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Mapping Intertidal Zone Extents and Seasonal Variations in Coastal Areas of Palawan Using Sentinel-2 Derived Bathymetry

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ABSTRACT

Intertidal zones are coastal wetland regions that support multiple ecosystem services and are significant carbon reservoirs. With the loss of intertidal extents worldwide over the past decades due to global sea level rise and anthropogenic factors, it is critical to map these areas to monitor any further losses and subsequent changes in tidal habitats. Being one of the most temporally and spatially variable marine habitats affected by diurnal tides, traditional survey methods can be quite difficult and expensive. On the contrary, remote sensing provides a more efficient and cost-effective way for mapping the intertidal zones at a high spatial resolution of 10 meters for sensors like Sentinel-2 Multi-Spectral Imager (MSI). These outputs can aid in coastal and biodiversity management practices including environmental planning, policymaking, and implementation. For this study, we have chosen the coast of Honda Bay in the eastern coast of Puerto Princesa City and Rasa Island in the biodiversity-rich island-province of Palawan, Philippines. While more popular methods to map the intertidal zone rely on measuring water occurrence frequencies using Normalized Difference Water Index (NDWI), this research aims to analyze the spatio-temporal variations using the satellite-derived bathymetry estimates to delineate the intertidal zone based on their vertical zone subdivision. The bathymetry is computed using a physics-based model inversion that retrieves water depth and bottom albedo from multi-spectral images. The model was applied over Sentinel-2 MSI products covering the study areas from March to August of 2023 to show both wet and dry season. After calibration, accuracy assessments have shown good correspondence with actual depths derived from Electronic Navigation Charts (ENC) in Palawan. The computed bathymetry from two different approaches in implementing the model were merged to map the spatial extents of the intertidal zone. As an evaluation of the raster statistics as factors, a submergence frequency map was produced.

Keywords: Intertidal zones, remote sensing, bathymetry, Sentinel-2

1. INTRODUCTION

1.1 Mapping Intertidal Zones

Intertidal zones are the areas across the coast which are either submerged in water or exposed to air in between the changing tides. These zones provide many ecosystem services such as coastal protection by acting as natural buffers against erosion and flooding. The intertidal zone supports a wide range of both marine and terrestrial species which have adapted to frequently changing conditions, often marking them as significant biodiversity sites. Intertidal wetlands are home to sea grasses, mangroves, and saltmarshes allowing them to sequester carbon, acting as a carbon reservoir (Chen & Lee, 2022). With the loss of intertidal extents worldwide over the past decades due to global sea level rise and anthropogenic factors (Wethey et al., 2011), it is critical to map these areas to monitor any further losses and subsequent changes in tidal habitats. As they are constantly experiencing drastic changes, mapping the intertidal zone is important in understanding the ecosystem services it provides (Fitton et al., 2021). These intertidal zone maps can aid in coastal and biodiversity management practices including environmental planning, policymaking, and implementation.

Being one of the most temporally and spatially variable marine habitats affected by diurnal tides, traditional survey methods can be quite difficult and expensive. Remote sensing provides a more efficient and cost-effective way for mapping the intertidal zones at a high spatial resolution of 10 meters for sensors like Sentinel-2 Multi-spectral Instrument (MSI). Other methods of measuring the intertidal zone with remote sensing uses of band ratios or indices to delineate the boundary between land and water and count the water occurrences based on a mask that shows land and water boundary. However, that comes with the limitation of other factors such as cloud contamination and limits the outputs to just the boundary at the specific time and date of satellite image capture. This study uses satellite-derived bathymetry for coastal shallow regions to measure the extents of the intertidal zone and an evaluation of submergence frequencies based on raster statistics.

1.2 Study Area

Two sites in the province of Palawan in the Philippines were chosen as the study area (Fig. 1). While Palawan is mostly known globally for being a tourist hotspot, it is also widely cited as the country's biodiversity corridor and one of its last ecological frontiers. The province serves as a refuge for a wide diversity of species including corals, seagrasses, mangroves, fishes, and birds. Several species are endemic to this region but are unfortunately threatened due to human impact on their habitats (Diwa et al., 2023).

