GEOMORPHOLOGY OF SMALL ISLANDS AND ITS SEAFLOOR PROFILES IN THE EASTERN AND WESTERN HALMAHERA WATERS

GEOMORFOLOGI DAN PROFIL DASAR LAUT PULAU-PULAU KECIL DI BAGIAN TIMUR DAN BARAT PERAIRAN HALMAHERA

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ABSTRACT: The geomorphology of small islands in the eastern and western parts of Halmahera Island encompasses diversities of geological processes, island forms and types, and topography. The typology of the small islands to the west of Halmahera Island is volcanic and are categorized as hilly islands. To the east, there are coral islands classified as flat islands with smaller area contrast to volcanic ones. This study aims to analyze the land mass elevation of the small islands and the sub-bottom profiles in the eastern and western Halmahera waters. Island elevation data was obtained from Sentinel-2B imagery, whereas seafloor topographic data was acquired from direct field measurements using a GPS sounder. First, the image data underwent atmospheric, radiometric, and sunlight corrections, while the actual depth was estimated through bathymetry correction using tidal data. Then, QGIS version 3.16.6 and ArcGIS version 10.8 were used to analyze the data. The results show that the slope degree of volcanic islands is higher and their seafloor topography is steeper than that of coral islands. The slope degree of Ternate, Maitara, Tidore, and Hiri Islands, abbreviated as Termadoreh, is more than 30º with elevation of more than 100 meters, characterizing hilly islands. While there is only Pakal Island in Buli Bay that has a slope of 33º and the highest elevation of only 100 meters, it is nevertheless considered a flat island. Significantly, the different typologies indicate different morphogenesis and sub-bottom topography; i.e., volcanic islands have higher slope degrees and steeper seafloor profiles compared to coral islands.

Keywords: geomorphology, seafloor profile, small island, volcanic island, coral island, Halmahera

***ABSTRAK**: Gomorfologi pulau-pulau kecil di bagian timur dan barat Pulau Halmahera memiliki keragaman proses geologi, keragaman bentuk dan tipe pulau dan keragaman topografi. Terdapat pulau-pulau vulkanik di sebelah barat Pulau Halmahera, dicirikan sebagai pulau berbukit. Pulau-pulau kecil dengan tipologi pulau karang di sebelah timur Pulau Halmahera dicirikan sebagai pulau dataran dengan luas pulau yang lebih kecil dari pulau vulkanik. Penelitian ini bertujuan untuk menganalisis elevasi masa daratan dan profil dasar perairan pada pulau-pulau kecil di bagian timur dan barat Pulau Halmahera. Data elevasi pulau di peroleh dari Citra Sentinel 2B dan data topografi dasar diperoleh dari hasil pengukuran menggunakan GPS sounder. Data-data tersebut dianalisis menggunakan QGIS versi 3.16.6 dan ArcGIS versi 10.8. Sebelum dianalisis, data citra terlebih dahulu dikoreksi yang terdiri dari koreksi atmosferik, koreksi radiometrik, dan koreksi sinar matahari. Data batimetri hasil pengukuran lapangan terlebih dahulu dikoreksi dengan data pasang surut untuk menemukan kedalaman yang sebenarnya. Hasil penelitian menunjukkan bahwa derajat kemiringan lereng di Pulau Ternate, Pulau Maitara, Pulau Tidore dan Pulau Hiri yang disingkat Termadoreh, lebih dari 30º dengan elevasi lebih dari 100 meter yang menjadi penciri pulau berbukit. Di Teluk Buli terdapat satu pulau yang memiliki kemiringan lereng lebih dari 10º yakni Pulau Pakal sebesar 33º, tetapi memiliki elevasi (kurang dari) 100 meter sehingga tetap dikategorikan pulau dataran. Pulau-pulau kecil dengan tipologi yang berbeda memiliki morfogenesa dan topografi dasar perairan yang berbeda. Pulau kecil vulkanik memiliki derajat elevasi yang lebih tinggi*

dibandingkan pulau karang. Topografi dasar perairan di pulau vulkanik lebih curam, sedangkan di pulau karang lebih landai.
***Kata Kunci:** geomorfologi, profil dasar perairan, pulau kecil, pulau vulkanik, pulau karang, Halmahera*

INTRODUCTION

According to Huggatt (2011), geomorphology studies landforms and geological processes that create the earth's surface. Formation, process, and the interrelationships between them are the key points to understanding the origin and development of landforms. Seafloor morphology deals with the formation, origin, and development of submarine features. In shallow marine environments, landforms include ripples, dunes, sand waves, sand ridges, shorelines, and subsurface channels. Submarine canyons, gullies, inter-canyon areas, intra-slope basins, and slump and slide scars are in the continental slope transition zone.

The Halmahera and Sangihe arcs in Eastern Indonesia are the only active arc-arc that are currently colliding. The Sangihe arc was constructed on the Eocene oceanic crust and initially formed at the Sundaland margin in the Early Cenozoic. The modern Halmahera arc was built upon older arcs, of which the oldest is a Mesozoic intra-oceanic arc that formed in the Pacific. Volcanism ceased, and there was widespread deposition of shallow marine limestones. Arc terranes moved westward within the Sorong fault zone. The present-day Molucca Sea double subduction system was initiated in the Middle Miocene, and volcanism began in the Halmahera arc about 11 million years ago. The Molucca Sea has since been eliminated by subduction at its eastern and western sides (Hall, 2009). These geological processes suggested the making of lands and small island groups in Halmahera.

Different island typologies may be found on small islands in North Maluku. To the west and east of Halmahera Island are volcanic islands and small coral island-like islands, respectively. Six small volcanic islands, specifically Ternate, Maitara, Tidore, Hiri, Makean, and Moti Islands, are located in the seas of West Halmahera (Mutaqin et al., 2021). The author applied an analytical method to geomorphological features, including morphology, morphogenesis, morphophonology, and morphological composition, to determine the typology of small volcanic islands in North Maluku water; where Englan, Plun, Lelewi, and Pakal Islands are growing coral islands with a flat island type located in Buli Bay in the eastern part of Halmahera Island. Referring to Bengen et al. (2012), coral islands were made of quaternary clastic sediments and are often bordered by coral reefs. The movement of tectonic plates controlled the formation of small islands off North Maluku. Hall et al. (1988) argued that the activities of the three plates, i.e., the Moluccas and the Philippine oceanic plates, and the Halmahera sub-plate, as well as the Sorong sub-fault, have an impact on the formation of small islands around Halmahera Island. Ternate, Maitara, Tidore, and Hiri Islands are small islands that, according to the geological map, were created in the Late Pleistocene, with the most recent volcanic materials making up the geological structure.

The movement of tectonic plates affected island creation and the seafloor topography of these small islands (Hall et al., 1988). Halmahera and the nearby small islands are situated in the western Pacific Ocean (on the Philippine oceanic plate), west off the Molucca Sea, as stated by Gorsel (2018). The Sangihe arc in the west and Halmahera Island in the east are where the Molucca oceanic crust is moving. The Sorong Fault Zone encloses the southern side, extending from the westward Australia-New Guinea plate. The movement of these plates stimulated the formation of small islands in North Maluku.

This research on the geomorphology of small islands in the eastern and western parts of Halmahera Island is based on the idea that these small islands have a diversity of geological processes, a diversity of forms and types of islands, and a diversity of topography. This study analyzes the land mass elevation and the sub-bottom profiles around the small islands to the east and west of Halmahera Island. The results of this study are expected to serve as reference material for policymakers drafting the management plan of small islands in North Maluku.

DATA AND METHODS

On January 10-17, 2021, bathymetry data were collected on Pakal, Plun, Lelewi, and Englan islands in East Halmahera, as well as on February 3-10, 2021, on Hiri, Ternate, Maitara, and Tidore islands in West Halmahera (Figure 1).

For this study, the Garmin GPSMAP 64s type was used to find the coordinate position with an accuracy of 3–6 meters, and the Garmin GPS Sounder 350C type was used to measure the depth of the water. The data used is satellite imagery from Sentinel 2B that was taken on April 5, 2021, with a cloud cover of 15.35% for the western part and 59.20% for the eastern part of Halmahera that can be accessed on Copernicus Open Access Hub (https://scihub.copernicus.eu/) with a spatial resolution of 10 meters as shown in Table 1. SRTM data with a spatial resolution of 30 meters can be accessed on EarthExplorer (https://earthexplorer.usgs.gov/). ESA SNAP version 8.0, QGIS version 3.16.6 Hannover, and ArcGIS version 10.8 were used for data processing.

