessment of geodiversity for geosite recognition can be carried out with the slope, roughness, and ruggedness models, which produce nearly interchangeable results, and TPI is also suitable for this type of assessment, while Geomorphon and total curvature should be avoided.

Additional data extracted from the field observations and New Zealand data on the Coromandel Peninsula show that the TPI model recognizes the highest number of areas with high and the highest values, followed by the slope and ruggedness models. In the case of roughness, despite similarities to the former models, a lower number of points are captured by the assessment. Once again, we stress the unsuitability of Geomorphon and total curvature for geosite recognition. Hence, after our additional justification of assessment accuracy, TPI can be considered one of the best models for geosite recognition utilizing our methodology, followed by slope and ruggedness.

Our assessment of geodiversity for geosite recognition demonstrates that for further observation, regions with high and the highest values must be studied at a lower scale utilizing non-grid assessment and preferably with more accurate data for elevation together with additional information about other aspects of abiotic nature. Hence, our next stage of research for geodiversity assessment of the Coromandel Peninsula will explore locations we have defined with high and the highest values to describe potential geosites more accurately with layers describing natural abiotic features to inform geotourism and geoeducation.

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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.

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Description: The next study focusses on Mayor/ Tūhua island located in the North Island of New Zealand, Bay of Plenty region. The island has been included into our study due to its more detailed volcanic heritage compared to Samoa which allow for the demonstration another evaluation system based of facies. Additionally, in this study I received an opportunity to utilize new LiDAR data, which improved the result of calculation of geomorphological elements. The main goal to utilize Mayor Island for the QQG assessment is to test our methodology with different evaluation systems to more precisely recognise potential geosites.

The published article can be accessed:

https://www.lyellcollection.org/doi/abs/10.1144/ SP530-2022-90 accessed 21st of August 2023

Reference: Zakharovskyi, V., Kósik, S., Li, B. and Németh, K., 2023. Geosite determination based on geodiversity assessment utilizing the volcanic history of a near-sea-level explosive eruption-dominated volcanic island: Tūhua/Mayor Island, New Zealand. Geological Society, London, Special Publications, 530(1), pp. SP530-2022.

In this research: the article has been changed to meet the style of the thesis.

5.4 Title: Geosite determination based on geodiversity assessment utilizing the volcanic history of a near-sea-level explosive eruption-dominated volcanic island: Tūhua/Mayor Island, New Zealand

Abstract: Tūhua/Mayor Island is located approximately 45 km off the NE coast of the North Island of New Zealand. This island was formed by various explosive and effusive volcanic eruptions commonly influenced by magma–water interaction eruption events occurring since the Pleistocene. The wider area of the SW Pacific contains numerous volcanic islands with a similar type of volcanic evolution. Tūhua/Mayor Island should be studied in more detail to understand the underlying volcanic mechanisms and apply this research to other volcanic islands in the SW Pacific. Mayor Island, also known by its indigenous Māori name Tūhua (obsidian in Māori), provides an ideal site for studying current volcanism. The present-day island was formed around 150 ka ago and contains several rhyolitic lava-flows from different time periods, pyroclastic-flow deposits generated by small-volume localized eruptions and ignimbrite deposited by large explosive eruptions. Our research utilized a qualitative–quantitative assessment of geodiversity estimates to highlight possible geosites for the collection of precise information about the geological evolution of this area, demonstrating the potential of geoeducational sites. The term geodiversity recognizes geological and geomorphological elements, which have shaped the Earth's surface and underly our abiotic environment. Additionally, volcanic heritage was included in our equation, specifically tailored for Tūhua/Mayor Island and based on expert views (qualitative model). This model allows for a wider diversity for the area of research compared with the original method, which utilized only geological elements. The results show that areas with pyroclastic deposits exposed on the cliffs and in the centre of the collapse caldera should be considered for the further study for geosite planning.

5.4.1 Introduction

The recent eruption of a partially submerged intermediate polygenetic caldera at the Hunga Tonga–Hunga Ha'apai volcano demonstrates the unpredictable explosive power of these types of eruptions, which in turn leads to questions about societies' preparedness for similar future events (Németh, 2022, Sekizawa and Kohyama, 2022). Such eruptions may occur with little to no warning in areas of the SW Pacific, where intermediate (basalt, andesite to dacite) complex volcanoes have evolved over tens of thousands of years with continuous magma recharge cycles (Brenna et al., 2022). These regions are commonly associated with young hydrothermal systems as an interface between hot magma and shallow marine volcaniclastic sediments (water-saturated) interacting with sea water (Nakayama et al., 2015). The most effective tool for predicting future eruptive activity remains the precise study of past eruptions and subsequent deposits and landforms, hence the importance of Tūhua/Mayor Island as research and geoeducation site. Geological evolution encompasses a range of past events occurring as interactions between tectonic and weathering/erosion processes, influencing the surface features of the Earth's crust and its composition with time. These manipulations create three main types of rocks: volcanic, metamorphic, and sedimentary. The first is volcanic (extrusive and intrusive), whereby new formations appear on the surface as the main source of minerals for the environment. Then sedimentary rocks are formed by weathered and/or eroded mineral products, which are transferred and hardened in situ or in more distant locations. The third is metamorphic rocks, which are sedimentary or volcanic rocks undergoing alteration through high pressure and heat. The three rock types create a basement for landscape features which tell the story of the formation of Earth's surface properties and forms, based on geological and geomorphological knowledge. Based on these definitions, the geology and geomorphology are the main parameters shaping geodiversity and resulting in the abiotic environment underlying and influencing all of nature (Zakharovskyi and Németh, 2021b). Therefore, geodiversity becomes a starting point for defining geosites based on geoheritage and geodiversity (Figure 5.3.(1)). We use these terms in the context of describing important sites demonstrating geological evolution, especially locations of active volcanism, whereby new rock formations appear on the surface (Manosso and de Nóbrega, 2016, Brocx and Semeniuk, 2007, Cengiz et al., 2021, Zakharovskyi and Németh, 2021a).

Many locations across the SW Pacific are crucial sites demonstrating the full spectrum of phreatomagmatic eruptions, ranging from mildly explosive through to climate-forcing events of significant destructive power (Plank et al., 2020, Vaughan and Webley, 2010, Oppenheimer, 2003, Witter and Self, 2007). The volcanic geoheritage provides a useful framework for the study of geological history and the dissemination of information relating to potential controlling parameters and the possible impacts of various eruption scenarios (Fepuleai et al., 2021, Guilbaud et al., 2021). However, we have limited tools to access the locations of currently submerged volcanic craters and/or calderas, where former eruptive products may be preserved within the boundaries of islands areas. These sites are key locations of volcanic geosites facilitating the development of geoeducation, geotourism and eventually geoconservation ventures and research.

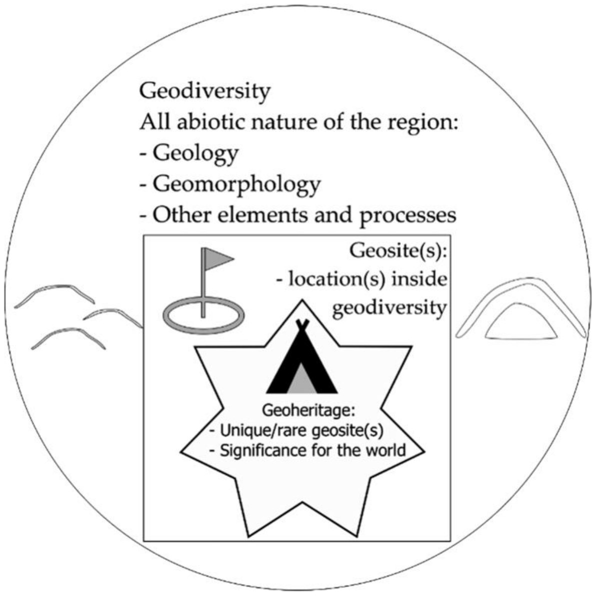

Figure 5.4.(1): Connection between geodiversity, geosite and geoheritage (Zakharovskyi and Németh, 2021a).

Tūhua/Mayor Island is a significant volcanic location in the Bay of Plenty, New Zealand. The island is formed by a volcanic complex with a 150-ka eruptive history evidenced by geological features formed by near-sea-level eruptions controlled by explosive water–magma interactions (Houghton et al., 1992). A recently completed LiDAR (LINZ, 2023) survey allows access to a high-quality digital elevation model of the island (Figure 5.4.(2)), combined with a systematic revision of the volcanic geology (Figure 5.4.(3)). This provides a unique opportunity to assess and inventory potential geosites based on their geodiversity values. This assessment will inform an improved geological understanding of the island's eruptive history, leading to more accurate modelling of future volcanic activity and the establishment of risk and hazard warning areas (Buck, 1985). In this research, we provide the first estimate of the island's volcanic history based on the methodology of geodiversity assessment as outlined in similar research in the Samoa Islands (Zakharovskyi and Németh, 2021b). Our results highlight the highest value areas based on the steepness of the landscape and the historical significance of rock formations for volcanic study. This geodiversity calculation method has been introduced and tested against a general geological scenario (Zakharovskyi and Németh, 2021b), which we have adjusted and specifically tailored to the evaluation scales for the mapped and recently reinterpreted volcanic system of the island, represented by young extrusive rock formations (Kósik et al., 2022). We suggest that the sites assigned high and the highest geodiversity values should be studied more precisely in the future to identify key geoheritage elements and geosites that could form the basis for future geotourism, geoeducation and geotourism developments.

5.4.2 Aim of research

The main goal of our research is to analyze readily accessible data about Tūhua/Mayor Island to select the most valuable sites for further research and more detailed descriptions of its geological evolution. This will lead to improved qualitative–quantitative assessments of geodiversity utilizing data relating to the volcanic history of the island as a unique element equally important as the island's geology and geomorphology. Finally, our method utilizes standard and accessible data and software, able to be repeated and/or improved by other researchers.

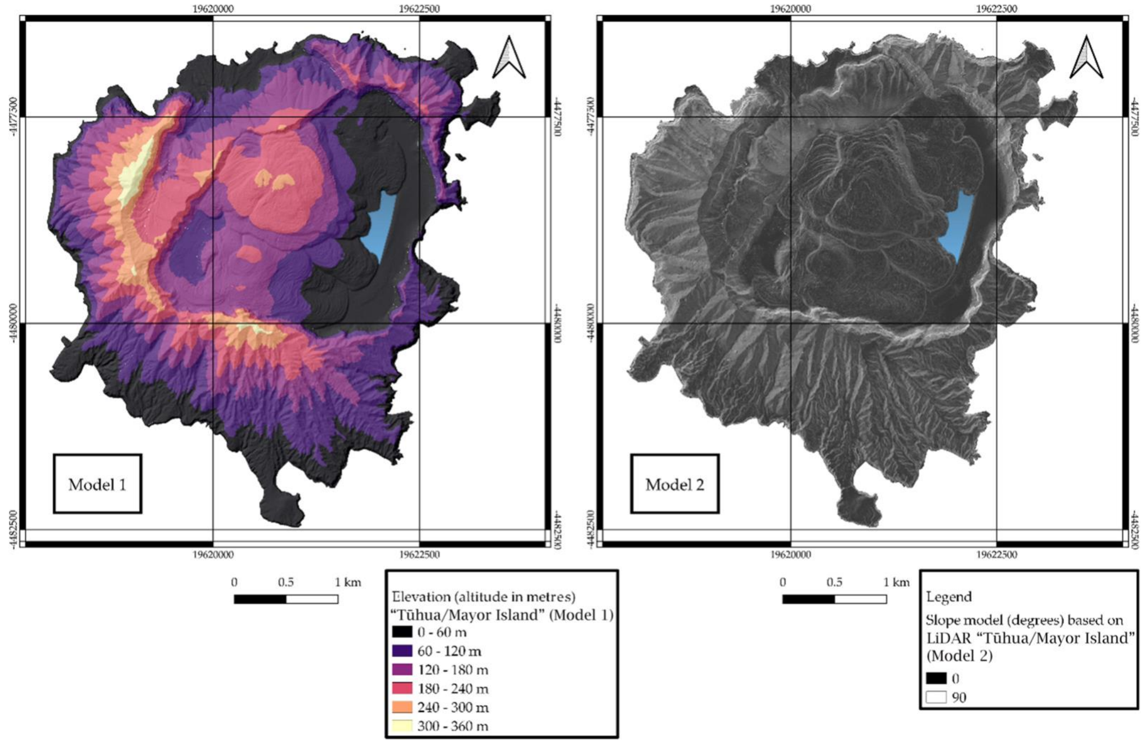

Figure 5.4.(2): Elevation model (model 1) and slope model (model 2) of Tūhua/Mayor Island based on the LiDAR data. The elevation model (model 1) provides information about altitude above sea-level up to 360 m. The slope model shows slope degree ranging from 0 to 90°, in a single greyscale (ranges of grey from black to white).

5.4.3 Geology and geomorphology of Tūhua/Mayor Island

Tūhua/Mayor Island is the subaerial portion of a per-alkaline shield-like volcanic edifice formed under an extensional tectonic regime within the western part of the Bay of Plenty (Wright, 1992, Houghton et al., 1992). The volcanic edifice reaches an elevation of 354.3 m above sea-level with an estimated 15 km-wide base rising from 420 m depth of the continental slope (Kósik et al., 2022). It is typical of volcanic systems surrounded by large lakes or occurring in a marine environment that the volcanic activity is heavily influenced by the availability of external water to fuel explosive eruptions (Houghton and Nairn, 1991, Wilson, 2001, Kósik et al., 2021, Brenna et al., 2022). The largest, 7.6 ka Plinian eruption of Tūhua was influenced by magma–water interaction, resulting in the Tūhua Tephra deposit, one of the most important Holocene marker horizons in the region (Lowe et al., 2019, Lowe et al., 2008). The island is dominated by a 3 km-wide nested collapse caldera and contains numerous vents active in three cycles of eruption over the last 150 ka (Houghton et al., 1992, Wilson, 2007, Kósik et al., 2022).

Cycle 1: 150–36 ka (nine effusive and 12 explosive) pre-Rotoehu eruptions (150–46 ka) and post-Rotoehu (46–36 ka) periods.

Cycle 2: 36–9.2 ka (two lava domes and two tuff/pumice cone eruptions outside the caldera, lava shield growth in the caldera with one sub-Plinian event and one probable small-scale caldera collapse event). This cycle ended with the 9.2 ka caldera collapse.

Cycle 3: 9.2 ka to present (Plinian eruption associated with the formation of the 7.6 ka Tūhua Tephra and subsequent predominantly effusive activity within the caldera).

A new updated geological map was utilized in this work (Kósik et al., 2022) to determine the geological heritage value of the island (Figure 5.3.(3)). As previously mentioned, the geological history of Tūhua/Mayor Island can be divided into three periods based on magmatic evolution over the past 150 ka. These events produced several geological units represented on the map in two broad categories of forms: lava flows and diverse, but mostly cone-building, pyroclastic deposits. In this study lava flows are assigned a lower geoheritage value compared with pyroclastic deposits as they contain less information about the volcanic history of the island, and they are more common rock types in general (a more precise description is given in the next section). The first cycle occurred at 150–36 ka, which can be seen in remnants of pre- and post-Rotoiti lavas with cone-building pyroclastics in the SW and the NE parts of the island. The second cycle occurring at 33– 9.2 ka is represented by a rim, 9.2 ka spatter-fed and extra-caldera lavas on the South part, and edifice 2 lavas and cone-building pyroclastics in the central-west. Finally, the third cycle occurring from 7.6 ka to the present contains eruptive products of Tūhua Tephra and subsequent intra-caldera lavas and pyroclastics. Hence, the geological history of Tūhua/Mayor Island is represented by eight types of lava flows and three types of pyroclastic deposits occurring throughout the territory of research, with the youngest features concentrated in the center, while older formations are found occurring around the circumference of the island.

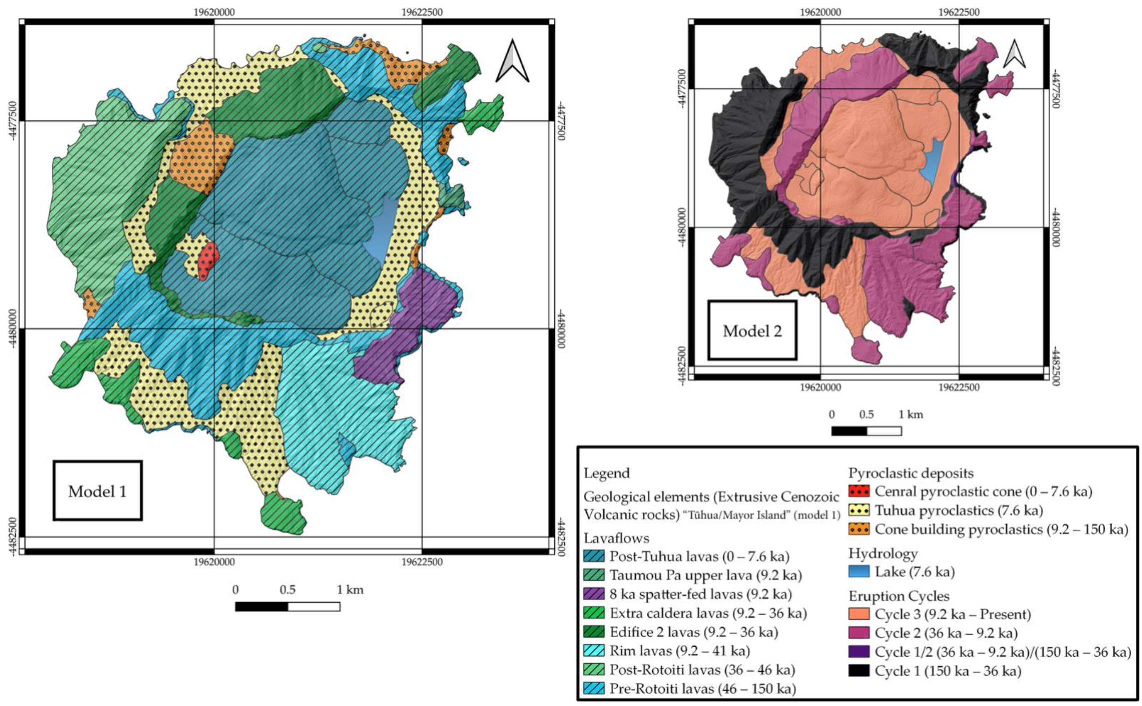

Figure 5.3.(3): Geological model of Tūhua/Mayor Island, with attention to volcanic heritage. Model 1 is a geological model of Cenozoic volcanic rocks presented by eight lava flows units with hashed lines, three units with pyroclastic deposits (pattern dots), and the blue color represents a lake. Model 2 provides additional information about three cycles of eruptions events: oldest, black; middle, red; and younger, yellow.

Tūhua/Mayor Island is currently a nature conservation area and important geo-cultural location for Māori tribes (Beehive, 2002). Visitation is restricted and formal landing permission is needed from the local Māori iwi. The island has no permanent settlement, however during early Māori occupation, it was a significant outpost of trading across the Bay of Plenty as it is located between the East Cape and the Coromandel Peninsula, two heavily populated regions with abundant natural resources (Phillipps et al., 2016, McCoy and Carpenter, 2014, Brown and Pitman, 2019, Moore, 2011). Tūhua/Mayor Island is also the source of a high-quality obsidian distinctive for its lack of flaws and greenish brown colour, occurring in peralkaline rhyolitic lava flows, that was widely traded throughout New Zealand and possibly in the wider Pacific (Phillipps et al., 2016, McCoy and Carpenter, 2014, Brown and Pitman, 2019, Moore, 2011).

5.4.4 Method of assessment of geodiversity

Our qualitative-quantitative assessment of geodiversity is based on an arithmetic average equation applied to values assigned to elements of an abiotic nature and their areas of occurrence. The equation is based on only three parameters: value points, area of spreading of each calculated element and the whole area of research.

5.4.5 Evaluation system

Evaluation systems were established as the qualitative part of our assessment of geodiversity, which contains five ranks (points) from the lowest, 1, to the highest, 5, values. Our evaluation system uses general geology and geomorphology principles, which are globally recognized and accepted in describing features of the Earth's surface and applicable in a global context.

5.4.5.1 General geological evaluation system

The value system of geology is based on the relative occurrences of different rock types and their age throughout the Earth's surface. Sedimentary rocks (except for those of the Paleozoic period) are the most widespread, then metamorphic (especially those of the Precambrian period) and finally extrusive and intrusive rocks are the least widespread and their occurrence is also dependent on their age (Table 5.4.[1]; Blatt and Jones, 1975). The age of a rock formation is based on the rock's evolution, so older formations contain more information about past events and provide more evidence of the Earth's crustal evolution. The resulting table shows that sedimentary Cenozoic rocks are assigned a value of 1 point (the lowest), sedimentary Mesozoic rocks a value of 2 points (low), metamorphic (Precambrian) rocks a value of 3 points (middle), sedimentary (Paleozoic) rocks a value of 4 points (high), and all intrusive and extrusive rocks a value of 5 points (Zakharovskyi and Németh, 2021b) as well as metamorphic (Mesozoic and Paleozoic) and sedimentary (Precambrian) rocks.

Refining the geological values will provide an important focus for future research. However, broadly speaking we can confirm that Tūhua/Mayor Island was formed by Pleistocene extrusive rocks which appear as an old caldera in the center of the island, with different types of lava flows and pyroclastic deposits (described in geological section) on its collapsed walls, which are assigned the highest value.

5.4.5.2 Volcanic heritage evaluation system

Volcanic values have been included in our equation to provide a more detailed description of our locations of research. Evaluation of volcanic heritage is based on expert views (qualitative method; Table 5.4.[2]), highlighting the most valuable places specific to Tūhua/Mayor Island. Volcanic history values are based on knowledge of volcanic facies which are formed during an eruption event, represented by different types of material such as lava flows, pyroclastic deposits and other features, including recognizable volcanic geoforms (e.g., vents, craters, caldera walls). Currently, they represent two types of volcanic eruption: subaerial andesitic stratovolcanoes (Table 5.4.[3]) and the rhyolitic caldera complex (Table 5.4.[4]) (Wohletz and Heiken, 1992). For this research, the rhyolitic caldera complex table was utilized to create a value system for Tūhua/Mayor Island, where medial lavas (post-caldera – flank) were assigned 1 point (the lowest), proximal lavas (intra-caldera – within caldera) were assigned 2 points (low), proximal lavas (clastogenic or spatter-fed – obsidian lava) were assigned 3 points (middle), proximal pyroclastic rocks (caldera-related ignimbrite or fall tephra) were assigned 4 points (high), proximal pyroclastic rocks (cone-building, e.g. stratocone) were assigned 4 or 5 points (the highest values), and proximal to distal pyroclastic rocks (cone building, e.g. intra-caldera or satellite vent cone) were assigned 5 points (the highest) (Table 5.4.[4]). However, our geological model (Figure 5.4.(1)) utilizes other names for volcanic features, which were assigned values as follows: extra-caldera lavas, post- and pre-Rotoiti lavas, Taumou Pa upper lava, Edifice 2 lavas and Rim lavas were assigned 1 point; post-Tūhua lavas were assigned 2 points; 9.2 ka spatter-fed lavas were assigned 3 points; Tūhua pyroclastics were assigned 4 points, cone-building pyroclastics were assigned 4 or 5 points; and the central pyroclastic cone was assigned 5 points (Table 5.4.[2]).

5.4.5.3 General geomorphological evaluation system

Our geomorphological evaluation system is based on slope steepness (e.g., slope map) as steeply sloping surfaces are more likely to expose rock formations suitable for more in-depth and targeted research (Table 5.4.[1]; Zakharovskyi and Németh, 2021a). Additionally, the slope degree is strongly coupled to geomorphological processes influenced by the rocks' erosion resistance and the age of the rock formation. Meanwhile, the slope degree is strongly coupled to geomorphological processes influenced by the rocks' erosion resistance and the age of the rock formation where any kind of formation evolves towards decreasing the slope, ultimately reaching equilibrium closer to sea-level (Davis and Sims, 2013, Phillips, 2016, Zhao et al., 2017, Arora et al., 2021, Zakharovskyi and Németh, 2021a). This evaluation was applied on the LiDAR image provided for Tūhua/Mayor Island, which was transformed into a slope model (Figure 5.4.(4)).

Table 5.4.[1]: Percentage of rock types exposed on Earth's surface as function of geological age (Blatt and Jones, 1975).

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

[1] According to the table extrusive and intrusive rocks are the rarest type, hence they have the highest value from geological perspective.

Table 5.4.[2]: Evaluation system for Tūhua/Mayor Island, based on previous research on the Coromandel Peninsula (Zakharovskyi and Németh, 2021b).

Subaerial Andesitic Stratovolcanoes		
5	Central Facies	• consanguineous dykes, especially those that are radial or randomly oriented. • consanguineous sills that are concordant with moderate to steep initial dips. • breccia pipes and stocks • hydrothermal alteration with steep lateral gradients. • coarse agglomerates. • thick, steeply banded siliceous lavas. • coarsely stratified but poorly sorted tephra. • steep initial dips. • thin lava flows that are volumetrically subordinate to fragmental ejecta. • ponded crater – and vent-fillings with sharply divergent cooling joints.
3.5	Proximal Facies	• dominated by broad, thick lavas. • intercalated coarse grained pyroclastics, poorly sorted pyroclastic breccias may be cut by consanguineous dykes • moderate to step initial dip.
2	Medial Facies	• pyroclastics dominate over lavas. • lahars with angular or subangular blocks up to 10 m or so in diameter • tephra layers with good sorting and grain sizes mainly in the lapilli to coarse ash range • zones of weathering and soil development (paleosols) between lava flows • clastic debris reworked by water. • moderate to shallow dips.

0.5	Distal Facies	• fine layered tephra with grain sizes in the range of coarse-to-fine ash, and with an outward increasing ratio of glass to crystals • lahars with blocks that rarely exceed a meter in diameter and have rounded or subrounded particles in the matrix • interlayered shallow-water sediments, soils, and organic debris. • lava flows restricted mainly to isolated vents, basaltic sheets, and intra-canyon flows.

Table 5.4.[3]: Scale of volcanic facies of subaerial andesitic stratovolcanoes.

Rhyolitic Caldera Complexes		
5	Intracaldera Dome Facies	• rhyolitic lava domes and short flows • autobreccia carapaces and aprons • near-vent pyroclastic falls • minor basalt scoria cones may be present
3.5	Intracaldera Fill Facies	• collapse breccias interbedded with ignimbrite • very thick crystal rich ignimbrites • co-ignimbrite lag fall breccias and interbedded epiclastics • lacustrine deposits
2	Extracaldera Proximal Facies	• interbedded, mainly thick, ignimbrite and airfall rhyolitic tuffs • minor rhyolitic domes • basalt scoria cones • welded centers • coarse lithic clasts
0.5	Extracaldera Distal Facies	• mainly un-welded ignimbrites with fine clasts • volcanogenic epiclastics

Table 5.4.[4]: Scale of volcanic facies of rhyolitic caldera complexes.

Rhyolitic Caldera Complexes		
5	Intracaldera Dome Facies	• rhyolitic lava domes and short flows • autobreccia carapaces and aprons • near-vent pyroclastic falls • minor basalt scoria cones may be present
3.5	Intracaldera Fill Facies	• collapse breccias interbedded with ignimbrite • very thick crystal rich ignimbrites • co-ignimbrite lag fall breccias and interbedded epiclastics • lacustrine deposits
2	Extracaldera Proximal Facies	• interbedded, mainly thick, ignimbrite and airfall rhyolitic tuffs • minor rhyolitic domes • basalt scoria cones • welded centres

		• coarse lithic clasts
0.5	Extracaldera Distal Facies	• mainly un-welded ignimbrites with fine clasts • volcanogenic epiclastics

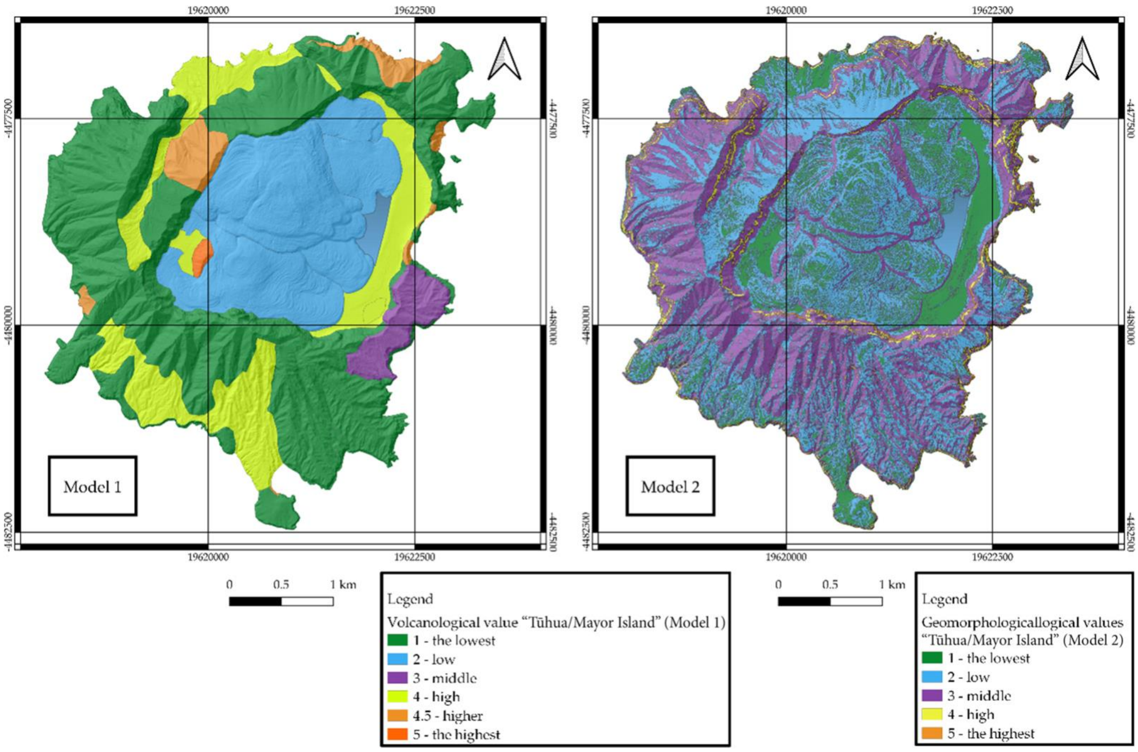

Figure 5.4.(4): Volcanological (model 1) and geomorphological (model 2) models of Tūhua/Mayor Island with our assigned value system (Table 5.4.[2]) based on the geological model (Figure 5.4.(3)) and LiDAR data (Figure 5.4.(2)).

Table 5.4.[5]: Evaluation systems for volcano heritage.