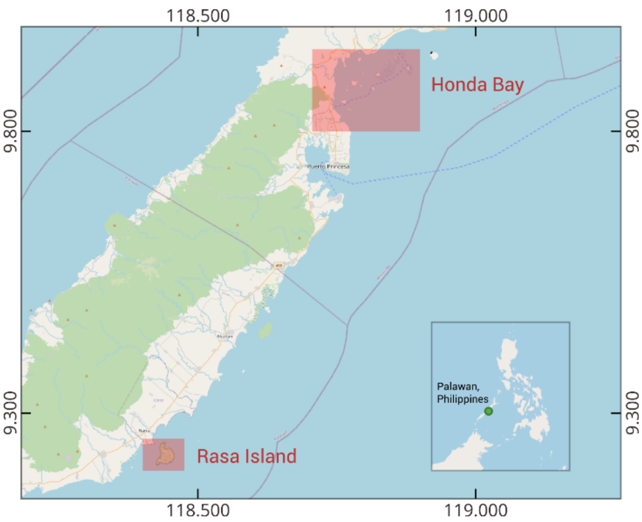


Figure 1. Location map of Rasa island and Honda bay in Palawan, Philippines

Rasa Island is in Narra, Palawan and is an intact coastal forest with coral reefs and seagrasses in its surrounding tidal flats. The island and its surrounding waters were declared by the government as a protected area and is currently a bird sanctuary known as Rasa Island Wildlife Sanctuary (Katala Foundation Incorporated, n.d.). The coast of Honda Bay in east of Puerto Princesa City is lined with mangrove forests, and offshore contains a group of small islands with the same cover of seagrass beds, coral reefs, abandoned aquaculture ponds and salt ponds (Castillo et al., 2018). In efforts to manage fishing activities in the bay and with its history of toxic water contamination and harmful algal blooms, the local government established fish sanctuaries in these island reefs.

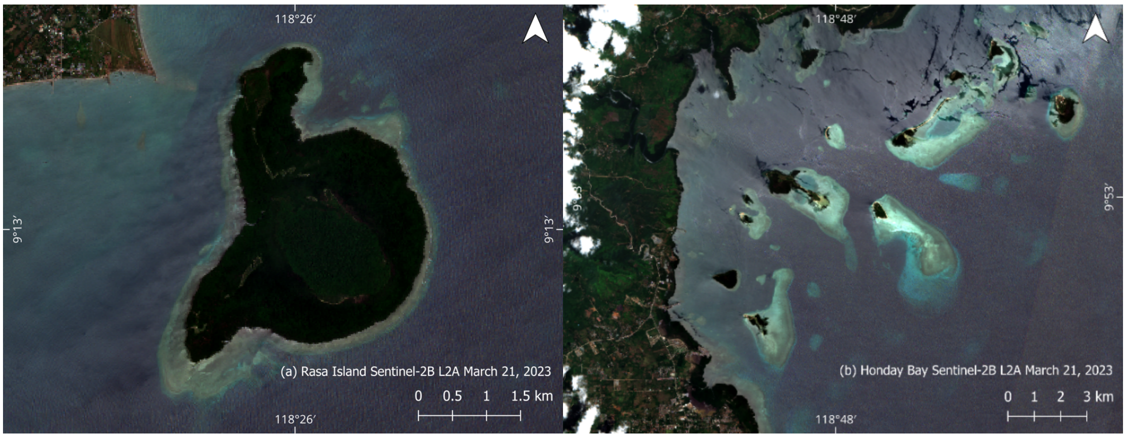


Figure 2. True Color Images of Rasa Island (L) and Honda Bay (R) in Palawan, Philippines (Sentinel-2B L2A Product March 21, 2023)

2. DATA AND METHODS

For this study, thirty-five (35) Sentinel-2 MSI images covering March to August of 2023 were downloaded and processed. These months were chosen based on the climate type in the site where dry season is represented by images from March to May and wet season by images in June to August. MSI Level-1C products were atmospherically corrected with SeaDAS to generate Level-2 products; Water depth and bottom albedo were derived from multispectral images as described in Liew and Chua (2016). A brief overview of the process to estimate bathymetry and then the spatial extent of intertidal zone is shown in Fig. 1.