ESA SNAP was used to process Sentinel 2 images, starting with the atmospheric correction process and continuing through image processing to produce bathymetry with actual depth using the sen2coral toolbox. QGIS version 3.16.6 Hannover was used to reconstruct bathymetric and topographic data to eliminate noise. ArcGIS version 10.8 was used to calculate land elevation, interpolation process, and vertical plot transects to obtain

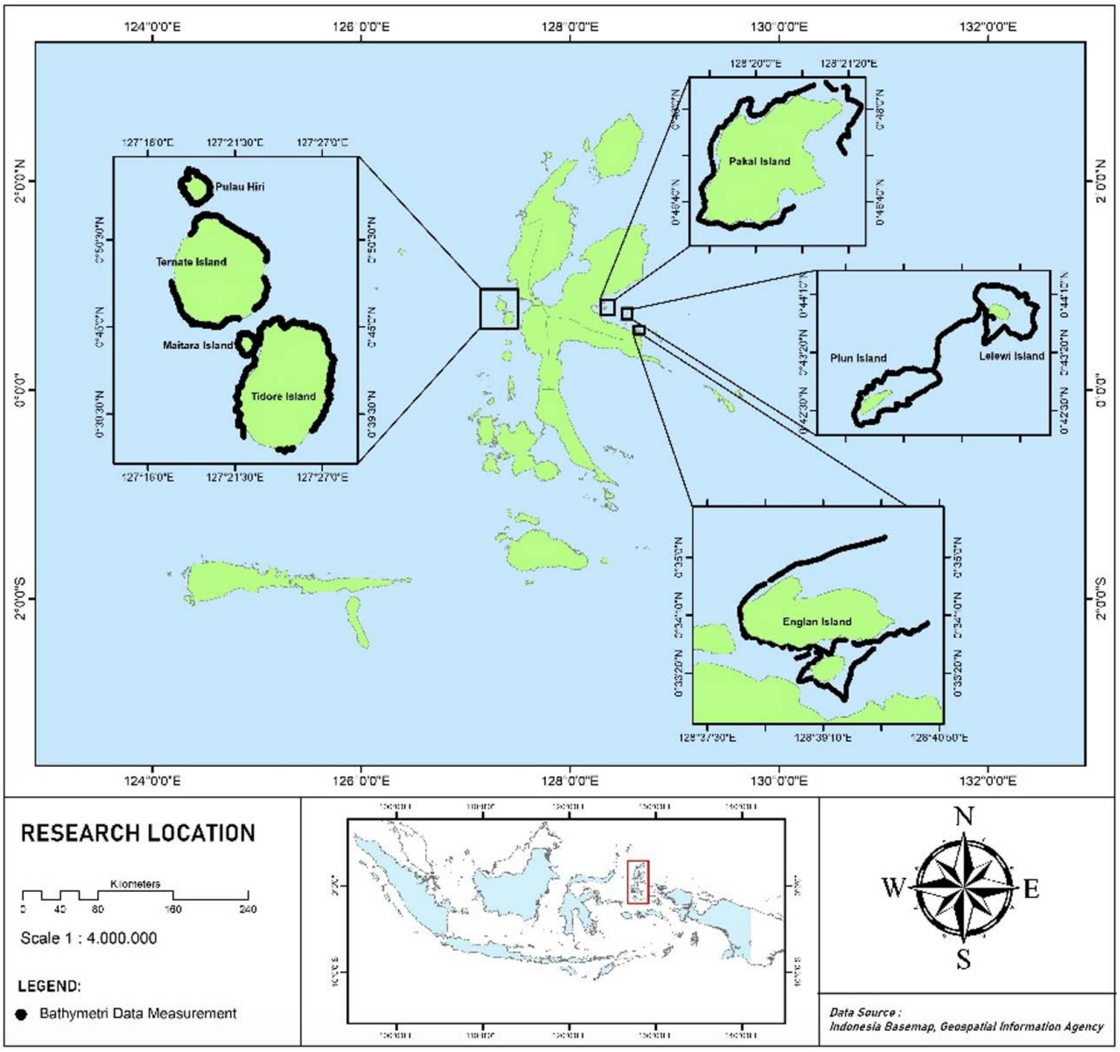
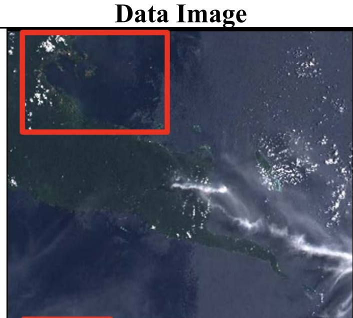


Figure 1. Area of research interest

Table 1. Sentinel 2B Satellite Imagery Data Acquisition (scihub.copernicus.eu)

No	Data Set Attribute	Attribute Value	Data Image
1	Entity ID Acquisition Start Date Acquisition End Date Cloud Cover	S2B_MSIL1C_20210405T015619_N0300_R117_T52NDF 2021-04-05T01:56:18.462Z 2021-04-05T02:02:44.493Z 59.20%	
2	Entity ID Acquisition Start Date Acquisition End Date Cloud Cover	S2B_MSIL1C_20210405T015619_N0300_R117_T52NCF 2021-04-05T01:56:18.462Z 2021-04-05T02:02:44.493Z 15.35%	

transverse profiles for topography and geomorphology. The process of data processing can be seen in Figure 2.

Data Analysis

a. Atmospheric Correction

Atmospheric correction is performed to remove the top of atmospheric (TOA) and bottom of atmospheric (BOA) disturbances from picture data to extra reflectance values from the image (surface and bottom reflectance). Atmospheric correction often uses the dark dense vegetation (DDV) technique, which assumes that the red-to-blue surface reflectance ratio is constant (Hsu et al. 2004). This algorithm's equation is:

$$\rho^s_{red} = k\rho^s_{blue} \quad \text{.......................................} \quad (1)$$

where ρ^s_{red} dan ρ^s_{blue} are the spectral surface reflectance angles at 0.66 μm and 0.47 μm, respectively, and k is a constant value.

b. Radiometric Correction

The simplest and most used way is to subtract the dark pixel value from the beginning value (Doxani et al., 2012), which is represented by the equation:

$$R_{ac} = R_i - R_{dp} \quad \text{.......................................} \quad (2)$$

where R_{ac} represents the adjusted pixel value, R_i represents the original pixel value, and R_{dp} represents the dark pixel value.

c. Sun Glint Correction

Using the simplified approach developed by Hedley et al. (2005) (in Doxani et al., 2012), sun glint was removed from the picture. This approach enhances the previous method by creating a linear link between the NIR and visible bands (RGB) using linear regression on an image pixel sample.

$$R'_i = R_i - b_i\,(R_{NIR} - Min_{NIR}) \quad \text{.....................} \quad (3)$$

where R'_i is the corrected pixel value, R_i is the initial pixel value, b_i is the slope of the regression line, and R_{NIR} is the minimum Min_{NIR} value in the pixel sample.

d. Bathymetric Inversion

Transformation of water depth images uses an algorithm developed by Stumpf et al. (2003):

$$Z = m_1 \frac{\ln(n*R_w(\lambda_i))}{\ln(n*R_w(\lambda_j))} - m_0 \quad \text{..................................} (4)$$

where:

Z: the estimated depth

m_1: the calibration coefficient

R_w (λ_i): the reflectance value per channel (i or j)

m_0: the correction factor

n: a constant that maintains a positive ratio

The coefficients m_1 and m_0 are produced from the regression results of the ratio of the selected channel to the depth of field (i.e., slope and intercept values), with m_0 being the absolute value of the regression intercept in this instance.

The depth estimation process using the channel ratio algorithm is generally carried out in two stages: relative depth estimation and actual depth calibration (Loomis, 2009; Madden, 2011). The relative depth in question is calculated by subtracting the values of m_1 and m_0 from the $\rho^s_{red} = k\rho^s_{blue}$ .... (1) ameters m_1 and m_0 using linear regression between channel ratio (relative depth) and depth of field. In addition, the parameter values are employed to calibrate the relative depth to the actual depth using equation (4).

e. Inverse Distance Weight

IDW is an interpolation method that assumes each input point has a declining local influence on distance. The IDW approach is often impacted by the distance inverse derived from the following equation by Azpurua and Ramos (2010):

$$Z^* = \sum_{i-1}^{N} w_i Z_i \quad \text{...................................} \quad (5)$$

where Z_i (i = 1,2,3,..., N) represents the value of the height of the data that you wish to interpolate using N points; and W_i has the following equation:

$$w_i = \frac{h_i^{-p}}{\sum_{j=0}^{n} h_j^{-p}} \quad \text{.......................................} (6)$$

where p is a positive value that can be varied and is usually called the power parameter (usually a value of 2) and h_j is the distance from the point distribution to the interpolation point, which is defined as follows:

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad \text{..............} \quad (7)$$

(x,y) represent the coordinates of the interpolated points, whereas (x_i, y_i) represent the coordinates of each point distribution. The weight variable function for the entire point distribution data fluctuates to a value near zero as the distance rises with the point distribution.