Main Values of Geodiversity			Additional Values of Geodiversity
Values (5-point system)	Elements of Geodiversity		
	Morphology	Geology	Volcanology
	Slope degree	Rock type (ages)	Facies according to Mayor Island
1 (the lowest)	0-7.5	Sedimentary (Cenozoic)	Lavas Medial (Post-caldera – flank)
2 (low)	7.5-22.5	Sedimentary (Mesozoic)	Lavas Proximal (Intracaldera – within caldera)

3 (middle)	22.5-45	Metamorphic (Precambrian)	Lavas Proximal (Clastogenic – obsidian lava)
4 (high)	45-67.5	Sedimentary (Palaeozoic)	Pyroclastic rocks Proximal (Caldera-related ignimbrite or fall tephra)
5 (the highest)	67.5-90	All Extrusive and Intrusive Metamorphic (Mesozoic and Palaeozoic) Sedimentary (Precambrian)	4.5 – Pyroclastic rocks Proximal (Cone building (e.g., stratocone) 5 – Pyroclastic rocks Proximal to Distal (Cone building (e.g., intra-caldera or satellite vent cone)

5.4.5.4 Geographical information system

QGIS (Quantum Geographical Information Systems) free software (QGIS, n.d.) was utilized for the modelling and calculation of the geodiversity of Tūhua/Mayor Island as it contains all the required tools (Baghdadi et al., 2018). For geological assessment, the geological model of Tūhua/Mayor Island (Figure 5.4.(3)) was utilized with application of the system of volcanic values (Tables 5.4.[2–5]). Meanwhile, geomorphological assessment was improved using the high-quality LiDAR elevation model (Figure 5.4.(2)) in contrast to our previous research on the geodiversity assessment of Samoa Islands (Zakharovskyi and Németh, 2021a), where the SRTM (Shuttle Radar Topography Mission) was used for the calculations. A short explanation of the main operation is presented in a flow chart (Figure 5.4.(5)).

5.4.6 Geodiversity of Tūhua/Mayor Island based on volcano stratigraphy and key features as additional values

Our original methodology was altered to specifically target our area of research as the territory of Tūhua/Mayor Island contains only volcanic rocks of different ages. To achieve this, we created an additional value table for geological assessment, following volcanic geology concepts and the notion of proximal areas (if preserved) (Table 5.4.[5]). This demonstrates a greater diversity of rocks, minerals, volcanic geoforms and their features linked to various near-vent to near-crater processes. A significant distance from the source (or where the source is eroded back significantly) results in a gradually decreasing geological value as the volcano-sedimentary system enters a more distal region such as a ring plain surrounding the volcano (Németh and Palmer, 2019). This area contains outcrops of poor quality and a limited number of preserved deposits, while their appearance becomes part of the general background rather than distinctive and outstanding features (Tables 5.4.[3–5]). However, these medial to distal sections can preserve tephra layers in a clear stratigraphic position, which are valuable in understanding volcanic system stratigraphy at a fine scale (Németh and Palmer, 2019). In these distal regions we find preserved tephra records, which are used to define volcano strata-types, describe the chronostratigraphy of deposits and demonstrate their link to geological history. In the case of Tūhua/Mayor Island, well preserved eruptive products almost exclusively represent the proximal or medial facies of eruptive products. While landslides are common features on active volcanic terrains and can offer significant volcanic geoheritage values of a terrain, we have only identified one possible location (Cathedral Bay) where the present and recent shore morphology represents a potential landslide scar. Unfortunately, the offshore bathymetry has low resolution, and it is impossible to assess if any major landslide fan is preserved on the seafloor or not. Moreover, there is a 500–1000-metre-wide abrasion platform around the volcano, so landslide scars may affect that area to a greater extent than the subaerial part. Current sea level was established around 7 ka, coinciding with the 7.6 ka Tūhua eruption, which would be an interesting point to examine but this is a significant volcano geology question, and it is not the subject of this work. In many near sea-level volcanic systems hyaloclastites and peperites can be abundant. Such rock types also carry geoheritage values. Onshore, however, such deposits are covered by the young Tūhua tephra, and the only possible surficial occurrence is inferred at Lake Aroarotemahine (Figure 5.4.(2)). This site is, however, very difficult to access owing to vegetation cover and probably has no outcrops ready to explore.

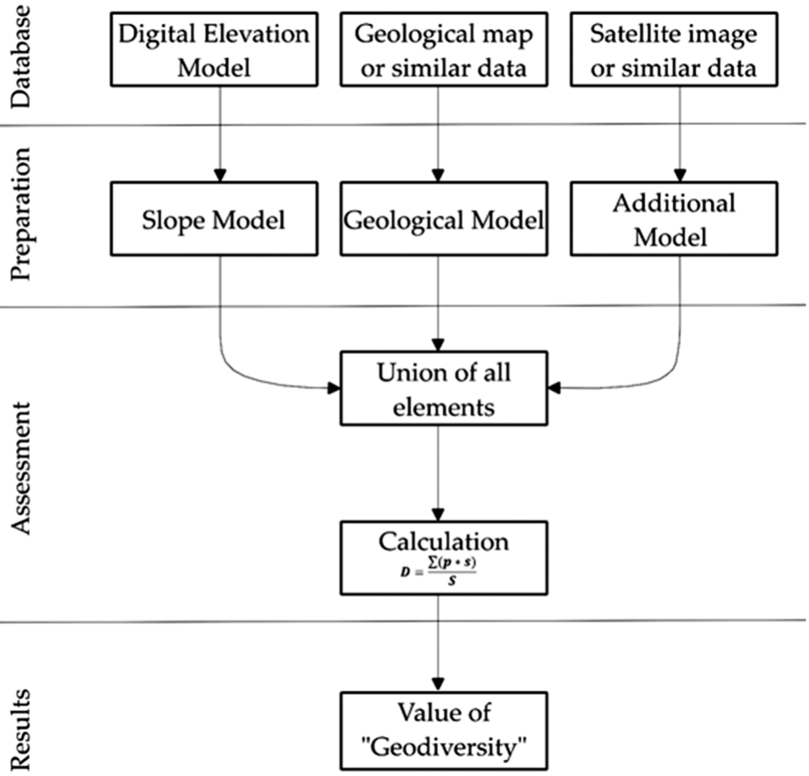

Figure 5.4.(5): Scheme of qualitative–quantitative assessment of geodiversity utilizing standard data about geology, geomorphology, and additional abiotic elements. This flow chart was based on the scheme for the assessment of geodiversity in Samoa (Zakharovskyi and Németh, 2021a).

5.4.7 Potential geosites with geoducation, geodiversity research and geotourism values in Tūhua/Mayor Island

The assessment of geodiversity is based on a non-grid system, which results in regions of different shapes defined by geological and geomorphological values (Figure 5.4.(6)). Tūhua/Mayor Island shows a relatively low value of geodiversity throughout the whole area of research, as most places would not be validated for study as they contain lava flows with gradual slope steepness. This results in areas that are difficult to access for field observations, providing limited information about the volcanic heritage. Meanwhile, green areas assigned the lowest values are visible mostly as small areas of blue colors (low value), also of limited value for further research. Purple areas assigned a middle value for geodiversity mostly appear as wide areas mainly on the east, SW, and central parts of the island. These could be considered as places with additional information; however, those values ranging from the lowest to the middle are not considered important for this research as they contain weak volcanological and/or geomorphological values and should not be considered as geosites.

The regions with high and the highest geodiversity values are the main targets of this research. Mapping these values demonstrates that those areas mostly appear near middle-value regions, which can be explained by the volcanic nature of this landscape. Volcanological values appear on areas of two different slope degrees, where the steeper part of a landscape will probably expose geological formations, providing more information. These regions are represented by yellow and orange colors for the highest values. Regions with high values can be seen in the south part of the island, on the west walls and in the center of the caldera, while the north and east sides expose valuable rock formations closer to the coastal areas forming cliffs. Additionally, a few small areas with the highest values for geodiversity appear only on the NW part of the Tūhua/Mayor Island and cliff sites.

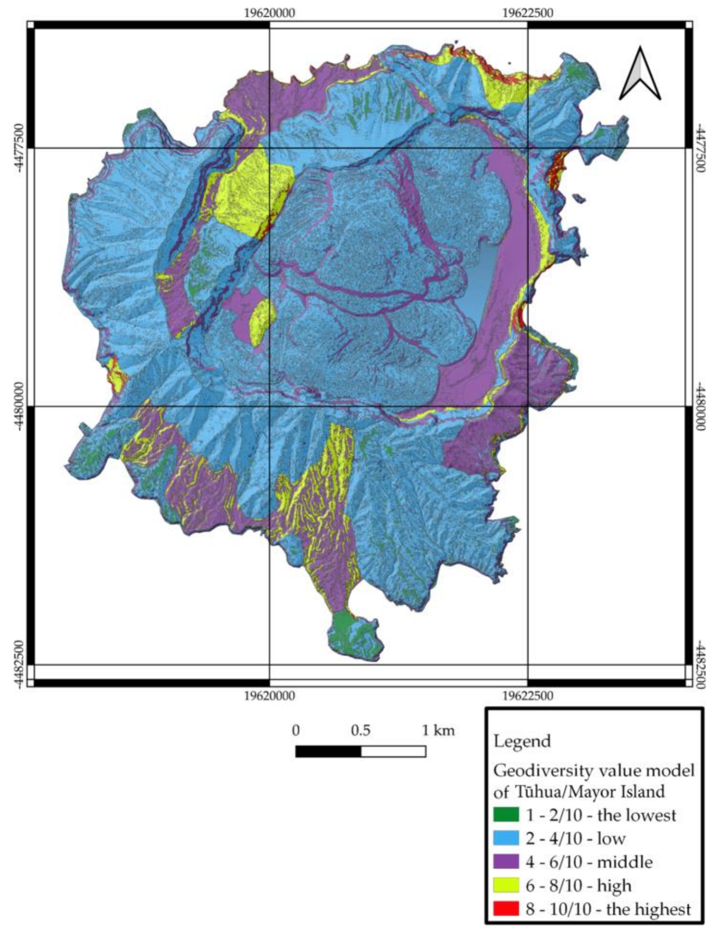

Figure 5.4.(6): Geodiversity value of Tūhua/Mayor Island based on volcanological and geomorphological values (Figure 5.4.(4)).

5.4.8 Discussion

We consider Tūhua/Mayor Island as one of the most important places for studying post-Pleistocene volcanism in a period ranging from around 150 ka up to the current time. This area contains evidence of 52 eruption events forming an island with youthful surface morphology of the lavas of the most recent eruptions (Figure 5.4.(7a); Houghton et al., 1992; Kósik et al., 2022). More precise study of this area can provide a valuable analogue for defining the role of external water in the volcanic eruptions of near-sea-level volcanic islands of the SW Pacific. Recognition of the geodiversity elements of such systems provides information to identify key geosites that can be used for geoeducation programs to develop community resilience for volcanic hazards.

The qualitative–quantitative assessment of geodiversity show that the SW coast (Figure 5.4.(7b)) and the north to NE (Figure 5.4.(7c)) cliff sides of Tūhua/Mayor Island are the most significant sites for volcanic geoheritage. We arrive at this conclusion using calculations based on information from geological and geomorphological models. The result of our assessment shows that cone-building, Tūhua and Central cone pyroclastic deposits are the most valuable geological formations. The significance of the pyroclastic deposits is derived from our table showing the evaluation system, as they contain material demonstrating a greater variety of elemental composition densities and hardness properties. Moreover, the Tūhua and central core deposits are young materials, which have not been highly weathered or eroded, while cone-building deposits contain material from all eruption cycles represented throughout the island, including those lava flows containing obsidian with a high geocultural significance (Figure 5.4.(7d)). Hence, the places with high and the highest values of geodiversity are suggested as target areas for volcanological studies of Tūhua/Mayor Island, with a goal of establishing a more accurate geoeducation plan in the context of the volcanic history of the island.

Figure 5.4.(7): (a) Tūhua/Mayor Island from the south. Note the conical geoform on the left side of the image as part of an old stratocone and the broad flat parts on the right side. (b) High-geodiversity regions in the SW of the island representing deep valleys formed by older lava flows and coastal regions with various younger pyroclastic successions. (c) High-geodiversity regions in the NNE side of the island where young eruptive products and the old stratocones expose complex volcanic successions in a complex morphology. (d) Obsidian lava flow in the southern coastal regions of the island as an important geocultural material source for early Māori civilizations in the region.

Our methodology for assessment of geodiversity is a highly practical tool for defining the most significant sites and target areas for further geoeducation, geotourism and geoconservation research. As geodiversity is a relatively young subject, a simple and economically viable method for assessment, inventory and targeted research is vitally important in establishing a foundation for geodiversity research which can be further refined and added to. Hence, the assessment presented in this article is based on the geodiversity, where geological and geomorphological values create the core elements of abiotic nature. A current limitation is that our model does not include hydrological resources and processes. Although these can be considered as unliving parts of the environment, we decided to reconsider them as processes which influence Earth's crust. The crust is formed by qualitative parameters (density, hardness, weight, porosity) expressed in rock composition, which in turn shapes the morphology and structure of surface forms. As new material is rising from the depths and erupts to the surface through volcanic activities, the hydrosphere, climate, anthroposphere and biosphere are constantly influencing rock formations by erosion and weathering processes. However, all these processes can make a noticeable impact only over thousands of years, which means that rock can be considered as a nearly unchanging structure in the context of the human timescale. Hence, for our assessment of geodiversity, hydrology, climate, and the human and biological footprint are additional values. Meanwhile, as previously stated, volcanic processes create new geological formations in a relatively short period of time, which supports the argument for assigning them higher values than the core parameters (geology and geomorphology).

5.4.9 Conclusions

Tūhua/Mayor Island is a superb location with well-preserved volcanic features demonstrating the interplay between the magma physical–chemical conditions and the external environment (e.g., water availability owing to near sea-level locations). The geodiversity estimates yielded high values in three types of pyroclastic deposits, which formed on the cliff areas on the SE, central and north parts of Tūhua/Mayor Island. High-geodiversity elements are found at distinct locations where the highest number of volcanic features can be seen, or their inferred processes render them visible. These areas should receive higher protection status and be accessible for the broader community for geoeducation regarding natural hazard resilience. Tūhua/Mayor Island is also in the vicinity of the Coromandel Peninsula, where coastal sections expose near sea-level calderas that are inferred to have formed through similar eruption types to those identified at Tūhua/Mayor Island. Taken together, we see a great opportunity to interlink these locations in a well-structured volcanic geoheritage promotion strategy as a future pillar of geoeducation and geotourism in the region.

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Author contributions VZ: data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), validation (lead), visualization (lead); SK: investigation (equal), validation (equal); BL: conceptualization (supporting), investigation (supporting), validation (supporting), writing – original draft (supporting); KN: conceptualization (lead), funding acquisition (lead), supervision (lead), writing – review & editing (lead).

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Description: The next step for the development of the QQG assessment is to include additional elements such as the hydrological element. In previous work I concentrated mostly on geological and geomorphological elements of geodiversity. Additional elements describe processes which influence the main values through the transformation of the landscape through hydrological, climate, anthropological, biological processes. I have decided to test a hydrological element in the QQG assessment presented through the channel network calculated from Strahler Order model. Strahler Order model has been chosen for this role as it is calculated from the DEM. Then, Manawatu Basin region has been used as case study of research because it contains developed channel systems of the Manawatu River catchment containing a range of sediments. These sediments though are considered of low geological and geomorphological value with respect to the QQG model. Additionally, high order river systems demonstrate a connection to the transport of different rock materials which has some geodiversity value.

The published article can be accessed: https://www.mdpi.com/2673-7086/3/1/11 accessed 21st of August 2023

Reference: Zakharovskyi, V. and Németh, K., 2023. Recognition of Potential Geosites Utilizing a Hydrological Model within Qualitative–Quantitative Assessment of Geodiversity in the Manawatu River Catchment, New Zealand. Geographies, 3(1), pp.178-196.

In this research: the article has been changed to meet the style of the thesis.

5.5 Title: Recognition of Potential Geosites Utilizing a Hydrological Model within Qualitative–Quantitative Assessment of Geodiversity in the Manawatu River Catchment, New Zealand

Abstract: Hydrology is one of the most influential elements of geodiversity, where geology and geomorphology stand as the main values of abiotic nature. Hydrological erosion created by river systems eroding rock formations (eluvial process) from streams' sources and then transporting and redepositing (alluvial process) the rock debris into the main river channels, make it an ongoing transformation element of the abiotic environment along channel networks. Hence, this manuscript demonstrates the influence of hydrological elements on geosite recognition, specifically for qualitative–quantitative assessment of geodiversity, which is based on a combination of geological and geomorphological values. In this concept, a stream system will be treated as an additional element. The basement area of the Manawatu Region has been utilized as the territory for the research of hydrological assessment. The region is in the southern part of the North Island of New Zealand and has relatively low geological and geomorphological values and diversity. The Strahler order parameter will be demonstrated as a hydrological element for geodiversity assessment. This parameter has been chosen as one of the most common and acceptable within geographical information system (GIS) environments. The result of this assessment compares the influences of Strahler order on qualitative–quantitative assessment of geodiversity and provides its drawbacks. Additionally, the places with high values will be considered for more accurate field observation to be nominated as potential geosites with an opportunity for geoeducational and geotouristic significance.

Keywords: Strahler order; river system; QGIS; geoeducation; geotourism; Cenozoic; Mesozoic; fluvial; sand; gravel

5.5.1 Introduction

The description and evaluation of abiotic nature for geosites and geopark establishments are currently the main goals of geodiversity assessments. Accurate geosite recognition will help a researcher to minimize the area of research and concentrate on the places with specific features valuable for geotourism (Migoń and Pijet-Migoń, 2023) and geoeducation (Gray, 2008a, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007, Zakharovskyi and Németh, 2021b, Zwoliński et al., 2018). They are the main ways to increase the educational level of students and tourists about the processes forming the abiotic environment such as volcanoes, sedimentary basins, soils, climate, eluviation and denudation, chemical (and biological) erosion, and solar insolation (da Silva et al., 2019, Dias et al., 2021, Pereira et al., 2013, Zakharovskyi and Németh, 2021a, Silva et al., 2013, Serrano et al., 2009, Pál and Albert, 2021). All these processes are always operating continuously, forming, and transforming the geological and geomorphological parameters of the Earth's surface. Here, geology and geomorphology as elements of geodiversity must be considered as the basement of the non-living environment, whereas other elements are its transforming agents (e.g., climate) or remnants (e.g., soils) of the rock formations. Currently, scholars include in the term of geodiversity the following elements: geology, geomorphology, hydrology, climate, soils, space energy (meteorites, gravitation, and solar insolation), tectonic processes, and biotic and anthropogenic influences

(Gray, 2008b, Kozłowski, 2004, Serrano and Ruiz-Flaño, 2007). Hence, understanding of the geological and geomorphological parameters help to create a general view on the surface, whereas other elements of the abiotic nature will describe the process of the rock cycle, where hydrology is becoming one of the most influential (Leopold and Langbein, 1962, Huggett, 2007, Zhao et al., 2017).

Hydrology within geodiversity is a special erosional element, simultaneously filling depressions on the surface and transforming and accumulating sediments. It links hydrology directly to geological elements in geodiversity description. Hence, the assessment of hydrological parts from a geodiversity perspective have been studied for the number of different locations to create geodiversity model. Some research has been concentrated on specific parameters such as rock fractures and their permeability, together with geomorphology and aquifer features (Ferrando et al., 2021, Perotti et al., 2019), whereas others have focused more on the water physical–chemical properties (de la Hera-Portillo et al., 2023). Furthermore, study of a waterfall demonstrates the importance of its hydrological features from cultural (Hudson, 2013), aesthetic (Hudson, 2006, Hudson, 2013), scientific (Hudson, 2013), economic (Wubalem et al., 2022), and touristic (Wubalem et al., 2022, Jo et al., 2022, Hudson, 2006) perspectives. Standard maps show hydrological elements through objects such as lakes, streams, rivers, marshlands, and others. These elements influence geological formations with eluvial and alluvial processes especially streams and rivers as active water flows (Shit et al., 2022). These processes start from the streams' sources (springs and underground water channels), coursing from the mountain areas to reach lowlands and depressions to achieve an equilibrium state, which is mostly presented with the marine basin supplying it with circulation, sediments, and nutrition (Broadley et al., 2022). River flows form valleys through their power to cut the surface of rock formations and transport its material downflow (Miller and Juilleret, 2020). This process, most of the time, creates a dichotomic merge of streams from various sources passing through diverse catchment areas. The merging flow generates a geologically more diverse and complex riverbed with an increasing variety of rock fragments to display transported material along the river source to its mouth (Langbein, 1964). Hence to emphasize the influences of a river system on geodiversity, this research utilizes the Strahler order, which expresses the rank of each channel, where the order grows with two channels (same order) merging into new within the assessed catchment area. Together with qualitative–quantitative assessment of geodiversity, the Strahler order will characterize the part of the studied river, which is likely to a contain high amount and diverse array of transported rock material (sediments). Then, it can be used as a proxy for geodiversity (sediment variety) along the stream networks from source to sink.

Qualitative–quantitative assessment of geodiversity (QQG) has been developed for recognition of locations with potentially high geodiversity based on the accessible (open) geospatial database (e.g., SRTM, geological and topographical maps) and simple methodology (Zakharovskyi and Németh, 2022a). Geology and geomorphology are the two main elements represented by the general state of the abiotic environment, whereas this research also adds the hydrological parameter into the equation to study its influence on the model (Zakharovskyi and Németh, 2021b). The Strahler order is a standard hydrological parameter, which can be calculated from any digital elevation model utilizing common geographical information systems (GIS) software (e.g., QGIS, ArcGIS, Grass GIS, Saga GIS). Hence, this parameter can be included into QQG without changes to the methodological goal to make the assessment applicable for any territory throughout the globe, making it acceptable for every researcher regardless of their level of knowledge of the GIS software.

The aim of this manuscript is to include the hydrological element into QQG methodology to test the locations with low geological values from the global perspective. Our working hypothesis is that the result of the assessment will show that the level of information from the hydrological element can have an influence on the general geodiversity values (geological and geomorphological elements) while recognizing the pitfalls of the hydrological modeling. The area of research is the catchment area of the Manawatu River in the lower North Island of New Zealand, which is geologically represented by Mesozoic greywacke and various post-Miocene siliciclastic rocks on the surface and their geological variety. Meanwhile, the additional goal of this work is to identify places with potential locations acceptable for further, more accurate description and establishment of geosites as places with high geoeducational and geotouristic values.

The manuscript identified two knowledge gaps we aimed to explore in this research. One is more global, whereas the second is more regional in relevance. The global knowledge gap is that we have very limited knowledge on how hydrology, river characterization, and catchment area investigation can contribute to the overall geoheritage valorization and geodiversity estimates. This is since only a handful of studies have addressed the significance of rivers in geoheritage works and most of them approached the problem in a very general way or used the rivers just as a link between otherwise important geological and geomorphological sites mostly along their aesthetic values. In this paper, we identify this is a knowledge gap and we intended to explore this.

On other hand, the Manawatu River is a main geomorphological element, the symbol of an entire region in the lower North Island of New Zealand and commonly appears in geoconservation strategies as a key element for nature conservation and future geotouristic works. Although we see this as a promising starting point to initiate such ventures, we identified a significant gap between this plan and the conducted or planned research to explore the real weight of the Manawatu River in geoheritage valorization and geodiversity estimates. In this paper we addressed this issue as well.

5.5.2 Overview of Manawatu Basin

Manawatu Basin is in the south part of New Zealand's North Island (Figure 5.5.(1)). Its area is 5850 km^2, which includes three NE–SW trending mountain ranges: Tararua in the south, Ruahine in the north, and Waewaepa in the east (Dymond et al., 2016, Dymond and Vale, 2018). The Tararua and Ruahine ranges are dissected by the Manawatu River in the central part, forming the Manawatu Gorge. Meanwhile, the east side of the axial ranges is typical rolling hill country, as part of the folded and faulted accretionary prism formed in front of the obliquely westward subducting Pacific Plate beneath the Indo-Australian plate (Manighetti et al., 2020, Keyes, 1984). The western side of the range is a broad coastal plain with spectacular marine and river terraces, recording the rapid uplift of the region in the last million years (Lo Re et al., 2018, Fuller et al., 2018).

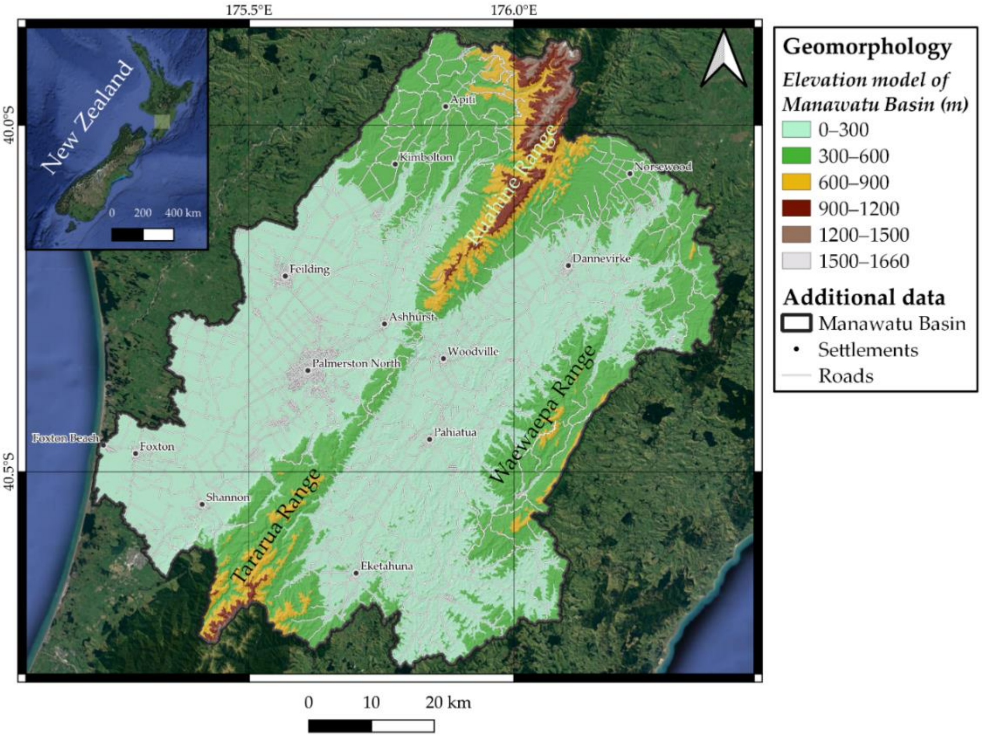

Figure 5.5.(1): Overview map and elevation model of Manawatu Basin created from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (EROS, 2015); background is Google terrain map. The coordinate system is WGS 84 (EPSG: 4327), the same in all other figures.

5.5.2.1 Geology and Geomorphology

The geological concept of the Manawatu Basin is formed by a range of different sediment formations from Jurassic to Holocene periods, which are remnants of the active Manawatu River system. Geological data presented for the Manawatu Basin has been extracted from a 1:250,000 scale New Zealand geological map (GNS Science, 2012) (Figure 5.5.(2)). Uniquely for the region, in the north part of the Tararua Range exposed in the Manawatu Gorge area, the rocks of the Kaweka Terrane formation present with Jurassic basalt. In general, the geological description of the Manawatu Basin is described with 32 different rock groups, which we decided to range according to their ages, where the oldest are from Mesozoic era (black and deep purple colors) (Figure 5.5.(2)), including mostly siliciclastic sedimentary rocks from the Jurassic period grouped into tectonostratigraphic units such as Torlesse Composite Terrane, Pahau Terrane, Rakaia Terrane, and Kaweka Terrane and the Cretaceous period presenting with Mangapurupuru Group and Tinui Group. Mesozoic rocks are dominated by greywacke, which is the most common basement rock type forming mountain ranges through the whole North Island of New Zealand. Here, greywacke as the main lithology of the axial ranges has been tilted and forms the mountain range dissected by the Manawatu Gorge. The Tararua Range in the south has an altitude 200–1300 m that increases towards the south, whereas the

Ruahine Range on the contrary grows to the north more rapidly to 1000 m height and then reaches to 1500 m. Moreover, there are some additional older rocks forming ranges on the east side of the main axial ranges such as the Waewaepa Range reaching up to 700 m above sea level. Then, there are Cretaceous rocks represented by mudstone and sandstone mostly cropping out in the northwest and covering the smallest surface area compared with other older Mesozoic rock groups. The whole west part of the Manawatu River catchment area as well as the base of the Manawatu Gorge and most of the land on the north covered by Miocene–Pliocene deposits of shallow marine sedimentary rocks (pink color) represent the history of an evolving accretionary prism along the convergent plate margin. These rocks were formally included in 15 lithostratigraphy groups such as the Hurupi Group, Makurim Group, Mangaheia Group, Mangamaire Group, Mangatu Group, Maxwell Group, Moa, Napier Group, Onoke Group, Pakihi Supergroup, Palliser Group, Soren Group, Te Aute, Te Hoe Group, and Tolaga Group. These areas are rolling hills today with heights from 200 up to 700 m. The largest area of the catchment is constructed with the youngest Pleistocene–Holocene sediment groups (orange colour), where Late Pleistocene sediments include the Kai-Iwi Group, Kidnappers Group, Okehu Group, Shakespeare Group, and Middle Pleistocene sediments and various Late Pleistocene, Middle Pleistocene, and Early Pleistocene sediments consist of mud, silt, sand, and gravel from shallow marine to fluviolacustrine origin. These areas are mostly flat-topped, hosting spectacular marine and fluvial terraces along the Manawatu River and small stream valleys draining from the north. The last formation is Late Pleistocene to Holocene periods (yellow colour), which have been merged into a single category in our model as they are the modern alluvial and riverbeds. Alluvial deposits are formed by three groups including Holocene sediments, Pleistocene–Holocene sediments, and Late Pleistocene–Holocene sediments. Their present-day altitude ranges from 0 to 100 m above sea level coming with riverbeds from the west, north-west, and north parts of the Manawatu Basin and transported to the south-west forming a large plain area from Palmerston North to Foxton Beach area, where the Manawatu River enters the Tasman Sea. Hence, the geological history of the Manawatu region is locked into 31 sedimentary and 1 igneous (basaltic) rock types formed since the Jurassic period and eroded through the Manawatu River system.

