Watershed Characterization Approach to Redefine Bioregions: A Case Study at Moro and Iagifu Bioregions in Southern Highlands Province, Papua New Guinea

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Abstract: A watershed is the natural laboratory of water, soil, flora, and fauna. It is the land area where all precipitation drains to a lake, sea, or river through a common outlet. Demarcation of the watershed is generally performed using the Digital Elevation Model through topographic analysis. However, this method doesn't consider environmental processes and ecological relationships. This study employed the watershed characterization technique to define ecoregions and subsequently merge them to delineate a bioregion, utilizing geographical information science and systems (GIS) and remote sensing. It incorporated empirical and statistical data from six significant environmental variables: physio-geography, soil, climate, natural communities (focusing on flora), ecological processes, and hydrology. There is insufficient recognition for the watershed approach used in environmental impact assessments or analyses in Papua New Guinea. The study has shown that this technique can be highly effective, particularly in supporting watershed management practices, environmental planning, and natural resource management. To utilize this technique, one must understand the 'system of relationships' among the six significant ecological variables and how they interrelate and correlate within this dynamic bioregion. This research delineates more precise boundaries of the defined bioregions based on the scientific approach compared to the existing bioregions.

Keywords: Bioregion, Ecoregion, Environmental Impact Assessment, Geographic Information System, Watershed

1. INTRODUCTION

A watershed is a land area that drains rain or snowmelt water into a specific type of water body, such as streams, creeks, rivers, reservoirs, seas, or bays. Watershed characterization is a method that assesses and analyzes the physical, chemical, biological, social, and economic parameters for managing water, soil, and vegetation within the specific watershed region (Flotemersch et al., 2016). A bioregion is a geographical area characterized by its unique flora and fauna, ecology, and landforms, which a watershed can define. Remote Sensing (RS) is acquiring information about the Earth and providing data, primarily satellite data. The Geographical Information System (GIS) is another tool that handles spatial data, analyzes spatial relationships, and displays geographical data. Both tools are handy in watershed-related studies, including characterization, mapping, and management.

Recognizing the importance of watershed characterization can significantly aid in implementing policies that address the natural environment and mitigate its associated effects, particularly in countries like Papua New Guinea (PNG). Understanding the ecosystem or 'System of Relationships' among the significant environmental variables or parameters is vital when delineating a holistic bioregion (Vilhena & Antonelli, 2015). A bioregion has been defined in this study as a region consisting of a cluster of watersheds with heterogeneous landscapes on a larger scale. The environmental impact assessment or statement (EIA/EIS) report by the PNG-LNG stated that the existing bioregions in the Kikori Catchment were defined based on physio-geography, as the biota is usually reflected in the physical habitat (ExxonMobil, 2009).

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However, comparative analysis has shown that six significant environmental variables have been used to define a holistic bioregion, namely physio-geography, Soil, Climate, Natural Communities (including flora and fauna), Ecological Processes, and Hydrology (Accad et al., 2005). This study identified that the watershed characterization technique is the most suitable and convenient approach for incorporating the six significant environmental variables to redefine the existing bioregions. Many countries have sought to apply this watershed characterization approach to delineate their bioregions (Berg, 2005), while in PNG, the watershed characterization approach remains a concept that is yet to be fully understood and implemented in environmental planning and Monitoring Policies. The method of computing watershed characterization falls under RS and GIS. The Moro and Iagifu bioregions, along the corridor of the PNG-LNG upstream project area in the Southern Highlands Province of Papua New Guinea, were selected to conduct this research.

Five (5) research questions were formulated to guide the research and anticipate the expected outcomes, which will be based on the study's aim and objectives. They are (i) How can watershed characterization techniques be used to capture the required parameters for delineating a bioregion? (ii) What is the relationship between the stated parameters, and how can they be combined to delineate a bioregion for the study site? (iii) Why were some existing bioregions defined using only the physio-geography parameter rather than applying other major parameters? (iv) What benefits can the watershed characterization technique provide regarding environmental planning, natural resource management, environmental impact assessment and monitoring, environmental conservation, and other related areas? Moreover, (v) What comparisons can be made between the existing and delineated bioregions about the different approaches used? The primary objective of this research was to determine the definitive boundaries of existing bioregions using the watershed characterization technique. Four fundamental objectives were identified in this research. Firstly, the watershed boundaries will be delineated using area-wide and pour-point-based methods. Secondly, to delineate the ecoregions for the study area based on the six (6) major parameters that define a bioregion. The third objective was to combine and recombine the first two objectives according to their 'system of relationships' to delineate the bioregion and, ultimately, to compare and contrast the delineated bioregion with existing bioregions to appreciate the importance of the technique used.

2. STUDY LOCATION, MATERIALS, AND METHODS

2.1. Study location

Two bioregions within the Southern Highlands Province of Papua New Guinea define the study area. It is located approximately between the latitudes of 6º 16′ 34″ S and 6º 28′ 3″ S and the longitudes of 143º 6′ 51″ E and 143º 26′ 46″ E, respectively. The Moro Bioregion covers a land area of approximately 250 square kilometers and is home to the largest lake in Papua New Guinea, Lake Kutubu. The Iagifu Agogo Bioregion, in contrast, spans a land area of approximately 332 square kilometers (Figure 1). These bioregions are classified as karst bioregions because limestone features characterize the dominant landform. Karst is a distinctive terrain formed on soluble rock, characterized by landforms related to efficient underground drainage (Waltham, 2008).

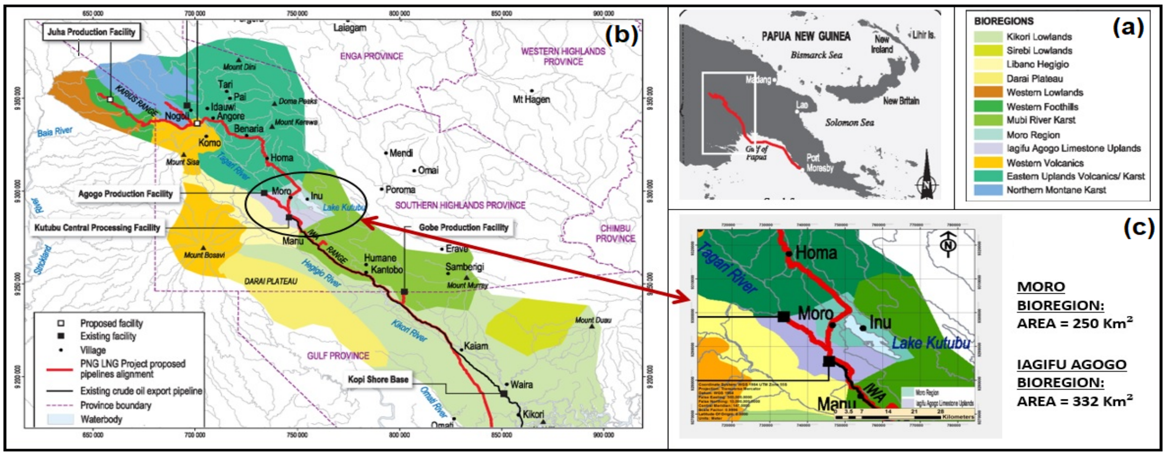

Fig.1. The locality map of the study Site: (a) Papua New Guinea, (b) Southern Highlands Province, and (c) Moro and Iagifu agogo bioregion (Source: PNG-LNG EIS Report and author's work).

2.2. Data used

Digital elevation models (DEMs) from SRTM and ASTER, with spatial resolutions of 90 m and 30 m, were used to compute the area- and point-based watersheds, respectively. Landsat8 optical land imager (OLI) data was used to classify land use and land cover within the bioregions. The vegetation cover was further classified using the 30 m resolution Landsat Tree Cover dataset. Topographic layers, climatic data, soil, and geology data were also incorporated from the Geo-book of PNGRIS. The details of these datasets are presented in Table 1. The leading software, ArcGIS 10.5, Erdas Imagine 8.5, MapInfo 11, and QGIS, were used to process all datasets.

Table 1. Data used for the study

Sl. No.	Data	Type	Scale/Resolution	Date	Source
1	Topographic Maps	Scanned	1:100,000	1966	School of Surveying and Land Studies, PNGUoT
2	PNG Topographic layers	Vector	MapInfo Table	2000	
3	Landsat 8	Raster	15m	2014	
4	SRTM DEM	Raster	90m	2001	
5	ASTER DEM	Raster	30m	2001	
6	PNGRIS	Geo-database	1:500,000	2010	
7	Landsat Tree Cover	Vegetation	30m	2000	

2.3. Methodology

The methodology involves data pre-processing, conversion and translation, creating and editing features, digitizing, sub-setting, feature extraction, and creating tables of attributes and geodatabases. Pre-processing was the initial step taken to analyze the data. It began by geo-referencing the scanned topographic map and other datasets to the WGS84 datum on UTM Zone 55 South. After that, the primary layers, such as roads, rivers, and built-up areas, were digitized. During that procedure, a table of attributes was also created for the vector files, which will later be added to or used in the geodatabase created in ArcGIS for editing and updating purposes. Additionally, all PNG topo layers and PNGRIS datasets were converted from tab files in MapInfo to shapefiles in ArcGIS. This was necessary because 85% of the analysis used ArcGIS software. Then, sub-setting and extraction were performed to clip out the Area of Interest (AOI) within the Southern Highlands Province (SHP). The DEM data was also clipped to extract the AOI of the study area.