This IDW interpolation's power number influences the effect on the input points, with the outcome being more substantial at closer points to provide a more detailed surface. The impact will diminish with increasing distance, resulting in a less complex and smoother texture. If the power value is raised, the output value of the cell becomes more localized and has a lower average value. A drop in power value will increase average output since it will affect a more extensive region. Reduce the power value to make the surface smoother. As pointed out by Philip & Watson (1982) (in Merwade et al., 2006), the average weight is the distance function derivative between the sample and interpolated points. The standard function of weighting is the inverse of the distance's square.

f. Slope

The slope is the surface gradient with the most remarkable change value at each elevation raster pixel

(Walbridge et al., 2018). The equation proposed by Horn (1981) for the computation of slope is as follows:

$$arctan\sqrt{(\frac{dz^2}{dx}+\frac{dz^2}{dy})} \text{ .... } (8)$$

where $\frac{dz^2}{dx}$ is the value of z on the x-axis and $\frac{dz^2}{dy}$ is the value of z on the y-axis.

Slope classification is based on the criteria of Van Zuidam (1985):

1. Flat = 0-3% (0-2º).
2. Gently slope = 2-7% (2-4º).
3. Sloping = 7-15% (4-8º).
4. Moderately Steep = 15-30% (8-16º).
5. Steep = 30-70% (16-35º).
6. Very steep = 70-140% (35-55º)
7. Extremely Steep = > 140% (>55º).

RESULTS

a. Bathymetry

Based on the Sentinel 2B satellite image, the water depth is estimated by comparing the two bands to the observed depth on the ground and by selecting the band ratio with the highest coefficient of determination (R^2). Based on the regression results, the band ratio with the most increased regression is the ratio of bands 2 and 3, as seen in Figure 3, with a range of values reported in Table 2.

The slope and intercept values derived from the regression between the band 2 and band 3 ratios in Table 2 are then utilized to translate the band ratio findings into actual depth using equation 4. Bands 2 and 3 are wavelength bands in blue (band 2) and green (band 3), respectively. Both bands have intense wave penetration in penetrating the water column to the bottom depth