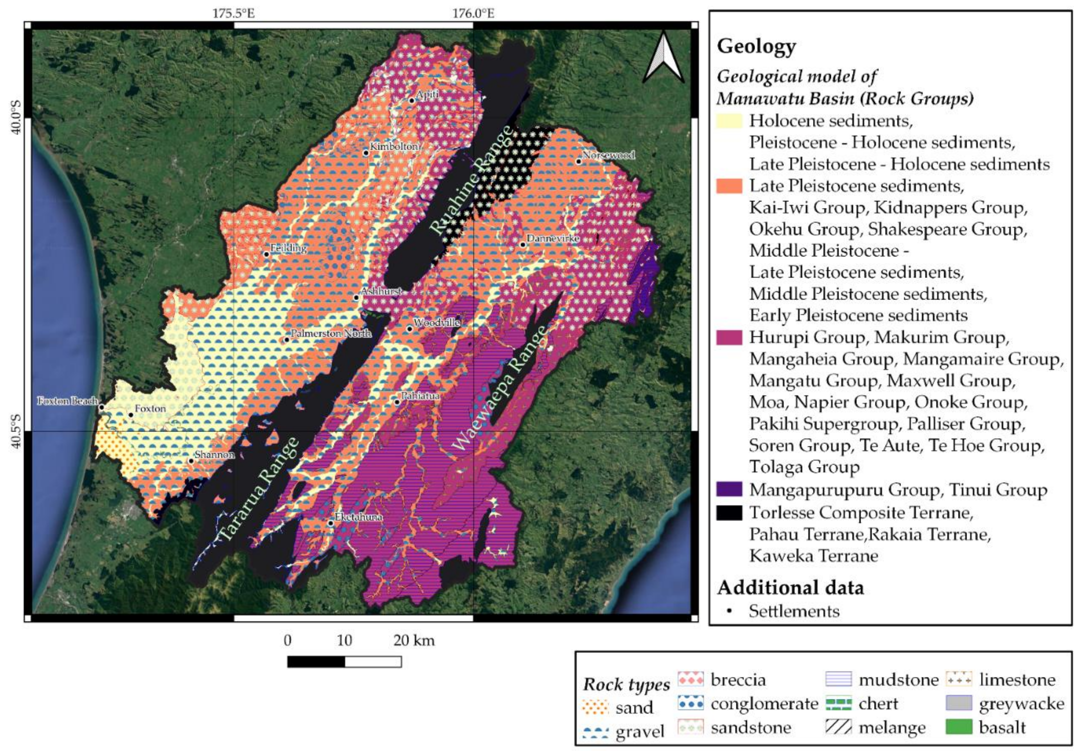

Figure 5.5.(2): Geological model of Manawatu Basin based at the 1:250,000 scale, New Zealand geological map (GNS Science, 2012); background is Google terrain map.

5.5.2.2 Hydrological System and Climate

The hydrological system of the Manawatu Basin presents with 160 streams and 46 creeks that fall into 13 rivers and 1688 lakes according to the data from the 1:50,000 topographic map of New Zealand and downloaded from Land Information New Zealand (LINZ) (LINZ, 2025a). Streams and creeks mostly come from the three mountain ranges and their surroundings and captured into the basin area (Figure 5.5.(3)): Ruahine (north), Waewaepa (west), and Tararua (south) (Dymond et al., 2016, Dymond and Vale, 2018). They supply 13 rivers, where 10 of them flow from different sources in the central and the eastern part of the Manawatu Basin and merge near Manawatu Gorge. Then, the formed river cuts through and gradually meanders to the south and falling into Tasman Sea. The upper part of the Manawatu River is sourced from the Ruahine Range from its east side (Figure 5.5.(3)) and flows to the south, where the Mangator and Taimaki Rivers merge with the Manawatu from the Waewaepa and Ruahine Ranges, respectively. Then, the river turns toward the west in the centre of the Gorge, where it has the Tiraumea, Makakahi, and Mangahao Rivers as its main inflows. Meanwhile, the Tiraumea River supplies the Mangaone and Ihuraua Rivers from the south and the Makuri from the east. There is a similar situation with Makakahi River, which supplies the Mangatainoka River sourced from the Tararua Range. The lower part of the Manawatu River starts from the Manawatu Gorge and continues towards the south up to Foxton Beach, where its mouth reaches Tasman Sea. In the lower Manawatu, three small rivers supply its flow. Pohangina and Oroua both come from the west slopes of the Ruahine Range, whereas the Tokomaru comes from the west slopes of the Tararua Range. Moreover, the Manawatu Basin contains 1688 lakes (average size 3198 m2) spread through the whole area of research, mostly concentrated in the western and southeastern parts. From them, three reservoirs are in the south part of the Tararua Range and the Karere Lagoon is located near the lower flow of the Manawatu River. Finally, two other named lakes are in the northeastern part of the basin: Mahangaiti and Rotoataha. Hence, the hydrological element of Manawatu Basin is formed by the Manawatu River sourced from the Ruahine Range that flows through Manawatu Gorge and leads more to the south, where it falls into Tasman Sea (Clement and Fuller, 2018). On its way it supplies 12 rivers and high number of creeks and streams. Furthermore, the region has 1688 lakes.

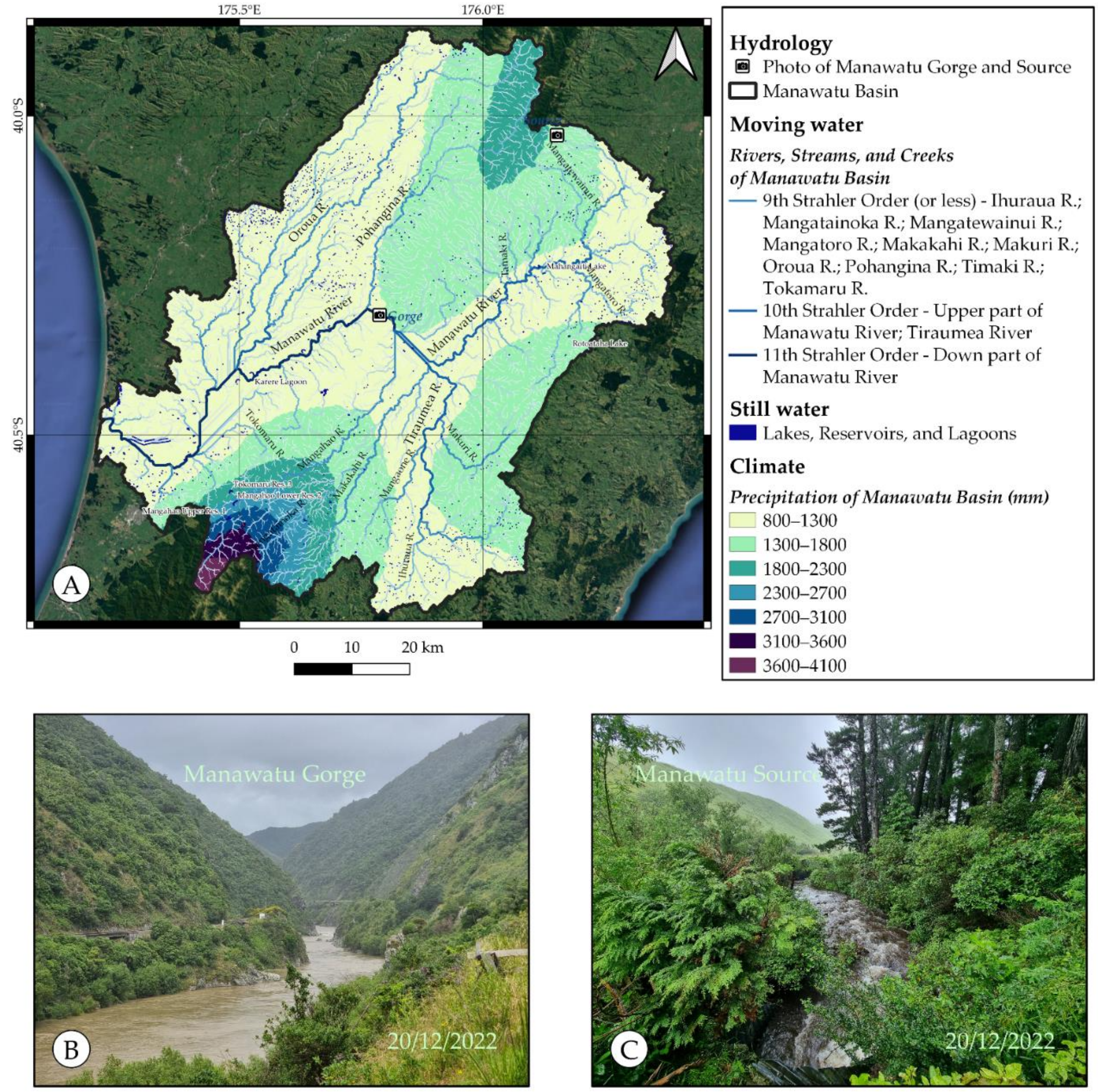

Figure 5.5.(3): (A) Hydrological model of Manawatu Basin based on channels model extracted from Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (EROS, 2015); the annual rainfall model downloaded from the site of Ministry for the Environment (LINZ, 2017); Lakes extracted from Land Information New Zealand (LINZ) (LINZ, 2025b); background is Google terrain map. Pictures of (B) Manawatu Gorge and (C) Manawatu source.

The climate of Manawatu Basin has been included into the description to show how precipitation supplies the region. The precipitation data have been downloaded from the site for the Ministry for the Environment (LINZ, 2017). The model demonstrates the average annual rainfall in Manawatu Basin. The flat areas and low hills formed under the biggest rivers, such as Manawatu, Tiraumea, Oroua, and Pohangina, contain annually around from 800 mm to 1300 mm of rainfall. Hilly areas around the mountain ranges have a higher amount of precipitation, from 1300 mm to 1800 mm, where it rises higher closer to higher altitudes, reaching 1800–2300 in the Ruahine Range. Meanwhile, the Tararua Range precipitation rate keeps rapidly increasing towards the south, reaching around 4100 mm per year. Hence, the annual rainfall conditions of the Manawatu region produce a high amount of water, which keeps suppling the creeks, streams, and rivers of the basin. For example, two photographs have been taken near Palmerston North to demonstrate the transformation of the lower Manawatu after a week of rainfall (Figure 5.5.(4)).

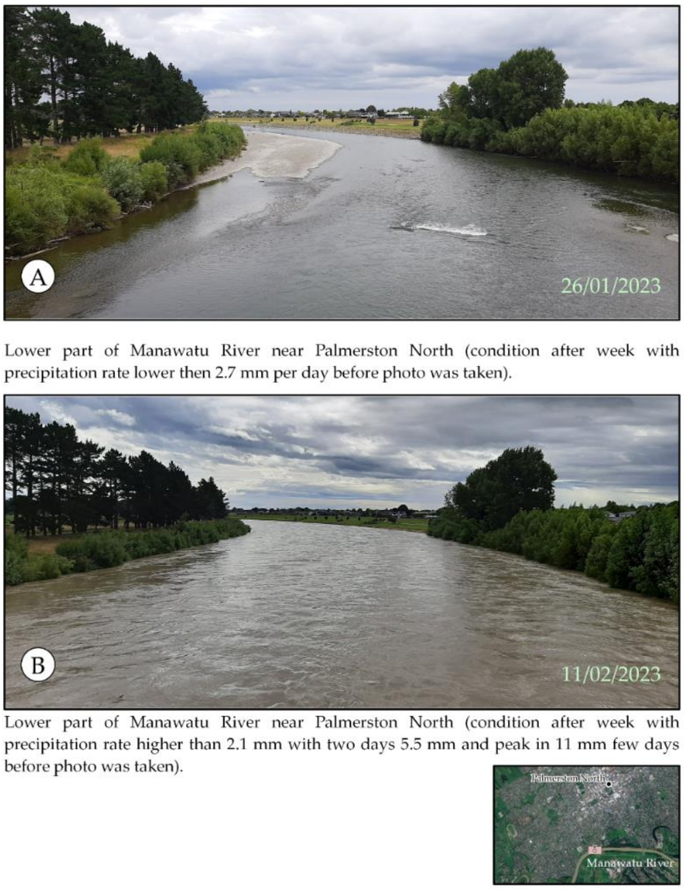

Figure 5.5.(4): Precipitation influences on the Lower Manawatu River near Palmerston North. (A) He Ara Kotahi Lookout during warm weather. (B) He Ara Kotahi Lookout after a week of precipitation. (C) Overview map of location, where photos have been taken.

5.5.3 Methodology

5.5.3.1 Assessment of Geodiversity

The methodology for assessment of geodiversity is currently versatile as researchers have their view on the range of abiotic elements that must be calculated. An important role in the assessment is the aim of the research, which Gray (2005) describes in terms of 31 geodiversity values (Gray, 2005), starting from scientific and economic aspects to historical and spiritual values (e.g., geocultural values). Moreover, also important are issues with the accessibility of data (e.g., accurate geological data for the Samoa Islands (Zakharovskyi and Németh, 2021a)) and software (e.g., ArcGIS) for specific areas of research, as well as the GIS knowledge of the scientists. Therefore, to avoid these issues we utilized the free access QGIS (3.16 "Hannover") (QGIS, 2024) software, with its plugin "SRTM-Downloader" (Duester, 2024), which allows download of the 30 m resolution Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global model (EROS, 2015). Additionally, Zwoliński (2018) describes more about three types of geodiversity assessment (Zwoliński et al., 2018) such as (1) qualitative—based on expert knowledge (Gray, 2013, Gordon and Barron, 2013), (2) quantitative—based on the amount and accuracy of the raw data (Bétard and Peulvast, 2019, Pereira et al., 2013, Silva et al., 2013), and (3) qualitative–quantitative—where less accurate raw data is evaluated with an expert view (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022b, Zakharovskyi and Németh, 2022a). Therefore, we decided to build our methodology on a qualitative–quantitative model utilizing basic geological data (rock type and age) combined with SRTM for geomorphological calculations. As a result, we have been developing a Qualitative–Quantitative assessment of Geodiversity (later in text QQG) with the aim to highlight places with possible locations of geosites applicable throughout the globe.

A geosite is a specific location an in abiotic environment that contains information about geodiversity and surface evolution. QQG methodology is based on calculation of geodiversity elements that have been divided into main and additional values (Pál and Albert, 2021, Pereira et al., 2013, Dias et al., 2021, da Silva et al., 2019). The main values of geodiversity are based on geology and geomorphology, as they describe rock formations, which is the core of abiotic nature, whereas other elements are influencing, transforming or altering material on the surface (Zakharovskyi and Németh, 2021b, Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022b). These elements of transformations are additional values including hydrology, climate, tectonics and volcanism, biological, and anthropological footprints. Therefore, QQG methodology assesses geological and geomorphological elements according to an 8-point evaluation system.

5.5.3.2 Evaluation System

The evaluation system is a qualitative part of QQG, which ranges all abiotic features to separate important from less informative objects or processes. In the next section, we describe the evaluation system for geological, geomorphological, and hydrological elements of geodiversity.

5.5.3.3 Main Values

Methodology of assessment of geodiversity utilizing the qualitative–quantitative model is based on calculations of several elements of abiotic nature, previously evaluated according to expert view (Table 5.5.[1]). Here, we present an 8-point evaluation system that has been developed for the main elements of geodiversity: geology and geomorphology. The geological evaluation system is developed around the rareness of rock formations exposed on the surface, which have been studied by Blatt, H. and Jones, R. L. "*Proportions of exposed igneous, metamorphic, and sedimentary rocks*" (Blatt and Jones, 1975). The result of his research is presented in percentage of different rock formations exposed on the surface, where sedimentary rocks are the most common (66%), metamorphic only from Precambrian era covers 17%, and extrusive and intrusive are 8% and 9%, respectively. Hence, all rock types divided with different eras have been transferred onto an 8-point evaluation system, where 1 is the lowest value containing all sedimentary Cenozoic formations, 2 (low value)—sedimentary Mesozoic, 3 (low to middle value)—sedimentary Paleozoic, and 4 (middle value) became metamorphic from the Precambrian era. The middle to high value rocks are much rarer rock types as they cover areas less than 6% of the total: value 5—intrusive Precambrian, value 6 high—extrusive Cenozoic, and value 7—Mesozoic. Meanwhile, value 8 includes all the rest of the rock formations as their areas cover 1% or less on the Earth's surface. Hence, the 8-point evaluation system is concentrated on all presented rock types exposed on the surface, making this method globally accessible and comparable with different territories throughout the world.

Table 5.5.[1]: The 8-point value systems for geodiversity assessment with hydrological element.

Main Values of Geodiversity			Additional value
Values (8-point system)	Elements of Geodiversity		
	Geomorphology	Geology	Hydrology
	Slope angles (degrees)	Rock type and ages	Strahler order
1 (the lowest)	0-11.25	Sedimentary Cenozoic	No required
2 (low)	11.25-22.5	Sedimentary Mesozoic	
3 (low to middle)	22.5-33.75	Sedimentary Palaeozoic	
4 (middle)	33.75-45	Metamorphic Precambrian	
5 (middle to high)	45-56.25	Intrusive Precambrian	
6 (high)	56.25-67.5	Extrusive Cenozoic	
7 (the highest)	67.5-78.75	Extrusive Mesozoic	
8 (the rarest)	78.75-90	Sed. (Precambrian), Met. and Intr. (Cenozoic, Mesozoic, Palaeozoic), Extr. (Palaeozoic, Precambrian)	

The geological element describes the parameters of rock formations, whereas the geomorphological element shows the forms that these formations present after the historical pressures of endogenic (tectonic and volcanic) and exogenic (weathering, erosion, and alteration) processes have been constantly changing the surface, known also as the geological–geographical cycle (Davis, 1899, Davis, 1922, Davis, 1973). However, geomorphological data mostly provide information about elevations of each point on a coordinate net. This information can be transformed and presented in a range of different parameters such as ruggedness, roughness, slope, aspect, or even something more complicated such as geomorphon, topographic position index (TPI), etc. Hence, the right model must be chosen, which can help to enrich the aim of the research, minimizes the areas of field observations, and highlights the locations that are likely to have an outcrop.

In our previous work, *"Geomorphological Model Comparison for Geosites, Utilizing Qualitative–Quantitative Assessment of Geodiversity, Coromandel Peninsula, New Zealand"* (Zakharovskyi and Németh, 2022a), we studied this issue. Six different models have been compared between each other: slope, ruggedness, roughness, geomorphon, TPI, and total curvature. The slope model presents the degree of slope angle (Zevenbergen and Thorne, 1987), whereas the ruggedness is the surface heterogeneity (Riley et al., 1999) and roughness is the rate of surface irregularity (Abbas et al., 2020). Total curvature is a combination of plan and profile curvatures (Meten et al., 2015), whereas the geomorphon (Stepinski and Jasiewicz, 2011, Jasiewicz and Stepinski, 2013) and TPI (Meten et al., 2015) are more complex models of a landscape that forms from depressions and valleys up to ridges and peaks. Both models are based on calculation of the central pixel in comparison to its neighbors. The result of geomorphological research shows that slope, ruggedness, roughness, and TPI give similar results and can be exchangeable between each other, whereas geomorphon and total curvature are inappropriate.

Therefore, the slope model has been evaluated with an 8-point system to make it a similar value to the geological one chosen for this manuscript. Furthermore, slope angles more than 45 degrees show that these areas are likely to be free from all loose material according to the angle of repose. It shows a critical angle for a pile of material, which can be held without sliding (Al-Hashemi and Al-Amoudi, 2018). Hence, we consider this law in an opposite way, the places with degrees higher than 45 are likely to be presented with hard rock or its loose material has been fixed with some different material such as vegetation. Hence, 45-degree angles are considered as a threshold between low and high values for geomorphology. However, we are not going to exclude all angles lower than the threshold, as often some rock formations can be found lying on the Earth's surface. In this situation the geological parameter will outweigh the low angle, as most sediments and metamorphic and volcanic rocks are high. The results show (Table 5.5.[1]) that the slope with the lowest values are areas with degrees less than 11.25—1. Then value 2—from 11.25 to 22.5 degrees, 3 points are (low to middle values) 22.5–33.75 degrees, and middle values have 4 points presented as slopes between 33.75 to 45. Then, values higher than 4 are considered more valuable, as they skip the threshold and are likely to expose an outcrop. The middle to high range is 5 points, which is 45–56.25 degrees; the high value is 6—56.25–67.5 degrees, and 7 points is 67.5–78.75 and represents the highest values. Finally, the rarest areas are presented by only some mountain areas and coastal cliffs with degrees 78.75 to 90. Hence, the evaluation system for the slope model has been tailored for global recognition, making it also like the geological model, acceptable for assessment for any territory throughout the world.

5.5.3.4 Additional Values

For additional values of geodiversity, this manuscript describes the study of hydrological elements of geodiversity. However, more accurate is the channel network presented by rivers, streams, creeks, and formed valleys with high amount of precipitation. This is one of the active parts of the hydrological element alongside marine processes, which are not considered in this research. The continuous activity of river systems provides various levels of erosion and transportation of sediments, which is valuable knowledge for understanding the surface transformation of hard rocks to sediments and sedimentary rocks. The riverbanks contain rock material from streams that enter the main river in the basin, providing a general lithological overview of the region’s geology. Additionally, anthropological, and cultural aspects can be considered along riverbanks as they are mostly selected by humans for settlements, fishing, and hunting. However, GIS does not provide many tools for the assessment of channel networks. The Strahler order is one of the simple types of assessment, which, considering possible places of water sources in the valleys or at least locations, is where precipitation can provide an additional temporal water source. Therefore, as a result the model will demonstrate a theoretical stream network, which also covers the real network. Then, all theoretical water sources are considered as the first order, so when two 1st order streams merge into one, the new stream becomes second order. The same process happens with two merged 2nd order streams, which creates 3rd order streams, whereas 1st order streams that fall into 3rd order streams do not influence the order number of the latter (Figure 5.5.(5)). Hence, this model provides good information about channels that are merging and carrying sediments from different sources, which is not a required evaluation as they already provide the correct value for QQG assessment. However, in this research, hydrology is considered as local diversity and its influence will highly depend on the territory of research.

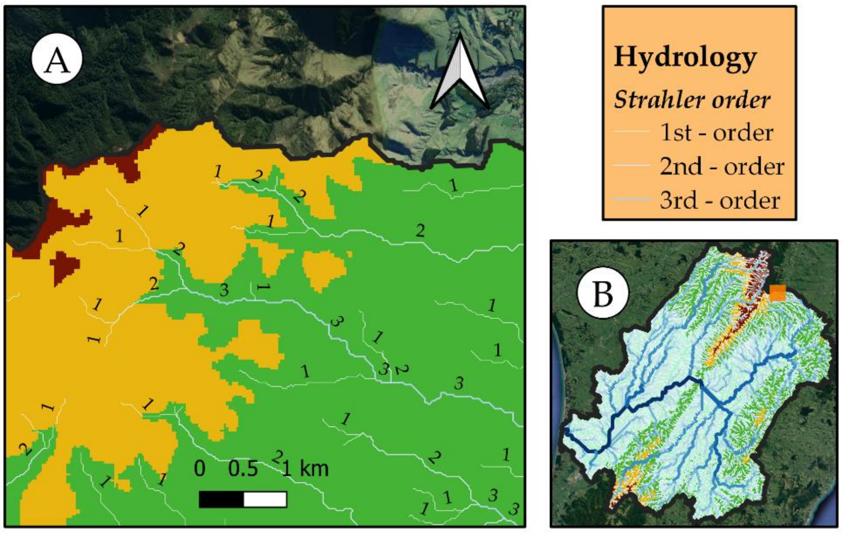

Figure 5.5.(5): (A) Demonstration of Strahler order methodology (numbers to show its stream order). (B) Overview map. The channel network calculated from SRTM model.

5.5.4 Results

The assessment of the Manawatu Basin has been completed in QGIS software utilizing the "Zonal statistic" tool, where a square grid with a 6.25 km^2 size for each cell was created. Then, the natural breaks (Jenks, 1967) mode is used to group the final parameters into areas.

The general geodiversity model of the Manawatu Basin is based on the multiplication of two main values: geology and geomorphology. Geological data have been extracted from a 1:250,000 scale New Zealand geological map (GNS Science, 2012) with next its evaluation according to an 8-point system presented in section 5.5.3.2. Evaluation System. Meanwhile, geomorphological data based on SRTM (Shuttle Reader Topography Mission) and transformed into the slope model utilizing "Slope, Aspect, Curvature" of "Terrain Analysis-Morphometry" tool of Saga GIS implanted into QGIS software. The calculation is based on default method "9 parameter 2-nd order polynom" created by Zevenbergen and Thorne (1987).

The result of the multiplication of geological and geomorphological data presents a range from 1 to 35 (Figure 5.5.(6)), where natural breaks mode divided it on five categories. The first is 1–2 and is the lowest values of geodiversity; these territories cover a quarter of the southwest and less in the central northeastern part of Manawatu Basin. These locations mostly presented with young sediments preserved by the Manawatu River, which formed a range of plain terraces. The second lowest has values ranging from 2 to 5 and is characterized by more hilly areas formed by some smaller river systems and older alluvial sediments from Miocene–Pliocene periods, which are the main sources for the Manawatu. Its locations spread in the northwestern and eastern parts of the basin. Geodiversity values 5–8 is presented only in the mountain ranges from the north to the south or around these formations, as well as small areas on the east; they are more connected with the oldest Mesozoic greywacke. Finally, the high and highest values contain 8–12 and 12–35 points, respectively, described together as they cover small areas mostly concentrated in the high areas of the mountain ranges and in the west part of Manawatu

Basin. Specifically, the highest values are only concentrated in the Manawatu Gorge presented with some basaltic sequences and some more towards the southwest of the Tararua Range. Hence, the area of the Manawatu Basin is mostly presented with low and the lowest geodiversity values based on geomorphological and geological elements. Meanwhile, the high and highest values are mostly concentrated in the mountain ranges and the Manawatu Gorge.

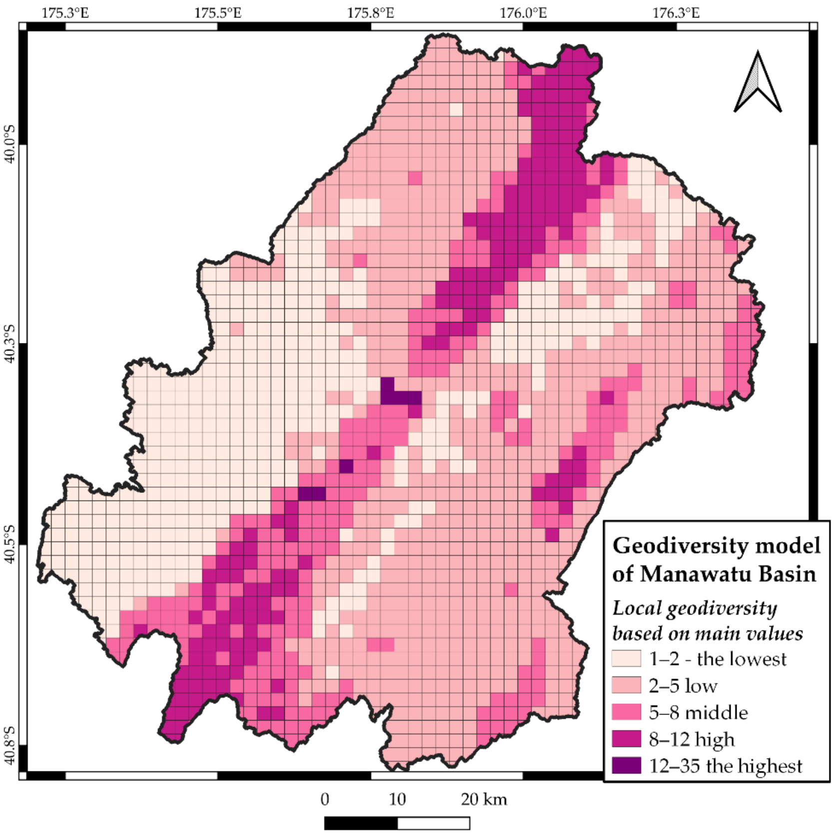

Figure 5.5.(6): Geodiversity model of Manawatu Basin. Values were weighted specifically for local perspectives to highlight the locations of interest.

To improve the QQG assessment for geosite recognition into the result of local geodiversity, we added the parameter of Strahler order (Figure 5.5.(7)), which is based on the same SRTM data previously utilized for calculation of the slope model. The "Strahler order" model has been analyzed with the accordingly named tool of "Terrain Analysis-Channels" proposed by the Saga GIS plugin in the QGIS software. The model is added on top of the previously described geodiversity model of the Manawatu region. The result of calculations shows that a range of important changes occurred along the main streams and rivers with a high range for Strahler order, which highly influenced the final model. First, the range for all values is increased by the natural breakers' mode, which simultaneously triggers a decrease in the number for areas with the lowest values for geodiversity. This has been provoked by the southwestern or lower part of the Manawatu River, which is flowing through plain areas and has the highest value for Strahler order so obtains a high value for local geodiversity by functioning as a major collector of the greatest variety of rocks sampled. Then, some areas with low values are raised to the middle range along tributary rivers flowing to the main flow from the northeastern part of the Ruahine Range and from the eastern part of the Manawatu Basin collecting in the Manawatu

Gorge. Meanwhile, except for the lower part of the Manawatu River, most locations with the high and the highest values remain unchangeable, especially in Manawatu Gorge and in the northwestern part of Tararua Range. Hence, the Strahler order has a significant influence on the general geodiversity model, especially for places with otherwise low values. In areas along the main flow channel, it became an important additional parameter to elevate the local geodiversity value. However, it has a small impact on geodiversity values in areas where the general geodiversity is high.

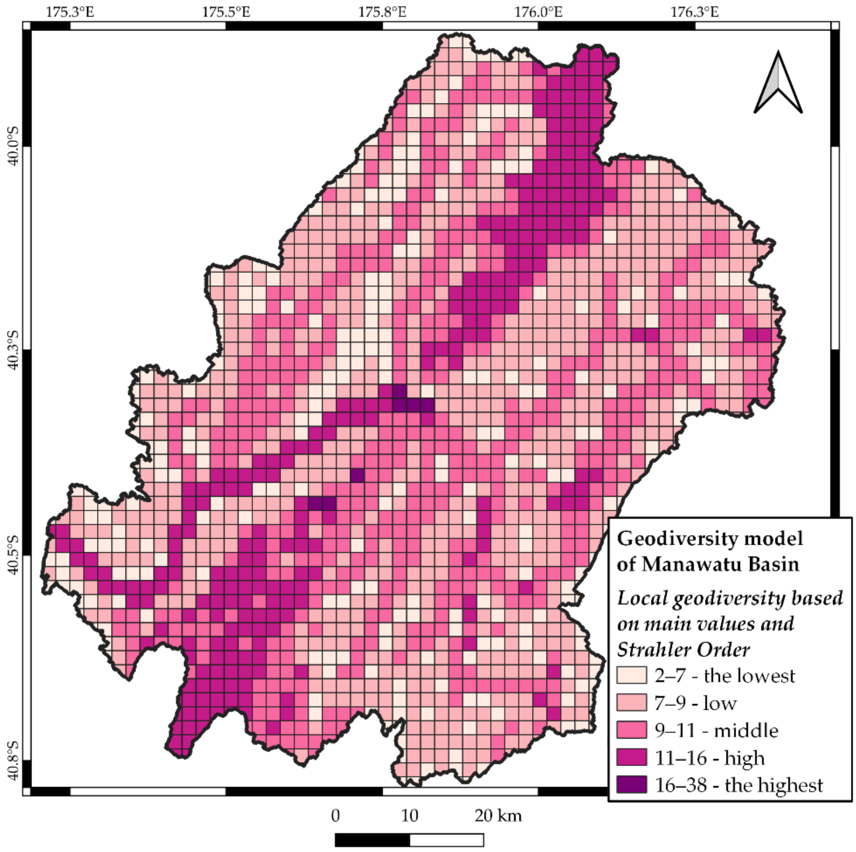

Figure 5.5.(7): Geodiversity model of Manawatu Basin improved with hydrological values based on the model of Strahler order. Values were weighted specifically for local perspectives to highlight the locations of interest.