The ArcGIS Spatial Analyst extension provides a toolset for analyzing and modeling spatial data. One of the tool sets under the Spatial Analyst extension is the Surface Analysis tool. DEMs of 90 m and 30 m were used to extract topographical features, including aspect, contours, hillshade, slope, and TIN (elevation), which were then used to compute the physio-geography ecoregion. A DEM of 90m was also used to delineate an area-wide watershed, capturing the extent of sub-watersheds within the area of interest (AOI). Then, a point-based watershed analysis was conducted to identify homogeneous catchment areas, which were used to delineate the diverse eco-regions for the study site. Image classification, also known as remote sensing classification, is a complex process that involves considering numerous factors. The significant steps of image classification include determining a suitable classification scheme, selecting training samples, selecting suitable classification approaches, performing post-classification processing, and assessing accuracy. Here, the research employs a strategy that involves unsupervised classification, followed by reclassification using supervised classification in Erdas Imagine 8.5 software. Spatial interpolation uses points with known values to estimate values at other points (Chang, 2006; Wu et al., 2005). In GIS applications, spatial interpolation is typically applied to a raster with estimates for all cells. Spatial interpolation is, therefore, a method of creating surface data from sample points, allowing the surface data to be used for analysis and modeling. The two datasets for the climatic variables, precipitation and temperature, were analyzed using the Inverse Distance Weighting (IDW) spatial interpolation (Chang, 2006). This method was applied to investigate how these two phenomena vary across the landscape within the study area and to examine their correlation with other bioregional parameters. Thiessen Polygons or Voronoi Polygons were also computed from the point data of rainfall precipitation to calculate the mean rainfall within each eco-watershed region.

About 60% of the study output was computed using these map overlay and map manipulation processes. This is a critical stage at which understanding the 'System of Relationships' or the ecosystem among the six significant environmental variables becomes crucial. The overlay operations depend on the source and target zones' geometric properties (points, lines, and polygons) (Chang, 2006). It superimposes the target zone on the source zone to obtain the proportion of each source zone in each target zone. All overlay operations are based on Boolean connectors. Four standard overlay methods exist: Union, Intersect, Symmetrical Difference, and Identity. The union preserves all features from both input layers. In contrast, the Intersect method preserves only those features that fall within the typical area extent of the two input layers. The Symmetrical difference method preserves areas common to only one of the inputs, and the Identity method preserves only features that fall within the area extent of the layer defined as the input layer. The Map Manipulation technique involves Dissolve, Clip, Append, Select, Eliminate, Update, Erase, and Split (Chang, 2006). In this analysis, only two layers combine spatial and attribute data from the two input layers into a single layer. Integrating map overlays and map manipulations has provided an avenue for delineating the Eco-Watershed Regions.

3. RESULTS AND DISCUSSIONS

The results produced under the six environmental variables were used to delineate the ecological regions. Ecoregions can be flexibly combined and reconfigured in various ways to accommodate changing conditions and specific purposes (Griffith et al., 1999). In this study, the ecoregions were combined to delineate the bioregions. This was all possible because watershed characterization sets the foundation for demarcating these ecoregions into bioregions.

3.1. Watershed characterization

The initial results were presented in an Area-wide watershed and a Point-based watershed. Both analyses followed the same procedures: using the DEM to compute flow directions, followed by flow accumulation. From there, stream order, streamline, and stream link were calculated to determine an Area-wide watershed (Figure 2a) and a Point-Based watershed (Figure 2b).

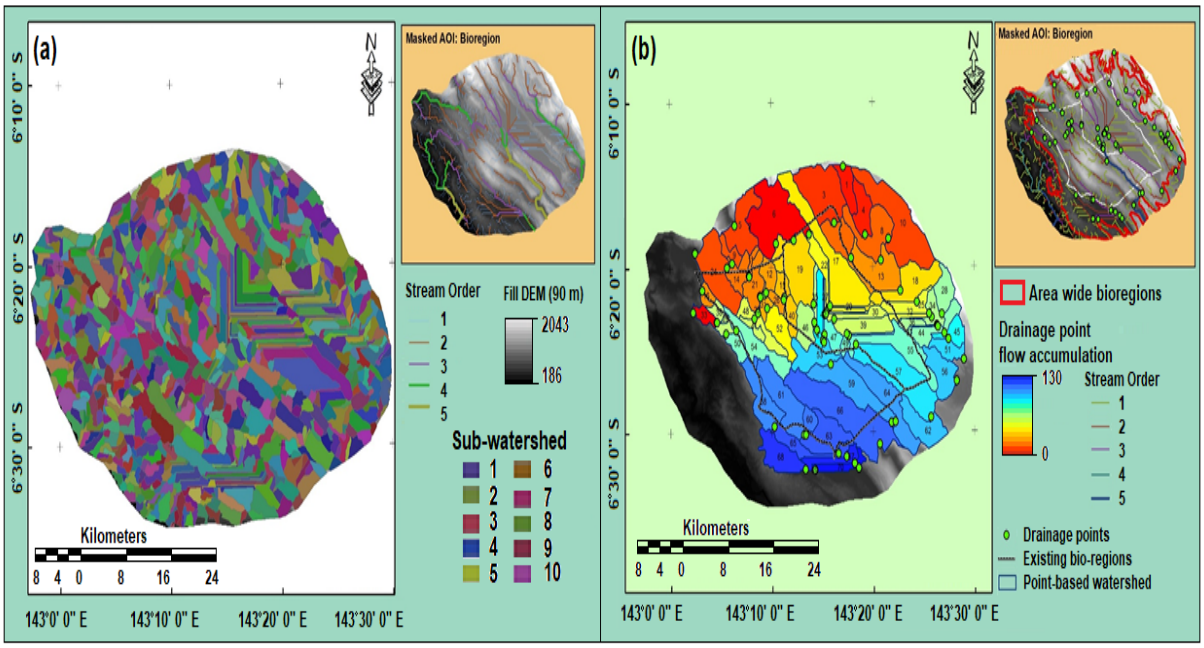

Fig.2. Area-Wide Watershed and Point-Based Watershed Delineations

The morphometric parameters, Bifurcation Ratio (Rb) and Drainage Density (Dd), were also developed to understand the general behavior of the watersheds (Pal et al., 2012). The results are presented in Tables 2 and 3.

Table 2. Calculating Bifurcation Ratio (Rb)

Stream Orders	Stream Length (km)	No/Streams per Order (Nu)	Bifurcation Ration (Rb)
1st	466	248	2.084
2nd	248	119	1.469
3rd	121	81	1.5
4th	44	54	4.5
5th	21	12	1
Total	**900 km**	**514 (number)**	**Mean Rb = 2.111**

Table 3. Watershed Basin Statistics

Watershed (Basin)	Area in Km^2	Perimeter (Km)	Total Length of Stream Orders	Drainage density
Eco-Hydro Region	662	705	900 Km	1.36 Km^{-1}

The bifurcation ratio has no dimension and is formulated as the ratio between the number of streams of one order and those of the next higher order in a drainage network (Strager et al, 2010). This ratio is of fundamental importance in drainage basin analysis, as it is the primary parameter for linking the hydrological regime of a watershed under topological and climatic conditions, and it also aids in interpreting the basin's shape and deciphering runoff behavior (Biswas et al., 1999). For instance, Rb of 2.111 can be classed as a drainage basin that is flat or rolling on the landscape. Whereas Drainage density (Dd) is the stream length per unit area in the region of the watershed (Kinthada et al., 2013), it is a better quantitative expression of the dissection and analysis of landforms (Pareta & Pareta, 2011). It measures how well or how poorly a watershed is drained by stream channels. Based on the results, it can be seen that the Dd for the eco-hydro region is 1.36 km^2, corresponding to an area of a basin that has Ied high Infiltration and low surface runoff, as evident In Its topographical and physio-geographical nature. This analysis falls under the realm of hydrology, considering altitude. The results yielded three transitional boundaries, which were used to delineate the study's Conducive Eco-Hydro Region (Figure 3).

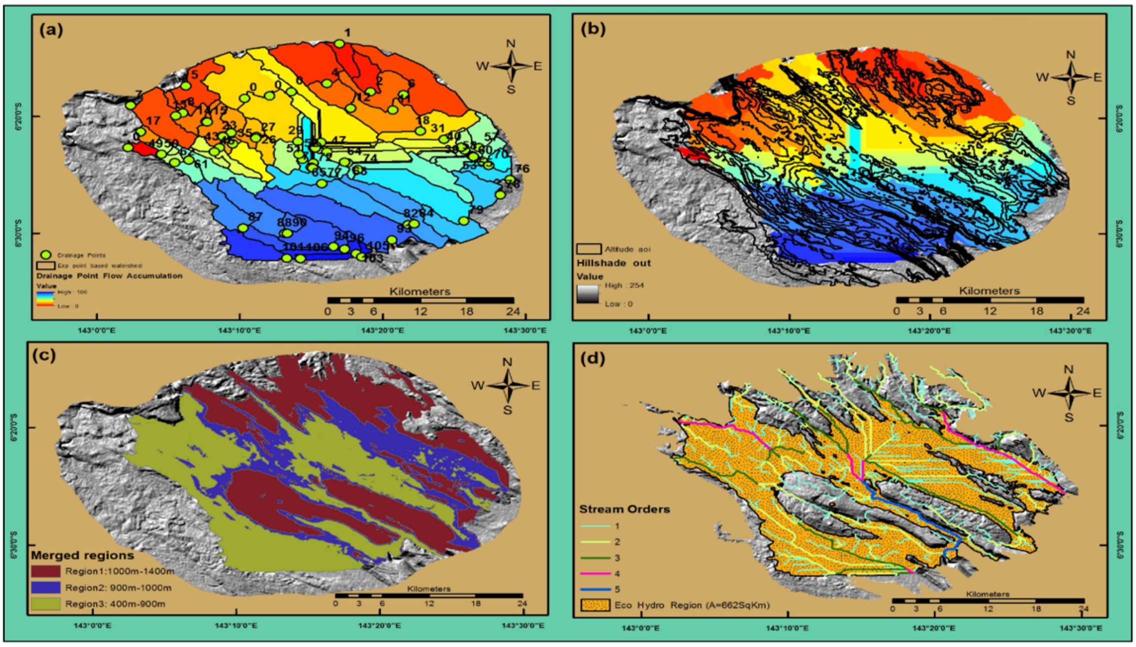

Fig. 3. Delineation of Conducive Eco-Hydro Regions: (a) Point-based watershed, (b) Sub-watershed class altitude, (c) Merged sub-watershed, and (d) Conducive Eco-hydro region

3.2. Physio-geographical Ecoregion

Under physio-geography, three main constituents, namely Topography, Landform, and Geology, have been used to delineate the physio-geographical ecoregion. The topographical features extracted from the SRTM 90-meter resolution dataset were Slope, Aspect, Hill-shade (or shaded relief), Contours, and Elevation (TIN). These topo layers were used because they provide a rigid landscape and terrain demarcation boundary within the area-wide bioregion (Jenson & Domingue, 1988) (Table 4 and Figure 4).