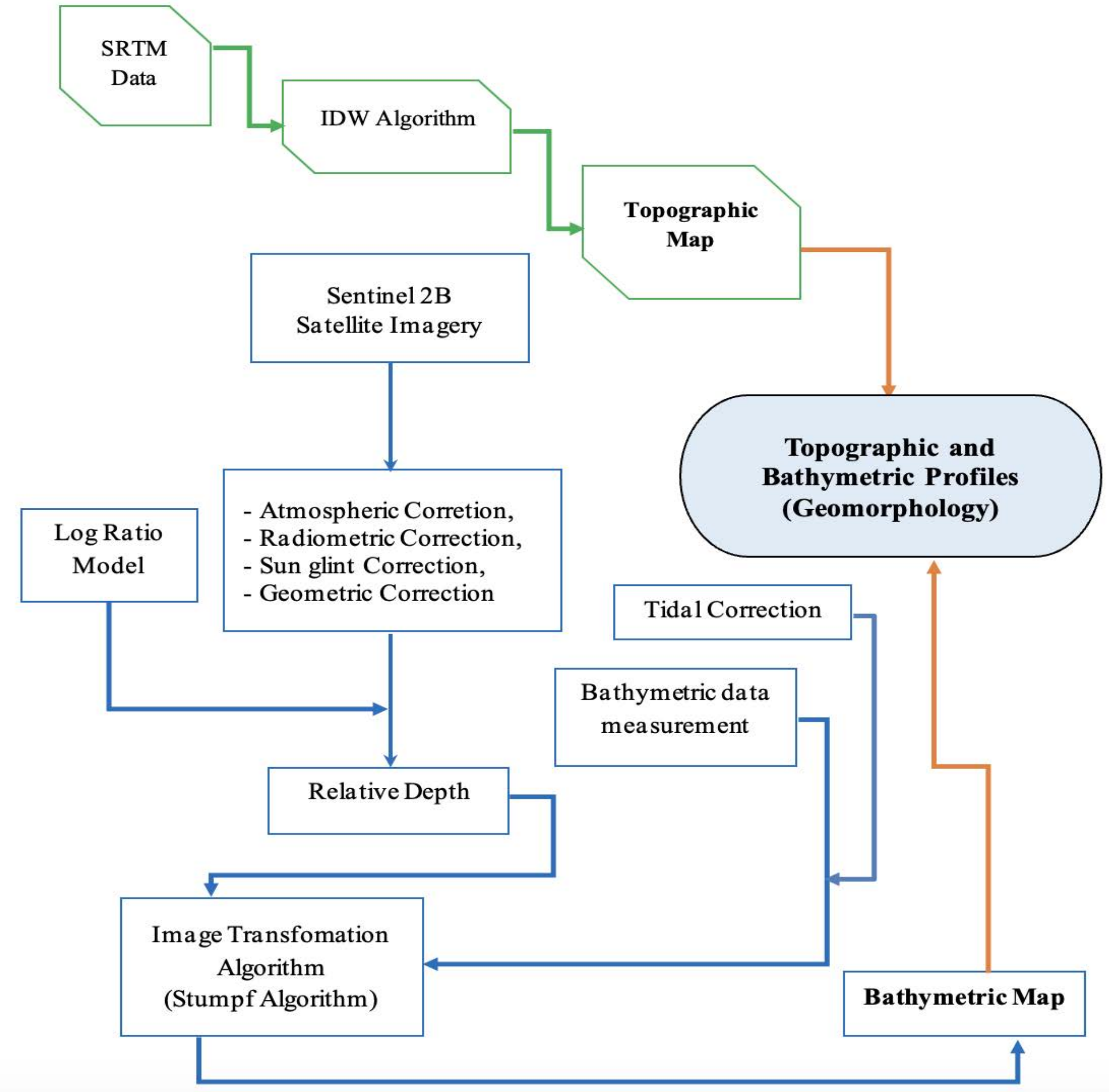


Figure 2. Flow Chart Research Process

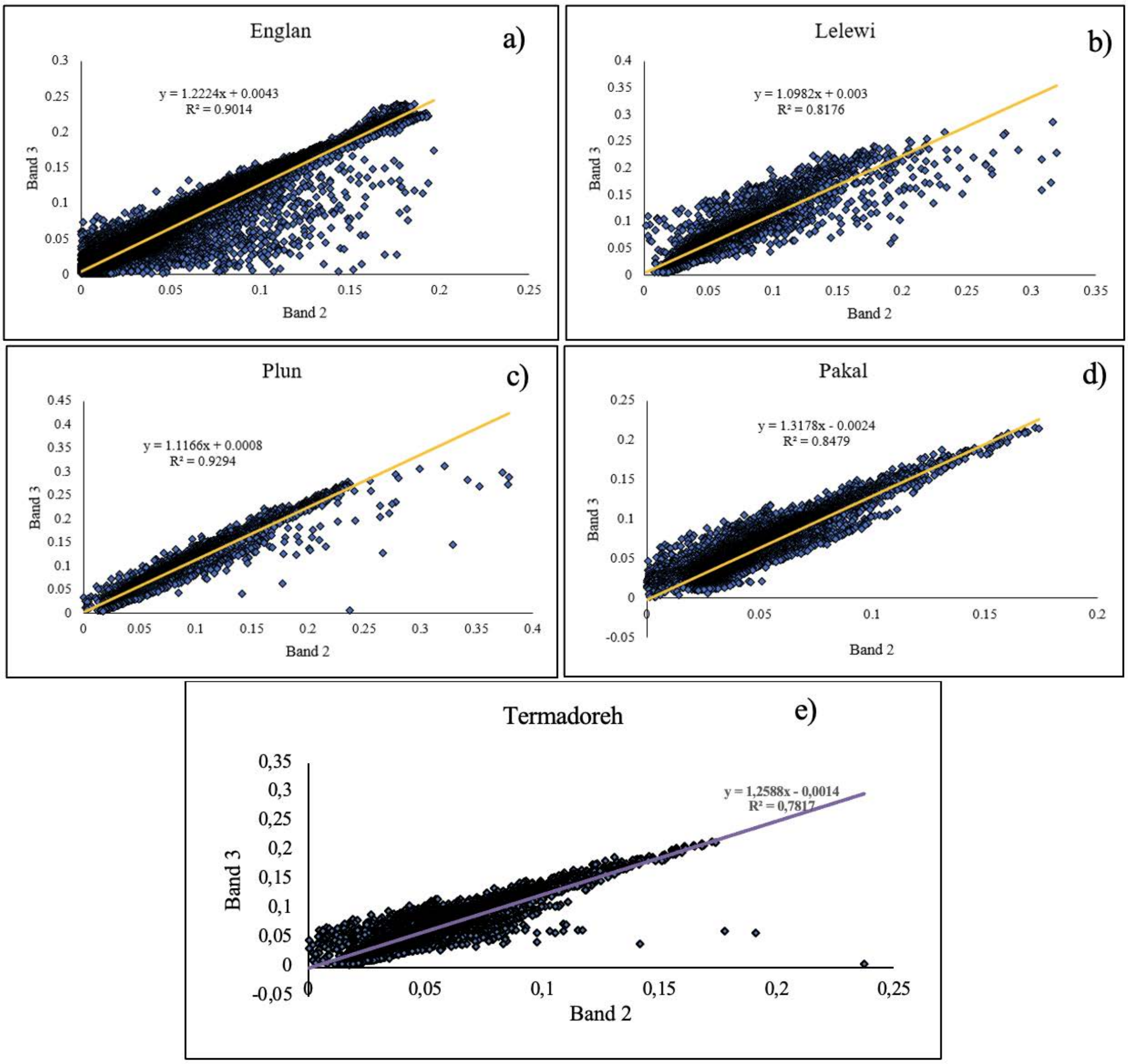


Figure 3. Band pair regression of 2 and 3: a). Englan; b). Lelewi; c). Plun; d). Pakal; e). Termadoreh

Table 2. Results of regression ratio of band 2 and band 3

Name	R^2	Slope	Intercept
Englan	0.9014	1.2224	0.0043
Lelewi	0.8176	1.0982	0.003
Plun	0.9294	1.1166	0.0008
Pakal	0.8479	1.3178	-0.0024
Termadoreh	0.7817	1.2588	-0.0014

compared to band 4 (red wavelength) (Lyzenga, 1981). Figures 4 and 5 display the reconstructed depth image.

The remaining four islands, namely Hiri, Ternate, Maitara, and Tidore, had their sea depths estimated by interpolating the depth of field hearing locations. The utilized interpolation technique is inverse distance weighted (IDW). This interpolation method posits that each input location has a local impact that diminishes with distance. When measuring depth of field, the sample point distance density will significantly impact achieving optimal findings. Figure 5 depicts the results obtained using this strategy.

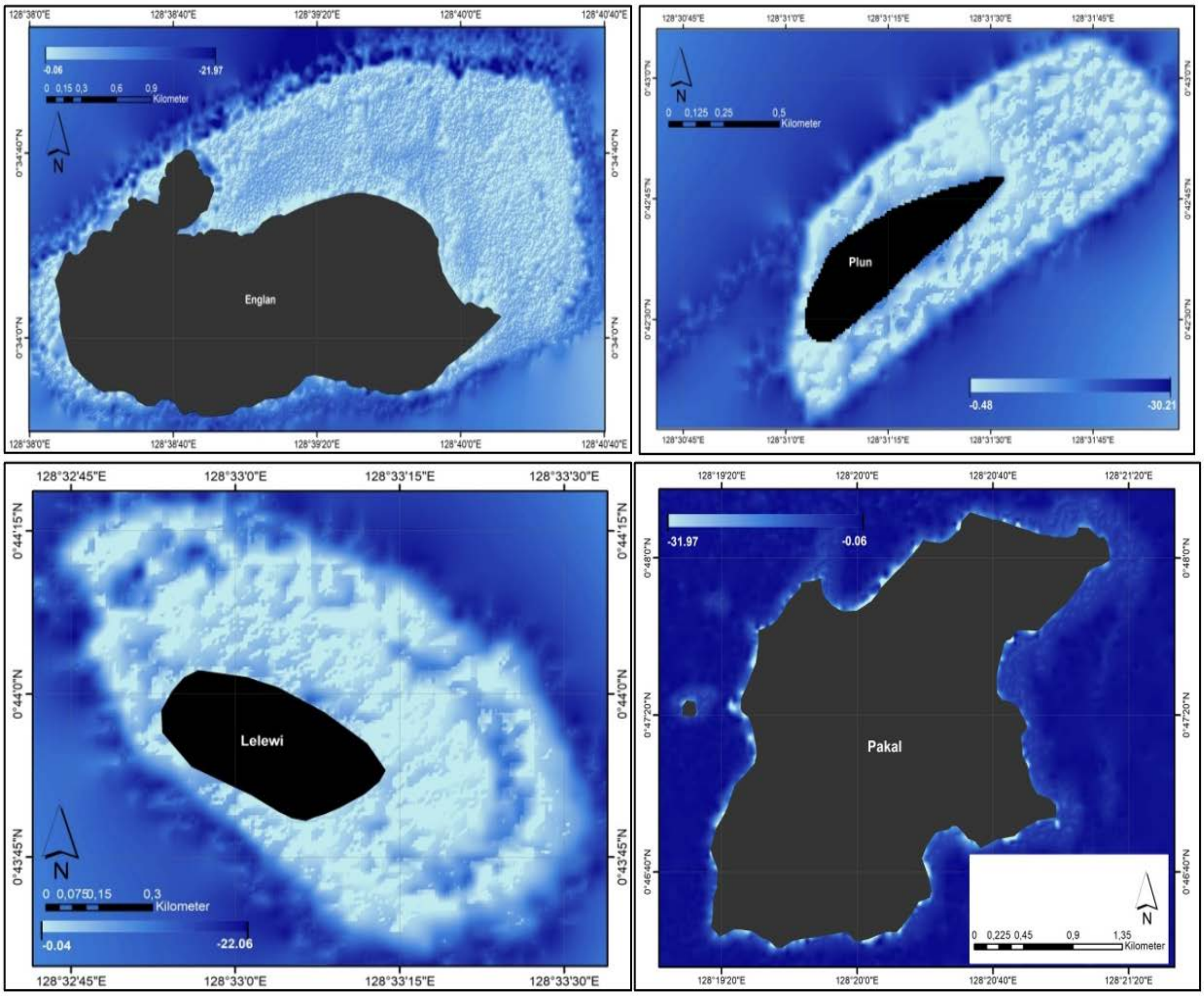


Figure 4. The actual depth of the ratio transformation of band 2 and band 3

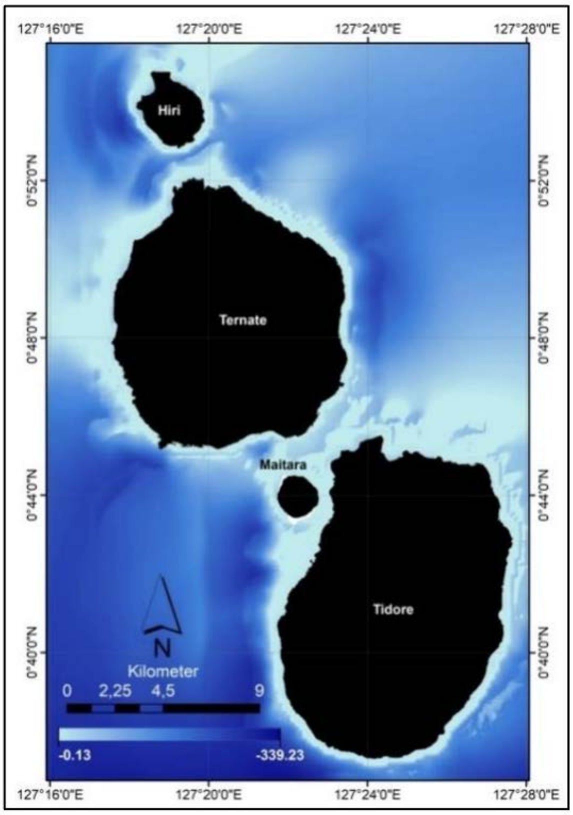


Figure 5. The actual depth of the interpolation using IDW in Termadoreh

Based on the spatial description of the actual depth in the Termadoreh island group (Figure 5), it shows that the islands with the distance between the coastline and the deep sea are Hiri Island and Ternate Island.

b. Seafloor Profile

The research area's small islands have a variety of bottom profiles. Except for Pakal Island (P.07), which has a high bottom profile with a distance between the coastline and shallow seas > 300 m, the islands in Buli Bay have a gently sloping bottom profile (Figures 6 and 7).