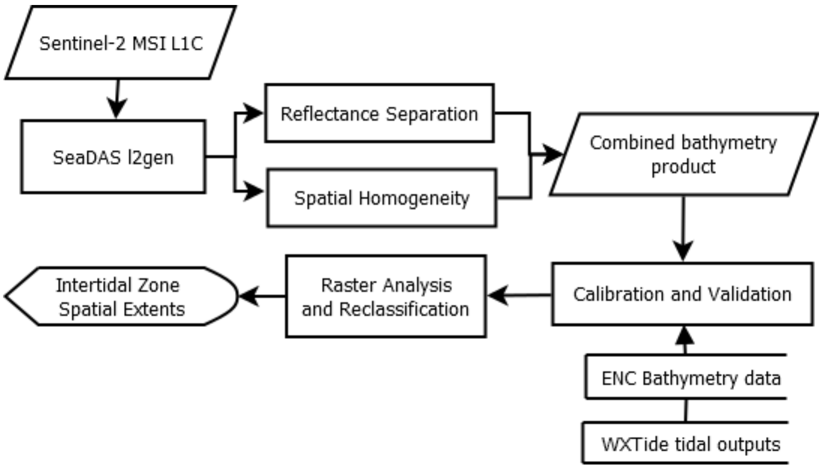


Figure 3. General workflow for extracting the extents of the intertidal zone.

Two approaches were implemented based on initial assumptions in estimating the bottom albedo. These two assumptions are called the Reflectance Separation (RS) and Spatial Homogeneity (SH) (Liew and He, 2008). The spatial homogeneity approach assumes that deep water pixels and shallow water pixels have the same optical properties up to a specific distance (Liew and He, 2008). The reflectance separation approach makes use of the ratio between the reflectance values at the green and blue bands as a proxy to solve for the fraction of bottom reflectance in shallow waters (Stumpf et al., 2003). Both these assumptions have their limitations; in dynamic nearshore waters SH does not hold true, meanwhile in offshore waters the sensitivity of RS is not enough to gauge the fraction of bottom reflectance. However, these two assumptions fill each other's limitations. Therefore, to make the bathymetry estimates throughput the coastal zone, the outputs of these two methods were merged by averaging both bathymetry products.

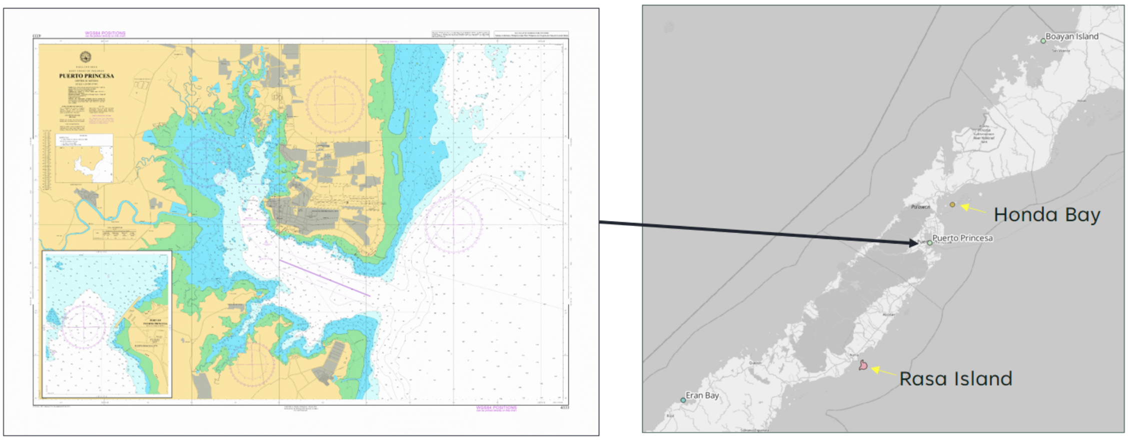


Figure 4. Puerto Princesa bathymetry and location map

Water depths from Electronic Navigation Charts (ENC) from International Hydrographic Organization, bathymetry and resource maps from the National Mapping and Resource Information Authority (NAMRIA) of the Philippines and tide levels from WXTide32 (Flater, 2010) were used to calibrate and validate the bathymetry estimates. The calibration was conducted by referring the satellite-derived water depths to the electronic navigation charts, bathymetry maps, and tidal harmonics data. The water depths are referred to in Mean Lower Low Water datum. Tide levels from WXTide32 were retrieved at the same date and time of all the Sentinel-2 images used. With the calibrated merged bathymetry output, the intertidal zone extent was selected as the depth based on the computed tidal data. Raster analysis was done to create a submergence frequency map of the study sites. The factors are based on the following a) water depth, b) count of water pixels classified, c) standard deviation. The Normalized Difference Water Index (NDWI) (McFeeters, 1996) utilizing the green and NIR bands to determine water was applied to all the images and the difference between two almost cloud free images from each season were calculated to estimate the intertidal zone.