5.5.5 Discussion

The aim of this research is to demonstrate the influence of Strahler order on the qualitative–quantitative assessment of geodiversity, which based on geological and geomorphological elements describe the core parameter of abiotic nature. The result of the assessment shows that Strahler order mostly influenced the places with low and middle values for local geodiversity. In this assessment, we cannot consider global geodiversity for hydrological description of the Manawatu Basin because we should make an objective calculation of Strahler order through the Earth's surface separately for each basin to find out the highest possible value to create an evaluation system for the hydrological aspect. Meanwhile, from a global perspective the Manawatu region is considered as a place with low and the lowest values for geodiversity, which can contain some specifically important locations (for example Manawatu Gorge);

however, they must be studied more accurately with larger amount of data, which requires more time and resources. Hence, here we demonstrate local geodiversity values for the Manawatu Basin, where the Manawatu River is the main flow. It compounds in the western part from the number of rivers that are merged into one flow up to the Manawatu Gorge. Therefore, all these streams contain values for Strahler order, which objectively increased the geodiversity values for the region with its terraces, especially in the lower part of the Manawatu River flowing from the Manawatu Gorge towards the southwest and falling into Tasman Sea. This part of the river raised the value of the area from the lowest to the high values. Meanwhile, the high and highest values remain on relatively the same areas. On the other hand, not all places get increased; the greywacke formation of the Waewaepa Range in the eastern part of the basin decreased the area of high values. This result was influenced by the natural breaks mode, which merged it with high values to the surrounding area (middle values). In conclusion, hydrological element calculated as the Strahler order must be included into the assessment, as it increases the importance of the places with geologically and geomorphologically low values and does not highly influence the places with the highest geological values. This phenomenon standardly correlates with the natural law of water to gather in the basins and lowlands, creating terraces of alluvial deposits along its flow. Hence, general geological and geomorphological elements work better for volcanic and metamorphic rocks with steep slopes, whereas hydrological elements presented with the Strahler order improves the opposite flatland and depression areas. In conclusion, the Strahler order is a good parameter to include into QQG assessment as it increases the value of geodiversity in lowlands, which makes a more complete region with possible geosites in the Manawatu region; however, this still requires more accurate study in the field.

The Strahler order as a hydrological implication of general geodiversity (geology and geomorphology) contains several issues. First, the poor accuracy of calculated channels, which often take completely different directions than in reality or on the 1:50,000 New Zealand topographic map (LINZ, n.d.). Meanwhile, the Strahler order accuracy is not dependent on the quality of DEM, as the same result is given for SRTM (30 m pixel) and DEM from the topographic map (8 m pixel). Next, the issue is that too many streams are calculated from the surface, where most of the time all channels from order one to around four are not real streams. However, we have left this drawback in the calculation, as to solve this problem the researcher needs to go through checking of all streams, deleting and correcting according to the available topographic map and satellite image. Additionally, low channel orders represent catchment areas that can be filled temporarily with precipitation. Hence, the hydrological model has not been changed as it still shows actual and potential water channels in the Manawatu Basin. The final issue is the result itself, which shows the whole river as important place; therefore, the researcher still needs to go along the whole stream on the field trip or at least utilize maps to highlight specific locations (possible geosites). In conclusion, despite all the problems described above, the assessment of Strahler order is fit for the aim of QQG assessment to minimize the areas for the search of geosites that still require more accurate checking of locations with high and the highest values. However, it must be improved with additional data about geodiversity and its accessibility.

The next possible step for improvements in geosite recognition in the Manawatu region is to apply more data about geodiversity elements, which can be presented as some specific features and/or locations with significances in a range of disciplines such as science, culture, history, aesthetical, and many others (Hudson, 2006, Hudson, 2013). Specifically, for the Manawatu region the LINZ database provides a decent number of locations that can be considered during the next field observation. These objects are historic sites and Māori Pā, which have cultural and historical significance; then rock outcrops, caves, and waterfalls that are mostly important for natural science and aesthetics (Figure 5.5.(8)). Meanwhile, with a geosite search along the streams, the LINZ data provides historical locations and a Māori Pā (fortress) located along the lower Manawatu. Next, the waterfalls can be studied in the Tararua Range in the south and southeast of the Manawatu Basin itself and the one in the Ruahine Range. Meanwhile, in the northern part of the basin, one cave and an outcrop can be found as well, which already makes this region scientifically important. Other outcrops can be found in the place with high value in the east side, as well as a final one in the far south in the already mentioned Tararua range. Therefore, this data has already improved the value for geodiversity in the Manawatu Basin, where flat areas with rivers contain places with historical and cultural values, whereas mountains have more scientific significance. In conclusion, future assessment requires improvement of the current geodiversity with additional data for establishment of locations with significance.

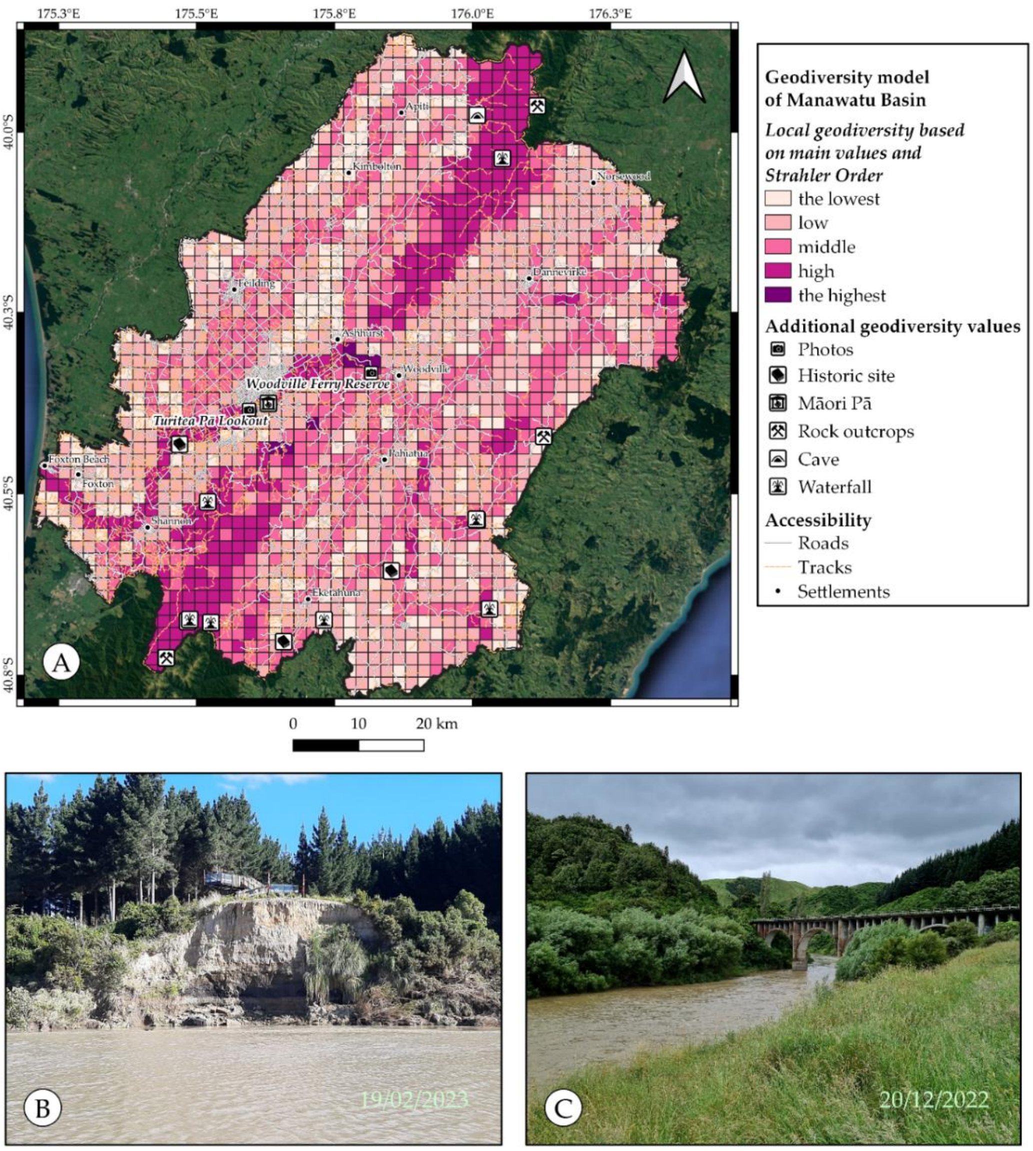

Figure 5.5.(8): (A) Geodiversity model of Manawatu Basin with hydrological model and additional locations of geodiversity significance. Values were weighted specifically for local perspectives to highlight the locations of interest; (B) Turitea Pā Lookout; (C) Woodville Ferry Reserve.

The role of rivers in geoheritage characterization and geodiversity estimates is still underutilized. There are only a few exceptions of recent works where the geological and geomorphological aspects of rivers are proposed to apply to a more widespread sense. These works, however, are very specific to major valley systems and their geology and landscape elements within high mountain regions such as those in Kashmir (Mir et al., 2023, Kil et al., 2019). Commonly, rivers are treated as zones along specific recognized geoheritage values such as the special rock formations along the Mekong River in Thailand; however, the focus of that research was on the rock formations and not on the role of the river in contribution to the geoheritage and geodiversity of the region (Udomsak et al., 2021, Álvarez-Vázquez and De Uña-Álvarez, 2017). A probably comparable approach to explore the role of the river in the geoheritage scene and how the river itself can contribute significantly to elevating the overall geoheritage value of a region was shown for the Belaya River in SW Russia, where other geoheritage values are not as obvious (Ruban et al., 2021). As our research also showed, rivers are important elements of the overall geoheritage, and they commonly function as well-defined regions with significant geocultural values as well as dramatic scenery that can have geotouristic value (Heitzmann, 2020, Guerra and Lazzari, 2021). There are very few works exploring the potential destruction of river systems from a geoheritage perspective, despite the rapid urbanization that can alter the natural geological and geomorphological features including raw material exploitation such as is the case for the river Nile along the greater Cairo region (Taha et al., 2020, Kharbish et al., 2020). On the bright side, there are good initiatives to specifically categorize fluvial- and hydrological-process-related heritage termed as geo-hydrological heritage within their specific sites (Testa et al., 2019). Also, the recognition of the geoheritage of rivers in geotourism and other niche tourism perspectives is a rapidly growing field and a promising direction for sustainable development (Muda and Tongkul, 2008, Mikhailenko et al., 2022).

Additionally, we provide some update to demonstrate catastrophic geomorphological changes, which happened to the Lower Manawatu River after flooding due to the high precipitation of cyclone “Gabrielle”. The Category 3 cyclone Gabrielle hit the North Island of New Zealand, causing extensive damage mostly in the Northland, Auckland, Coromandel, and Hawke’s Bay areas. The cyclone formed on the 6 February 2023 and had largely dissipated by the 16 February 2023. Alongside the destruction in the narrow core of the storm, extensive intense rainfall affected much of the territory of the North Island, including the Manawatu River region. Although there was less damage in the Manawatu Basin in comparison to other regions within the path of the cyclone, it generated intense rainfall that triggered flooding across the country. The overflow of the Lower Manawatu River channels happened through collection of most streams from the north coming from the Ruahine Range. Hence, the Manawatu River overflowed its banks, especially the true right side around Palmerston North (Figure 5.5.(9)). This demonstrates the rate of changes for the river in the area with the highest Strahler order (Figure 5.5.(3)). This flood event is comparable to the major flood recorded in 2010 (Figure 5.5.(9)). This flood demonstrates the rate of influences from the northern streams during high-intensity rain events.

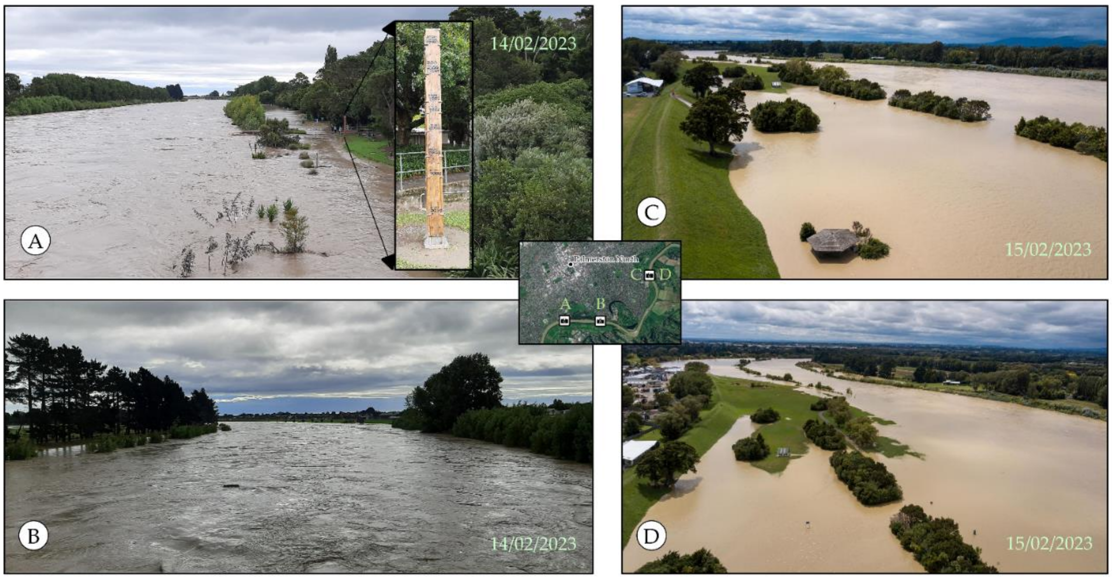

Figure 5.5.(9): Photos on the topic of a flood that happened in the middle of February 2023. (A) Fitzherbert Bridge, Palmerston North; (B) He Ara Kotahi (can be compared with Figure 5.5.(4)), Palmerston North; (C, D) upstream Manawatu near the Higgins Industrial Area, Palmerston; (Photos (C, D) were taken by Matthew Irwin (Massey University, Palmerston North, New Zealand). (E) Overview map of locations, where photos have been taken.

5.5.6 Conclusions

Hydrological data expressed as Strahler order has a decent and positive influence on QQG assessment of geodiversity. It has an impact on the places with low and the lowest values as hydrological data fills all kinds of valleys and depressions throughout the area of research. Hence, the areas with low values have been increased to high. Particularly, this can be seen in locations along the Lower Manawatu. Hence, the Strahler order has a positive effect on the QQG assessment, especially for locations with evolved river systems.

The Strahler order model has number of issues during assessment, with inaccuracy compared with reality and the topographic map being the main drawback. Moreover, a high number of channels can be neglected even though most of them are potential channels; they are considered as potential drainage systems activated during high precipitation. The last issue is a result that highlights the whole river as an important place that still must be studied further to select the most significant parts. However, it is a consideration for the future research for geosite description, whereas it still fits the aim of this manuscript. Hence, the Strahler order model has several issues that can partly be solved through more precise correction, whereas others can be neglected as they do not influence the aim of research.

The information from the LINZ database provides a better picture of the geodiversity of the Manwatu Basin, which must be considered for future research to be included into QQG assessment of geodiversity as additional values along with hydrology. Cultural significance provides data about historical sites and Māori Pā, whereas data regarding rock outcrops, waterfalls, and caves can be considered important for geotourism and geoeducation. Hence, additional information about the uniqueness of the Manawatu Basin can significantly increase its geodiversity value.

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Chapter 6 – Geosites of the Coromandel Peninsula

Description: The main goal of the research is the recognition of exact locations of important geodiversity sites in the Coromandel Peninsula. Our modelling used a new 8-point evaluation system for analysing the geological and geomorphological elements. With the new evaluation system, we concentrated on the regions of high and the highest values shown in the assessment of different geomorphological models. I maximize the regions of assessment without applying 6.25 km^2 grid system. All potential geosites are identified through the model and described further through fieldtrip observations and literature reviews. The result of research identified several potential geosites as candidates for tourism.

The published article can be accessed:

https://link-springer-com.ezproxy.massey.ac.nz/article/10.1007/s12371-024-00933-1
accessed 13st of March 2024

Reference: Zakharovskyi, V., Németh, K., Gravis, I. and Twemlow, C., 2024. Geosite Recognition Based on Qualitative-Quantitative Assessment in the Light of Core Geological Features of a Mio-Pliocene Volcanic Arc Setting of the Coromandel Peninsula, New Zealand. Geoheritage, 16(1), p.19.

In this research: the article has been changed to meet the style of the thesis.

6.1 Geosite Recognition Based on Qualitative-Quantitative Assessment in the Light of Core Geological Features of a Mio-Pliocene Volcanic Arc Setting of the Coromandel Peninsula, New Zealand

Abstract

The far north part of the Coromandel Peninsula can be considered a good place for geoeducation and geotourism, which is justified by the remnants of Miocene-Pleistocene volcanic integration with marine environment. These processes in collaboration with old Jurassic and quaternary sediments create diverse geological and geomorphological constructions forming the abiotic environment of areas surrounding Port Jackson and Fletcher Bay. These two locations have been chosen as two main campsites of the north Coromandel Peninsula, which are maintained by the Department of Conservation (DOC) of the Coromandel Peninsula. They campsites should be considered as main places for camping for the trips of different purposes. They provide an access coastal way and/or trails leading to the main geologically important locations presenting some knowable features like Pinnacles and Sugar Loaf spread through the region. To highlight these locations of interests, "geosites," we developed qualitative-quantitative assessment of geodiversity for geosite recognition based on 8-m DEM and 1:1250,000 scale geological map and QGIS (3.28 "Firenze") software. The methodology utilizes an 8-point evaluation system applied for geological formations of the studied region and its multiplication with morphological slope degree. The result of assessment has been expanded and justified with geological, cultural, and geomorphological database acquired from literature review and direct field trips of the studied areas. The conclusion demonstrates the main geological knowledge of recognized geosites together with description of drawbacks and possible obstacles for tourism and education in the region of the northern Coromandel Peninsula.

Keywords: Geodiversity, Geotourism, Geoeducation, Geosite, GIS modeling, Coromandel Peninsula, QQG assessment

6.1.1 Introduction

Geosite is a term used to define specific locations, often on the basis of geodiversity, which may demonstrate information about formation of abiotic nature in the area of research (Brilha, 2018, Gordon et al., 2018, Gray, 2018, Brilha, 2016). Recognition of geosites is the first step in several types of research on topics like geoeducation, geotourism, and geoconservation. However, recognition of geosites requires field observations describing geological formations and structural elements interlinked with landforms and landscape features. This may lead to critical issues related to the size of research areas, commonly viewed as the scale problem (Zakharovskyi and Németh, 2021b, Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022b, Zwoliński et al., 2018). Geodiversity is a description of all abiotic nature and may describe a number of different elements like geological, geomorphological, hydrological, biological and human footprints (Gray, 2008a, Gray, 2005, Gray, 2008b, Zakharovskyi et al., 2022). This term has been refined for the last 40 years as an analogy to biodiversity. Currently, it is seen as important within the scientific community and relevant to conservation strategies.

Additionally, geodiversity forms one of the scientific pillars to establishment of geoparks under the recognizable global brand of United Nations Educational, Scientific and Cultural Organization (UNESCO). According to UNESCO definition: geopark is location of protection of geological heritage with unique geological significance, visual attractiveness, and knowledge of geological history (Patzak and Eder, 1998). The first criteria for proposition of UNESCO Global Geopark is unified geological area with significant sites and/or landscape suitable for main purposes of geopark: protection, education, and economic development (Henriques and Brilha, 2017). Hence, recognition and description of specific geological locations is the first step for proposition of geopark. To solve this issue, several methodologies have been developed for geodiversity assessments and geosite recognition. The most recognized method for describing geodiversity is applying systematic literature reviews to geoheritage values (Gordon and Barron, 2013, Gray, 2013), geological and geomorphological mapping (Pereira et al., 2013, Najwer et al., 2023), and direct field observations of specific geological and geomorphological features. In our research we demonstrate the strength of combining these three ways, based on modelling utilizing Geographical Information Systems (GIS), literature review and direct field observation based on territory of the north part of the Coromandel Peninsula.

Qualitative-quantitative assessment of geodiversity (QQG) has been proposed in previous research as a specific tool for quick recognition of potential geosites (Zakharovskyi and Németh 2021b; a; Zakharovskyi et al. 2023), based on the range of abiotic elements and their evaluation system mainly concentrated on global parameters for geological and geomorphological elements (rock rareness and slope angle respectively). In our current research this methodology is utilized to minimize the area of geosite search, utilizing general database provided by open access 1:250,000 scale New Zealand Geological Map (GNS Science, 2012) and a digital elevation model (DEM) downloaded from Land Information New Zealand (LINZ) (LINZ, 2023a). QQG assessment is not able to recognize geosites by itself due to limitation of information, which can be included into methodology, but it is a good tool to minimize area of the search for next field observation, description, and confirmation of recognized sites. In our view, GIS calculation is a tool which helps researchers to concentrate on some specific locations for their description, then scientific literature reviews and discussion with other researchers must occur to claim statues of geosite. Hence, several potential geosites have been studied in period of 2021-2022 with their description. Then, additional data have been extracted from scientific literature reviews of the north part of Coromandel Peninsula. All this information has been utilized for description of each geosite in the studied area. The description of geosites have been made for students and tourists interested in understanding of geological processes which formed the north part of the Coromandel Peninsula.

The territory of research is the northern region of the Coromandel Peninsula in the North Island of New Zealand. This region has several geosites with important features for education and tourism spread throughout the Peninsula. Our research will concentrate on describing two specific locations: Port Jackson and Fletcher Bay (Figure 6.1.(1)) as these areas demonstrate a variety of geomorphological data, including superb coastal exposures combined with an aesthetically pleasing rolling hill country within the landmass. In addition, geological features in the region are associated with attractive phenomena of volcanism known to act as a magnet for tourism. The region represents a graphic example of the interaction of Miocene intermediate volcanism with shallow marine and coastal terrestrial sedimentation. Fletcher Bay contains information about interactions between Miocene volcanism and marine sedimentations, while Port Jackson represented by the remnant of Miocene andesite volcanic rock formations clearly visible at the north-western Coromandel Peninsula. The result of our research is a description of geosites in Port Jackson and Fletcher Bay to evaluate the interest for this area for geotourism and geoeducation. Geotourism is natural area tourism oriented toward geology and landscape, which also promotes learning and conservation (Newsome and Dowling, 2010), while geoeducation is primary tool to introduce knowledge about geological environment (Farsani et al., 2011). Both terms are highly connected as geotourism promotes geoeducation for public increasing their awareness about geology and provide recreational activities (Hose, 2012).

The aim of our research is to describe potential geosites, which have been recognized through qualitative-quantitative assessment of geodiversity, direct field observations that occurred in 2021-2022 in the Coromandel Peninsula, and literature reviews. Additional goal of this manuscript is to provide guidance for travellers interested in geological formations and scenic views. Establishing potential geotrail routes for walking or driving may provide geoeducational and geotouristic benefits to visitors and residents, thereby providing a holistic overview of the natural and geological environment of the north part of the Coromandel Peninsula.

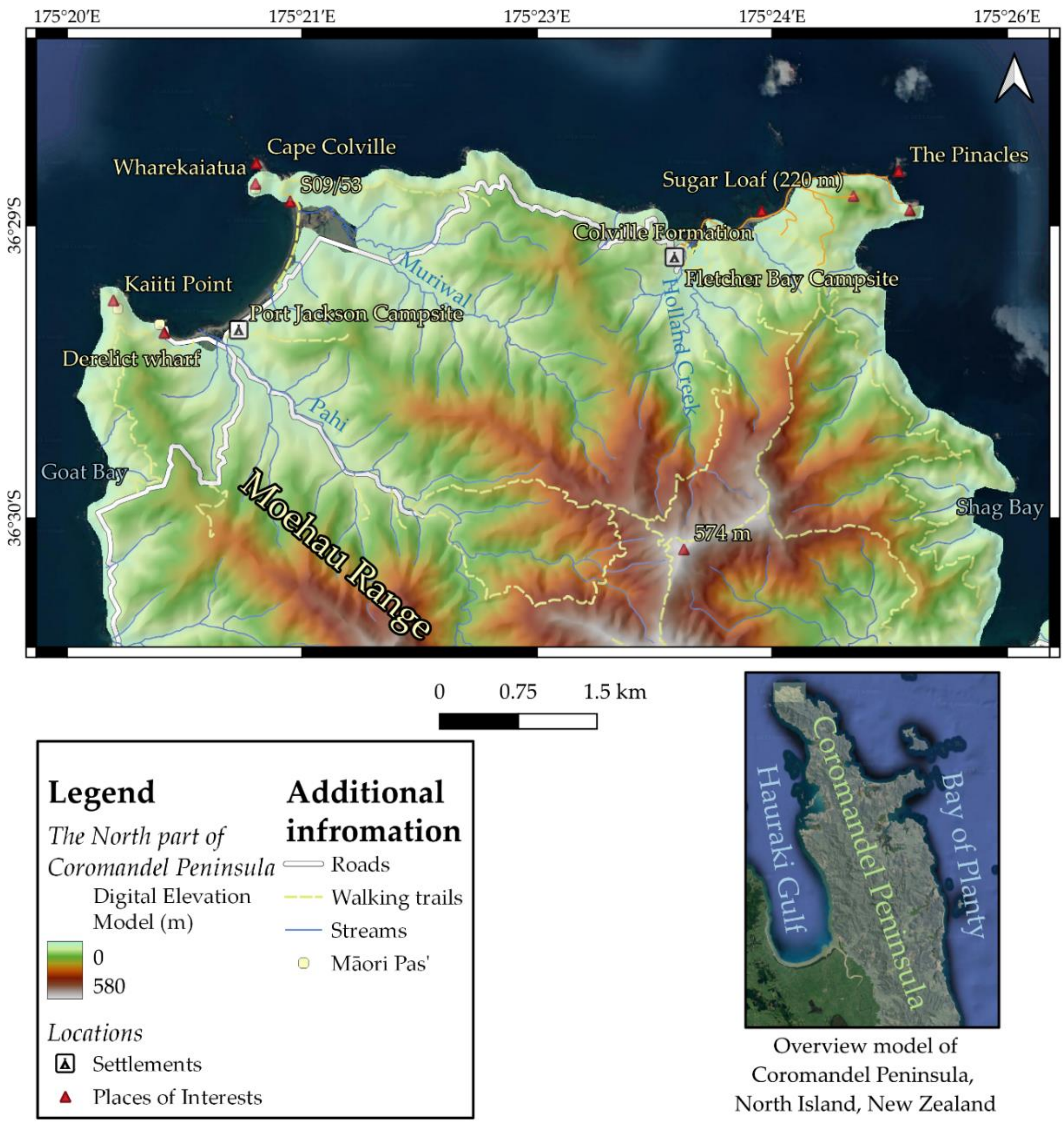

Figure 6.1.(1): Overview of the northern region of the Coromandel Peninsula. The elevation model made from 8-m DEM based on topographic map of the Coromandel Peninsula (LINZ, 2023a). All additional information also has been downloaded from Land Information New Zealand (LINZ) roads (LINZ, 2025a); walking trails (LINZ, 2023b); streams (LINZ, 2025 b); Māori Pas' (LINZ, 2025 c). Settlements and Places of Interests have been extracted from Topographic map of New Zealand (LINZ, 2024). Overview model of the Coromandel Peninsula made from Google satellite image (Earth, n.d.a).

6.1.3 State of art of knowledge of abiotic nature in the northern Coromandel Peninsula

6.1.3.1 Geodiversity, Geosite, and Geoheritage Context

Our research will describe geological locations in the northern region of the Coromandel Peninsula, which will be defined as geosites. By defining them as geosites we connect the term together with geodiversity and geoheritage. Geodiversity is a broad definition applied to abiotic nature and within the environment, in contrast to biodiversity which describes flora, fauna, and other biotic factors. The definition includes sequences of elements grouped under two broad categories: main and additional (Zakharovskyi et al. 2022). Main values include geological and geomorphological elements, which are describing parameters and forms of rock formations.

Additional values include other abiotic elements which are influencing the main ones' (geology and geomorphology) such as: climate, hydrology, solar and cosmic energies, tectonics, biological and anthropological footprints, and soils. Assessing geodiversity allows researchers to select specific locations which may be defined as geosites. These locations will demonstrate abiotic processes and may contain a record of specific geological processes and associated deposits and formations. Historical significance, and value for research and education is recognized through geoheritage values applied to the geosite. In our research we concentrate on recognizing and describing geosite locations, which we will describe in a geotouristic and geoeducational context.

6.1.3.2 Fletcher Bay

The research area for this assessment concentrated on two known Department of Conservation (DOC) camp sites: Port Jackson campsite (DOC, n.d.a) and Fletcher Bay campsite (DOC, n.d.b) and their surrounding territory on the north Coromandel Peninsula: Port Jackson and Fletcher Bay (Figure 6.1.(1) and 6.1.(2)). Fletcher Bay is one of the furthest north points accessible by road, reached by a 36.6 km long (around an hour) unsealed road suitable only for 4WD vehicles from the nearest town Colville. It includes a public campsite, and house with basic facilities owned by DOC, which can be rented by visitors Fletcher Bay campsite (DOC, n.d.b). A search through scientific data bases like Google Scholar (Google Scholar, n.d.) and Web of Science (WOS, n.d.) provide only few articles considering the geological context of Fletcher Bay. Firstly, we consider the most important published research "*Colville Formation-A new formation possibly correlative with the Waitemata Group*" written by Skinner (1969). This geological study describes Colville Formation (Figure 6.1.(1)) (Tertiary sedimentary rocks) and its correlation with Waitemata of the Auckland Region. Moore and Wallace (2000) describe petrified wood in Miocene volcanic sequences of the Coromandel Peninsula and describe samples from the intermediate volcaniclastic successions exposed in the coastal cliffs of Fletcher Bay (Moore and Wallace, 2000). Port Charles andesite (Sugar Loaf Rock, and Sugar Loaf rocks) (Figure 6.1.(1)) consists of intermediate coherent and clastic volcanic rocks that are inferred to be the remnant of Miocene stratovolcanoes. The petrified wood has been captured in volcanic breccia of hot pyroclastic flows and some laharic successions. In addition, these volcanics are known to be the oldest volcanic unit through the entire Coromandel Peninsula, hence it represents the onset of the arc volcanism of the Miocene volcanic arc of New Zealand (Ballance et al., 1982, Ballance et al., 1985, Hochstein and Balance, 1993, Hayward et al., 2001). "*K-Ar ages of early Miocene arc-type volcanoes in northern New Zealand*" published by Hayward et al. (2001) concentrate on the late Cenozoic eruption history of the Northland Volcanic Arc (Hayward et al., 2001), where Fletcher Bay is noted only for the presence of basaltic cobbles. Four other researchers have focused on andesite volcanological formations exposed on the north-east side from Fletcher Bay nearby the exposures of the Colville Formation (Figure 6.1.(1)). Once more Fletcher Bay has been mentioned in the description of the Waitemata Group of Auckland by Benson (1976) (Balance, 1976), where the Colville Formation is described as a distal, fine-grained, and thin bedded flysch of the Waitemata Group. Finally, the territory of Fletcher Bay has also been referenced in research into the Moa bird and its habitat areas in Auckland and the Coromandel Peninsula regions (Gill et al., 2020). Hence, Fletcher Bay contains some scientific information, providing specific details to a range of disciplines studied in the region. However, it is notable for a lack of general geological or environmental descriptions in the context of geoheritage or geodiversity.