The bottom profile of the small islands of Termadoreh has a steep topography (Figures 8 and 9), except at the observation points, namely Hiri Island (T02), Maitara Island, (T05) and Tidore Island (T08).

The description of the water's bottom profile in Figure 9 shows that the P. Hiri T01 station is the steepest observation point. The bottom slope of the water forms a slope of 25 degrees. Hiri Island is located to the north of the Termadoreh Island group, which is directly opposite the movement of water masses in the Molucca Sea.

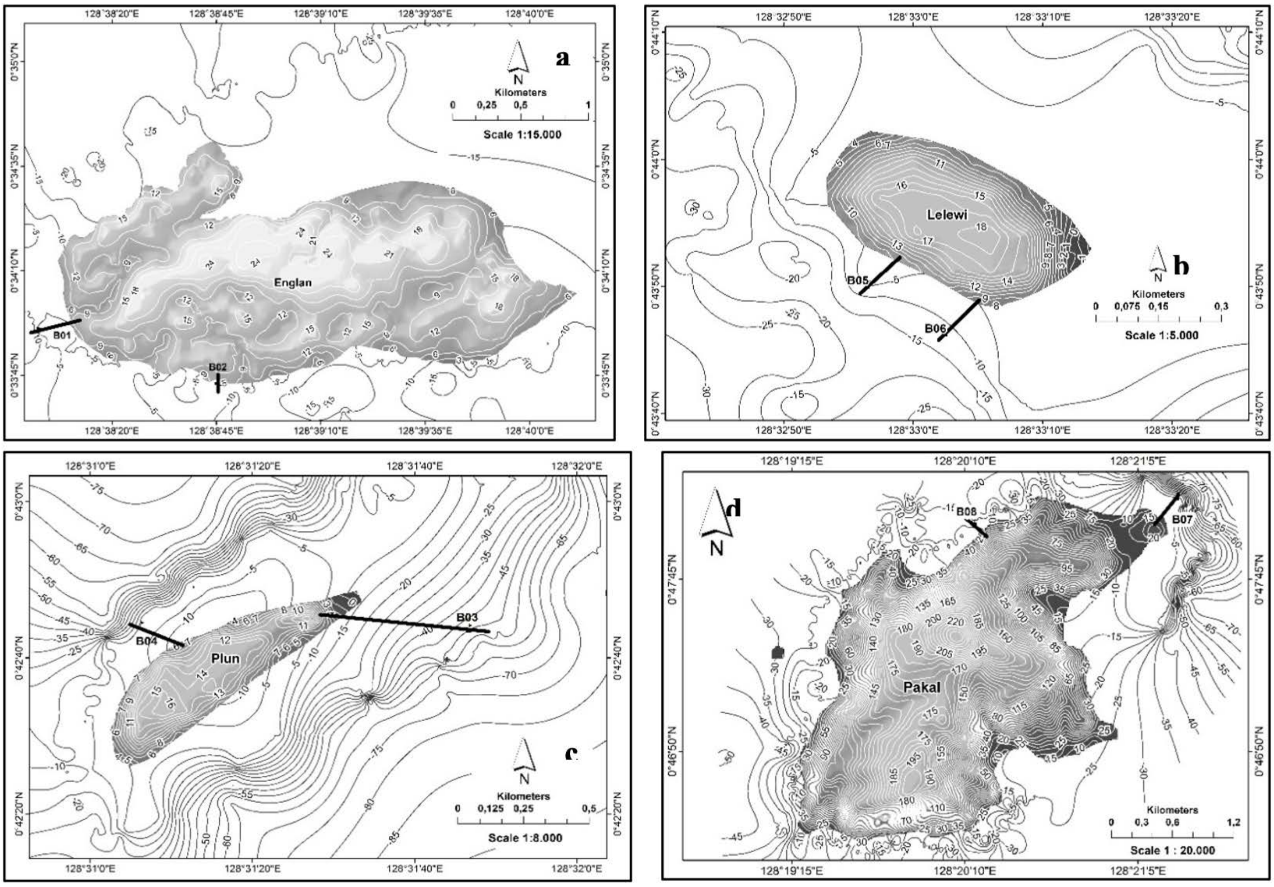


Figure 6. Contours of island elevation and bathymetry around islands in Buli Bay (a. Englan Island, b. Plun Island, c. Lelewi Island, d. Pakal Island). The cross-section is the data for the seafloor profile in figure 7.