Table 4. Extraction of Topographical Layers

Sl. no.	Topographical layers	Feature extractions	Descriptions
1	Slope	15 degrees - 61 degrees	Represents the ridgelines for watershed boundaries
2	Aspect	Southwest & Northeast side	Captures of shaded areas of valleys and drainage systems
3	Hill shade	Shaded Relief	Terrain simulation with topo-features
4	Contours	50m interval	Simulates elevation intervals
5	Elevation (TIN)	250m – 2000m	Watershed drainage areas

The lithology of an area best describes its geology. This study has utilized referenced PNGRIS data (scale: 1:500,000) and identified six major lithology classes. This is evident in Table 5. The lithology "Tmd1" was recognized as the dominant feature within the area-wide watershed. These six classes were merged to delineate the Lithology–Eco watersheds. The results are presented in Figure 5. The landform data was also obtained from PNGRIS with the exact resolution. The three significant landforms were identified within the area of interest (AOI) or area-wide watershed, where Landform 55 (Polygonal Karst) covers most of the area. This is illustrated in Table 6 and Figure 6 accordingly. This type of landform is referred to as a braided stream system resulting from highly permeable material with underground drainage channels and is commonly characterized by sinkholes (Paine & Kiser, 2003). Generally, the lithology is the geological factor that determines the type of landforms. Therefore, Lithology Tmd1 (Massive-thick-bedded limestone) describes the characteristics of this type of limestone. Due to weathering and erosion over time, it is exhibited in Landform 55 of the polygonal karst region. Thus, the areas or boundaries within the intersection between the delineated lithology ecoregion and landform ecoregion were dissolved to aggregate the overall region, known as the Physio-geographical Ecoregion, for the study site. This is illustrated in Figure 7.

Table 5. Lithological Features in Area of Interest (AOI)

No	Lithology Type	Feature Extracted	Area (Km^2)
1	Lithology Qa4	Gravel, sand, silt, mud, clay, peat	109
2	Lithology Qv1	Basaltic & andesite lava, agglomerate tuff	63
3	Lithology TQK2	Volcaniclastic andesitic & basaltic breccia	121
4	Lithology Tmd1	Massive to thick-bedded limestone	707
5	Lithology Tmup2	Blue-grey calcareous mudstone, shale	102
6	Water (Lake Kutubu)	Waterbody	52

Table 6. Landform features in the area of interest (AOI)

Sl. No.	Landform Type	Feature Extracted	Descriptions	Area (Km^2)
1	Landform 55	Polygonal Karst	Plateaux or broad ridges of limestone covered with numerous rugged hills	680
2	Landform 51	Mountain & Hills	Weak or no structural control	126
3	Landform 32	Dissected volcanic foot-slopes	Little-dissected volcanic foot-slopes and volcano alluvial fans	70

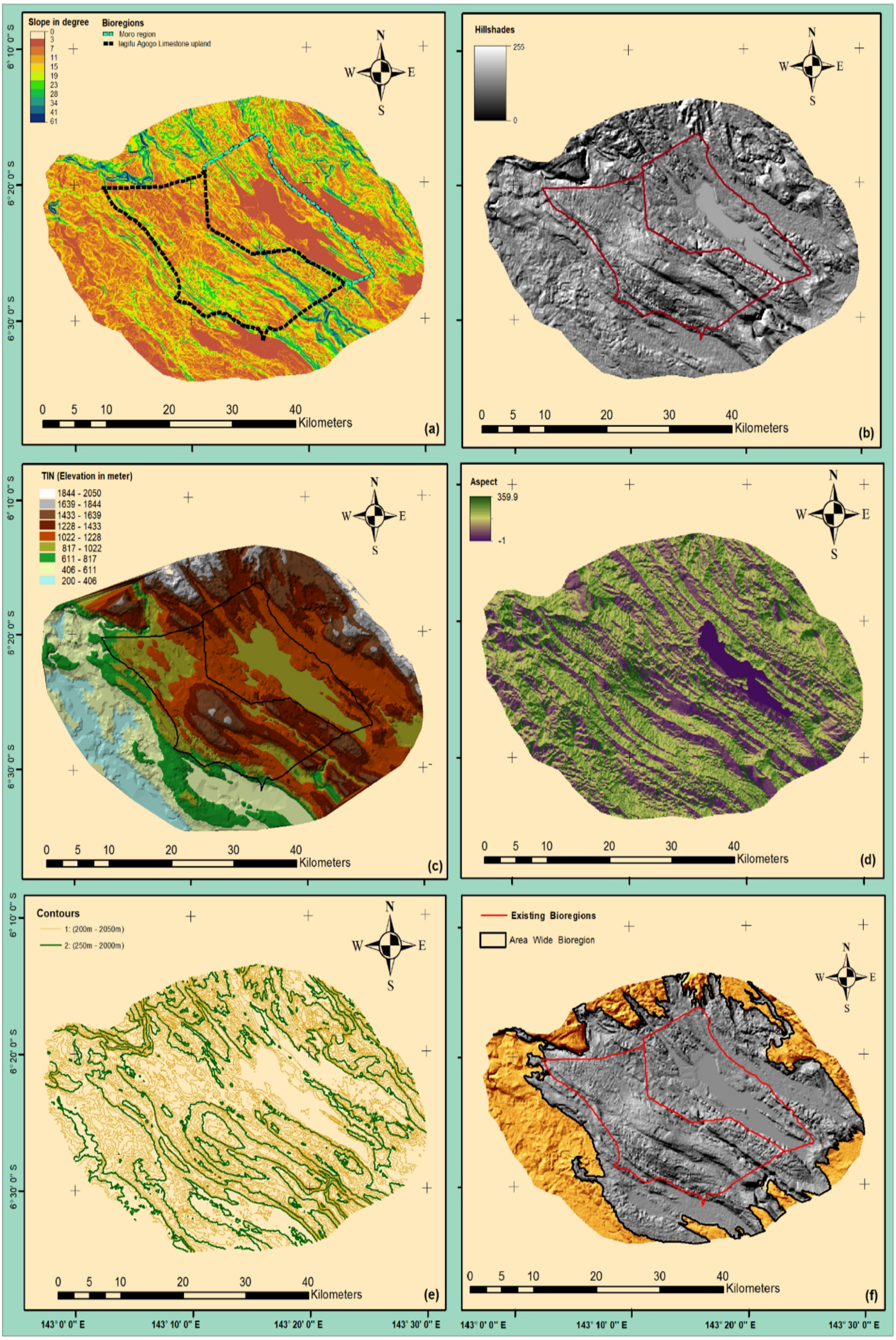

Fig. 4. Topographical features to calculate Area-Wide Bioregion: (a) Slope characteristics, (b) Hill shades, (c) TIN, (d) Aspect, (e) Contours, and (f) Existing bioregions within Area-Wide bioregions.

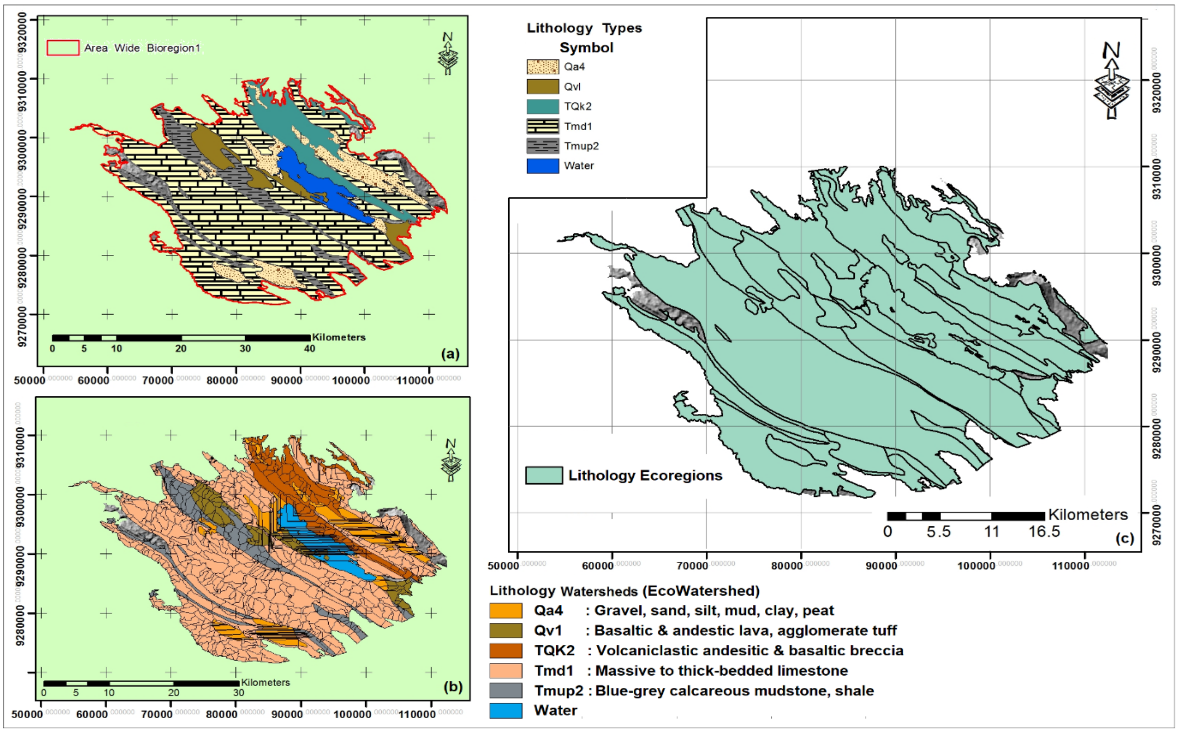

Fig. 5. Delineation of Ecoregion from lithology: (a) Lithology types, (b) Lithology intersected with Area-Wide Watershed, and (c) Delineated Lithology Ecoregion