3. RESULTS AND DISCUSSION

3.1 Merged bathymetry output and intertidal zone extents

As stated earlier, both RS and SH assumptions have its advantages when computing bathymetry at certain depths. By averaging the output values, we were able to produce a better consolidated bathymetry map. The computed depths were masked out at 25 meters. The shallow waters around Rasa Island extend from 300 to 500 meters off the mangrove forested area (Fig. 5a, Fig. 7a). The coast and islands of Honda Bay are mostly shallow and falls steeper after 8-10 meters (Fig. 5b). The visibly shallow areas and land boundaries are quite consistent with the base maps used in the figures from OpenStreetMap (OpenStreetMap contributors, 2023). The merged bathymetry output after calibration has a Pearson's correlation coefficient of 0.76 when validated against an ENC depth values for Balabac (8.21 N, 117.16 E), a town south of the same province of Palawan.

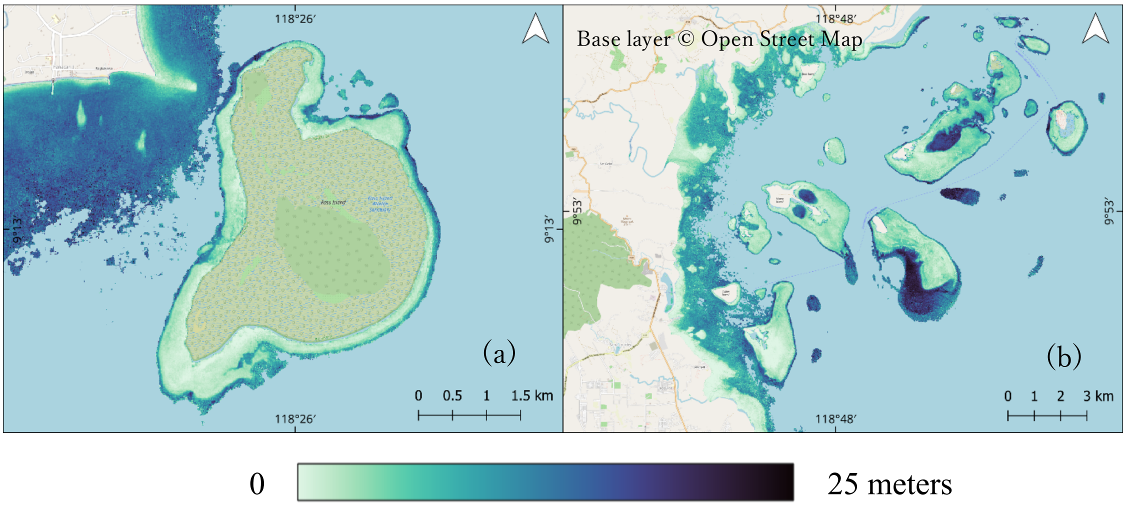


Figure 5. Merged bathymetry product for Rasa Island (L) and Honda Bay (R).