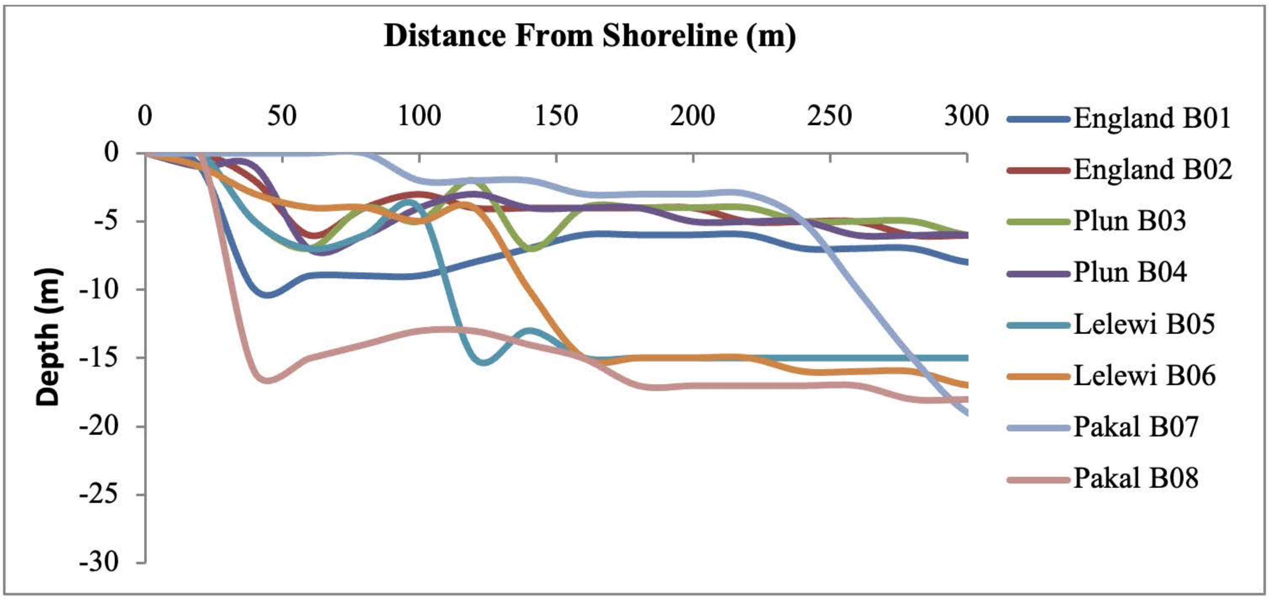


Figure 7. Seafloor profile of small islands in Buli Bay

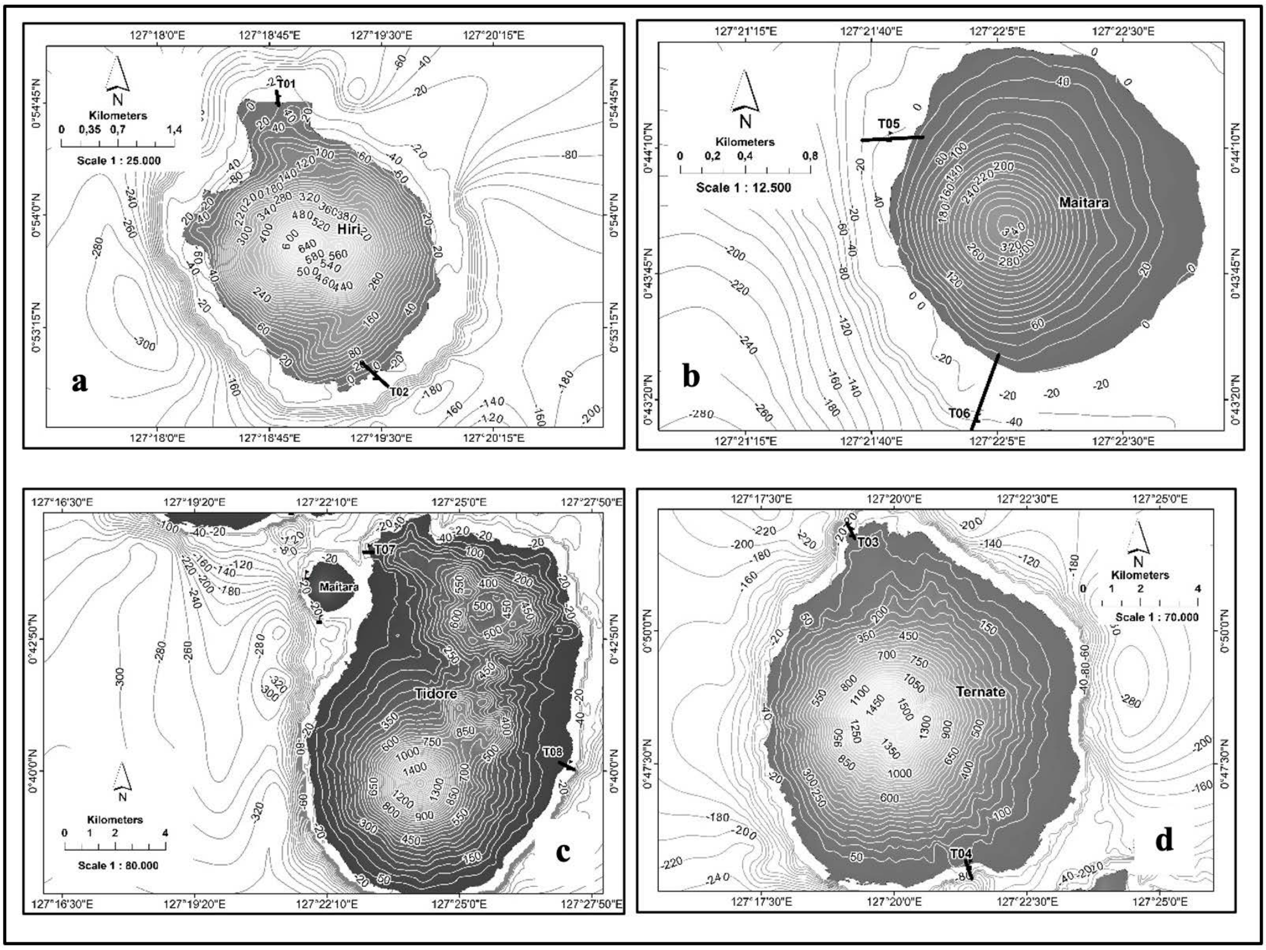


Figure 8. Contours of island elevation and bathymetry in the waters of the small islands of Termadoreh (a. Hiri Island, b. Ternate Island, c. Maitara Island, d. Tidore Island). The cross-section is the data for the seafloor profile in figure 9.

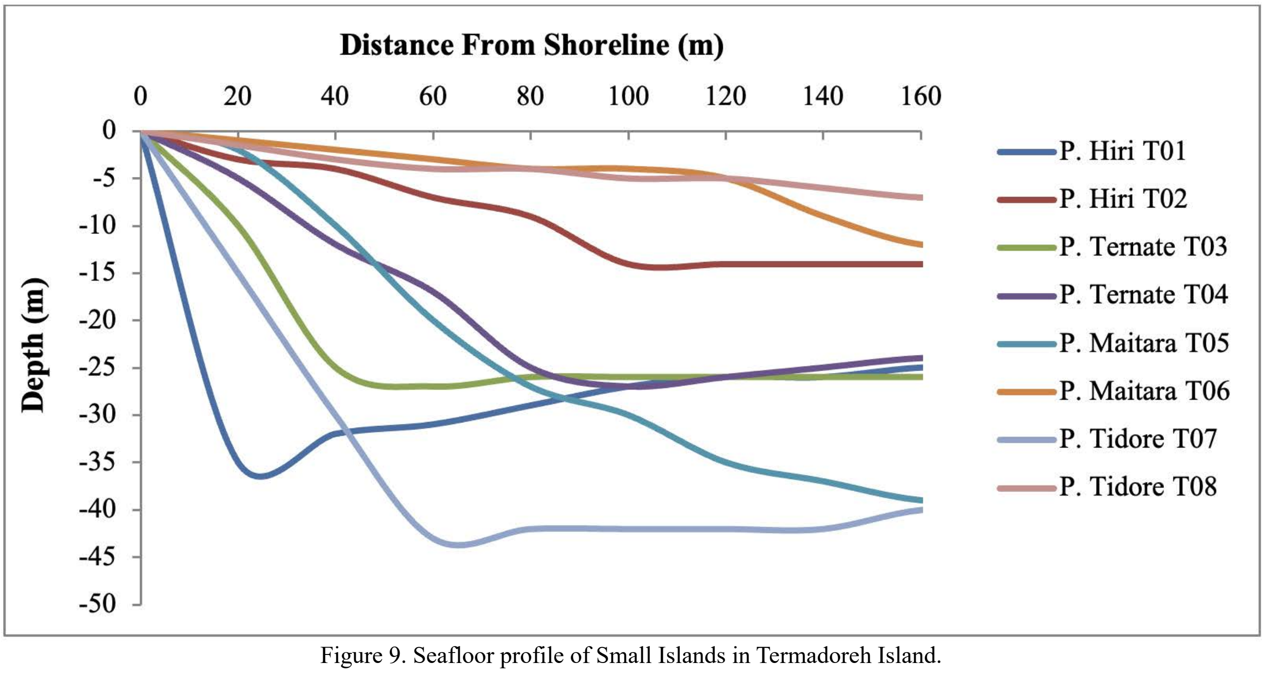


Figure 9. Seafloor profile of Small Islands in Termadoreh Island.

c. Slope Gradient of Island's Topography

The slope or gradient of the surface is the elevation raster pixel with the most significant change value (Walbridge et al., 2018). In this study, the slope value is calculated to modify the SRTM picture so that the land elevation on the water base profile may be interpreted. The resultant slope value is expressed in degrees, with 0 representing a level plane, and the maximum value depends on the properties of the base surface (Figure 10).

Variations in fundamental surface features affect the resultant slope value for each island. The range of computed slope values is shown in Table 3. The lowest average slope value is on coral islands such as Englan, Lelewi, Plun, and Pakal, and the highest is on volcanic islands such as Hiri, Ternate, Maitara, and Tidore.

Table 3 shows slope calculation values that indicate a substantial difference between the small islands in Buli Bay and the Termadoreh islands. The slope of small islands in Buli Bay runs from 0 to 33°, but in Termadoreh island, it ranges from 0 to 44°. According to Bengen et al. (2012), flat islands have a land mass elevation of less than 100 meters and hilly islands have an elevation above 100 meters. Except for Pakal Island, the coral islands of Englan, Lelewi, and Plun islands have gently sloping category ranging from 0 to 10.14º or 0 to 2.85%. Therefore, Englan, Pakal, Plun, and Lelewi islands are flat islands, as their elevation is less than 100 meters. Ternate, Maitara, Tidore, and Hiri islands are steep volcanic islands, categorized as hilly islands since their slope is

Table 3. Slope calculation results on each island (according to Van Zuidam, 1985)

Name	*Slope* (^{0})	*Slope* (%)	*Category*
Englan	0.003 – 10.04	2.85	Gently Slope
Lelewi	0.006 – 10.01	2.78	Gently Slope
Plun	0.02 – 10.14	2.81	Gently Slope
Pakal	0.03 – 33.91	9.41	Sloping
Hiri	0.38 – 44.82	12.45	Sloping
Ternate	0.04 – 41.71	11.58	Sloping
Maitara	0.19 – 39.85	11,06	Sloping
Tidore	0.07 – 39.99	11.08	Sloping