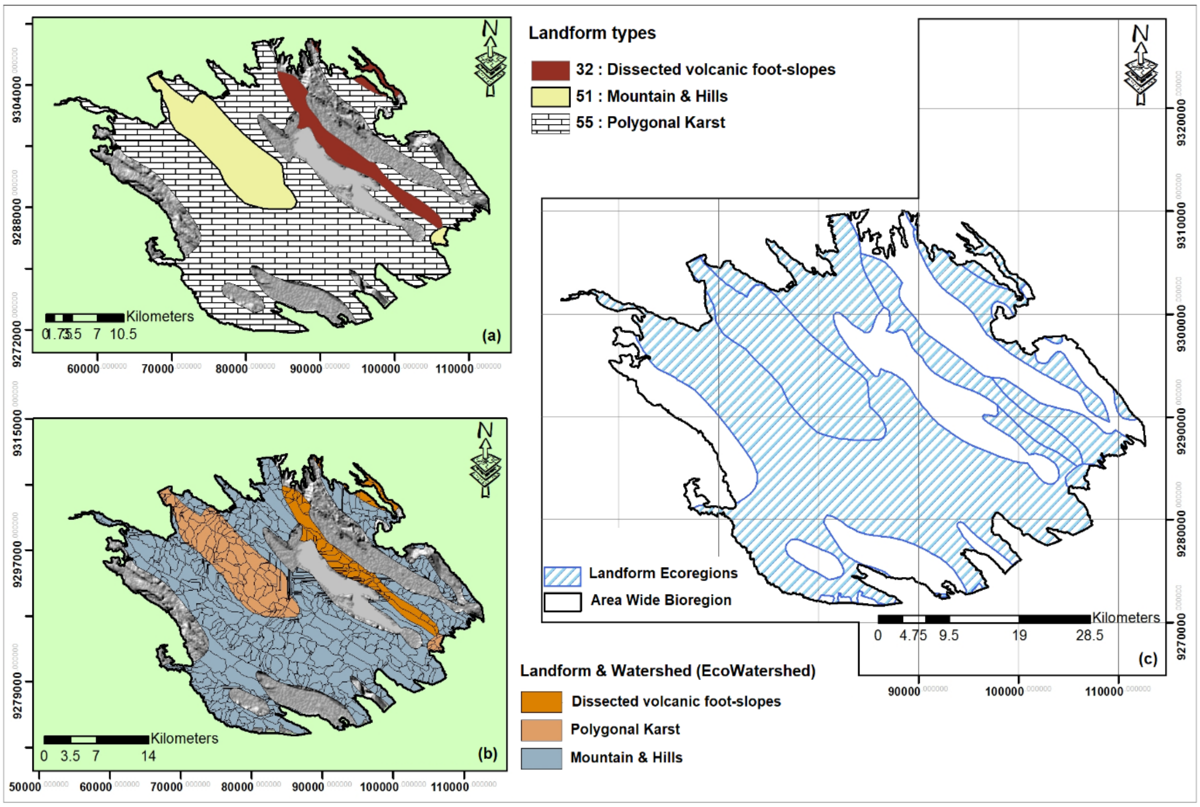

Fig. 6. Delineation of Ecoregion from Landform: (a) Landform types in Area Wide Bioregion, (b) Landform intersect with Area Wide Watershed in an Area Wide Bioregion, (c) Delineated Landform ecoregion.

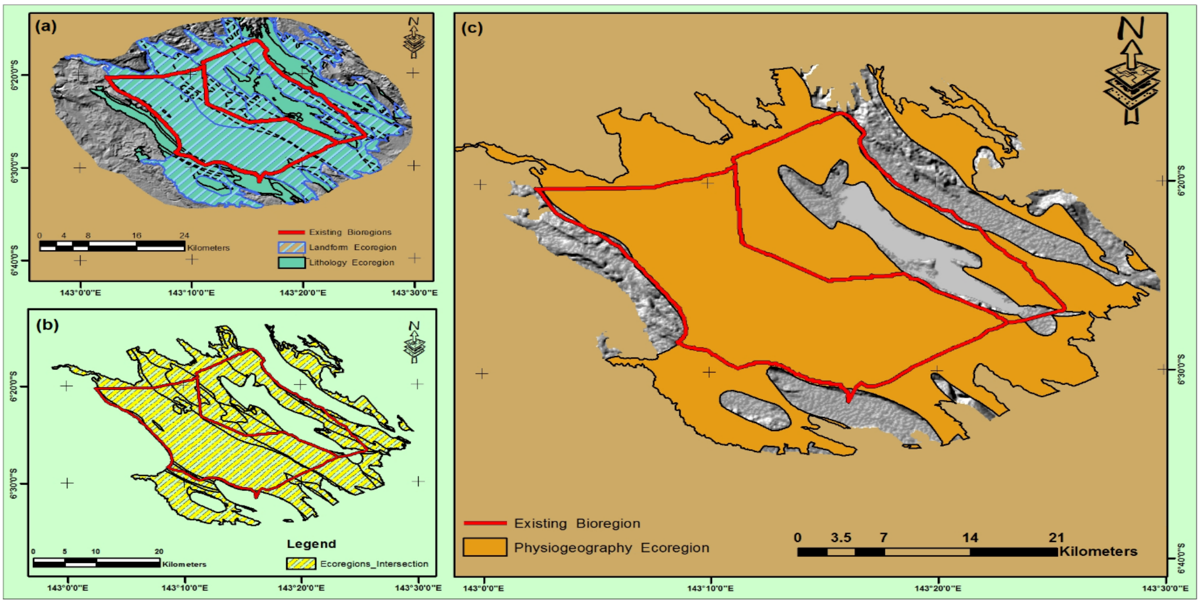

Fig. 7. Delineation of Ecoregion from Physio-geography: (a) Overlay of Lithology Ecoregion and Landform Ecoregion, (b) Lithology and Landform intersection, and (c) Physio-geographical ecoregion

3.3. Soil characteristics within the Physio-geographical Ecoregion

The study independently examined soil as one of the six significant environmental variables. This is because soil is an ecosystem component of many ecoregion properties, including vegetation and land use (Johnson et al., 1995). Regarding soil descriptors, the study has focused on Soil Type and Soil Texture. Six major soil types are identified within the physio-geography ecoregion, of which Eutropepts is the most dominant. Eight soil textures were identified, of which Sandy Clay appears to be the most dominant, occurring within an elevation range of 1100 m to 1200 m. The results are presented in Figure 8. The soil data analysis utilized physio-geography ecoregions and sub-watersheds merged based on altitude.

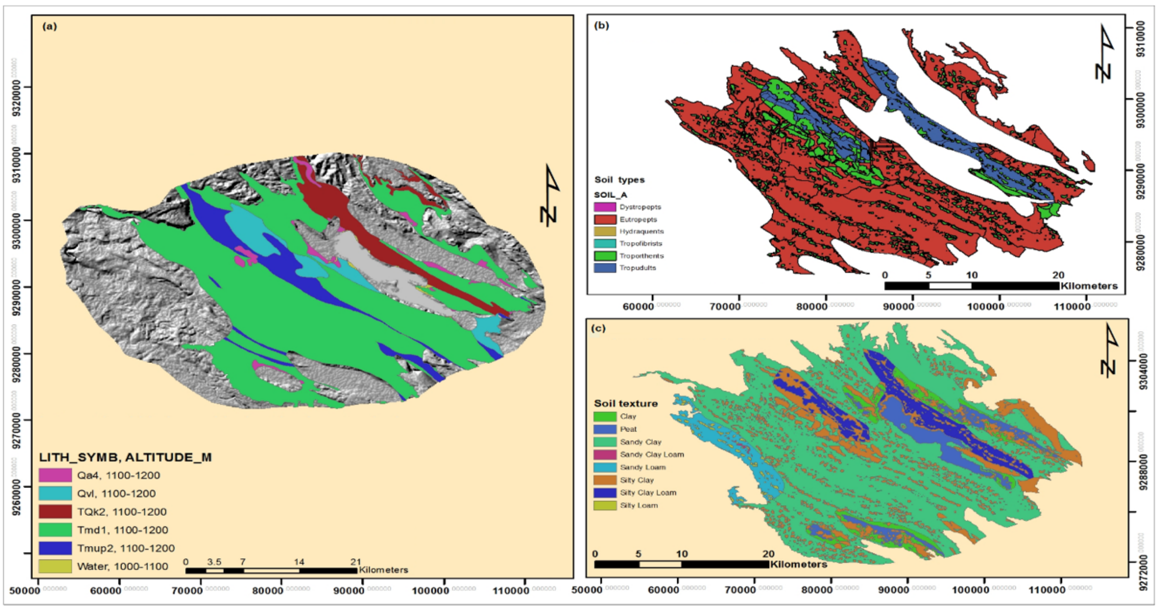

Fig. 8. Delineating Soil within Physio-geographical Ecoregion: (a) Physio-geographical Ecoregion merged with altitude, (b) Soil type-A within Physio-geographical Ecoregion, and (c)Soil texture within Physio-geographical Ecoregion

3.4. Sub-Transitional Climate Zone for Eco-Watersheds

Climate largely determines the boundaries of ecosystems. In tropical regions, rainfall, precipitation, and temperature are the primary factors considered, as they are typically used to define terrestrial biomes. Furthermore, the inner structure of the ecoregion is organized as a series of intersecting gradients; temperature and precipitation change with elevation in alternating belts of vegetation along windward and leeward sides of a parallel series of mountain ranges, with biodiversity thinning towards the edges (Griffith et al., 1999; Dinerstein et al., 1995). As such, the interrelationships between precipitation, temperature, elevation, and vegetation were analyzed to help delineate holistic ecoregions, which enabled the computation of the final biome region, commonly referred to as a bioregion. The climatic data were obtained from PNGRIS in 2000 and analyzed, as shown in Table 7.