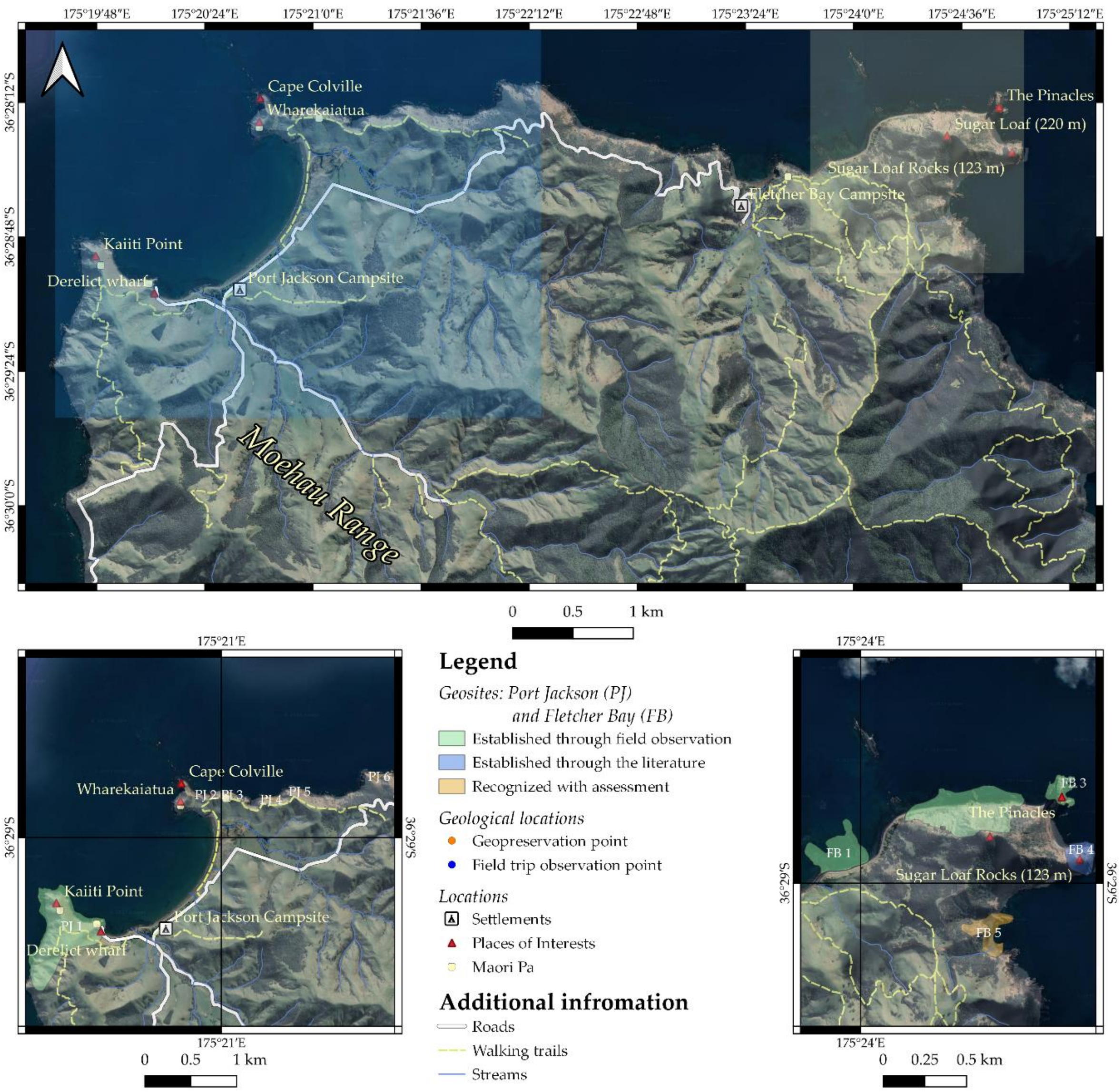

Figure 6.1.(2): The model demonstrates Google satellite image (Earth, n.d.b). Geosites are based on results of assessment of QQG for territories of Port Jackson (Figure 6.1.(3)) and Fletcher Bay (Figure 6.1.(5)) and then assessed with Google Satellite imagery to highlight vegetation-free areas.

6.1.3.3 Port Jackson

Port Jackson has been subject to more research on a variety of scientific subjects. This research has not necessarily concentrated on Port Jackson as an area, but rather focused on specific subjects, which happen to be related to this location. The most popular topics of research we have observed relate to archeology, flora, fauna, and geology. The earliest recorded archeological excavation is S09/53 (Figure 6.1.(1)), which has been described as a location of preserved fossils of shellfish, fish, birds, and marine mammals (Smith and James-Lee 2010).

Evidence of past flora and fauna (James-Lee 2015) such as New Zealand moa (e.g., *Dinornis robustus* and *Dinornis novaezelandiae*) (Gill et al., 2020, Gill, 2022), remnant of leeches' populations (*Richardsonianus*) (Burreson, 2020), New Zealand kākā (*Nestor meridionalis*) (Davidson, 2018), lands nails (Brook, 2000) have provided dating constraints and proof of earlier habitats. Additionally archeological sites have provided evidence of human use of bone resources for producing implements such as fish-hooks (Furey, 1990). Then, some publications also mention this place as a point of transportation of Kauri (*Agathis australis*) timber before early 1900, until kauri-logging became unsustainable due to poor management and over-exploitation of resources (Boswijk, 2010). Port Jackson is noted as an observation location for research into native lizard habitats in the northern region of the Coromandel Peninsula (Towns, 1971, 1972, Benson, 1976, Woolley et al., 2022). The research we have noted demonstrates the high scientific value of Port Jackson; however existing research is heavily weighted to biotic nature of this area. Research outputs on abiotic elements of the region such as geology and geomorphology are relatively rare. Of particular significance, published research by Skinner (1975) described the Moehau Range (Figure 6.1.(1)) (Skinner, 1975), which includes andesite and dacite plugs and dikes. This led to formatting the rock assemblages formally grouped into the Kaiiti Porphirities lithostratigraphy unit and the granodiorite and quartz-diorite of the Paritu Plutonics informally described as the "*Coromandel Granite*." In addition to focusing on the intrusive rocks, he has also described the Kaiiti Point (Figure 6.1.(1)) – Miocene andesite Formation (Figure 6.1.(3)) occupying the region just east of Port Jackson. Distribution of eruptive products of the 1314 AD (± 12 years) Kaharoa eruption has been researched by Hogg et al. (2003) and Sahetapy-Engel et al. (2014) (Hogg et al., 2003, Sahetapy-Engel et al., 2014) This research has described accumulated tephra horizons from the Kaharoa volcanic eruption found in the Bay of Islands, the Coromandel Peninsula, eastern Bay of Plenty and northern Hawke's Bay. Tephra identified in Port Jackson's dunes is most likely from the last eruption of the Kaharoa series (Furey et al., 2008). Finally, in a geoheritage context, we note research describing distributions of lead-zinc-copper-silver-gold mineral deposits in the Hauraki region extending from Port Jackson to Te Aroha (has not been demonstrated on Figure 6.1.(1) as located out of the studied region) (Brathwaite and Rabone, 1985). In summary, the Port Jackson region has been subject to extensive scientific research describing geological and archeological aspects of the area, which has importance for promoting geoeducation and geotourism perspectives.

6.1.3.4 Geomorphology and geology of the north part of the Coromandel Peninsula

The study area for our research on the Coromandel Peninsula is all the territory to the north of Goat Bay on the west coast to Shag Bay (Figure 6.1.(1)) on the east coast, featuring mainly gradual hills mostly of a north-western orientation known as Moehau Range (Figure 6.1.(1)). All of them have been shaped by erosion and current orography presented by Jurassic greywacke as basement and the oldest rock found on through the Coromandel Peninsula. Geomorphologically, the elevation of the region increases from the north-west to south-west, with the highest point 574 m (Figure 6.1.(1)) above sea level. Greywacke hills are dissected by several streams derived from high hills all convolving into two large streams: Muriwal and Pahi (Figure 6.1.(1)). Both streams flow toward the north-west, falling to the ocean from the north and south part of Port Jackson. A few streams originate closer to the east, and merge into Holland Creek (Figure 6.1.(1)), flowing to Fletcher Bay, where it discharges into the ocean. Geological elements of the northern part of the Coromandel Peninsula consist of four different rock formations. The Jurassic greywacke, which forms nearly 70 % of the surface rocks of the entire territory. Miocene andesites form two notable features: Kaiiti Point (Figure 6.1.(1)) in the west and Sugar Loaf (Figure 6.1.(1)) on the north-east. Both rock assemblages are important for the study of Cenozoic volcanism. Miocene marine sediments outcrop at the south-east borders of Sugar Loaf and on the northern part of the research area. Finally, some young, Quaternary sediments are observed concentrated around the streams and creeks mentioned above. Hence, geomorphological and geological settings on the north part of the Coromandel Peninsula shows sufficient variety to describe locations demonstrating enough geological values to define them as geosites.

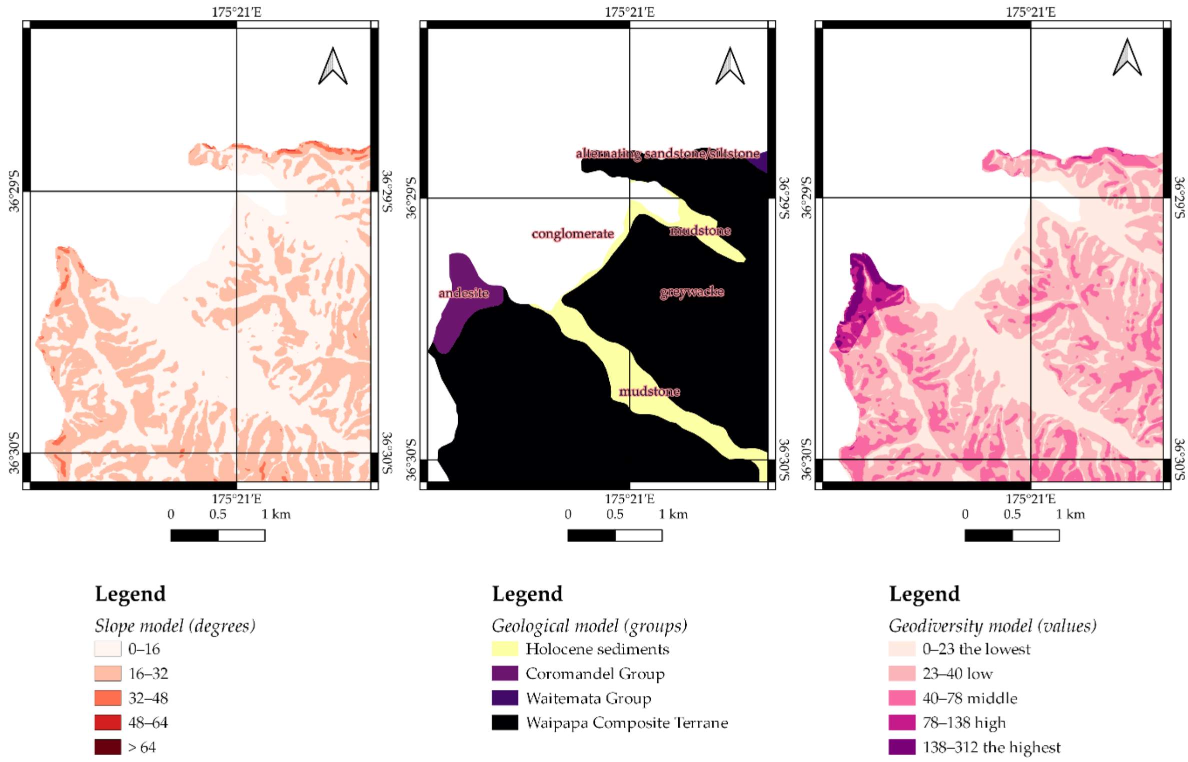

Figure 6.1.(3): Geomorphological data base on Slope model created from 8-m DEM based on topographic map of Coromandel Peninsula (LINZ, 2023a); Geological model based on 1 to 250, 000 scale geological model of New Zealand (GNS Science, 2012); Geodiversity model is calculated utilizing QQG assessment for geosite recognition, where high and the highest values can be considered as potential locations of interest.

6.1.4 Methodology

Qualitative-quantitative assessment of geodiversity (QQG) for geosite recognition is a tool to target areas for field observations to minimize the area necessary for field observations. QQG assessment is based on standard multiplication of geodiversity elements and basic geological and geomorphological data (Zakharovskyi and Németh, 2021b, Zakharovskyi and Nemeth, 2023, Zakharovskyi and Németh, 2022a). The qualitative part of the methodology is seen in the evaluation system, which also is the main drawback of QQG. The correctness of result is always dependent on the evaluation system and its ranking, which always can be argued by other researchers. QQG methodology is an open tool, which can include as much additional information as possible, but it must be attached to appropriate location and evaluated. Another issue is inability for a tool to recognize by itself good scenic views, which we tried to solve through visibility model calculated with "*viewshed*" module of QGIS (Saga GIS plugin) (Figure 6.1.(12) see the "Discussion" section). Our evaluation system has been developed specifically for geological components, based on the rareness of rocks found on the surface, based on the work of Blatt and Jones (1975) "*Proportions of exposed igneous, metamorphic, and sedimentary rocks*" (Blatt and Jones 1975). This framework utilizes an 8-point evaluation system, where 1-point is the most abundant type of rock and 7-points are rare in addition, the value of 8 points has been added specifically for the rarest rock types, which are distinctive from the rest with less than 1% found on the surface (Zakharovskyi and Nemeth, 2023, Zakharovskyi and Németh, 2022a). Geomorphological values can be also used for evaluation, but recent research on comparison of geomorphological models for geosite recognition demonstrates that this type of evaluation system can be avoided (Zakharovskyi and Németh, 2022a). This is especially the case with low resolution Digital Elevation Models (DEM) such as Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (EROS, 2015). Using a 30-m spatial resolution this model is unable to accommodate steep slopes at a scale of less than 30 m. We consider slope model as one of the best data sources for qualitative-quantitative assessment of geodiversity, as it acts as a proxy for geomorphological element classification (Zakharovskyi and Németh, 2022a). The quantitative framework of the assessment describes the number of geodiversity elements, which provides a more accurate description of the abiotic environment. However, the limitation of the tool requires additional field observation for recognition of specific geological and geomorphological features, which can be occurred in outcrop or scenic view. Currently, our methodology concentrates more on geology and geomorphology assessments, with an aim to find out the locations of interest, rather than provide a full description of the abiotic environment. Subsequently, our qualitative-quantitative assessment of geodiversity for geosite recognition is based on multiplication of geomorphological and geological data. Geological aspects have been previously evaluated with the 8-point system according to rock types of rareness. However, for geomorphological values and descriptions we use parameters of slope angle as a proxy.

For the assessment of the northern region of the Coromandel Peninsula, we utilized information from our earlier research on geomorphological influence for geodiversity assessment (Zakharovskyi and Németh, 2022a), whereby the 1 to 250,000 scale geological model of New Zealand (GNS Science, 2012) has been calculated with a slope model based on SRTM (Zakharovskyi and Németh, 2022a, Zakharovskyi and Németh, 2021b). The result has been presented in a grid formation with cells 6.25 km^2 used to define general locations for further assessment. Here, applied our model at a higher resolution to two areas in the northern region of the Coromandel Peninsula, namely Port Jackson and Fletcher Bay as described here in sections 6.1.3.2 & 6.1.3.3. Additionally, to improve the result, the SRTM model has been replaced with the 8-m DEM model based on the topographic map of the Coromandel Peninsula (LINZ, 2023a). Then the geological model was evaluated according to the 8-point system and multiplied with default values of the slope model. The final step is ranging the results based on

Natural breaks (Jenks) mode (Jenks 1967) to clarify the local geodiversity, which highlights 5 categories of region from the lowest to the highest (Figure 6.1.(3)).The results of the assessment have been magnified and applied specifically to the Port Jackson and Fletcher Bay areas located in the northern region of the Coromandel Peninsula. Then the sites with high and highest values of local geodiversity have been corrected utilizing Google Satellite imagery (Earth, n.d.c) to highlight vegetation which may conceal geosites in otherwise high value areas. To date this process has not been automated, and here we apply it to a select few geosites. Development of an automated process would be of benefit for larger projects and study areas. In the "Results" section, we describe geosites with more precise details based on information found in existing literature and field observations made on the Coromandel Peninsula over 2021 and 2022. Moreover, description of geosites will also include information about settlements, places of Interest, locations of historic Māori settlement, roads, walking trails, and streams (Figure 6.1.(2) see the "Discussion" section) (downloaded from Land Information New Zealand (LINZ) (LINZ, 2023a). Such holistic descriptions applied to the area and it's geosites will be of benefit to touristic and educational ventures.

6.1.5 Results

In this section, we provide a detailed description of geosites recognized through a combination of modeling, literature review, and field observations on the Coromandel Peninsula (2021-2022). Areas of study are Port Jackson and Fletcher Bay. More in-depth information will be provided for each territory separately.

6.1.5.1 Geosites of Port Jackson

Location: West side of the north part of the Coromandel Peninsula (Figure 6.1.(2)).

Geomorphology and geology: The research area we define as Geosites001 contains two hills, which are visible from both sides of the sand beach located east section. The standalone volcanic south hill is comprised of various rocks of the Miocene andesite assemblages while the other hill is formed by rocks of the Jurassic greywacke also forming a number of gradual hills growing to the east part.

Result of assessment: Our QQG assessment demonstrates that Port Jackson contains around 6 potential locations of interests with high and the highest values. However, only the site PJ 1 is considered a geosite, as this location contains geological information and is readily accessible to tourists, while potential geosites located in the north of this study area (Geosites001) may have obstacles to safe access.

6.1.5.1.1 Geosite Port Jackson 1

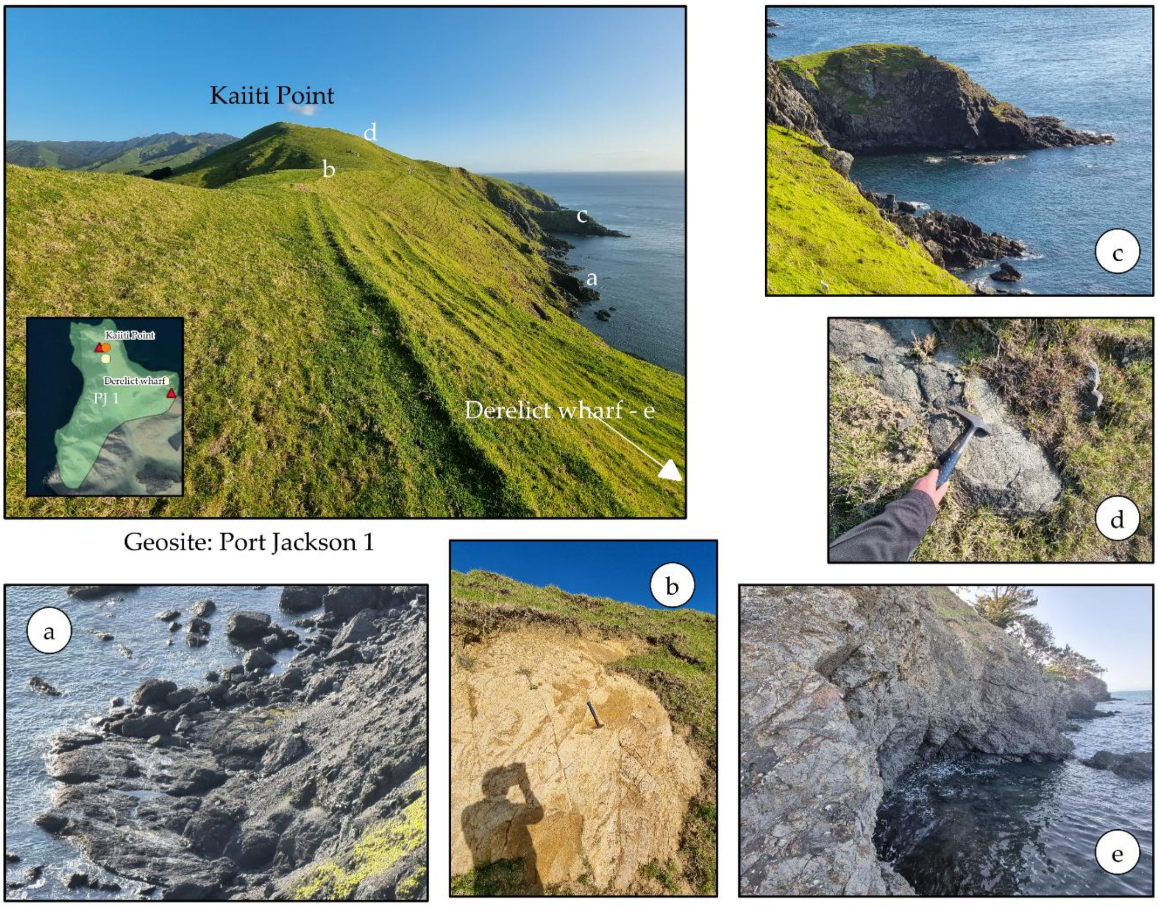

Figure 6.1.(4): Port Jackson geosite 1 (PJ 1).

Description: The geosite Port Jackson (Figure 6.1.(4)) represented by remnants of Miocene andesite, which is a part of the Coromandel Volcanic Group of the Coromandel Peninsula. Named Kaiiti Point it is present within a mixture of andesitic volcaniclastic rocks and greywacke.

Purposes: Valuable for the study of Miocene volcanism, especially to demonstrate the explosive nature producing block-and-ash flows that accumulated in a coastal region where they entered the shallow marine environment. Therefore, this location provides a graphic example of this geoenvironment where intermediate volcanism has interacted with marine sediments.

Difficulty of recognition: This site is readily recognized through modeling, well described in literature, and highlighted on the topographic map of the Coromandel Peninsula.

Obstacles to visitation: The site is situated on the far north of the Coromandel Peninsula. With its remote location visitors must come prepared for poor connections and lack of food supplies. However, it is located nearby to the Port Jackson campsite (DOC, n.d.a).

Result: Geosites 001 could be considered important for geoeducational, heritage, and touristic ventures. However, with its remote location in the far north of the Coromandel Peninsula with the nearest substantial settlement, the township of Coromandel, up to 2 hours each way, a vehicle is required to reach the site. Additionally, it is inconvenient for general tourism, as each point of interest is separated by long walking distances. However, with suitable commitment and support, the site could have benefits for geoeducation and niche geotourism.

6.1.5.2 Geosites of Fletcher Bay

Location: East side of the north part of the Coromandel Peninsula.

Geomorphology and geology: Geologically speaking, the east part of Fletcher Bay contains large remnants of Miocene andesite volcanological activities (Coromandel Group). This area features a large hill surrounded with ocean on the north and east, while Jurassic greywacke forms gradual hills extending from the south and west parts.

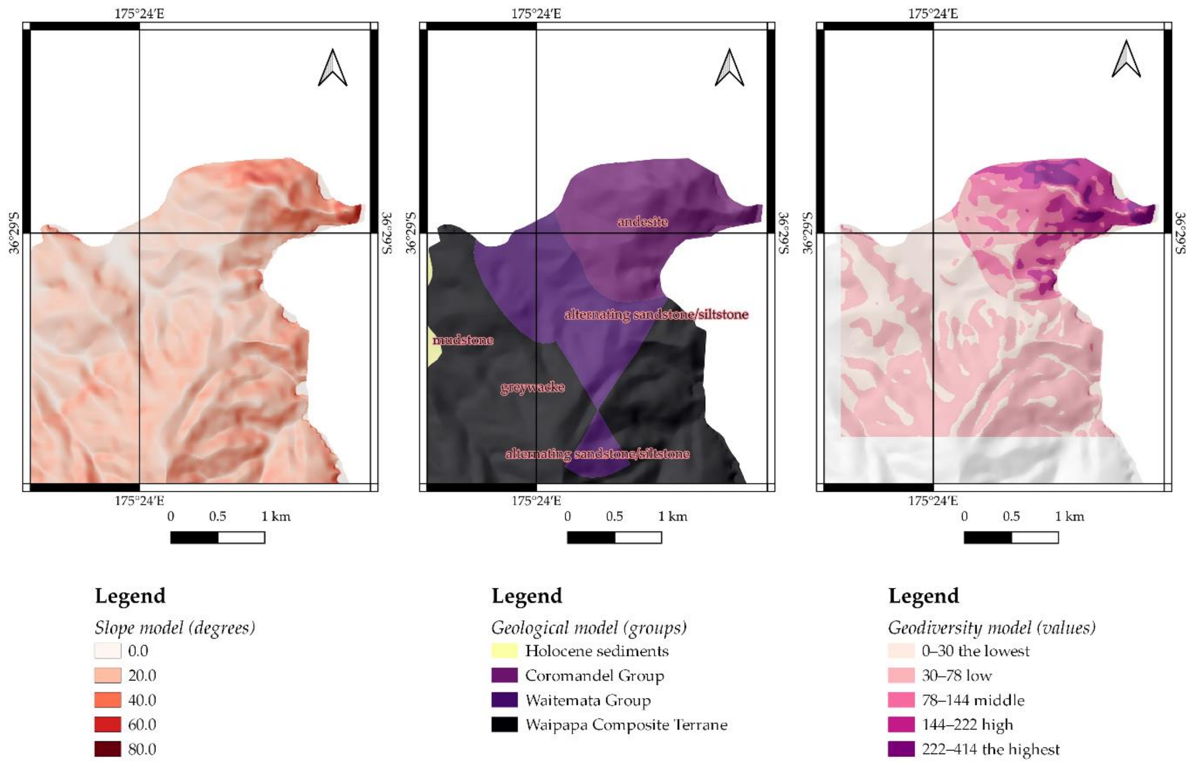

Figure 6.1.(5): Geomorphological data base on Slope model created from 8-m DEM based on topographic map of the Coromandel Peninsula (LINZ, 2023a); Geological model based on 1 to 250, 000 scale geological model of New Zealand (GNS Science, 2012); Geodiversity model is calculated utilizing QQG assessment for geosite recognition, where high and the highest values can be considered as potential locations of interest.

Result of assessment: The result of our QQG assessment (Figure 6.1.(5)) has highlighted a relatively large area, which could be considered a location with geological interest. To refine our results, we utilized Google satellite imagery to highlight the locations devoid of vegetation cover. Additionally, we include the Colville formation, which was not recognizable by our QQG methodology as geological and geomorphological data were not included for this area. Fletcher Bay (FB 1-5) contains 5 locations with geological significance, which could be considered geosites. However, Fletcher Bay 5 has not been include in our assessment as it has been recognized by our QQG modeling, but without supporting information from literature reviews or field observations.

6.1.5.2.1 Geosite Fletcher Bay 1

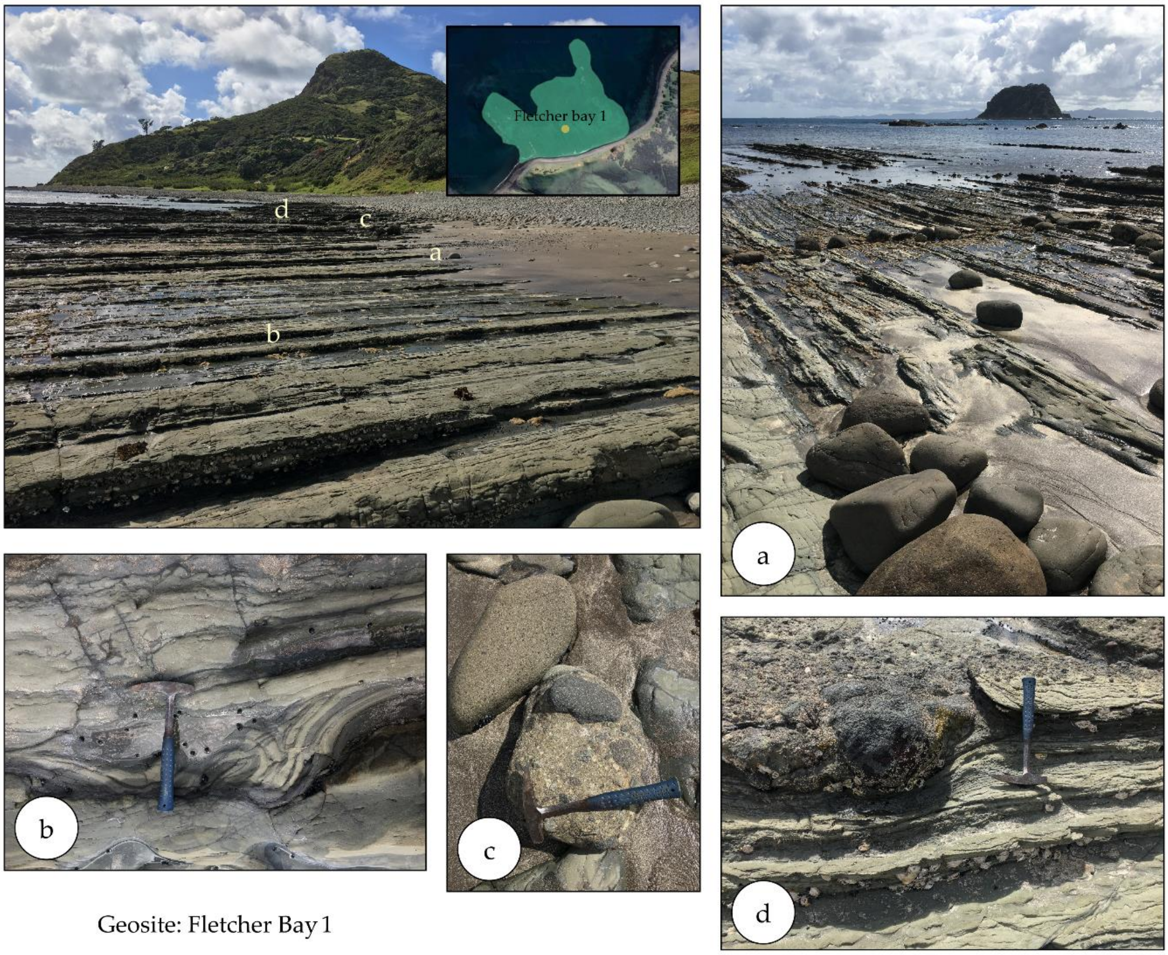

Figure 6.1.(6): Fletcher Bay 1. The "main" picture presents overview of geosite and contains letters "a–d," which are magnified pictures of respected symbol.