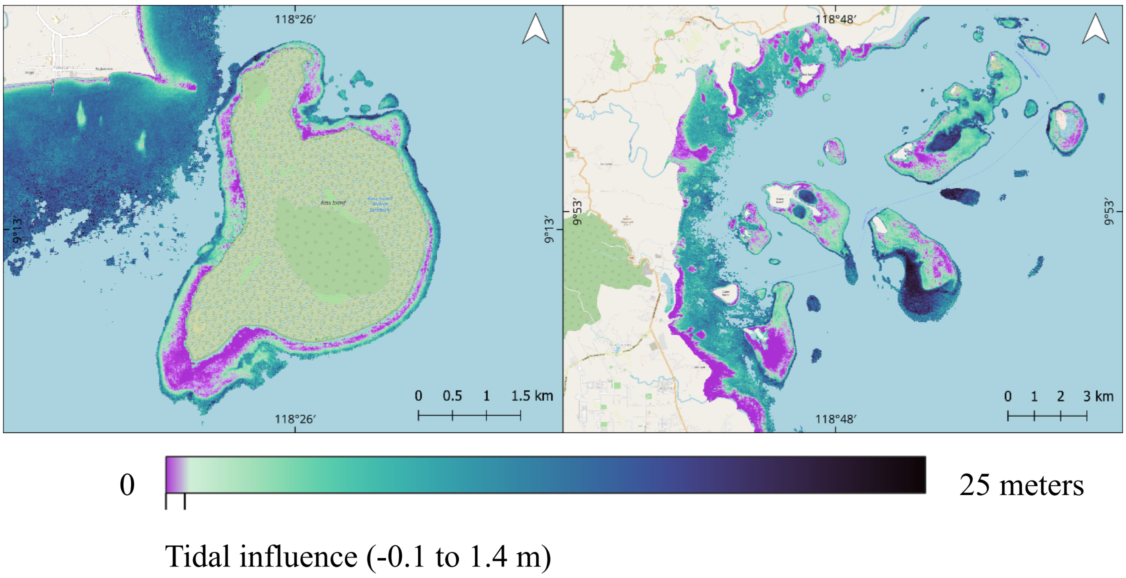


Figure 6. Intertidal zone extents Rasa Island (L) and Honda Bay (R)

The range of depth affected by tidal influences are displayed in magenta in Figure 6. This is based on the concurrent tide heights from –0.1 and 1.4 meters. This shaded area is considered as the parts of the coast that are intertidal. This also corresponds to the boundaries in ENCs and land cover maps or coastal resource maps (Fig. 7) in both study areas.

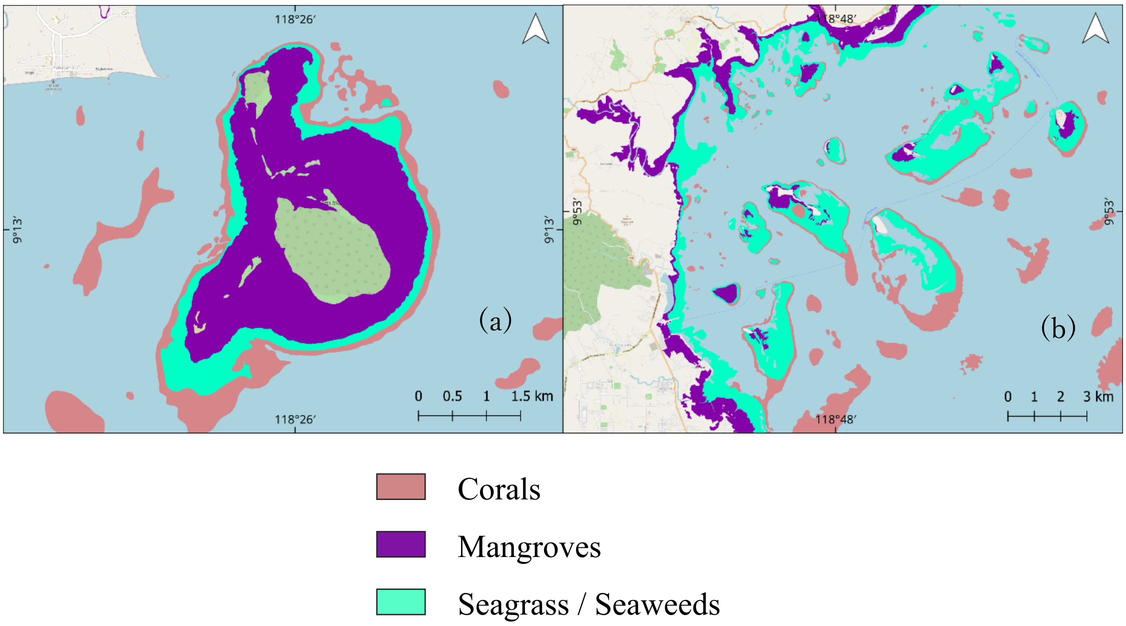


Figure 7. Intertidal zone extents Rasa Island (L) and Honda Bay (R)