Table 7. Extracting Rainfall Precipitation and Temperature for the AOI

No.	Climate Data	Feature Extracted	Descriptions
1	Rainfall (mm)	(3400mm) – (4700mm) with every 100mm interval	Gives the annual rainfall but does not specify which month the values were obtained.
2	Minimum Temperature	(11°C - 20°C) With every 1 °C interval	Minimum temperature range found within the delineated bioregion
3	Maximum Temperature	(22°C - 31°C) With every 1 °C interval	Max. The temperature range found within the delineated bioregion.

The rainfall data were merged based on similarities in the attribute table, and the average rainfall in millimeters for each rainfall range (3400 mm – 4700 mm) was estimated. After that, the feature class was converted to point data for spatial interpolation. Inverse Distance Weighted (IDW) interpolation was applied to the overall rainfall data to produce the study site's mean or average rainfall data (Dobesch et al., 2013). IDW was also performed separately on the minimum and maximum temperature datasets (Samanta et al., 2012). Their outputs were merged to produce the final result of Average Temperature across the study site. The IDW results for the annual average rainfall precipitation and average temperature were intersected to observe the correlation between these two phenomena and, more specifically, to help identify the physical transition zones for delineating the ecoregions within the biome. The statistics output from this intersection are presented in Table 8. In general terms, there is a negative correlation between rainfall and temperature. For instance, as the temperature increases, the rainfall decreases and vice versa. However, the results from this analysis show that the annual average rainfall precipitation remained constant at approximately 4350 mm, while its temperature gradually increased from 13.5 °C to 19.5 °C and from 27.5 °C to 30.5 °C. There was a drop in rainfall (3550 mm) when the temperature was at 24.5 °C. This is a classic example of regional weather variations (Samanta et al., 2012), such as an ecoregion or bioregion.

Table 8. Average temperature and rainfall data within the AOI

Mean Temperature (°C)	Average yearly total rainfall (mm)	Mean Temperature (°C)	Average yearly total rainfall (mm)
11.5	3750	22.5	4050
12.5	4450	23.5	3850
13.5	4350	24.5	3550
14.5	4350	25.5	4350
15.5	4350	26.5	4250
16.5	4350	27.5	4350
17.5	4350	28.5	4350
18.5	4350	29.5	4350
19.5	4350	30.5	4350

Hence, the study area is in a tropical region subject to the seasonal influence of the Northwest Monsoon (December–March) and the Southeast Trade Winds (May–October). Based on the statistics in Table 9, a line graph was created that resembles a biome similar to the Tropical Rainforest. This graph is illustrated in Figure 10. Therefore, the study has concluded that, regardless of the seasonal rainfall over the study area, it is the tropical rainforest cover, having its own Micro-Climate has seemed to influence the amount of precipitation and evapotranspiration in terms of regulating the ecological processes such as water cycle, nutrient cycle, and energy flow, taking into consideration of the topography and elevation within a region (watershed, ecoregion, or bioregion) (Nowak, 2018), as seen in this case study. The values obtained for the phenomenon were then used to delineate the temporal transition zones. Two zones were delineated; one zone used data from 13.5 °C to 19.5 °C, and the other used data from 27.5 °C to 30.5 °C, where the rainfall precipitation is constant at 4350 mm. The process began by creating a new layer for each dataset. After that, both layers were intersected to delineate a region based on average precipitation and temperature. The research described this region as a transitional Climate Zone Delineation within a bioregion (Figure 9).

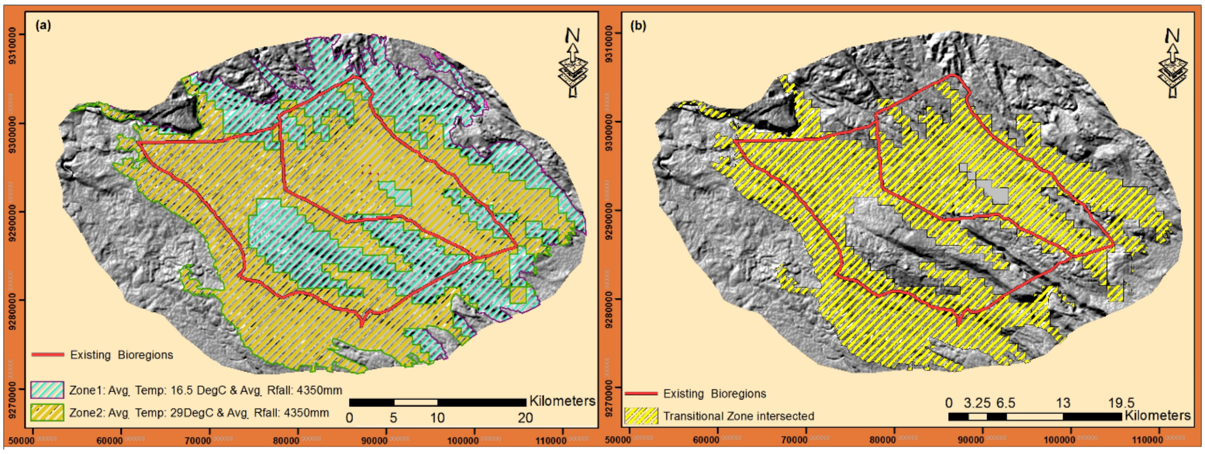

Fig. 9. Delineation of transitional climate zone: (a) Overlay of average rainfall (4350 mm) and temperature (16.5° °C & 29° °C), and (b) Transitional climate zone

3.5. Eco-Watershed Region Delineation

Ecological Process, considered in this study as one of the six significant environmental variables defining a bioregion, was analyzed at the watershed scale. The ecological process encompasses the water cycle, nutrient cycle, energy flow, community dynamics, and succession, all vital for sustaining biodiversity (Acreman, 1999). Thus, biodiversity varies from place to place or from region to region, and so watershed divides have been applied to naturally demarcate the biodiversity regions into ecoregions (Bothale et al., 1998). In line with the study analysis, the water cycle was considered because precipitation and surface runoffs play vital roles in the cycling of different elements within the ecosystem (Bennett et al., 2009). Surface runoff was already computed in the first part of this study as part of the watershed characterization. This part is an extension of precipitation analysis that identifies rainfall estimation within sub-watershed levels. The process began by utilizing the rainfall point data to create Thiessen Polygons or Voronoi Polygons. The Voronoi polygons within the sub-watersheds were merged based on similarities in their attribute tables. Its output was then intersected with the Transitional Climate Zone data, taking elevation or altitude into account this time. The study has termed this output as the Eco-Watershed Region. Hence, it represents an ecological region characterized by watersheds. Table 9 and Figure 10 accordingly present the statistical output from this analysis. The production of the Voronoi polygon reveals 13 classes of rainfall precipitation, ranging from 3400 mm to 4700 mm, which are distributed across the study site. However, the focus is within the existing bioregion, so intersecting this data with the transitional climate zone data resulted in the Eco-Watershed Region. In this region, the average rainfall precipitation throughout the year is 4350mm with a mean temperature of 16.5 °C, which is distributed throughout the bioregion with altitudes ranging from 1000 meters to 1100 meters (Figure 10)

Table 9. Table of Attributes for Eco-Watershed Region

Rainfall range (mm)	Average Rainfall (mm)	Perimeter (km)	Area (km^2)	Average Temp (°C)
4300 - 4400	4350	541	737	16.5