Description: This geosite features layers of Miocene sediments (Waitemata Group), which have been tilted and exposed on the tidal platform (Figure 6.1.(1. a)), however a large proportion is under water. At low tide an extensive shoreline platform can be accessed on foot. Additionally, some volcanic conglomerate can be observed, adding value to the volcanic heritage of the region as it demonstrates the earliest manifestation of Miocene volcanism in the Coromandel Peninsula and graphically showing the interaction between volcanism and marine sedimentation (Figure 6.1.(1.c)). The shore platform is particularly valuable for demonstrating biological weathering (Figure 6.1.(1. d)).

Purposes: Valuable for the study of Miocene sedimentology and marine weathering processes.

Difficulty of recognition: This site place is not recognized with our modeling as it was not included in our assessment due to lack of geological information on maps completed to date, and the flat homogenous terrain. The site can be observed from nearby high value sites in the Fletcher Bay area and has been studied by Skinner (1969) and Benson (1976) (Skinner 1969; Ballance 1976) and described in Literature review section.

Obstacles to visitation: The site is in the far north of the Coromandel Peninsula, with no mobile reception, lifelines, amenities, and food supplies. The Fletcher Bay camp site has some facilities for backpackers provided by the Department of Conservation (DOC) (DOC, n.d.b), however visitors must be well prepared and supplied. Colville formation (Fletcher Bay 1) can be accessed only by walking tracks and during low tide period, which must be considered as well.

6.1.5.2.2 Geosite Fletcher Bay 2

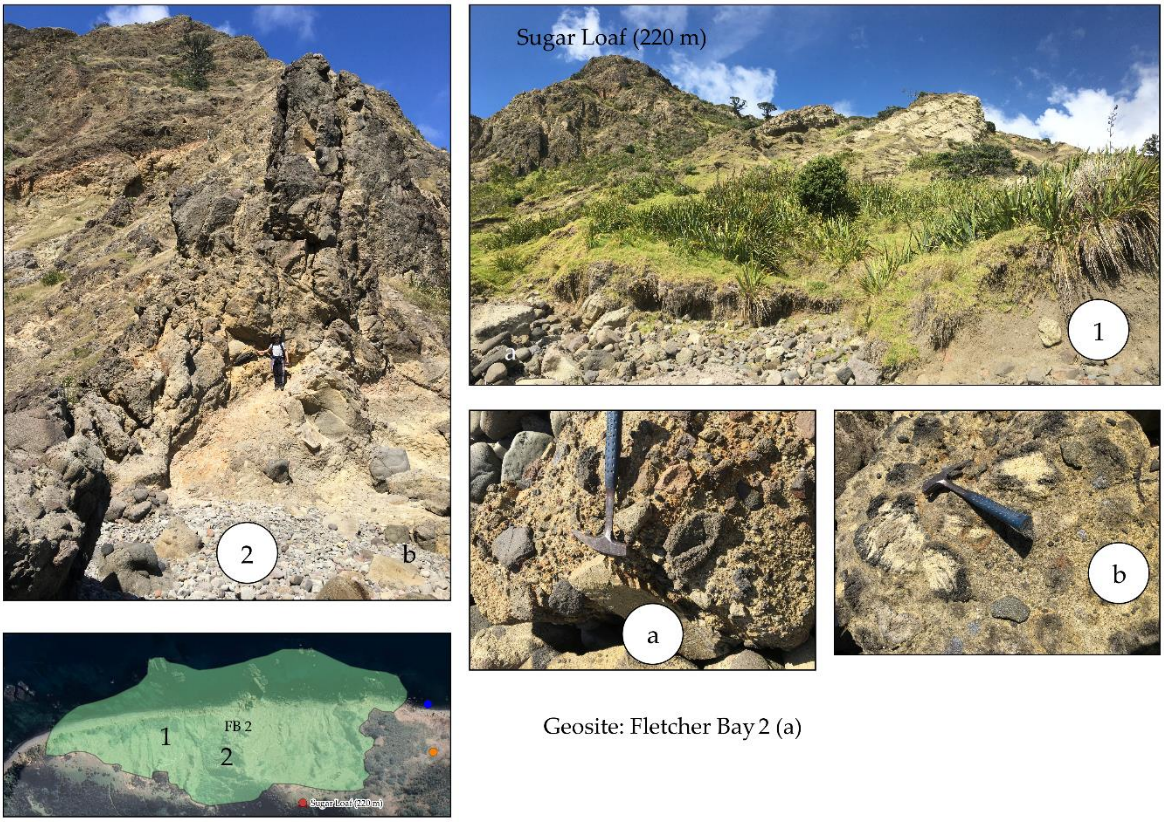

Figure 6.1.(7): Fletcher Bay 2 (a). The pictures "1" and "2" presents geosite and contains letters "a" and "b" respectively, which are magnified pictures of respected symbol. "Overview" model has been separated and has no arranged symbol.

Description: Geosite FB 2 (a) (Figure 6.1.(7)) features remnants of Miocene andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Sites 1 and 2 (Figure 6.1.(7. 1 and 2)) are part of the Sugar Loaf (SL) formation with a 220m peak forming the highest point on the nearby coastal stretch area. SL formation is surrounded with Miocene sediments on the western flank, as described in Fletcher Bay 1, while Jurassic greywacke (Basement of the Coromandel Peninsula) forms rolling hills towards the south-west. Within the boundaries of this geosite many breccia deposits can be observed.

Purposes: Valuable for demonstrating the growth of a composite volcano as part of the Miocene arc volcanism of the region against a background of historic and active marine sedimentation. Geological value of the geosite is enhanced by examples of dynamic marine shoreline weathering processes.

Difficulty of recognition: This site is readily recognized with remnant andesite formations visible on the geological map, with marine weathering processes creating a cliff structure, which can be seen on the slope model.

Obstacles to visitation: The same situation as Fletcher Bay 1 but located about 800 meters further.

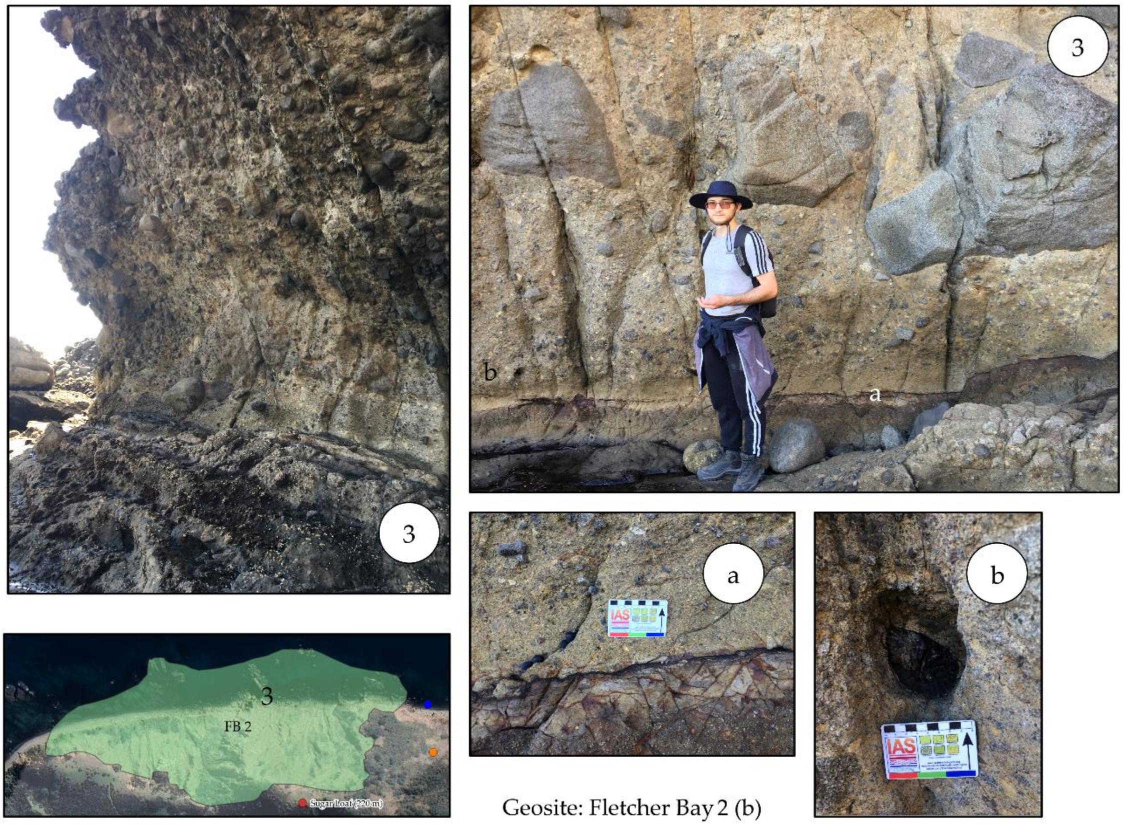

Figure 6.1.(8): Fletcher Bay 2 (b). The picture "3" presents geosite and contains letters "a" and "b," which are magnified pictures of respected symbol. "Overview" model has been separated and has no arranged symbol.

Description: Geosite FB 2 (b) (Figure 6.1.(8)) is formed by remnants of Miocene andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Sites 3 (Figure 6.1.(8.3)) is included as part of the Sugar Loaf rock, which is separate from the main cliff side. This site contains several charcoal and mineral inclusions clearly visible within the main rock formation.

Purposes: Valuable for the study of Miocene Volcanism and marine weathering, as the site is an exposed marine cliff. This location is also a key site where charred wood can be seen preserved in a volcaniclastic succession formed by a hot pyroclastic flow (block-and-ash flow) that accumulated in a proximal section from to the source vent. This outcrop is also a place for relative chronology.

Difficulty of recognition: This site is not recognized in our geomorphological or geological model as a definitive geosite location, as it is very small, and beyond the low resolution of tens of meters of the DEMs used in our modeling. Forming a section of the beach and often submerged, it is unlikely to be incorporated into standard cartographic assessments. However, this place can be recognized during direct field observations and from satellite images such as Google Satellite ones (Earth, n.d. d).

Obstacles to visitation: The same situation as Fletcher Bay 2 (a). It is relatively easy to walk on shore.

Figure 6.1.(9): Fletcher Bay 2 (c). The picture "4" presents geosite and contains letters "a–c," which are magnified pictures of respected symbol. "Overview" model has been separated and has no arranged symbol.

Description: The geosite FB 2 (c) (Figure 6.1.(9)) is represented by remnants of Miocene andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. This site forms part of a cliff side of the Sugar Loaf rock (Figure 6.1.(7-1) and contains pyroclastic deposits (Figure 6.1.(9-4, b and c)).

Purposes: Valuable for study of the proximal volcanic succession of a growing stratovolcano as it interacted with its shallow marine background geoenvironment in the Miocene. It is also a superb site where coastal erosion processes and shallow marine weathering are clearly visible. The site is also a place for mass movement processes such as rock and debris fall.

Difficulty of recognition: The place is easy recognizable with modeling like FB 2 (a).

Obstacles to visitation: The same situation as Fletcher Bay 1 but located 1000 meters further.

6.1.5.2.3 Geosite Fletcher Bay 3

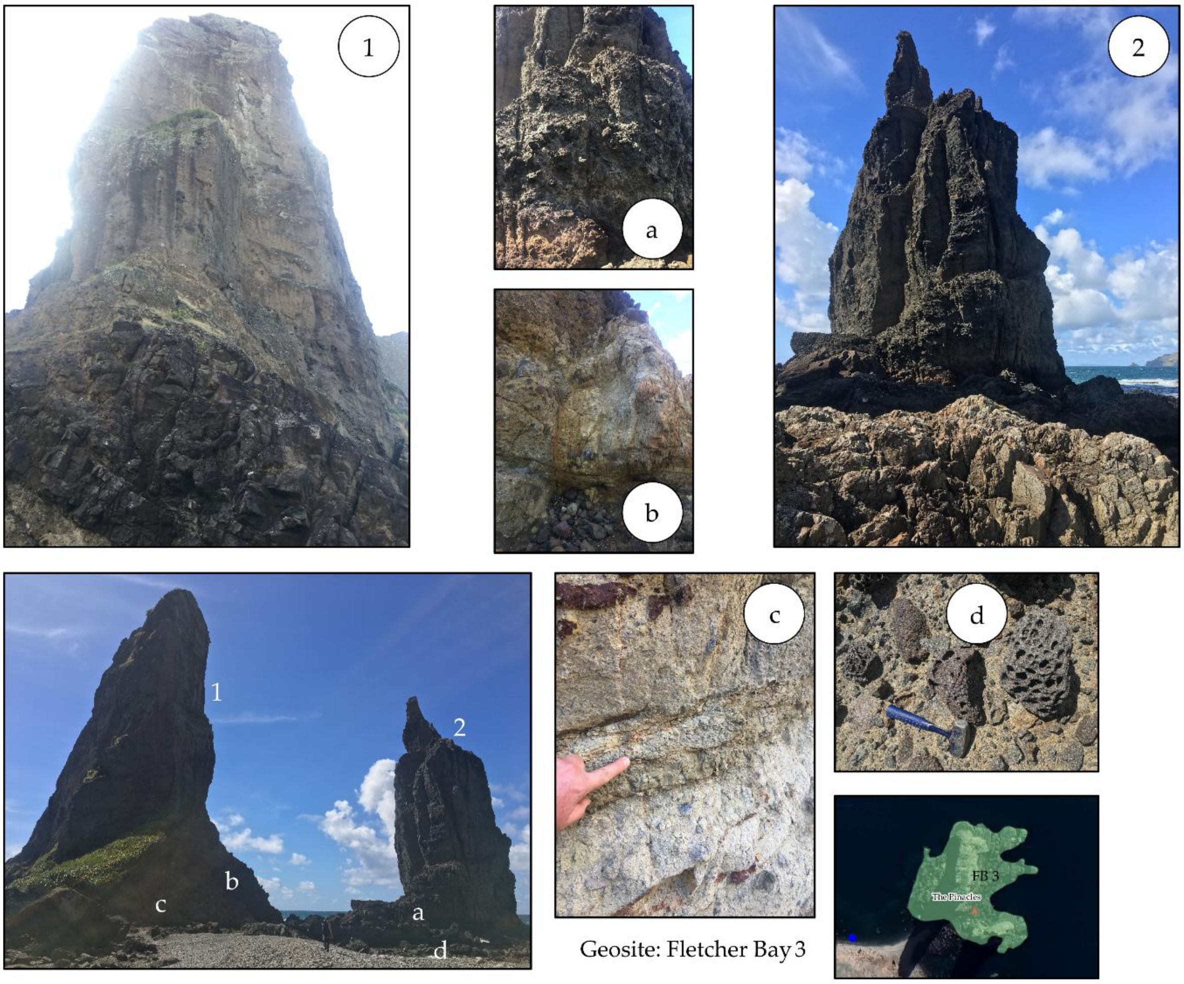

Figure 6.1.(10): Fletcher Bay 3. The picture "1 and 2" presents two-part geosite. Two "Overview" model has been separated and has no arranged symbol, which contains letters "a–d," which are magnified pictures of respected symbol.

Description: The geosite FB 3 (Figure 6.1.(10)) is formed by remnants of Miocene andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Sites 1 and 3 are formed by distinctive pinnacles (Figure 6.1.(10. 1 and 2)) and are separated from the main andesite formation of Sugar Loaf rock. The pinnacles reach 75 and 35 m above sea level (Figure 6.1.(10) "overview" on the left) according to 8-m DEM based on topographic map of the Coromandel Peninsula (LINZ, 2023a) and feature a succession of pyroclastic rocks.

Purposes: Valuable for study of the core, proximal elements of an intermediate andesitic volcano that has been dissected by coastal and shallow marine abrasion and erosion. This location is nearly 100% exposed and shows evidence of explosive eruptions that formed the polygenetic volcano considered one of the first during the onset of the Miocene arc volcanism in the region. The location is also a perfect site to see coastal erosion processes and a dynamic interface between the land and marine environment.

Difficulty of recognition: Hard. Pinnacles are readily recognized at the location during observation and are labeled on the topographic map as well as mentioned in literature (Hayward et al., 2001, Hochstein and Ballance, 1993, Ballance et al., 1985, Ballance et al., 1982). However, the geological map has no information about this area.

Obstacles to visitation: The same situation as Fletcher Bay 1 but it is at the end of the coastal accessible shore. Note that it is reachable only in low tide.

6.1.5.2.4 Geosite Fletcher Bay 4

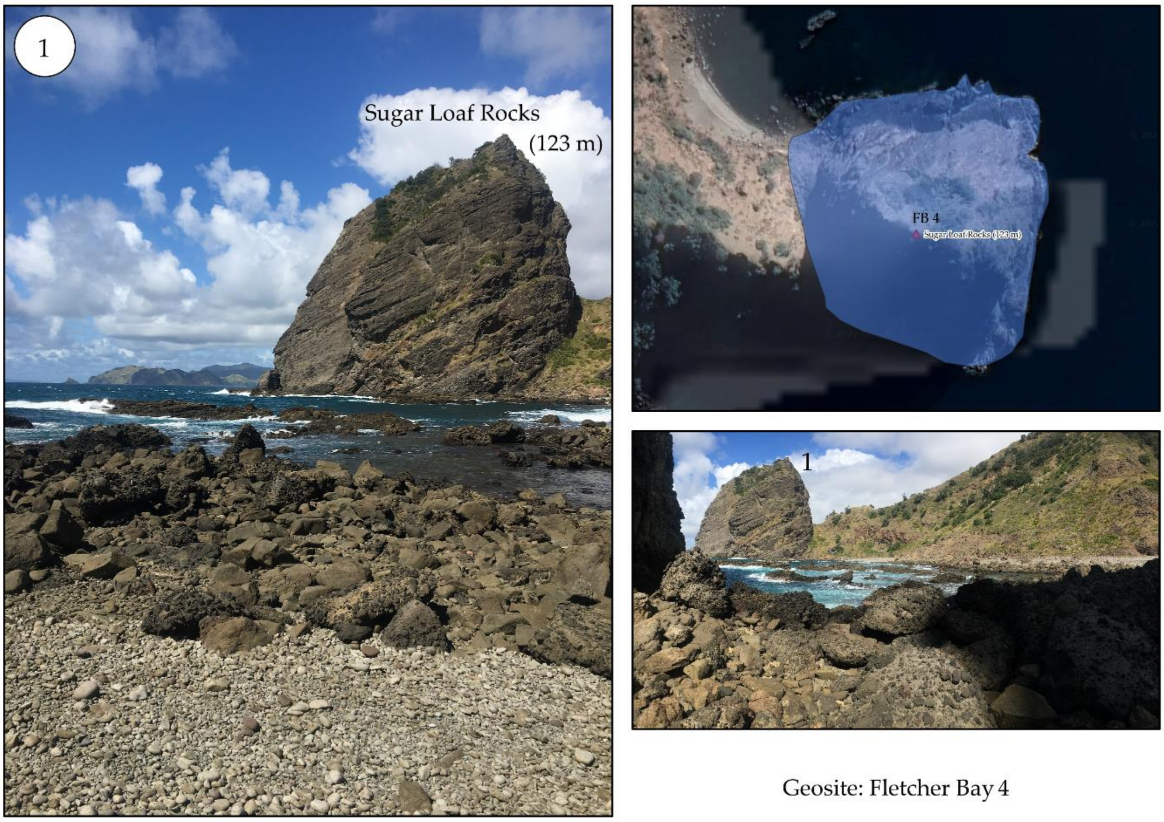

Figure 6.1.(11): Fletcher Bay 4. The picture "1" presents geosite. Two "Overview" model has been separated and has no arranged symbol.

Description: The geosite FB 4 (Figure 6.1.(11) is represented by remnants of Miocene andesite, which is a part of the Coromandel Volcanic Group occurring on the Coromandel Peninsula. Site 1 is Sugar Loaf rocks (Figure 6.1.(1.1)) which are separated from the main andesite formation generally referred to as "Sugar Loaf".

Purposes: Valuable location to observe volcaniclastic successions on the completely exposed shore platform. Fine details of the depositional processes are visible within the accumulations of these volcaniclastic successions. Coastal erosion and abrasion provide dramatic and aesthetic qualities to this site, which may give it greater appeal beyond niche geotourism.

Difficulty of recognition: Easy. This site is well defined in our modeling and well covered by published literature (Hayward et al., 2001, Hochstein and Ballance, 1993, Ballance et al., 1985, Ballance et al., 1982) and mentioned on topographic map of the Coromandel Peninsula.

Obstacles to visit: The same situation as Fletcher Bay 1 but this is the most remote geosite (1600 meters) and return time must be calculated for safe walk back.

6.1.6 Discussion

Our qualitative-quantitative assessment of geodiversity resulted in defining 10 arguably superb locations in the northern part of the Coromandel Peninsula, which have been allocated high, or the highest possible value, for geosite recognition within our study area subject to QQG assessment. Four locations have been selected in the east extending from the Fletcher Bay (FB) area and include sites featuring outcrops of the Colville Formation, Sugar Loaf, Pinnacles, and the Sugar Loaf rocks. The first FB site features tilted Miocene sediments which are exposed and clearly visible during low tide named "Colville Formations." The Colville Formation is not recognized well by our geodiversity modeling as this site is not featured in geological and geomorphological models, but it is scientifically recognized and visible during field observations. The Sugar Loaf, the Pinnacles, and the Sugar Loaf rocks were formed by Miocene andesite, creating several geological formations such as lava remnants, breccia, dike, and coal measures associated with abundant organic material burned and subsequently incorporated into block-and-ash flow deposits. These locations have all been highlighted through our geodiversity modeling and we have labeled them as FB 2-4.

Meanwhile, our QQG assessment recognizes 6 locations on the territory around the Port Jackson campsite. The first and largest area contains high, and the highest value sites, in the south-western part. Miocene andesite forms a site known as Kaiiti Point, allowing scenic views to other areas of the Peninsula and surrounding waters, is covered with grassland, and features exposed rock cliffs on the coastal areas. Meanwhile, 5 other locations of interests on the northern shore east of Cape Colville have not been included due to difficulty accessing them and associated safety issues. The main geological values of these sites are all associated with Jurassic greywacke Therefore, our modeling has described 10 locations with high or the highest values, but only 5 of them are in readily accessible areas making them suitable for touristic and/or educational purposes.

Additionally, a visibility map has been created for our area of research to demonstrate the most visible parts of the landscape in the northern part of the Coromandel Peninsula (Figure 6.1.(12)). The visibility model is based on a viewshed tool which recognizes a binary value for visibility of areas, based on the point of observation. Using this tool highlights areas which can be observed on distance 5 km (default parameter). For our modeling, walking tracks and roads have been analyzed, showing a range of areas with a color range from dark to light, where lighter areas mean a higher number of overlapping visible areas from different points. The darkest areas on the map show those areas which are areas, not observable from tracks and roads. Hence, the central part of the north Coromandel is highly visible, especially north-east, and south slopes leading to Kaiiti Point and south-east slopes to Fletcher Bay.

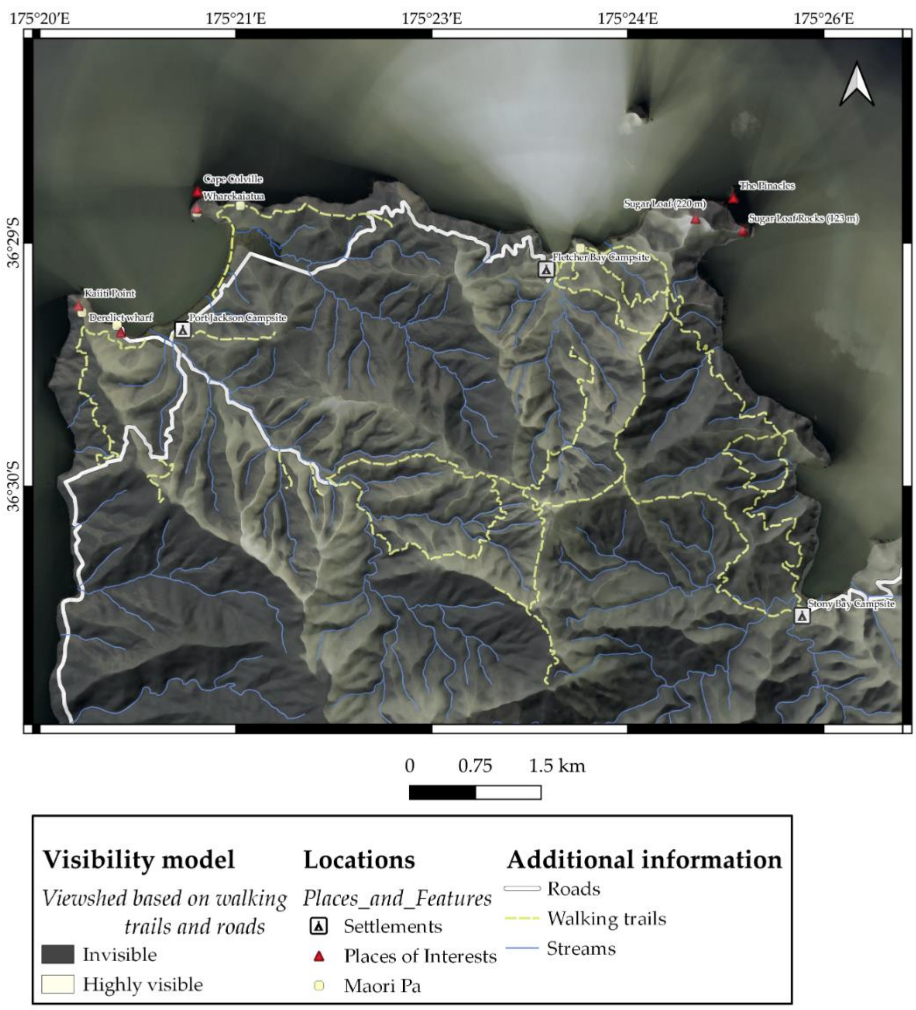

Figure 6.1.(12): Visibility model of the north part of the Coromandel Peninsula made utilizing "viewshed" module of QGIS (Saga GIS plugin) based on 8-m DEM based on topographic map of the Coromandel Peninsula (LINZ, 2023a). All additional information also has been downloaded from Land Information New Zealand (LINZ) roads (LINZ, 2025a); walking trails (LINZ, 2023b); streams (LINZ, 2025b); Māori Pas' (LINZ, 2025c). Settlements and Places of Interests have been extracted from Topographic map of New Zealand (LINZ, 2024).

Overall, according to the maps Port Jackson and Fletcher Bay campsites (Figure 6.1.(1), 6.1.(13)) can be easily visited by car, and moreover convenient for short stay (around a week). However, some decent drawbacks are present as well, like no access to phone connection and no main food or tool stores in nearby distance. Hence, currently the journey to any of the mentioned geosites must be planned, especially for food, petrol, and first aid perspectives. Then any kind of a trip will require at least one full day for observations due to the long distances, which must be covered by foot. Port Jackson is the most convenient option as it is still located not far away (one hour by car) from Colville, which contains general shop, fire station, and coffee place. But, in emergency you must be ready to drive up to the Coromandel Township (1 hour 30 minutes). Therefore, Port Jackson can be studied in two days as the main geosite "PJ 1" is located 5 min walk from the campsite. Meanwhile, Fletcher Bay contains even more problems such as distances to closest towns prolongs driving by 20 minutes. But staying in this region must be considered for 2 days at least as the closest geosite FB 1 “Colville Formation” is located 1 kilometer walking distance by stony beach area starting from Fletcher Bay campsite using coastal trails (Figure 6.1.(13)), then to reach the FB 5 “Sugar loaf rocks” is 2700 m long walk. Hence, for visiting all geosites the trip will take at least whole day just to get to the final point with time suspended for geosite descriptions and resting. Additionally, it requires around an hour to reach the highest point in “Sugar Loaf,” which opens a view toward Moehau Range and “Pinnacles” (Figure 6.1.(14)). Meanwhile, Port Jackson and Fletcher Bay relates to numbers of walking trails with length around 11800 m, which can become a good opportunity for sport tourism and studying of geomorphology of the central-north part of the region which clearly opens visibility toward the north-east from the walking ways according to visibility model (Figure 6.1.(12)). Hence, the north part of the Coromandel Peninsula contains a range of opportunities for geotourism and geoeducational perspectives, however due to lack of facilities in these areas the field trips must be planned.