3.2 Submergence frequency zones

The submergence frequency map (Fig. 8) was processed by evaluating the water depth, water pixel classification count, and standard deviation into four zones: occasionally submerged (<25%), periodically submerged (25-50%), frequently submerged (50-100%), and consistently submerged (100%). A downside however with using the water classification count as a factor is that it comes from a water mask layer. It was not accounted whether the pixel had been flagged out as cloud or glint. Although an implicit way to map water occurrence frequencies, output map could be improved by incorporating the pixel mask classification and period covered. This may also be useful in further assessing coastal habitat type.

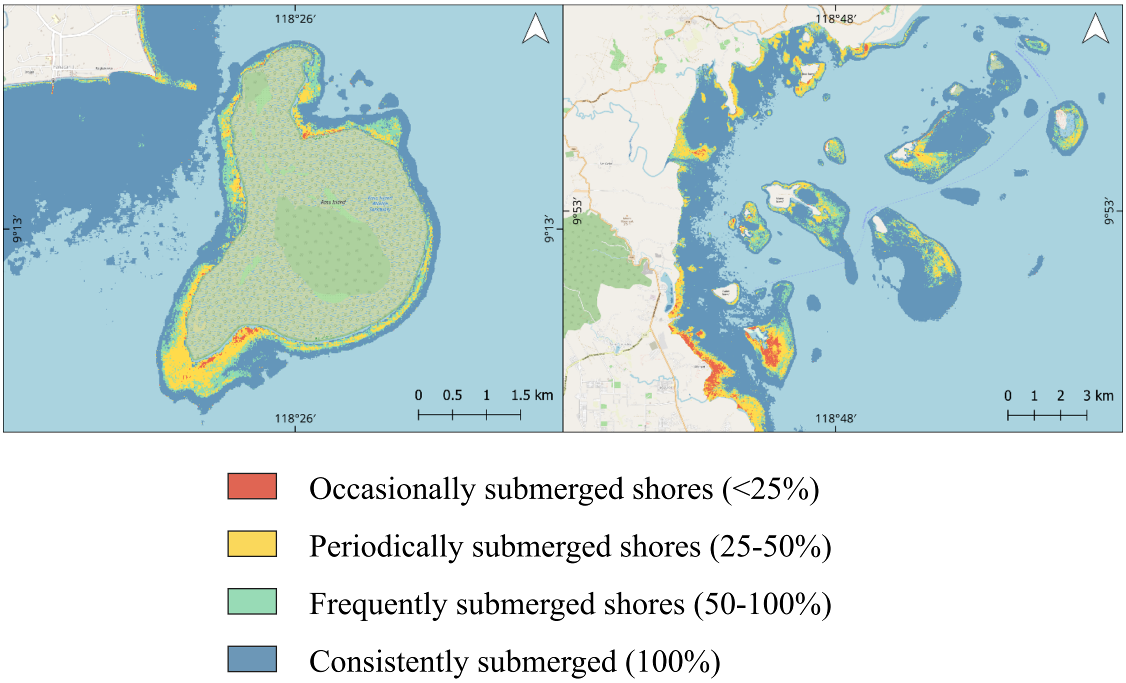
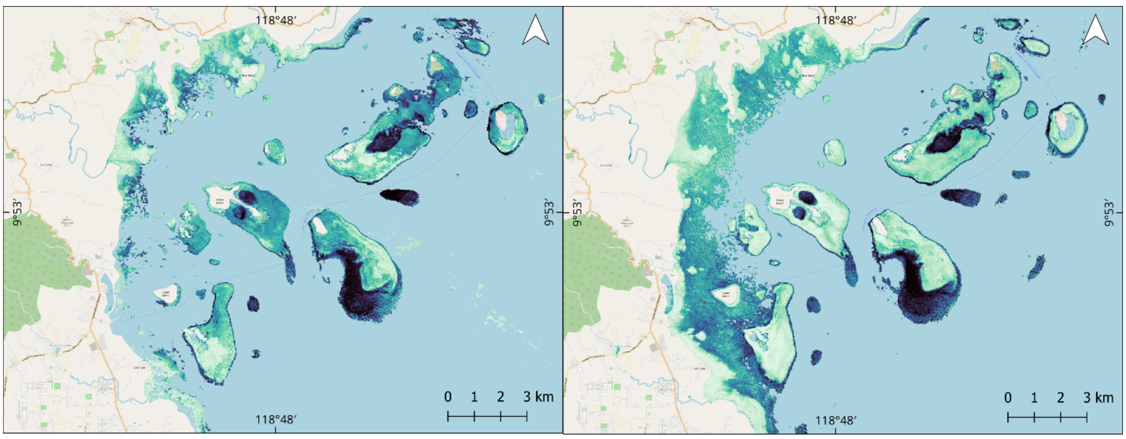