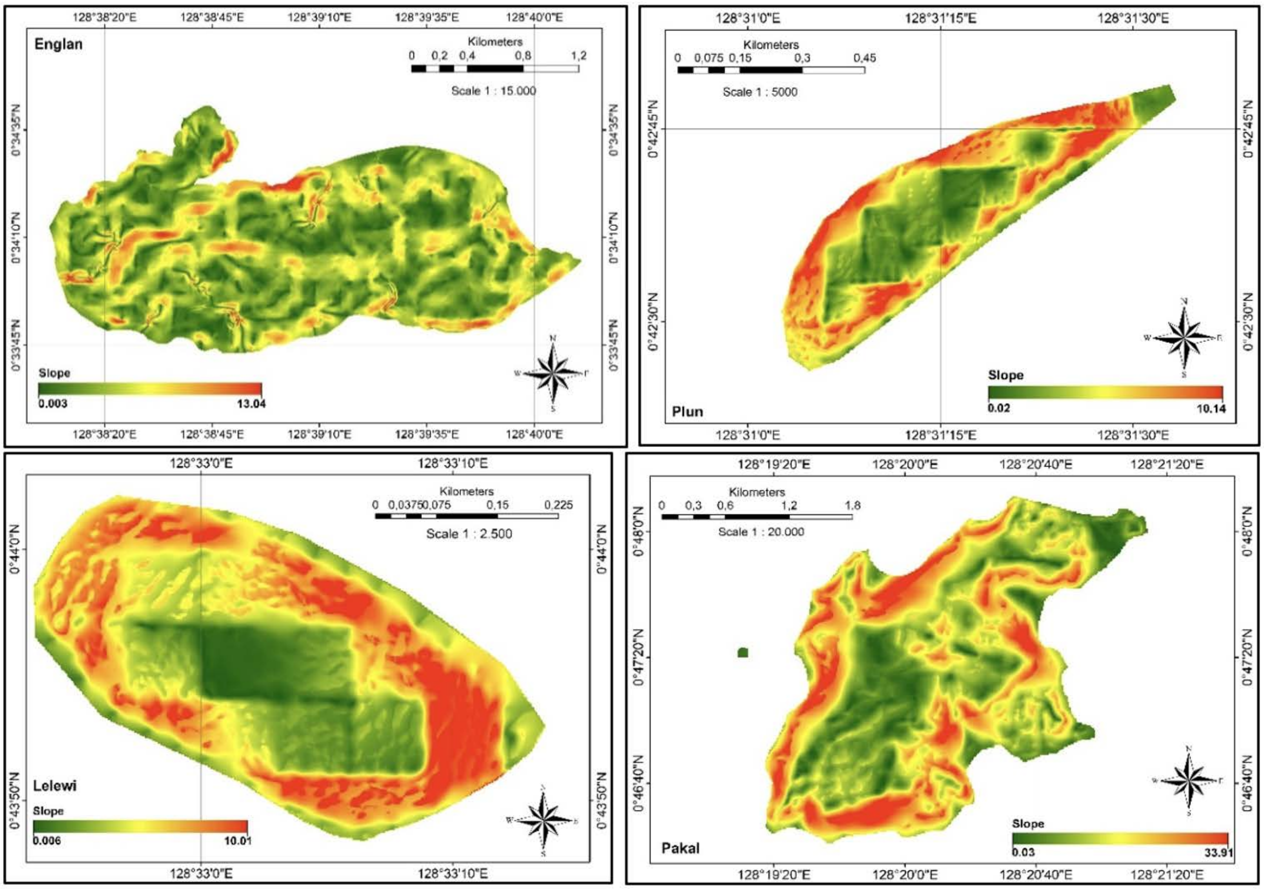


Figure 10. The land surface slopes of the islands in Buli Bay (England, Plun, Lelewi, and Pakal islands).

greater than 30º and their elevation is more than 100 meters.

Coral islands are composed of shells and coral sediments that contain calcium carbonate. Coral islands have sparse vegetation. There are delicate vegetation, coconuts, and new trees, generally post- to pre- vegetation. It has a narrow freshwater lens, so it is not easy to find freshwater sources, except on Englan Island. The hilly volcanic islands (Termadoreh islands) are composed of pyroclastic rocks, have dense vegetation, and act as freshwater absorbers. It has a broader freshwater storage area; thus, many freshwater sources are found.

island that has the highest degree of slope in Buli Bay, which is 9.4%. The island with the lowest slope is Lelewi Island, at 2.78%.

The islands in the Termadoreh island group describe the hilly characteristics of the island. Table 3 shows that the island with the most significant slope value is Hiri Island at 44.82° or 12.45% (sloping or hilly island). The island with the lowest slope degree is Maitara Island, with a slope value of 39.85º or 11.96%, categorized as a sloping or hilly island.

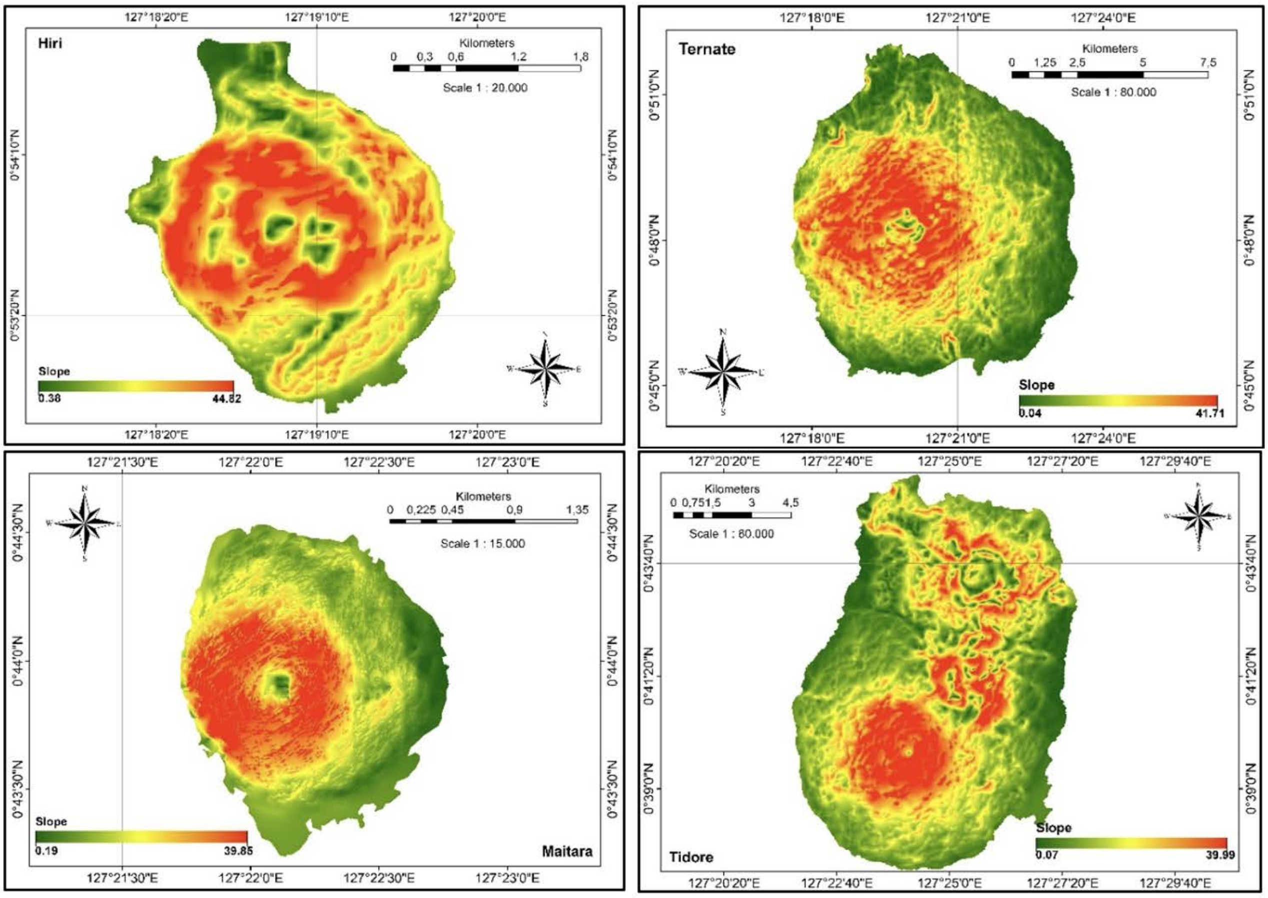


Figure 11. The land surface slope of the small islands of Termadoreh (Hiri, Ternate, Maitara, and Tidore islands).