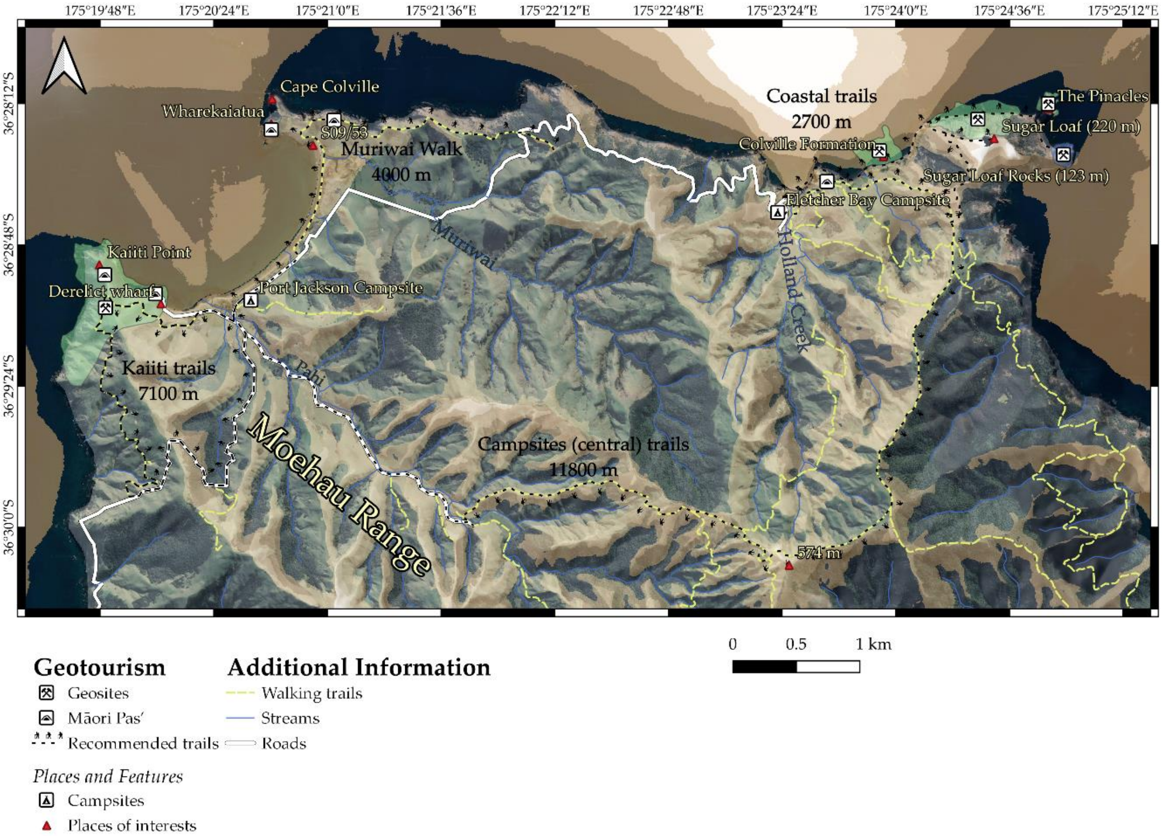

Figure 6.1.(13): Geotouristic model of the north part of the Coromandel Peninsula. All additional information also has been downloaded from Land Information New Zealand (LINZ): roads (LINZ, 2025a); walking trails (LINZ, 2023b); streams (LINZ, 2025b); Māori Pas’ (LINZ, 2025c). Settlements and Places of Interests have been extracted from Topographic map of New Zealand (LINZ, 2024).

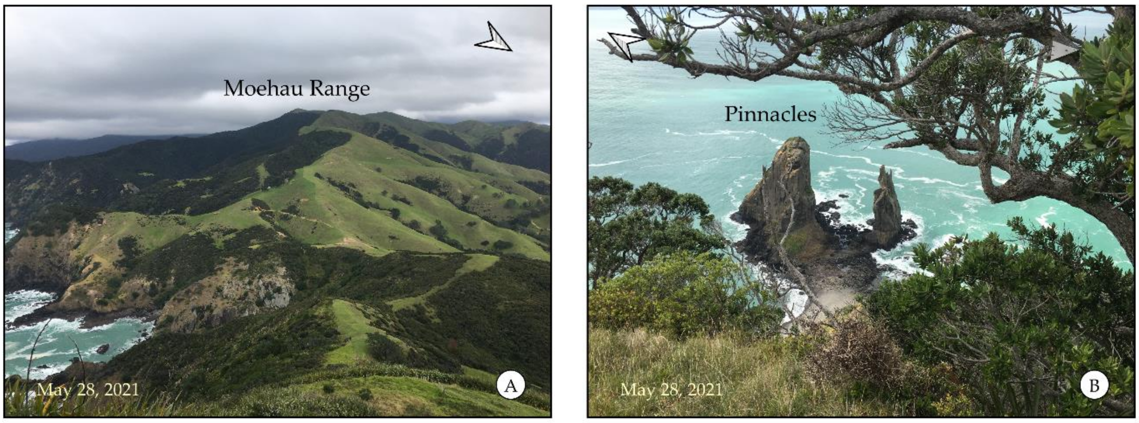

Figure 6.1.(14): Photos taken from Sugar Loaf on 28th of May 2021, during the field trip to the north part of the Coromandel Peninsula. A) View toward the south-west demonstrating Moehau Range. B) View toward north-east picturing "Pinnacles".

Results of QQG assessment can be utilized for further direct field observation, but it is not guaranty us that every point obtained by calculation can be a geosite. The last statement contains some potential drawbacks connected with location of research, such as inability to come close to the cliffside, where we rejected around 5 possible geosites (PJ 2-6) in the north side of Port Jeckson area (Figure 6.1.(2)). Other, issue is vegetation, which can be avoided utilizing data about walking trails and satellite images with plant covering for example Natural Differences Vegetation Index (NDVI). Furthermore, improvement can be done to the 8-point evaluation system with additional values of geodiversity such as hydrology, which have not been utilized in this research to concentrate more on demonstration of geological location and introduction of it for tourism and education to encourage visitation in this area. Finally, the assessment can be improved by increasing the scale of research and create a model of the Coromandel Peninsula with all geosites. However, this kind of project require a long time for calculations, direct observation, and descriptions, which can take a year, but result of this project would be a full model with touristic and educational spots for geological information of the peninsula. Hence, everything still can be improved and corrected to acquire the best result, which allow us to increase geological awareness of New Zealand.

6.1.7 Conclusions

The result of QQG assessment for geosite recognition, provides 6 locations for Port Jackson, and 5 locations for Fletcher Bay areas. However, only PJ 1 and FB 1-4 have been included for description, because other sites are inaccessible, so they have not been recognized through field observations and literature reviews. Selected geosites have been described according to information presented in literature reviews from previous year of geological research in this area. Hence, it resulted in one large geosite around Kaiiti Point nearby Port Jackson, and 4 geosites nearby Fletcher Bay started with "Colville formation" and surrounding areas around "Sugar Loaf," "Pinnacles," and "Sugar Rocks."

Port Jackson and Fletcher Bay campsites can be utilized as starting point for geotourism and geoeducation in the north Coromandel Peninsula. These areas contain an interesting geological formation constructed through the interaction of Miocene-Pleistocene volcanism and marine processes. Moreover, the campsites contain some general utilities giving an opportunity to stay in the north for few days to explore geomorphological and geological features of the region. However, the group should be ready for some challenges and preparations before to come to the region. All geosites selected in this manuscript can be reached by walking trails and coastal areas from the nearest campsites. However, sometimes tide level must be considered some places can become inaccessible with high tide. In average all walks are around 7 km long, where stopes for observations must be included into planning of a trip. Hence, this manuscript can become a guide for people, who considered to visit this region.

Additionally, visibility map has been demonstrated in the research to show that roads and walking trails open the view on the landscape of the region, where north part and Kaiiti Point are areas with the highest visibility from the most parts of roads and trails. This manuscript is demonstrations of possibilities, which can be done utilizing QQG assessment with collaboration of direct field observations and literature reviews of the region. In further observations we are planning to improve evaluation system and utilize more additional information for more accurate calculation. Then, the scale of research should be increased to acquire a full geotouristic model of the Coromandel Peninsula with demonstration and description of all geolocations and facilities to increase geological awareness for travelers and students.

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Data availability All data used in this article is in the published version of the article. For further details and queries the authors can be reached directly by email.

Declarations

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Chapter 7 – Discussion and conclusions

7.1 Discussion

7.1.1 Geodiversity terminology and concepts: geoheritage, geosite, and geopark

The primary aim of this research is to examine terminology related to geodiversity in order to clearly define its fundamental elements and philosophical foundation (Chapter 1.3 (Aim 1)). This aim can be further divided into two core objectives, and one additional. The first objective is to define the overarching concept of geodiversity and to describe associated terminology through a systematic literature review of previous research on this topic, thereby describing development of the concept and its associated terminology. Results of the literature review demonstrate that terminology around geodiversity remains to be clearly defined and recognized. Some researchers still use their own subjective definitions of this term, as well as a highly variable range of associated elements. For example, some may include palaeontology, mineralogy, and archaeology apart from the geological elements, while others may combine these elements into one framework (Gray, 2018). In some cases, oceanic processes may be included (González Trueba, 2007), and in other cases weather conditions (Milnes et al., 1987). Soils may be recognized as an element where the abiotic sphere intersects with the biotic sphere (Bétard and Peulvast, 2019, Lausch et al., 2019, Rangel et al., 2019, Stavi et al., 2019, Fossey et al., 2020, Reverte et al., 2020, Santos et al., 2020, Zaady et al., 2021) and act as a transit zone between biodiversity and geodiversity.

Definitions of the terms geosite, geomorphosite, and geoheritage may be applied with some variability (Brocx and Semeniuk, 2007, Bentivenga et al., 2019, Cengiz et al., 2021). Definitions of the term geosite have been applied variably throughout the literature, one of the most applied to define a geological location with aesthetic, scientific, and educational uniqueness (Vujičić et al., 2011), while Brilha (2016) focuses predominantly on strictly scientific values (Brilha, 2016). An additional definition of geosite proposed by Ruban (2010), refers to the term as geological objects exposed on the land surface that are readily accessible for visiting and studying (Ruban, 2010). The term geoheritage can be used to define a value applied to geosites that are significant for the understanding of Earth's history (Brocx and Semeniuk, 2007, Cengiz et al., 2021) or can be applied to locations with preserved geological features (Brilha, 2016, Brilha, 2018). In a hierarchy of terms and values described by those terms, geoheritage is usually recognized as higher than geosite individually. Additionally, the term geomorphosite can be used to describe a geosite displaying unique geomorphological structures, where the importance may also be represented by strictly geological features (Carrión-Mero et al., 2020, Reynard, 2009). The main differences between geosite and geomorphosites is their primary focus (geological composition and form respectively). A geosite reflects the information about geological evolution of the chosen region. For example, an outcrop on a volcanic field, which displays stratigraphy of tephra layers reflecting the chronology of eruptions. Meanwhile, geomorphosite refers to a site or geological feature with a unique structure and/or form shaped by the sequences of processes. For example, a monolithic block of limestone cliffside uniquely weathered because of oceanic processes. However, distinctions between these definitions are not always clear, as all three definitions (geosite, geomorphosite, and geoheritage) may overlap and influence each other. For example, Reynard (2009) define geosite and geomorphosite as "portions of the geosphere that present a particular importance for the comprehension of Earth history" (Reynard et al., 2009), which is like the definition of geoheritage suggested by Brocx and Semeniuk (2007). Therefore, the scientific community is still to agree on clear definitions and distinctions for the terms geosite, geomorphosite, and geoheritage. Nonetheless, they are still be considered as crucial in defining and describing key locations for establishment of a geopark (Ruban, 2017, da Silva et al., 2022).

Based on the research of Nemeth, B et al. (2021), the term geodiversity is also subject to variation in definitions. In addition to definitions not being clearly defined, variation in definitions may also result in conflict between competing interests and ideas (Nemeth et al., 2021). Their research defined four main concepts underpinning geoheritage; "i) a geoscience focus; ii) a call for aligned conservation methods for geo- and biodiversity; iii) the concept of geomorphosites as the leading resource for geoparks; iv) and emphasis on community involvement for sustainability" (Nemeth et al., 2021). Despite recognition of the term geodiversity including all elements of abiotic nature, most researchers remain focussed on geology and geomorphology. Meanwhile, other elements such as palaeontology (Pereira et al., 2013b, Pereira et al., 2013a), hydrology (Zakharovskyi and Nemeth, 2023, Silva et al., 2013, Manosso and de Nóbrega, 2016), and soils (Pereira et al., 2013b, Pereira et al., 2013a), and/or any other elements of abiotic are rarely included in geodiversity research and assessments. Some researchers may introduce specific data about geosites to facilitate geoparks and evaluate geoheritage status of a region rather than considering a holistic view of geodiversity (Henriques and Brilha, 2017). This has subsequently resulted in divisions between different values (for example: scientific, aesthetic, spiritual, cultural, economic and others) (Gray, 2008), and a lack of objective weighting for each value within assessment and research frameworks. Therefore, these variations in definition and differences in understanding of geodiversity terminology and its associated concepts creates a range of issues, which can drive researchers to understand terminology from one narrow point of view only.

The second objective focusses on the recognition of the core parameters of geodiversity in order to clearly describe and establish its philosophical and conceptual foundation (Chapter 1.3 (Aim 1)). It is recognized that the term is subject to a range of definitions that may be fundamentally similar, however they diverge when further examined at a detailed level. For the purposes of clarity in our research and to avoid misinterpretation of terminology, we step back from deep description and instead focus on a holistic view of abiotic nature and its many aspects. Therefore, the elements of geodiversity have been divided into main and additional categories (Figure 7.1.(1)) (see Chapter 2). Main elements are geology and geomorphology, as they are often used as the key descriptors for assessment of geodiversity. Moreover, they are defined as the "the core" of abiotic nature and associated processes, seen in every aspect of the whole of the Earth's surface and its landscapes (geological elements) and forms (geomorphological elements) (Figure 7.1.(1)). Meanwhile, all other elements of geodiversity (those we have named "additional") describe processes which transform the surface of the planet and will leave their mark in some areas (Figure 7.1.(1)). For example, the hydrological element is not relevant to dry desert environment, while cryosphere elements apply more to polar regions and high altitudes. Therefore, geological and geomorphological elements have the highest influence on description of the abiotic environment, being always present, whereas additional elements may be altered or in some cases altogether neglected (Zakharovskyi and Németh, 2021b).

The third and final objective is to compare studies of geodiversity and biodiversity and to examine the integration of the two terms into omnidiversity (Chapter 1.3 (Aim 1)). It has not been examined in detail as a significant theme of research of this thesis, however it is necessary to describe and define the conceptual differences between the two terms. Biodiversity describes the population of the species of flora and fauna in the studied environment, while geodiversity describes composition of the territory, which forms the landscape and abiotic environment of the region. For example, sedimentary rocks in riverbanks cannot be defined as separate elements of a region, because they are fundamental in forming the region. In contrast, mineral composition can be assessed in the same way one would assess biodiversity, through demonstration of the abundance and visibility of a chosen mineral in the region. Population types of assessment can be used for anthropological elements such as different types of architectural constructions (especially in the context of source rock material). For example, historical quarries with Prezandães granite, which also has been used for construction of São Tiago de Folhadela Parish Church, Portugal (Freire-Lista et al., 2023); "Scholars' stones" used for construction of royal palaces, private houses, and scholar desks (Kong et al., 2023); and Red Ereño (limestone) in Basque Country (Spain) (Damas Mollá et al., 2023). In addition to constructions, mining areas may also be considered as part of anthropological values, for example the Thames Goldfield in the Coromandel Peninsula, New Zealand (Cocal-Smith et al., 2023) and iron ore mining in Serifos Island, Greece (Vlachopoulos and Voudouris, 2022). This information can be utilized for geoeducation, geotourism, and geoconservation purposes. Returning to biodiversity, it applies only to the biological sphere and only considers other spheres influences on living beings, while geodiversity can be fully described through the assessment of all other spheres, mainly focused on the lithosphere. Therefore, geodiversity can be presented in a similar way to biodiversity for some specific elements of abiotic nature such as mineral composition or the inventory of some specific formations in a region, this being most appropriate for archaeological, anthropological, and paleontological elements. However, geological structures should not be counted as such, rather they are assessed as representations of the foundational basement of the environment.

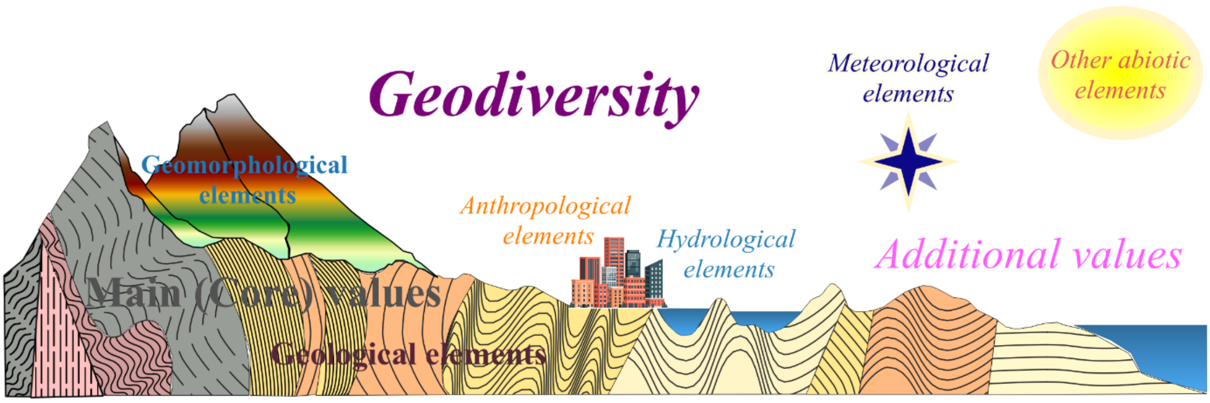

Figure 7.1.(1): Main and Additional elements of geodiversity. Main elements: geological and geomorphological (Ferrer-Valero, 2018, Zakharovskyi and Németh, 2022a, Zakharovskyi and Németh, 2021b). Additional elements: hydrological (Zakharovskyi and Nemeth, 2023, Silva et al., 2013, Manosso and de Nóbrega, 2016), anthropological, meteorological, and others (Pereira et al., 2013b, Pereira et al., 2013a).

7.1.2 Qualitative-quantitative assessment of Geodiversity for geosite recognition and its role in description of geodiversity

In this section I discuss the third principle aim of the research, development of a new assessment of geodiversity for the Coromandel Peninsula (Chapter 1.3 (Aim 3)). This comprises the practical aspect of the complete research for this PhD and consists of six main objectives and four additional. The first two objectives can be integrated into the development of the QQG assessment and its evaluation system, based on a literature review on geodiversity and its associated elements. In presenting the results of the review, all elements have been divided into two categories: main and additional (Figure 7.1.(1)). The categories subsequently form the foundation for development of our qualitative-quantitative methodology for geodiversity assessment (QQG) (Chapters 4-6). Even though geological and geomorphological elements are main elements of geodiversity, their parameters for estimation can differ due to variations in accessibility of data for these main elements. Then, we turn our focus towards parameters, which can be applicable to the whole of the Earth and expressed through comparable ranking systems. For this methodology we utilized the research results of Blatt and Johns (1975) "*Proportions of exposed igneous, metamorphic, and sedimentary rocks*" describing rareness of rock types found at Earth's surface (Blatt and Jones, 1975). In their research, the proportion of different rock types have been analysed from 3,000 points of data, extracted from geological maps ranging from the most predominant scale1:5,000,000 to the most accurate 1:300,000, and avoiding all water bodies. The authors scrutinised North America at a range of scales for comparison of results, demonstrating there were no systematic or significant differences. For calculations to define values, they utilized sedimentary, metamorphic, igneous, and plutonic rocks from four eras' (Cenozoic, Mesozoic, Palaeozoic, Precambrian). Their results confirmed 66 % of Earth's surface is covered with sedimentary rocks, 17 % with metamorphic, 9 % intrusive, and 8 % extrusive volcanics, all with 95 % confidence (specifically for sediments) (Blatt and Jones, 1975).

These results then became the main parameters for the evaluation system of geological elements for QQG assessment. However, applying only the parameters of rock types and age rareness does not provide a full description of geological elements. It misses the range of unique features and processes, which shaped the surface specific to a defined area under investigation. Sedimentary rocks, which are the most abundant rock type on the surface of the globe naturally have low values for rock rareness, but locally they also contain a range of hidden scientific data on geological evolution and climate history (Boggs, 2009). It is possible to calculate rock abundance with more accurate typology and age ranking, specifically tailored for the assessed region, however the assessment cannot then be described as globally comparable (Chapter 5.1, 5.2, and 5.4). For the geomorphological element, slope angle values from 0 to 90 degrees are utilized as these are also globally applicable. Slope angle does not necessarily describe the form of the surface, but it can highlight areas with possible morphological uniqueness. It can be legitimised by considering “the angle of repose”, which accepts that piles of loose material will form slope angles less than 45 degrees (for most type of material) (Al-Hashemi and Al-Amoudi, 2018). In contrast, locations with angles higher than 45 degrees are likely formations of hard rock or cemented material, which can be defined as an outcrop. However, in some cases rocky formations may be concealed by vegetation or artificial constructions. Because geological and geomorphological elements utilized for QQG assessment do not result in detailed high-resolution information about geodiversity of the study area, the locations recognized as potential areas of high geodiversity should be further assessed through direct field observations and literature reviews to legitimately define them as geosites. Therefore, rock rareness and slope angle became core parameters for geodiversity assessment specifically in a global ranking system. Even though they are not fully describing geodiversity, they can be used for comparison with other areas throughout the Earth and can be utilised for recognition of areas with potentially high geoheritage values and significant geosites.

The presented methodology is focused on the scientific aspects of geodiversity. Therefore, at the current stage of development for the model it is targeted for the scientific audience for further testing. However, other parameters can be included to shape outputs that include other aspects of geodiversity. For example, inclusion of anthropological parameters will rearrange the focus of the model toward cultural, geographical and historical aspects. These parameters also require more attention on issues such as security, facility, logistics, education, environmental protection and will be focussed more on touristic and conservational aspects of geodiversity, which have not been considered in this research. A real benefit of QQG modelling is the evaluation system itself which is focused on objective parameters to determine rankings rather than overly relying on subjective parameters.

The next three objectives on development of geodiversity assessment of the Coromandel Peninsula, focused on testing of the QQG methodology on different territories, to recognize the main drawbacks and direction for its improvements (Chapter 1.3 (Aim 3)). This paragraph is focused specifically on the drawbacks and developments, which have been made during the research. The main idea behind this evaluation of geological and geomorphological elements is recognition of potential geosites, utilizing low amounts of data then analysed through the qualitative-quantitative methodology for geodiversity (QQG) assessment. Open access QGIS software was the main tool for all calculations because of its user-friendly interface, well documented theoretical underpinnings, and a global developer and user group associated with it. However, all calculations are standard and can be readily assessed with other GIS software. Additionally, the model requires a standard geological map and a common SRTM model for general assessment. The development of QQG methodology was described in detail in Chapter 5. The QQG methodology is not a description of geodiversity, rather a tool for defining “hotspots” of potentially significant geosites and high geoheritage values to minimize the search area requiring further expensive and time-consuming investigation. Therefore, the results of the assessment are presented as potential geosites ranked according to the global system, which should then be subject to field observations and literature reviews to justify the significance of the recognized locations. These locations could be described as “geodiversity hotspots” in the same way some regions of the world are recognized as “biodiversity hotspots”

(Reid, 1998, Norman, 2003, Mirski et al., 2024). A shortcoming in this methodology is some potential geosites may be missed due to low accuracy of SRTM models and inaccurate or dated information presented in geological maps. For example, geomorphological features with boundaries less than 30 meters, which is smaller than one pixel of the SRTM model, may be omitted in the results of the assessment. Moreover, some locations may be rejected after the process of justification due to inaccessibility or limited educational or touristic significance. For example, in the northern region of the Coromandel Peninsula, the QQG methodology recognized 6 protentional geosites in the region of Port Jackson, however five of them were rejected, due to their distance and poor accessibility from general tourist routes while their geological information is identical to the one geosite that has been justified (Section 6.1.5.1 Geosites of Port Jackson).

Despite the above issues, the methodology itself is presented as an open system, able to be refined by addition of better-quality data and/or additional elements (hydrology, anthropology, archaeology, palaeontology, etc.) further refining the assessment for application to the studied region at a localised scale (local values) (Figure 7.1.(2)). The local values are best assessed as an additional layer to the main elements, to preserve the utility of the framework for comparative assessments utilizing the same ranking system throughout the globe. Moreover, additional data may highlight the significance of some areas at a local scale and in some cases carry a greater weight than global value, for example cultural elements observed in an area with an otherwise low geological and geomorphological values. However, the QQG methodology can became a useful tool for description of geodiversity, after refinement with more accurate data, and inclusion of most abiotic elements therefore providing a full and holistic model of geodiversity. In conclusion, research and development of this geodiversity assessment led to further refinement of the QQG methodology for recognition of high value areas at a broad global scale, with further refinement providing more detail and a more useful model at a local scale. In short, the result is a more accurate description of the study area, including areas of high geodiversity values and potential geosites. At the current state of development, the QQG methodology can be implemented with a minimal amount of data, which can usually be readily extracted from the standard geological map showing rock types and their age.

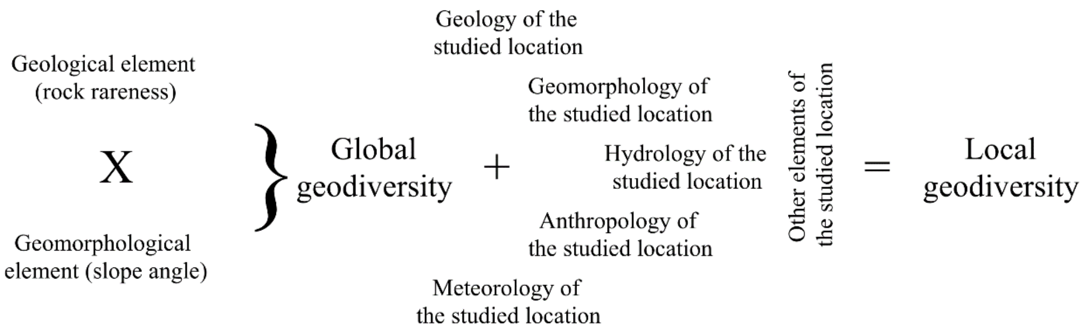

Figure 7.1.(2): Scheme of qualitative-quantitative assessment of geodiversity. Global geodiversity consists of geological and geomorphological elements (for QQG assessments these are rock rareness and slope angle respectively). Local geodiversity can be expressed through more detailed description of the studied region on subjects like geology, geomorphology, hydrology, anthropology, meteorology, and other elements of abiotic nature.

7.1.3 Assessment of the Coromandel Peninsula and other locations utilizing QQG assessment – results

The primary aim of this thesis is to document development of a new methodology for geodiversity assessment and use the results to create a geodiversity model for the whole Coromandel Peninsula. This has been described in detail in the research paper "*Geomorphological Model Comparison for Geosites, Utilizing Qualitative–Quantitative Assessment of Geodiversity, Coromandel Peninsula, New Zealand*" (Chapter 5.3). Moreover, this research underlies the last objective for the third aim in development of the QQG assessment (Chapter 1.3 (Aim 3)). It presents the global values for the territory of the Coromandel Peninsula with different geomorphological parameters (Figure 7.1.(3)) (Zakharovskyi and Németh, 2022a). Results demonstrate that the central region, the east coast, and the northern part of the Coromandel Peninsula contain regions with high and the highest geodiversity values at the comparative global scale. These results show the necessity for further ground observations to highlight and describe the geodiversity of the peninsula. This research fulfils the second additional objective for the development of the QQG assessment as documented in Chapter 1.3 (Aim 3). There, the hydrological element was represented by the Strahler Order model, which refined results for the areas with low global values like those observed in the south-west part of the Coromandel Peninsula (Figure 7.1.(3)). Furthermore, the model can be improved by including a geological layer for the peninsula, highlighting volcanological heritage as based on ideas investigated in research applied to the western islands of Samoa (Zakharovskyi and Németh, 2021a, Zakharovskyi and Németh, 2022b) (Chapter 5.1 and 5.2) and Tuhua/Mayor Island (Zakharovskyi et al., 2023) (Chapter 5.4).

An issue encountered during creation of a geodiversity model for the whole of the Coromandel Peninsula is insufficient and/or heterogenous data subjects such as archaeology, hydrology, climate, and anthropology, when the region as a whole is considered. Here we briefly discuss results stemming from completion of the second aim of the research its objectives, on describing the current scientific knowledge about the Coromandel Peninsula as a whole (Chapter 1.3 (Aim 2)). A systematic literature review as documented in Chapter 3 demonstrates that most published (and unpublished) research applied to the Coromandel Peninsula concentrates on highly localized locations and associated features such as hot springs and/or gold and silver epithermal deposits (Zakharovskyi and Németh, 2021c) (Chapter 3). This is due to a well-documented historic mining industry, and a high level of applied scientific research. In the present-day the area is well-recognized for conservation initiatives and biodiversity management applied to local indigenous flora and fauna. Therefore, the main strategy to improve awareness of geodiversity on the peninsula is to collect and record general information about the geological, geomorphological, hydrological, and climactic state of the region, and then overlay anthropological and archaeological data. In combination this information will shape a more holistic description of its geodiversity. Despite the shortcomings described, we were able to apply the QQG methodology to assess the whole of the Coromandel Peninsula, thereby defining geologically important locations from a global perspective and supported by literature reviews and direct field observations, which could form the basis of further research. This step will result in an inventory of the primary first locations for geotourism and geoeducation with particular focus on geodiversity.

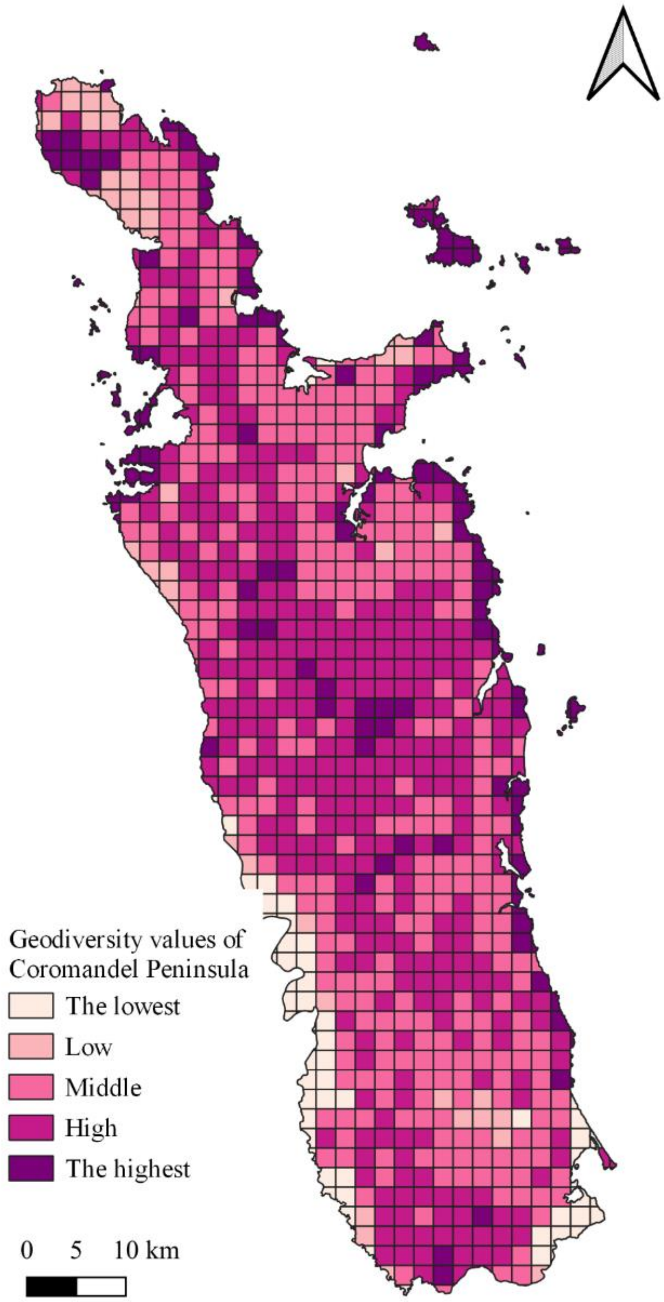

Figure 7.1.(3): Model of global geodiversity values of the Coromandel Peninsula based on qualitative-quantitative assessment for geosite recognition (Zakharovskyi and Németh, 2022a).