Figure 8. Submergence frequency map for Rasa Island (L) and Honda Bay (R)

3.3 Water depth seasonal variation

The seasonal variation for both study sites is quite difficult to quantify given the difference in the number of clear images between the two seasons, as expected the cloud covers most of the images captured during the wet season. In Rasa Island, the computed differences in water depths in the shallow areas are in the range of 1.5 to 2 meters (Fig. 9, bottom panels). In parts of Honda Bay (Fig. 9, top panels) however, the differences are more pronounced at about 5 meters for the moderately deeper regions. However, the measured depth in the deeper pixels for both study sites seem to be consistent.



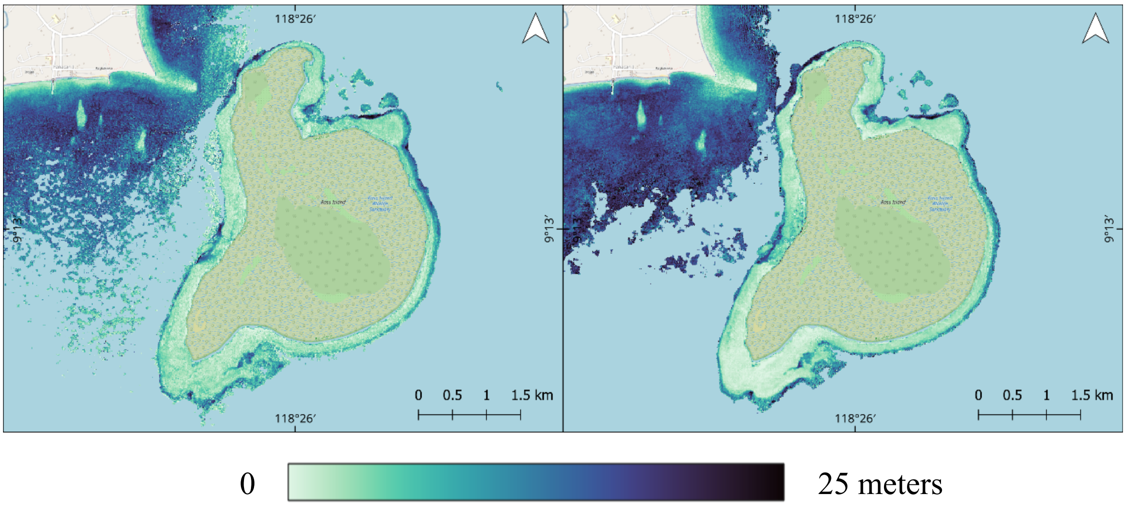


Figure 9. Merged bathymetry output from the wet season (L) and dry season (R) for Honda Bay (T) and Rasa Island (B)

3.4 Bathymetry method vs NDWI water mask

The yellow shaded areas in Figure 10 are the estimated intertidal zone using the NDWI between two images in each season. The disadvantage of using the NDWI alone is that it's highly affected by clouds. Consolidating NDWI values over a period is less likely to show the actual boundary between water and land, compared to mapping the actual water depths. This is sufficient for initial assessments since it is easier to compute.