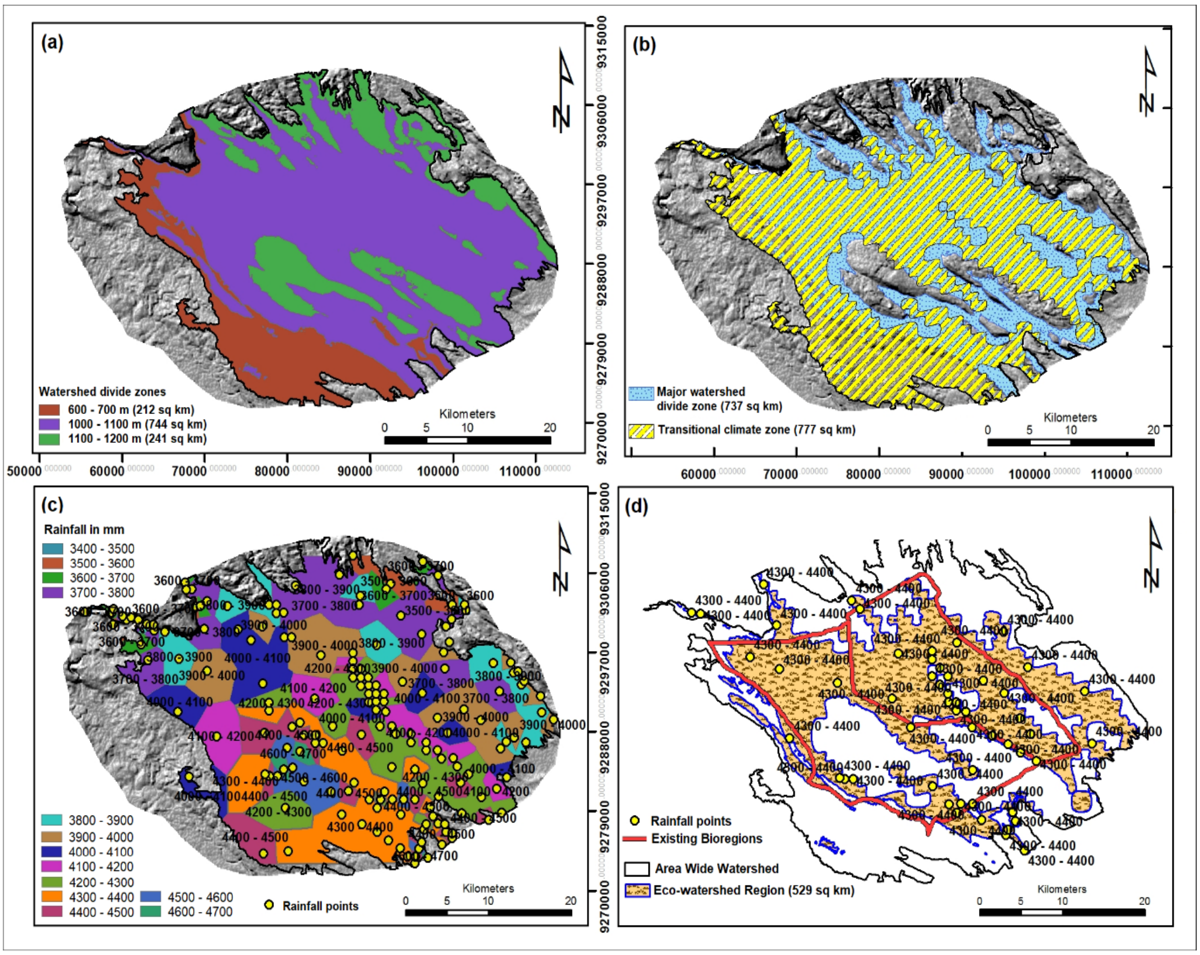

Fig. 10. Delineation of Eco-Watershed Region: (a) Watershed divider, (b) Intersection of transitional climate zone with central watershed divider, (c) interpolated rainfall using Thiessen polygon, and (d) Eco-watershed region based on water dividers and transitional climate zone

3.6. Natural Communities (Forest Cover)

Another important environmental parameter to consider when defining an ecoregion or bioregion is the presence of the flora and fauna, which are regarded as biotic factors and their relationships with the abiotic factors within an ecosystem. Since the study focuses on delineating ecoregions into bioregions on a larger scale, it has considered forest cover because it plays a significant role in natural communities' dominant feature (Connell & Slatyer, 1977). As defined in climatic analysis, the tropical rainforest is the primary vegetation cover that has provided a basis for classifying forests using the PNG Forest Inventory Management System (FIMS). The PNG FIMS is used to classify forests based on their altitude or elevation above mean sea level, measured in meters (m). The forest dataset was obtained from MOD44B Vegetation Cover data from the MODIS Satellite over the Southern Highlands Province (SHP) in 2000. This dataset was then intersected with the watershed ecoregion, yielding four major forest classes across the study area (Table 10).

Table 10. Forest Classification on Altitude

No	Altitude (meters)	Descriptions (PNG FIMS)	Area (Km^2)	Perimeter (Km)
1	300 – 700	Low-altitude forests on plains and fans	20, 141	378
2	700 – 1000	Low-altitude forests on uplands	56, 945	887
3	1000 – 1200	Low Montane Forests	31, 215	1014
4	1200 - 1500	Mid-Montane Forests	8, 894	487

3.7. Forest Ecoregion Delineation

After combining all the analyses, the final result for the forest classification was then delineated into an ecoregion, which can be seen by integrating the average rainfall in a watershed. This is illustrated in Figure 13. The computed forest ecoregion within the watersheds has four distinct classes throughout the terrain, with undulating topography dominated by karst regions. The average annual precipitation varies within each watershed, but not to a great extent. The perimeters computed using the altitude to classify the forest have been considered here as transition zones for the forest classes and for other upland ecotones and thus were used to delineate the boundary of the bioregion for the AOI, together with other delineated ecoregion parameters. Regarding physio-geographical changes, an increase in altitude typically reduces the size of forest tree crowns (Nowak, 2018).

3.8. Forest on Physio-geography

The forest classes were then intersected with the physio-geography ecoregion to understand the natural structure of the forest within the AOI. From this result, it was observed that the tropical rainforest classes were dominated by Landforms 32 and 55, which are characterized by limestone with varying degrees of karstification. Due to its geological structure, most low-altitude forests on uplands (700m – 1000m) appear open, giving the impression of an open forest. This output was then compared with the rainfall within the watershed regions to help understand the influence of climate on the forests.

3.9. Classified Forests within Watersheds (Voronoi)

The classified open forests were then intersected with the rainfall estimates within a watershed to analyze the relationship between the natural growth and distribution of the forests from different altitudes. Their results have shown that most watersheds are dominated by low-altitude forests on plains and fans, spreading across the bioregion, with few low-altitude forests on uplands. The rainfall distribution varies from watershed to watershed; however, it appears to have a limited influence on the forest cover, in contrast to altitude, topography, soil, and geology, which significantly impact the forest's natural structure and classification within the study area. For example, the increase in altitude has affected the species diversity and tree sizes, which tend to decrease.

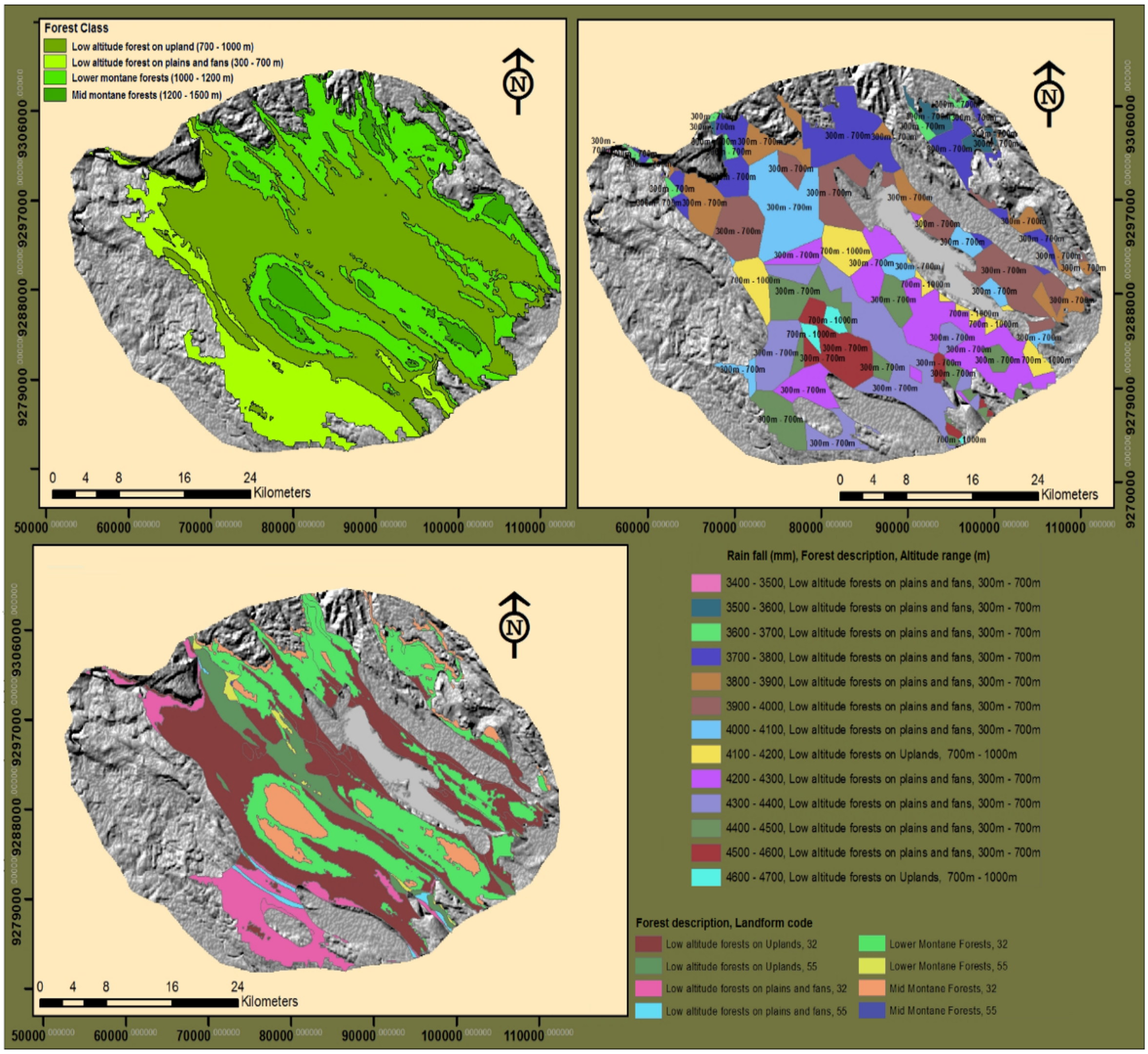

Fig.11. Delineation of Forest Ecoregion: (a) Forest classification within the bioregion based on altitude, (b) Combination of forest and rainfall, and (c) Intersection of forest with physio-geography.