The slope maps in Figures 10 and 11 vividly illustrate the various island inclination gradients. Figure 10 depicts islands in Buli Bay with a green peak, indicating that these islands belong to the flat group. The green hue has a slope of 0 to 10°, which, when translated to a percentage, spans from 0 to 3%. Except for Pakal Island with a slope of 0 to 33.9° or 0 to 9.41%, their terrain is hilly. All the small islands in the Termadoreh islands have a slope degree of more than 30° or greater than 10%, placing them in the category of sloping, thus hilly islands.

Based on this view, Figure 9 describes the geomorphology of small islands in Buli Bay. Punched from the island's area, Englan Island is wider than other islands. Based on the degree of slope, Pakal Island is the

DISCUSSIONS

The forming process of small islands in Halmahera is influenced by the movement of the Sangihe and Halmahera arcs. According to Hall (2009), both arcs first collided about 3 million years ago. This contact was followed by repeated thrusting of the Halmahera fore-arc and back-arc toward the active volcanic arc. The collision has formed a melange wedge in the central Molucca Sea, including ophiolite slices from the basement of the Sangihe arc. There are small fragments of continental crust between the splays of the Sorong Fault Zone. The western part, according to Gorsel (2018), is the Molucca Sea complex, where the oceanic crust of the Molucca Sea plate is subducting under the Halmahera arc to the east and the

Sangihe arc to the west, and is bordered by the Sorong Fault Zone to the south. A significant strike-slip area separated the Pacific plate, which is moving to the west, and the Australia-New Guinea plate, which is moving to the north. The islands, which intrude into and overlie the collisional complexes of Jurassic or Cretaceous ophiolites, are composed of Late Cretaceous to Middle Eocene fragments and a younger volcanic island arc. Except for parts of the islands in the Sorong Fault Zone complex, no pre-Tertiary sediments or continental crust material have been reported.

The small islands in Buli Bay (East Halmahera) are embossed coral islands, whose bottom sediments of the beach consist of a length of white sands derived from processing coral material. Coral islands were produced when coral reefs were raised above sea level due to the uplift and subsidence of the seafloor caused by geological processes (Bengen et al., 2012). The process of forming small islands in East Halmahera was influenced by geological processes on Halmahera Island and its surroundings. In addition, Hall (2009) stated that the initiation of eastward Halmahera subduction probably resulted from the fault strand locking of the left-lateral Sorong Fault Zone at its western end in Sulawesi.

The volcanic islands of Termadoreh are distinguished by the black sands that formed the coastline due to the breakdown of waste rock debris resulting from volcanic eruptions. On volcanic islands, the coastline is composed of relics of volcanic eruptions in the form of rock islands. Bengen et al. (2012) stated that volcanic islands consist of pyroclastic deposits, lava, and ignimbrites. Volcanic islands were entirely generated by volcanic activity progressively rising from the ocean floor to the surface. According to Mutaqin et al. (2022), the small volcanic islands, i.e., Ternate, Maitara, Tidore, and Hiri islands in North Maluku, were produced by three plate subduction zones (Philippines, Indo-Australia, and Eurasia).

A group of volcanic islands, namely Ternate, Maitara, Tidore, and Hiri islands, are a group of islands abbreviated as Termadoreh. This island group has a steep bottom topography located to the west of Halmahera Island. Maitara Island is an island with more expansive shallow waters (Novico et al., 2021). The small coral islands in Buli Bay have a simple island typology, and the sloping sub-bottom profile dominates the bottom topography. The sub-bottom profile of the minor volcanic islands of Termadoreh is steeper than that of the coral islands in Buli Bay (Englan, Pakal, Plun, and Lelewi islands). It is believed that this discrepancy resulted from the geological process of island development. Volcanic islands were generated by geological events that occurred in the past. The seas around the small islands in Buli Bay are shallow and vastly expansive. The water depth ranges from 0 to 500 meters, separating the beach and the deep water. The small islands of Termadoreh have a steep terrain and shallow, confined seas. The volcanic islands of Termadoreh are a collection of volcanic islands generated by plate collisions (Gorsel, 2018 and Mutaqin et al., 2021). It is a mountainous island chain with a steep seafloor topography.

One island in Buli Bay, notably Pakal Island, has a slope of more than 10°, which is exactly 33°, and is classified as a hilly island. According to van Zuidam (1985), an island with a slope value of 16 to 35º has a steep category. Bengen et al. (2012) stated the hilly island has an altitude of more than 10° or an elevation greater than 100 meters. Besides, Wicaksono et al. (2021) stated that Pakal Island is an island with the morphology of hills and elevation variety up to 250 meters MSL. Stratigraphically, the research area is dominated by ultramafic rocks, consisting of peridotite and dunite, but entirely covered by the marine environment of coral reefs. As basement, dunite has a greenish-yellowish color and is fine- to very-fine-grained, while peridotite is dark grey. In this rock, gabbro and basaltic fractures commonly occur. The mineralization in the ultrabasic rock produces serpentinite and garnierite.

The hydrological conditions of small islands in Buli Bay are closely related to the island morphology and geologic rock type. Englan, Lelewi and Plun, and Pakal islands are coral islands that were formed from a pile of fine white sand due to the bioerosion process of sea shells and coral organisms. According to Falkland et al. (1991), small islands present a broad spectrum of geological and hydrogeological conditions. Bengen et al. (2012) reported that the geologic rock types of coral islands are generally young in the form of fluviatile clastic deposits with a base layer consisting of massive layered-sediments or coral/coral fragments.

These islands are morphologically thought to have a freshwater lens, which explain the availability of fresh water found there. On Englan Island, there is a source of freshwater discovered by the community with a depth of 5 meters. From its content, the water is still categorized as brackish because of its close distance to seawater, occurring mixing from seawater intrusion. Englan Island is close to Halmahera Island. As mentioned by Falkland et al. (1991), freshwater sources on small islands are directly influenced by their close position to large islands, hence share the same aquifer.

The freshwater lens on flat islands is very thin, influenced by the morphological structure of the island and the sediment and substrate that formed on the island. These two things are closely related to forming a water reservoir layer or aquifer. White et al. (2002) proved groundwater occurs as a thin lens of fresh water floating above seawater in coral sands and limestone aquifers. Furthermore, Marganingrum and Sudrajat (2018) mentioned that the availability of fresh water on small flat islands is minimal because it depends on the presence of a freshwater lens. A typical freshwater lens on a small island is generally influenced by several primary factors, namely the area of rainwater catchment, the type of island aquifer, climate, and local community activities. The rainwater catchment area is an internal natural limiting factor. The island aquifer factor is also an internal factor that depends on the type of geologic rocks and soil. In addition, there are also external limiting factors, namely the influence of rain and tides. Falkland (1991) suggested that the substrate on the atoll islands is mostly coarse coral sand. Minimal surface runoff yields a small opportunity for groundwater storage on the substrate surface. According to Marganingrum and Sudrajat (2018), the ability of the soil to store water on small islands is not only influenced by the characteristics of the soil itself (internal factor) but also by rain and tidal influences (external factor).

The Termadoreh island group comprises volcanic islands with pyroclastic rock types (Mutaqin et al., 2021). It has a dense and wide green open area with a strong vegetation structure acting as freshwater absorber and reservoir. These islands have fresh water sources that come from mountain water and groundwater. According to Falkland et al. (1991), cone-shaped volcanic that were produced by subduction are hilly islands with heights that can reach hundreds and thousands of meters above sea level. Volcanic islands are generally known as high-elevation islands and are covered by new, more porous material that extends to the shoreline. Thus, the condition of groundwater flow can be accommodated.

CONCLUSIONS

It is proven that different typologies of small islands, especially in North Maluku's water, have diverse morphogenesis and basic topography. Based on this analysis, it can be concluded that small volcanic islands have a higher degree of island elevation than coral islands. The bottom topography of the waters on volcanic islands is steeper, while on coral islands, it is gentler. The small islands in Buli Bay have a sloping bottom profile; the most profound depth is 20 meters, with the furthest distance from the shoreline as far as 320 meters. The steepest bottom topography is found on Hiri Island at the observation point T01, and the lowest is on Maitara Island (T06). The bottom topography of the waters of small islands in Buli Bay is steep on Pakal Island (B07) and gentle on Englan Island (B02). Based on the percentage of island slope, there are three flat islands in Buli Bay and one hilly island. In the Termadoreh islands, all four islands are hilly. Hiri Island has the highest slope percentage level of 12.45%, or 44.82°.

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