7.1.4 Future development of QQG. What steps in QQG development have not been reached, and why?

During the development of the QQG methodology, some elements of geodiversity have not been included into the assessment, but they were mentioned in our first article exploring the conceptual philosophy behind the term geodiversity (Zakharovskyi et al., 2022), and as documented in Chapter 2 of this thesis. A five-point evaluation system was developed for different elements of geodiversity: geology, geomorphology, caves, hydrology, weathering, and volcanic facies. However, most of them have not been used or examined as our principal strategy was to develop the geological and geomorphological elements to an appropriate level for the QQG methodology. At the current stage of research documented here, the main elements have been described, defined, and applied to territories with different geological and geomorphological compositions for comparative case-studies. Subsequent improvements of the QQG assessment will add other elements of geodiversity, including hydrological, anthropological, archaeological, and meteorological, to create a full description and detailed model of geodiversity. Furthermore, geological, and geomorphological elements may also be improved with more detailed and specific information including volcanic heritage, sedimentology, glaciology, and other factors reflecting the local geodiversity (Chapter 5.1 and 5.4).

The pedological (soils) element can be considered unique as it creates a bridge between biodiversity and geodiversity while being of both fields at the same time. Soils can act as the interface between the biotic (biodiverse) and abiotic (geodiverse) environments acting as a "glue" for their connection and shaping the overarching description of environmental diversity recognized by the term "omnidiversity" (Crisp et al., 2022). Additionally, the QQG methodology can be developed into a plugin for GIS software and used as a tool for geosite recognition or geodiversity description shaped by a high amount of included data. Therefore, we acknowledge great potential for further refinements and improvements to the methodology itself, building on the initial and proven framework presented in this thesis.

During this research, three additional objectives from the first and third aims (Chapter 1.3 (Aim 1 and 3)) have not been fulfilled due to the time and resources required, and divergence from the main goal of the thesis. However, they are presented here to highlight potentially valuable areas of further research and development.

The first objective was comparison of the Coromandel Peninsula with the Carpathian Mountains in Eastern Europe, based on their similar geological history (Chapter 1.3 (Aim 3)). The geological composition of the Carpathian Mountains is greywacke basement with Miocene-Pliocene subduction-related bimodal volcanism (andesite to dacite/rhyolite) and flysch successions (Rădulescu and Săndulescu, 1973, Fielitz and Seghedi, 2005, Melinte-Dobrinescu et al., 2017b, Melinte-Dobrinescu et al., 2017a). These lithologies are similar to the Jurassic greywacke basement with Miocene-Pleistocene land-based volcanic activity of andesitic-dacitic (Coromandel Group) and rhyolitic-ignimbrite (Whitianga Group) types in the Coromandel Peninsula (Hayward, 2017, Briggs and Fulton, 1990, Adams et al., 1994, Malengreau et al., 2000, Nicholson et al., 2004, Smith et al., 2006, Booden et al., 2012, Homer and Moore, 1992). However, there are also significant differences between the two regions. The Carpathian Mountains are a cold predominantly alpine climate while the Coromandel Peninsula is relatively temperate; alpine morphology and associated process are predominant in the Carpathian Mountains, and the area of study is much larger (1700 km long compared to 85 km of the Coromandel Peninsula). Furthermore, the Carpathian Mountains contain 10 national parks (four of them recognized by UNESCO) located in Slovakia and six (two of them recognized by UNESCO) more in Poland (Oszlányi et al., 2004). Therefore, further comparative research could bring benefits for development of geoconservation, geotourism, geoeducation programs for the Coromandel Peninsula, which is currently recognized as a valuable bioconservation asset in New Zealand. This direction of research remains to be followed, due to the commitment and resources that would be required, and currently poor access to geological data of this region.

A further missed objective is clearly defining the correlation between geodiversity and biodiversity (Chapter 1.3 (Aim 1)) and establishing the nature of dynamic relationships between the two fields. This could be aligned with study of the influence of flora on the recognition of geosites utilizing satellite images to avoid vegetated locations during the QQG assessment. This correlation has been discussed in the scientific community (Gordon et al., 2021, Crofts, 2018), however geodiversity is still considered as the supportive agent for biodiversity. Moreover, soils must be better understood as the dynamic interface between both types of diversities (Thwaites, 2000, Ibanez and Brevik, 2019, Ibáñez and Brevik, 2022, Ibáñez and Brevik, 2023). We assume that geodiversity must be considered as holding a higher position than biodiversity as it is geodiversity that shapes the range of parameters which dictate rules for living organisms and ecosystems in the environment. We suggest that higher geodiversity may correlate to lower biodiversity and vice-versa, as cliff sides and high mountains may often display sparse vegetation cover, however this is not always the case as deserts have low geo- and biodiversity at the same time. Furthermore, as documented in chapters 1 and 2 of this thesis, terminology and types of assessment remain areas for further research to further clarify definitions and descriptions and testing and comparison of methodologies.

The last missed objective is a detailed and systematic comparison of QQG with a strictly quantitative assessment of geodiversity (Chapter 1.3 (Aim 3)). The quantitative assessment method is more common in the scientific community as it is believed to avoid subjectivity and bias, through the direct counting and inventory of geodiversity elements presented in the region (Pellitero et al., 2011, Serrano and Ruiz-Flaño, 2007, da Silva et al., 2019a, da Silva et al., 2019b, Micić Ponjiger et al., 2021). However, quantitative type of assessment does not result in any meaning behind the number, as the results must be further interpreted for establishment of values for geotourism, geoeducation, and geoconservation (Burnelli et al., 2023). Applying a quantitative approach to the Coromandel Peninsula model could be useful, however there is not enough accessible data for the abiotic elements to usefully include them into a quantitative assessment. Moreover, the same data must be included into the QQG methodology as the framework is further refined and developed. However, this objective could be fulfilled in other regions, where a quantitative assessment has been already done. However, that would not align with the main aim of this thesis, which is based strictly on the territory of the Coromandel Peninsula.

Although each of these objectives are important for the exploration of geodiversity and the QQG methodology, they require deeper investigation and access to detailed databases. Additionally, they have not been included as they do not support the main goal of this thesis. In conclusion, the QQG methodology has been well established at a foundational level, however from here several directions of further research, testing, and application could be used to further refine and improve the methodology. This type of geodiversity assessment is a useful tool for geosite recognition, especially for areas where there are only coarse or unreliable data-sets available. Furthermore, the QQG methodology is practically established and remains flexible for the inclusion of additional data and refinement of global values with new evaluation systems and additional detailed information at a local scale.

7.2 Conclusions

Geodiversity is a term representing and describing the abiotic nature of the environment, which contains a range of different elements. The philosophical and conceptual framework of the term is shaped by division of the abiotic environment into main and additional values. Main values describe the Earth's surface using geological and geomorphological elements, which are the most stable and fundamental parameters. Meanwhile, all other elements including hydrology, climate, archaeology, tectonics, anthropology, and pedology, are defined as additional values of geodiversity as they mostly represent processes, which influence and act on the global parameters: geology and geomorphology.

"*Geodiversity estimation of the Coromandel Peninsula through a digital model analysis*" documented development of a new qualitative-quantitative type of assessment of geodiversity, which has been demonstrated as a useful tool for recognition of geosites. This methodology is particularly useful through any region of the Earth's surface. It utilizes rock rareness and slope angle as proxies for geological and geomorphological elements, thereby defining values for geodiversity at a global scale. Meanwhile, all other parameters describe and define the local geodiversity, emphasising regional uniqueness, which cannot be directly compared with areas not included into the assessment. QQG assessment is a tool created to recognize areas of high geoheritage value and associated geosites ("geodiversity hotspots"), especially in cases where minimal data is available.

The assessment of the Coromandel Peninsula defines several areas showing high values for geodiversity from a global perspective. However, local description and inventory of geosites and demonstration of local values requires further resources and time to apply this level of assessment to the whole of the Coromandel Peninsula. Resulting from the research project as documented in this thesis, the northern region of the Peninsula has been assessed with the QQG assessment and well supported by literature reviews and direct field observations. The results can be utilized for further establishment of geoeducational, and geotouristic locations. The same level of description could be applied to the whole of the Coromandel Peninsula, but this will require investment of more time and resources, due to the large area in question and a high number of potential geosites in the region.

The development of the QQG assessment has reached a fundamental theoretical and practical stage. However, it cannot be considered complete as many other elements of geodiversity remain to be included in assessments, or subject to further examination due to the sporadic and coarse nature of available datasets including hydrology, meteorology, anthropology, soils, and others. Further development of the methodology should concentrate on inclusion of other elements into the assessment. Additionally, other projects may be undertaken to refine and improve the methodology. Firstly, comparison of results for the Coromandel Peninsula and other similar locations must be considered; comparative studies should be undertaken between the QQG assessment with other methodologies for geodiversity and geosite recognition; and finally, relationships between biodiversity and geodiversity need to be better understood. Therefore, the QQG methodology shows some areas for improvement, while geodiversity as a whole would benefit from research at a deeper level, considering both theory and practice.

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APPENDIX A - Field trips' diary and the Coromandel Peninsula sketch

1. The first trip to the Coromandel Peninsula

The description of the trip is presented here. The first part will be the copy of information from the travel diary.

We visited 32 places in 7 days.

Day 1

1) Karangahake - Dangerous Road! A 50 km restriction for this place should be provided. Even in pandemic time it is a popular place. *Rhyolitic solidified, ignimbrite impregnated with silicon quartz, mercury.*

2) Komata Reefs - 37 21 14 South 175 44 20.4 East 164m. E1842600 N5862345 167m. *Dacite brassica CaCO3 calcite carbonate, andesite.*

3) Debris Avalanche - 37 20 47.7 South 175 42 15.2 65m.

4) Nevelshvilie from the North-West side - 37 11 17.6 South 175 39 32.8 East 294m. *Opal, ignimbrite and andesite. Volcanic conduit*.

5) Kirita Hill outcrop on the road - *Argelitic grain*. 36 52 33.7 South 175 26 13.0 East 170m. *Lahar* by the road.

6) *-//- - Pumices pyroclastic flow (lahar deposits)*, 36 52 16.2 South 175 26 17.2 East.

Day 2

7) Sugar loaf - E 1816225 N 5961162 11m, *lava flows, erosional surfaces, temperature pyroclastic, brassica.*

Day 3

8) Kennedy bay road - 36 43 44.8 South 175 30 59.4 284m. *Intermediate volcanic rock between dacite and andesite alteration green cold (probably lava flow).*

9) Stone bay - 36 30 41.6 South 175 25 18.5 East 18m. *Mineralised mudstone (silicified). Faulting and volcanic activity made mobilization. Pyrite and quartz. One of Greywacke was close to sugarloaf.* Ideal location for tourist perspective. Explore more in future.

10) On the village road - 36 31 23.7 South 175 29 34.9 East. *Basaltic andesite (a lot of yellow boulders nearby stream).*

11) Slightly far - 36 31 22.9 South 175 29 43.7 East 42 m. -//- + *"andesite"?.*

12) Write the name - 36 38 42.6 South 175 34 15.7 East 12m. *Dark color andesitic flow body. All shore angular brassica tabular coherent andesitic not highly altered (fresh).* Accessible for tourists (one of the oldest) + data will be added. Can be seen Mercury Islands, Ottama beach, Koatonu, Black Jack. + good geoeducational location.

13) Kennedy Bay - 36 41 12.2 South 175 33 33.5 6m. *Coherent lava, brassica moderately vesicular andesite.*

14) Coromandel wharf - *altered intermediate rock.* New outcrops the sequence *alteration (arsenic sulfide, leaching of acid environment spongy surface. (ore formation).*

Day 4

15) 309 road (river) - 36 51 18.9 South 175 37 22.3 East 29m. *Andesite and Quartz (agate ? limonite ? citrine ?)* part of the river.

16) New road cut small stratigraphic - 36 52 28.2 South 175 38 07.0 87 m. *Weathering of andesite rock covered by soil horizons.* Within its quaternary mass movement *Argenite (ignimbrite) facialized leaves. Explosive eruption of pumice ignimbrite mix with nubble of andesitic roots.*

17) Hot water beach - *Andesite on the right and ignimbrite on the left side. Oceanic weathering (can be seen Quartz, Jasper?, inclination in the matrix of ignimbrite.*

18) The place between two Pa (cliffs) - 36 50 28.2 South 175 49 05.6 East 50m. From the one Pa is a good visibility on the different islands as well as Black Jack rocks. *Altered rhyolite, biotite (small crystals).*

19) -//- on the shore

20) Ferry to Whitianga - 36 49 54.0 South 175 42 42.2 East 18m. *Ignimbrite on the left is Pa with stares made by Māori. One the right side the same rock with good weathering like caves. Pumpkin ignimbrite.*

Day 5

21) Black Jack road high point to Opito bay - 36 42 38.9 South 175 46 47.9 East 121m. *Andesitic lava flow (weathered) Plagioclase, amphibolite turned into clay (quartz absent). (Altered).*

22) Opito bay - 36 41 56.9 South 175 47 28.5 East 18m. *Andesite weathered by oceanic activities and climate. Plate joints + small peninsula low tide access. Mafic rock wide biodiversity.*

23) Shore - 36 43 05.2 South 175 49 04.7 East 4m. *Strange weathering Dome kind of structure. No horizontal pattern Basaltic - Andesite?*

24) Outcrop on the Beach - 36 43 19 South 175 48 40 13m. *Columnar joined Basalt (Mercury ?).*

25) Black Jack road - 36 42 43.8 South 175 44 20.2 East 137m. *Silicified mineralization of (Graywacke Sand - cloud stone). Epithermal mineralization (flux mineralized by water). Flint stone Quartz and others.*

26) Waiau Falls - 36 49 55.8 South 175 32 49.0 East 119m. *Andesite.*

Day 6

27) New Chum Beach - 36 42 02.2 South 175 36 44.4 East 13m. *Basalt? Jointing probably filing dish lava remnant likely sporadic large distantly distributed.*

28) The same -//- - 36 42 02.0 South 175 36 33.0 East 1m. *Andesite brassica (volcanic) pyroclastic floor.*

29) -//- - 36 41 31.6 South 175 36 22.1 East 3m. *Andesitic lava flow (basaltic). Brassiation is different then previous Some jointing.*

30) Whangapoua beach - 36 42 58 South 175 37 42.8 6m. *Andesite lava -//- more weathered, probably is there alteration processes more brachared (unknown kind?).*

Day 7

31) Tairua - 36 59 58.5 South 175 51 40.7 32m. *Rhyolite* on the road.

32) Quarry (old) - 37 15 35.7 South 175 50 09.2 East 41m. *Andesite jointing columnar. Columns are horizontal (like something coming from below).* Accessibility is a very poor track from the road Parakiwai.

The Second trip to the Coromandel Peninsula.

We visited 13 places and made a more accurate observation of Fletcher Bay with a drone.

Day 1

33) Cathedral Cove. *Ignimbrite homogeneous (from Whitiana Caldera). Lava dome (Rhyolite).*

Day 4

34) The end of Mill creek road - 36 55 06.3 South 175 37 05.7 East 126m. *Altered andesite.*

35) Stream crossing the road - 36 54 56.6 South 175 37 24.9 East 106m. *Basaltic-Andesite*.

36) Next road stream - 36 54 37.2 South 175 37 30.4 69m. *Basaltic-Andesite.*

37) The same place. *Amphibole andesite (part of lava dome).*

38) Te Karo Bay. *Lava dome complex. Altered andesite, quartz multiple dikes.*

39) Tairua Beach. *Rhyolite flow banded**.***

Day 5

40) Broken hills. *Rhyolite (alteration). River (amethyst, jasper).*

41) Pauanui. *Rhyolite (jointed weathered?)*

Day 6

42) Whangamata bay. *Ignimbrite, base breccia. Volcanic lithics.*

43) Right side of Whiritoa beach. *Highly altered and weathered ignimbrite (blowhole).*

44) Waihi beach on the left side. *Andesite? Small grains.*

45) Waihi beach on the right side. *Rhyolite weathered (oceanic and biologic).*

The Third trip to the Coromandel Peninsula.

We visited 12 places.

Day 1

46) Papakura bay. Rhyolite caves. Dome.

47) Tairua on the other side. The same as the previously weathered Rhyolite dome.

48) Hahei beach is on the other side. Rhyolite.

49) Cooks beach. Ignimbrite pumice and rhyolite pieces.

50) North Whitianga. Mercury Basalt (basaltic andesite) brachia lava flow.

Day 2

51) Kuaotunu beach. Quarry point Greywacke.

52) Rings beach and Matarangi. Andesite honeycombs.

53) Opoutere beach. Lava flow andesite.

Day 3

54) Onemana. Rhyolite, dacite (ignimbrite?) Left side alteration processes, Opal quarzitic, spherulite. Right side lava flow, archeological site, opal.

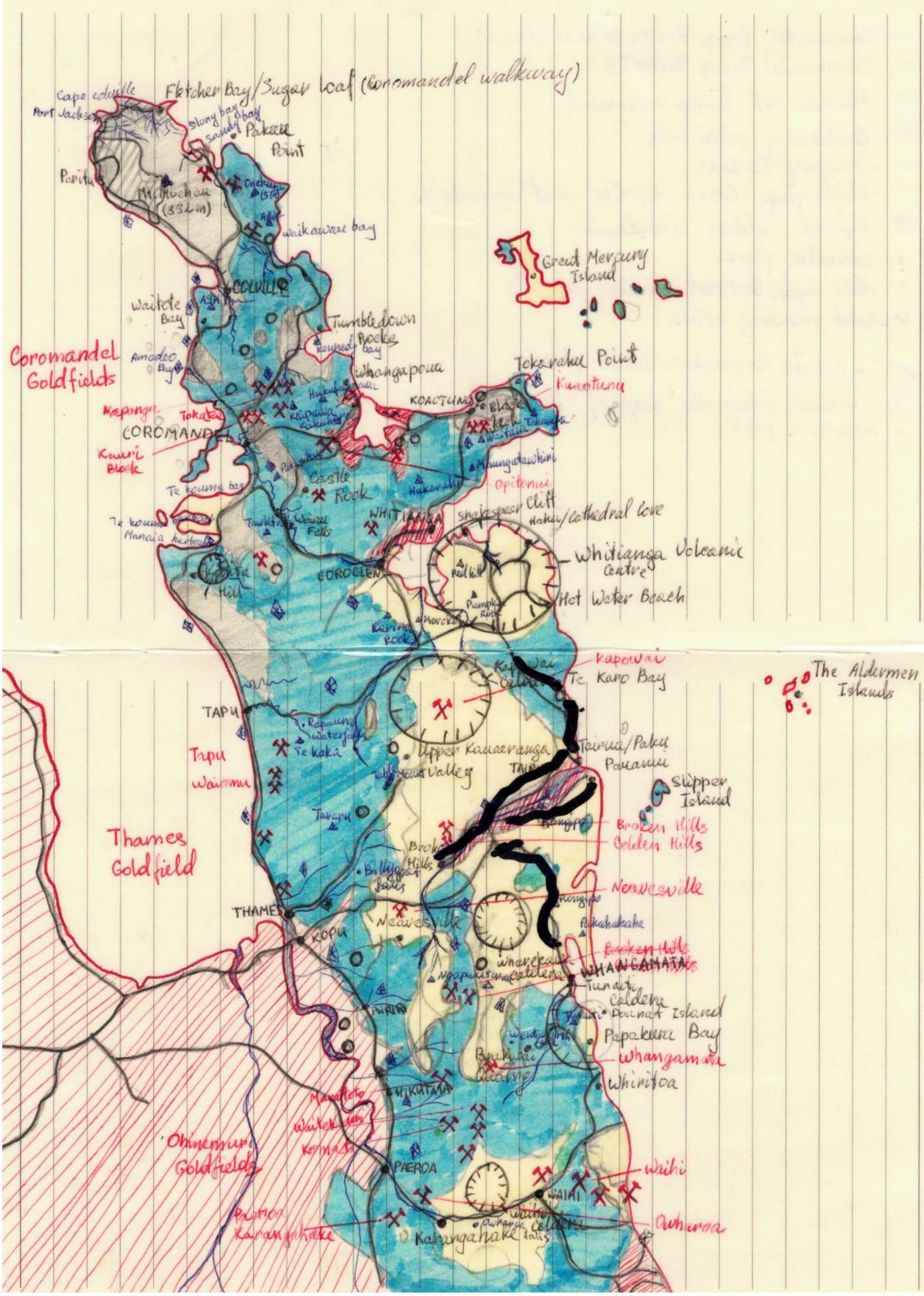
55) North Onemana small aggressive beach. Rhyolite, quartzite everywhere, cave.

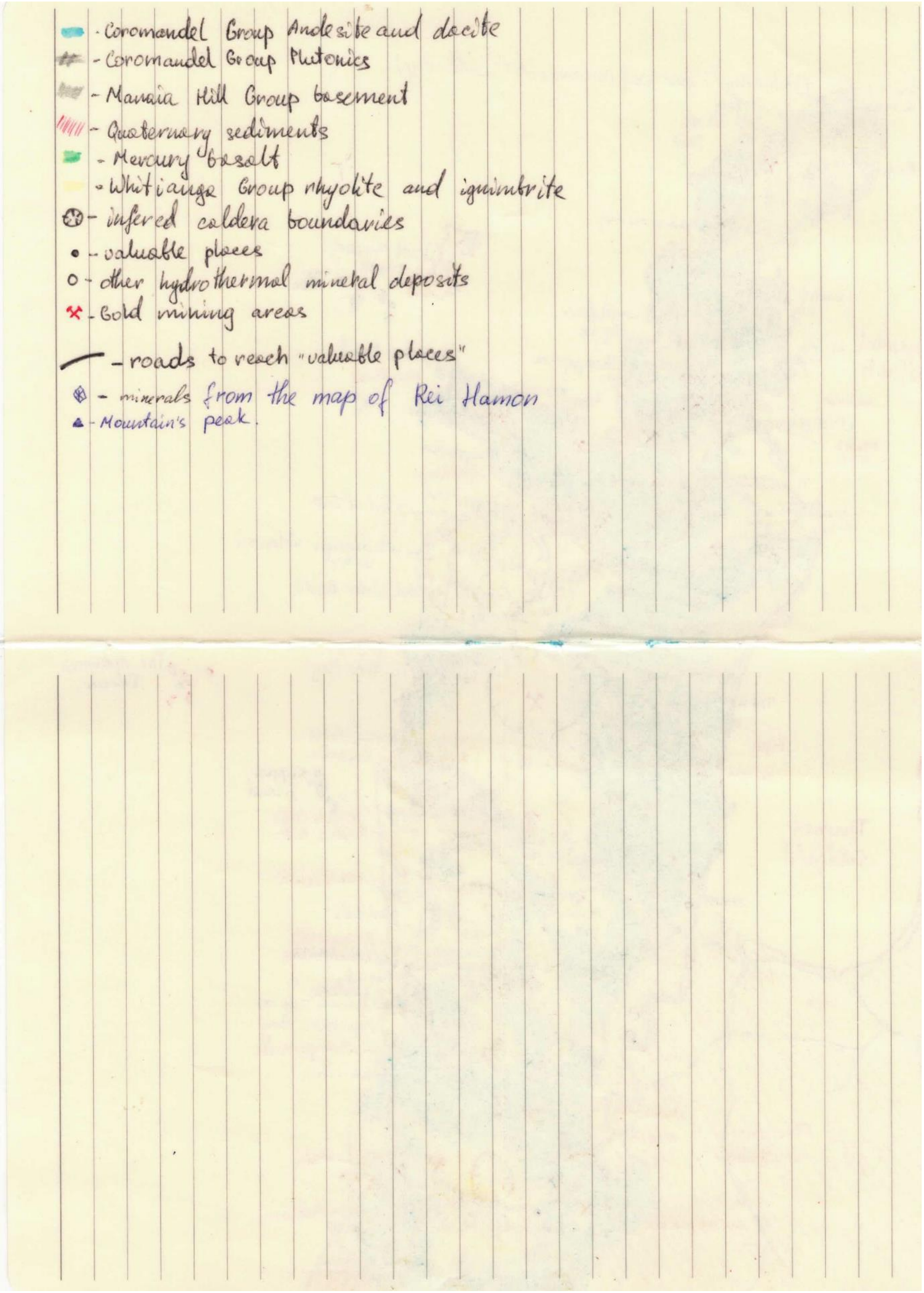
56) South Onemana. Rhyolite, like 54.

Day 4

57) Valley. Andesite streams.

2. The Coromandel Peninsula sketch




- Coromandel Group Andesite and dacite
- Coromandel Group Plutonics
- Manaia Hill Group basement
- Quaternary sediments
- Mercury basalt
- Whitianga Group rhyolite and ignimbrite
- infered caldera boundaries
- valuable places
- other hydrothermal mineral deposits
- Gold mining areas
- roads to reach "valuable places"
- minerals from the map of Rei Hamon
- Mountain's peak

APPENDIX B - Unpublished literature about the Coromandel Peninsula on geological subjects

Author	Title	Publisher	Year
Fraser C.	The geology of the Thames subdivision, Hauraki, Auckland.	NZ Geological Survey	1910
Bell J.M. & Fraser C.	The geology of the Waihi-Tairua subdivision, Hauraki division.	NZ Geological Survey	1912
Grange L. 1. & Kear D.	N30 Great Barrier Island	NZ Geological Survey	1956
Skerman T. M.	Seasonal variations in sea-water surface temperatures within New Zealand harbours	New Zealand Journal of Geology and Geophysics	1958
Kear D., Schofield J. C.	Te Kuiti group	New Zealand Journal of Geology and Geophysics	1959
Kear D.	Geology of the Kamo Mine area	New Zealand Journal of Geology and Geophysics	1959
Kear D.	Stratigraphy of New Zealand's Cenozoic volcanism north-west of the Volcanic Belt	New Zealand Journal of Geology and Geophysics	1959
Kingma J. T.	The tectonic history of New Zealand	New Zealand Journal of Geology and Geophysics	1959
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Barretto J., Tontini F. C., Davy B., Edbrooke S. W., Stagpoole V.	Inversion of magnetic and gravity data reveals subsurface igneous bodies in Northland, New Zealand	New Zealand Journal of Geology and Geophysics	2016
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Adams C. J., Campbell H. J., Jongens R.	Triassic age for a conglomerate clast in the Waipapa Terrane, North Island, New Zealand	New Zealand Journal of Geology and Geophysics	2017
Adams C. J., Mortimer N.	An Early Miocene granite clast in a tuffisite dike at Miners Head, Great Barrier Island	New Zealand Journal of Geology and Geophysics	2017
Robinson J. H.	Early Miocene brachiopods of the Waitemata and Waitakere groups, Auckland and Northland, New Zealand	New Zealand Journal of Geology and Geophysics	2017
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Barker R. G., Brathwaite R. L., Christie A. B., Simpson M. P.	Exploration for epithermal Au-Ag deposits in New Zealand: history and strategy	New Zealand Journal of Geology and Geophysics	2019
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Christie A. B.	Preface to the special issue - Exploration models for New Zealand's hard rock gold deposits	New Zealand Journal of Geology and Geophysics	2019
Barker S. L. L., Moon V. G., Pittari A., Prentice M. L.	Volcanogenic processes and petrogenesis of the early Pleistocene andesitic-dacitic Maungatautari composite cone, Central Waikato, New Zealand	New Zealand Journal of Geology and Geophysics	2020
Barrier A., Beggs M., Bischoff A., Cole J., Nicol A., Sahoo T.	Volcanoes buried in Te Riu-a-Māui /Zealandia sedimentary basins	New Zealand Journal of Geology and Geophysics	2020
Cooper A. F., Ireland T. R., Norman M. D., Reay A.	Cretaceous molybdenite in metasomatic epidosite associated with the Pounamu ophiolite, New Zealand	New Zealand Journal of Geology and Geophysics	2020
Christenson B. W., Cole R. P., Conway C. E., Cronin S. J., Gamble J. A., Hurst T., Kennedy B. M., Leonard G. S., Miller C. A., Procter J. N., Pure L. R., Townsend D. B., White J. D. L., Wilson C. J. N.	Ruapehu and Tongariro stratovolcanoes: a review of current understanding	New Zealand Journal of Geology and Geophysics	2021
Cronin S. J., Smith I. E. M.	Geochemical patterns of late Cenozoic intraplate basaltic volcanism in northern New Zealand and their relationship to the behaviour of the mantle	New Zealand Journal of Geology and Geophysics	2021
Hopkins J. L., Horrocks J. L., Lowe D. J.	Tephrochronology in Aotearoa New Zealand	New Zealand Journal of Geology and Geophysics	2021
Clark K., Morgenstern R.	The paleotsunami record of the Auckland region and implications for understanding tsunami hazards	New Zealand Journal of Geology and Geophysics	2022
Lawless A. S., Nelson C. S., Nodder S. D., Zwingmann H.	Latest Miocene (Kapitean/Messinian) glauconite and the central Chatham Rise greensand: an enigmatic, highly condensed, relict/palimpsest deposit on the modern seafloor	New Zealand Journal of Geology and Geophysics	2022
Barr A., Carden Y., Glassey P., Seward A., Wells C.	Decarbonising primary industries with geothermal heat - a pathway to greater direct use	New Zealand Journal of Geology and Geophysics	2024

Beu A. G., Blom W., Collins N., Hayward B. W., Stolberger T. F.	A diverse Late Pliocene fossil fauna and its paleoenvironment at Māngere, Auckland, New Zealand	New Zealand Journal of Geology and Geophysics	2024
Schofield J.C.	Geological map of sheet N57, Te Aroha.	Institute of Geological & Nuclear Sciences	undated

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Zakharovskyi, V., Nemeth, K., Gravis, I. and Twemlow, C., 2022. Geoheritage and geodiversity assessment framework for practical application to geoconservation of the Coromandel Peninsula, New Zealand. Geoconservation Research, 5(1), pp.59-88.

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K. Nemeth: validation; resources; data curation; writing—review and editing; supervision; project administration; funding acquisition.
I. Gravis: writing—review and editing; resources. C. Twemlow: writing—review and editing; resources.

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      Zakharovskyi, V. and Németh, K., 2021. Systematic Literature Review of the Natural Environment of the Coromandel Peninsula, New Zealand, from a Conservation Perspective. Conservation, 1(4), pp.270-284.

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Zakharovskyi, V. and Németh, K., 2021. Qualitative-quantitative assessment of geodiversity of Western Samoa (SW Pacific) to identify places of interest for further geoconservation, geoeducation, and geotourism development. Geographies, 1(3), pp.362-380.

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