3.10. Heterogeneous Landscape Delineation

The study here focused on merging all the delineated ecoregions (homogeneous landscapes) into a bioregion. A bioregion can be classified as a heterogeneous landscape on a larger watershed scale (Hartwell & Welsh, 1994; Waissbluth, 2016). The approach taken here to understand environmental diversity within heterogeneous and homogeneous landscapes is using the Land Use and Land Cover (LULC) classification method. Environmental classification at a larger scale can capture diverse ecological variables, including different vegetation cover types, agricultural land, water bodies, human-built structures, and topographical features (Lu & Weng, 2007). The analysis began by mapping the LULC for the entire study area. The LULC analysis used a 15-meter resolution Landsat 8 image from 2000. It has seven spectral bands, which have been used to perform the ISODATA unsupervised classification by assigning 50 classes with a maximum iteration of 6. The target LULC classes selected were: lake/water body, marshland/wetlands, clear land area, light vegetation, dense vegetation, cloud cover and haze, and built-up zones. After merging the classes in the signature editor, the unsupervised image was reclassified by performing supervised classification. Finally, recoding was performed using the secondary data sources, resulting in an overall classification accuracy of 93.33%. This is illustrated in Table 11 and Figure 12, respectively.

Table 11. LULC Classification Statistics for Heterogeneous Landscape (Area Wide)

No	Class Name	Area (hectares)	Area (%)
1	Lake / Water Body	5133.02	4.29
2	Marsh Land / Wetlands	8769.33	7.33
3	Clear Land Area	5106.00	4.27
4	Light Vegetation	43344.16	36.22
5	Dense Vegetation	37488.94	31.33
6	Cloud Cover and Haze	18138.78	15.16
7	Built-Ups	1676.18	1.40

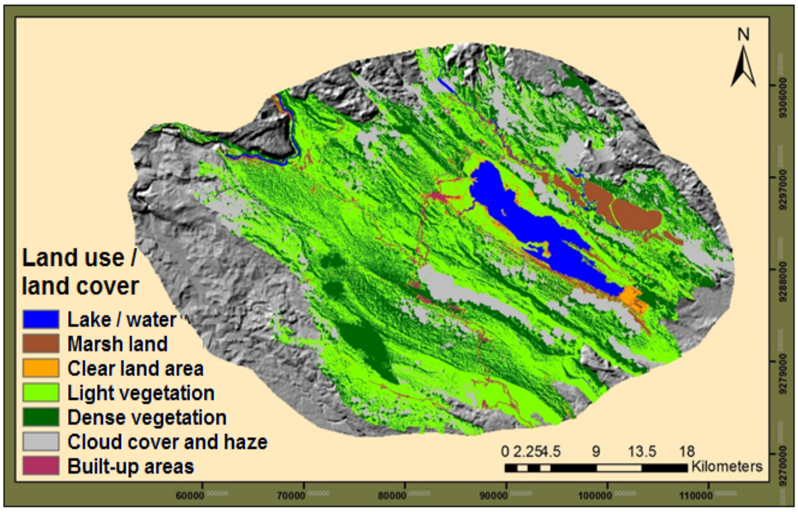

Fig.12. Heterogeneous Landscape Delineation (Area-Wide Bioregion)

3.11. Eco-Watershed Region Classification

The heterogeneous landscape was then intersected with the eco-watershed region, which was computed under the water cycle analysis to extract the Land Use and Land Cover within the catchment zone. The result still displays vegetation diversity, capturing all seven significant classes. This heterogeneous eco-watershed landscape was created as it is vital in providing a holistic definition of bioregion delineation (Omernik, 2004). The boundaries of the eco-watershed heterogeneous landscape also depict transition zones (Figure 13 and Table 12).

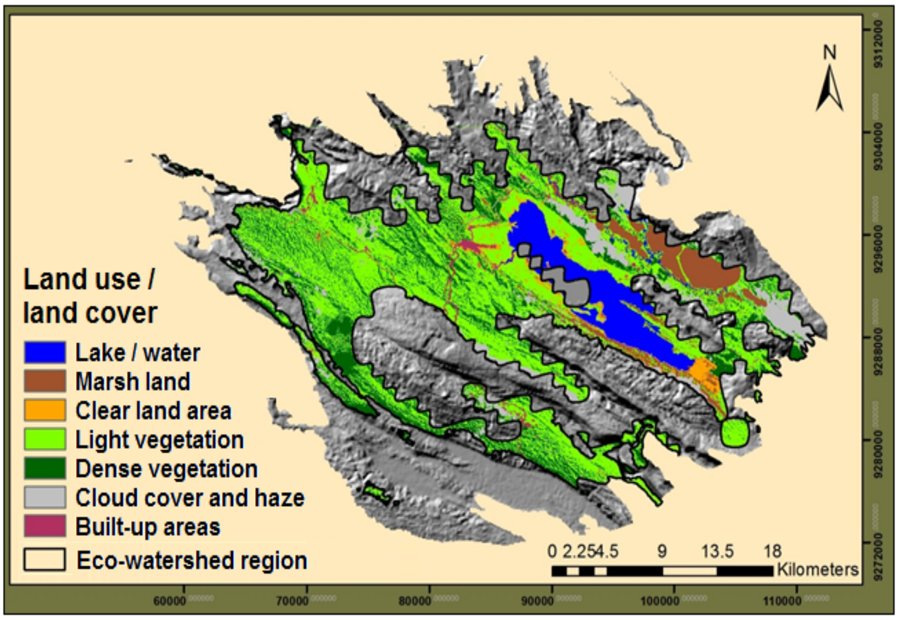

Fig. 13. Eco-Watershed Heterogeneous Landscape Delineation

Table 12. LULC Classification Statistics for Eco-watershed Region

No	Class Name	Area (hectares)	Area (%)
1	Lake / Water Body	4634.71	8.79
2	Marshland / Wetlands	3853.22	7.31
3	Clear Land Area	1205.12	2.29
4	Light Vegetation	25602.73	48.55
5	Dense Vegetation	12227.40	23.19
6	Cloud Cover and Haze	4290.48	8.14
7	Built-Ups	920.97	1.75

3.12. Bioregion Delineation

The study delineates a holistic bioregion by considering the six main environmental variables and understanding how their 'system of relationships' correlates and interrelates (Nas & Berktay, 2010). The watershed characterization technique is the most suitable and convenient approach. The watershed characterization technique provided the avenue in which the following ecoregions were delineated, namely (i) Conducive Eco-Hydro Region, (ii) Physio-geographical Ecoregion, (iii) Transitional Climate Zone, (iv) Eco-Watershed Region, (v) Forest Ecoregion, and (vi) Eco-Watershed Heterogeneous Landscape. Practically, ecoregions can be flexibly combined and recombined in various configurations to accommodate changing conditions and specific purposes (Bailey, 1983). The delineated ecoregions fit the homogeneous landscape, environment, or climate description. These delineated ecoregions were then merged or intersected to delineate the bioregion for the study site (Figure 14).

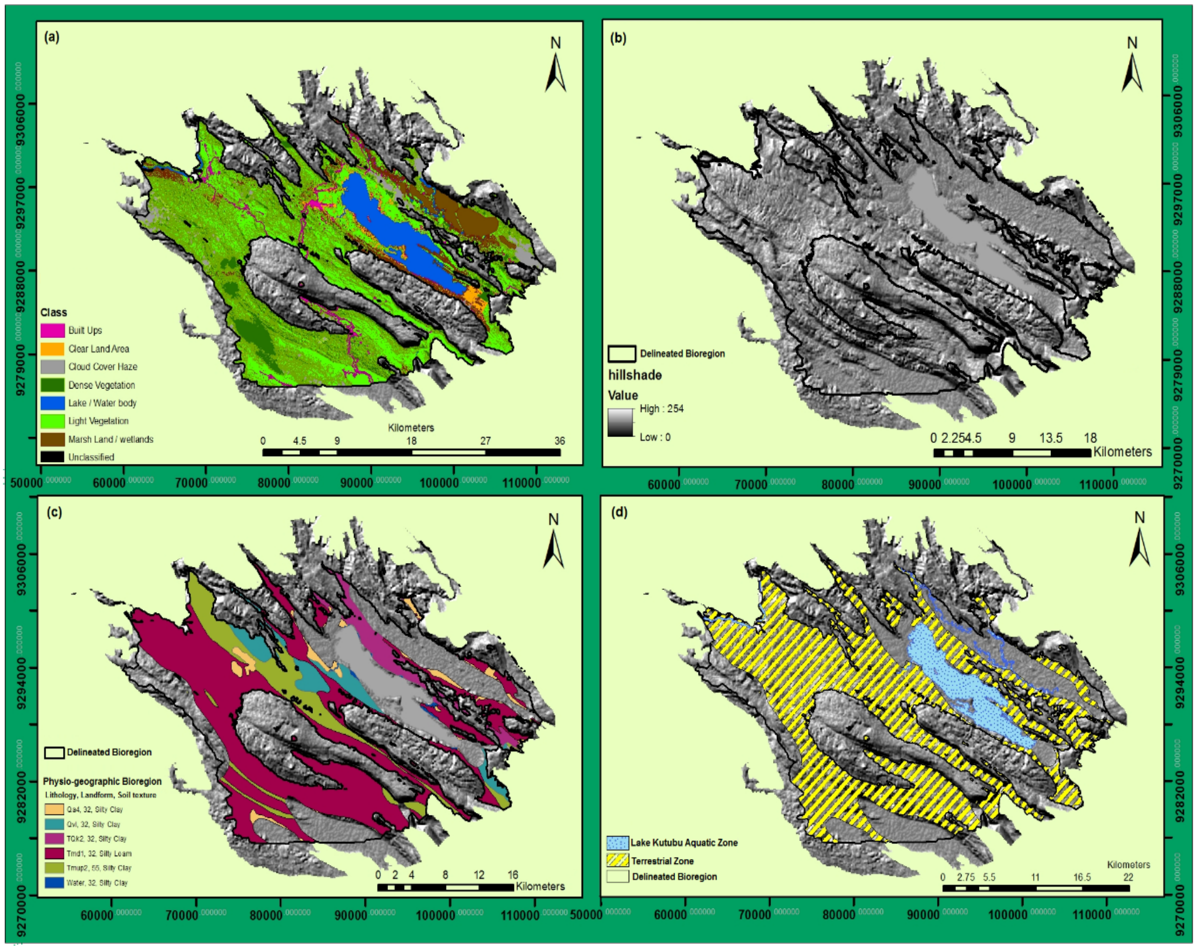

Fig.14. Delineation of Bioregion: (a) Land use/ land cover region, (b) Bioregion on hillshades, (c) Physio-geological bioregion, and (d) Transitional zone in Bioregion

The boundary of this delineated bioregion represents transition zones for climate, including precipitation and temperature. The study utilized census units (CUs), settlement data, and historical topographical maps, supplementing these with secondary data for the Southern Highlands Province to demarcate the boundary between the two bioregions. It was noted that these two bioregions were located within the Nipa / Kutubu Local Level Government (LLG) (Figure 15).

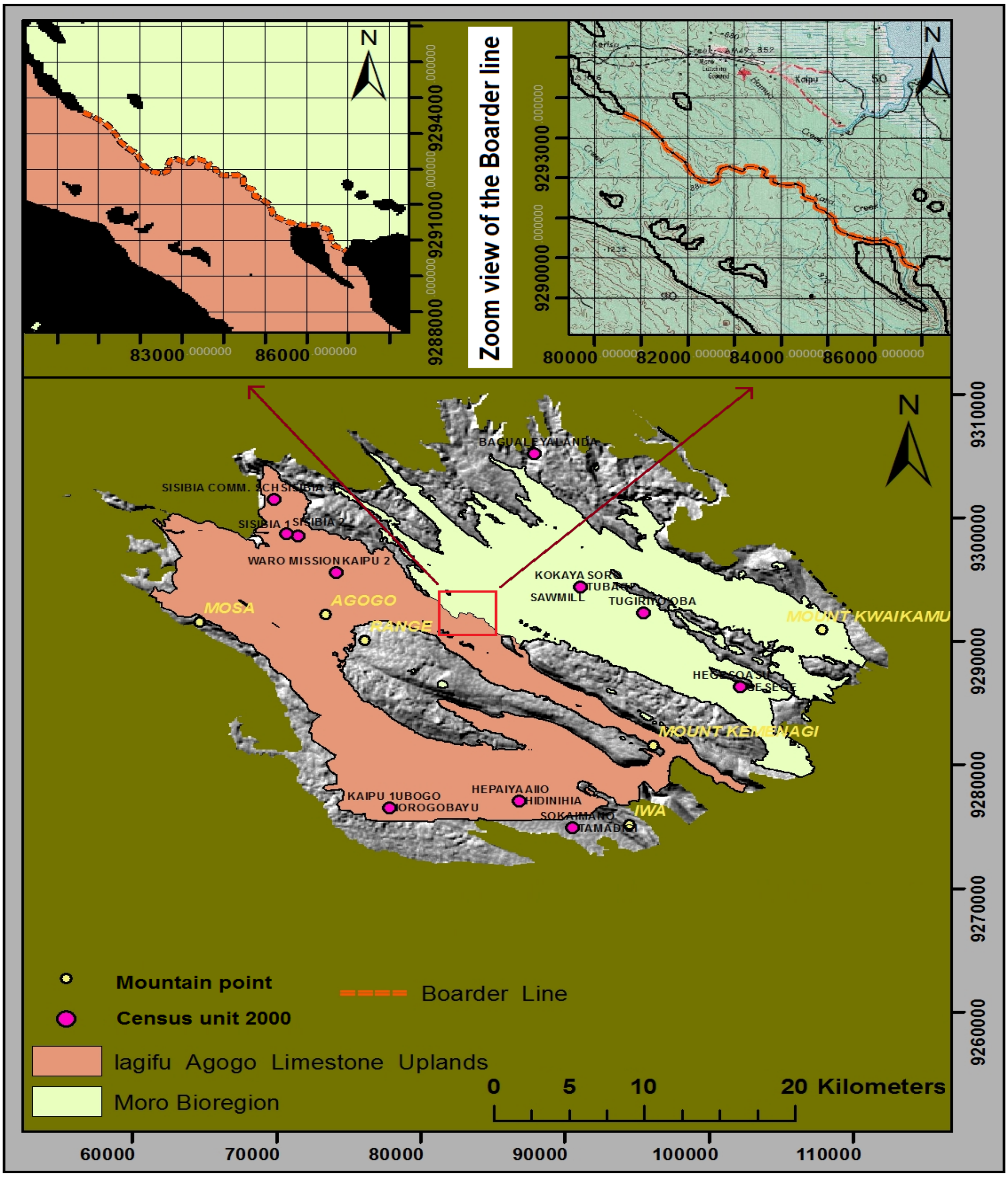

Fig.15. Border Demarcation Between Moro Bioregion and Iagifu Agogo Bioregions

While overlaying the existing bioregions on the delineated bioregions, the significant difference observed between the delineated and the existing bioregions is their shapes and sizes (Figure 16). This can also be understood from the computed statistics (Figure 16).

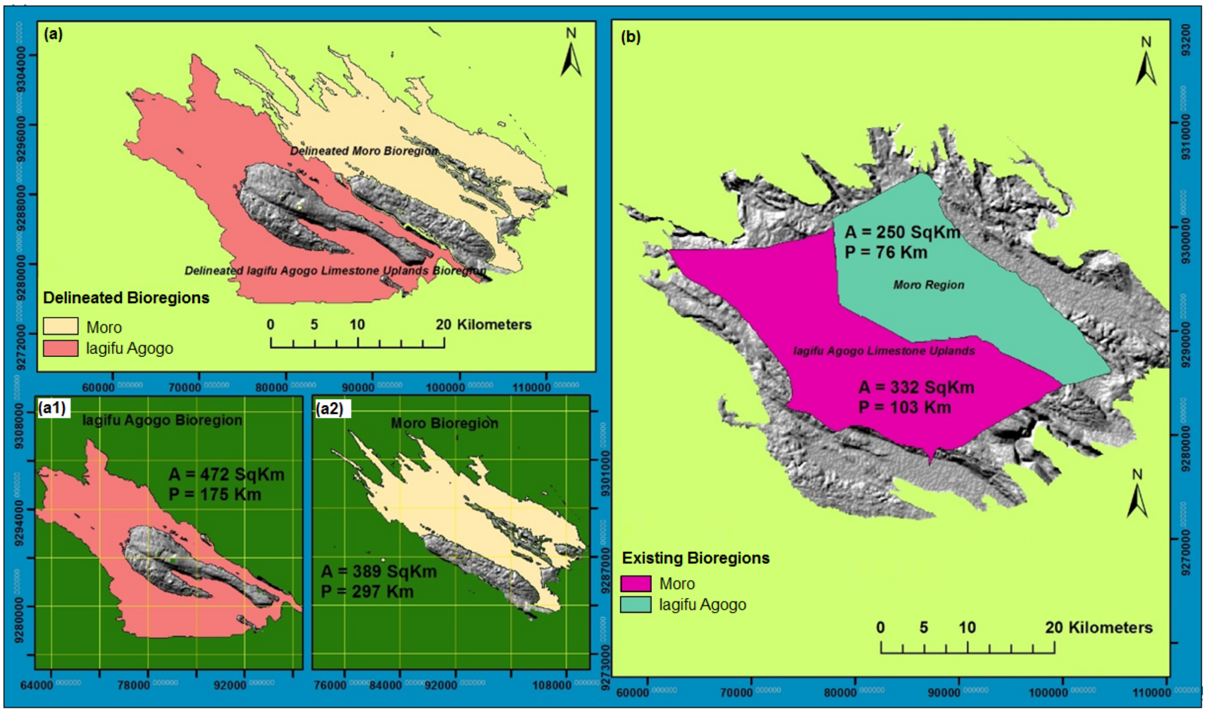

Fig.16. Delineated vs Existing bioregions: (a) The Delineated bioregions, (a1) Moro Bioregion, (a2) Iagifu Agogo Bioregion, and (b) Existing Bioregions (A = Area, P = Perimeters)

The boundaries for the delineated bioregions look more natural and scientific. The shapes blend in with the natural physical landscape and the geography. It is more scientific because it involves a statistical approach and scientific reasoning to analyze the 'system of relationships' among the different environmental parameters and variables. In contrast, the existing bioregions do not deeply reflect that information but show the variables used under the physio-geography parameter. The boundaries appear to be straight and rigid. Manual digitization was done to define the boundaries. When looking at the borderline demarcating between the two bioregions, it was observed that the delineated bioregions follow the scientific approach. At the same time, the research anticipated that the existing bioregions would demarcate their boundaries using the social mapping approach.

4. CONCLUSION

The delineated bioregion looks more natural and scientific. This means the shapes blend seamlessly with the natural and physical landscape and geography. It is more scientific because it involves a statistical approach and scientific reasoning to analyze the 'System of Relationships" among the significant environmental variables. For the borderline separating the two bioregions, it was also noted that this line aligned with the Lake Kutubu Wildlife Management Act (WMA). The two delineated bioregions, Moro and Iagifu, were among the 12 existing bioregions defined along the Kikori Catchment due to the development of the PNG-LNG Project. The development of the gas pipeline project seems to have influenced the initial demarcation of the 12 existing bioregions. However, the study has remained true to its course and incorporated significant environmental variables to delineate its site's bioregion. The outcome is more natural and scientific compared to the existing bioregions.

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