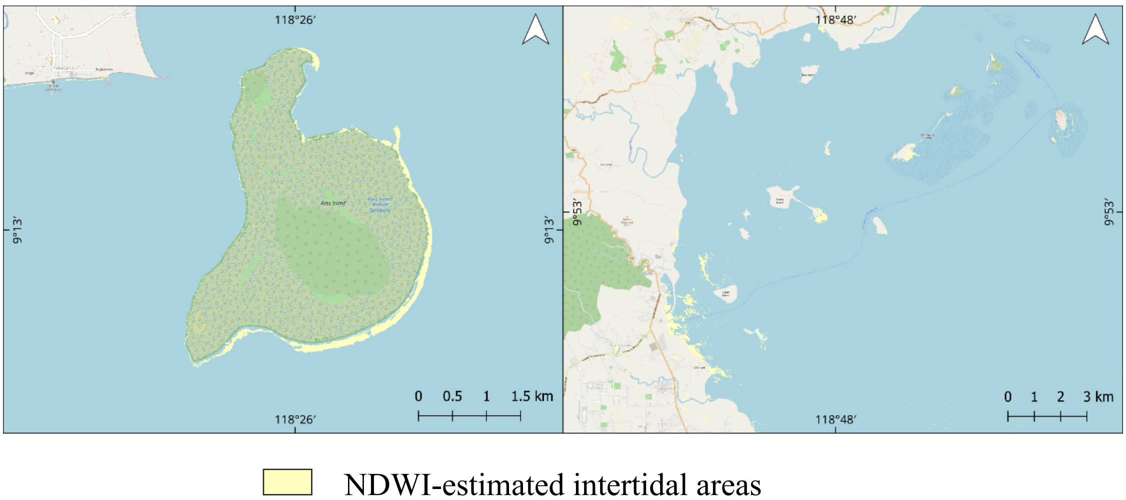


Figure 10. Intertidal zone estimated using NDWI between two clear images in each season.

4. CONCLUSION

Combining the outputs from the two approaches in satellite-derived bathymetry estimation produced a clear composite bathymetry map from over six months of image capture. From the calibrated bathymetry data, the spatial extents of the intertidal zone were defined by the influence of the tide heights concurrent with the satellite overpass. Water depth, water classification count, and standard deviation were also used to map out the likelihood of which areas in the intertidal zone are more frequently submerged or exposed. Due to the limited amount of clear image captures in the wet season, the seasonal variation could not be evaluated conclusively, however, we saw differences in the moderately deeper areas in Honda Bay. It is suggested to retrieve more images completing the whole span of the two seasons to better estimate the seasonal differences and subsequently produce a submergence frequency map for each season.

REFERENCES

Castillo, J. A. A., Apan, A. A., Maraseni, T. N., & Salmo, S. G. (2018). Tree biomass quantity, carbon stock and canopy correlates in mangrove forest and land uses that replaced mangroves in Honda Bay, Philippines. *Regional Studies in Marine Science*, *24*, 174–183. https://doi.org/10.1016/j.rsma.2018.08.006

Chen, Z. L., & Lee, S. Y. (2022). Tidal Flats as a Significant Carbon Reservoir in Global Coastal Ecosystems. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.900896

Diwa, R. R., Deocaris, C. C., Geraldo, L. D., & Belo, L. P. (2023). Ecological and health risks from heavy metal sources surrounding an abandoned mercury mine in the island paradise of Palawan, Philippines. Heliyon, 9(5), e15713. https://doi.org/10.1016/j.heliyon.2023.e15713

Fitton, J. M., Rennie, A. F., Hansom, J. D., & Muir, F. M. E. (2021). Remotely sensed mapping of the intertidal zone: A Sentinel-2 and Google Earth Engine methodology. Remote Sensing Applications: Society and Environment, 22, 100499. https://doi.org/10.1016/j.rsase.2021.100499

Flater, D. (2010). WXTide32- a free Windows tide and current prediction program.

Katala Foundation Incorporated. (n.d.). Rasa Island. https://katalafoundation.org/pccp/rasa-island/

Liew, S. C., & Chua, K. M. (2016). Operational derivation of water depth and sea bottom albedo from high resolution multispectral images. IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 3796–3798.

Liew, S. C., & He, J. (2008). Uplift of a Coral Island in the Andaman Sea Due to the 2004 Sumatra Earthquake Measured Using Remote Sensing Reflectance of Water. IEEE Geoscience and Remote Sensing Letters, 5(4), 701–704. https://doi.org/10.1109/LGRS.2008.2004208

McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. International Journal of Remote Sensing, 17(7), 1425–1432. https://doi.org/10.1080/01431169608948714

OpenStreetMap contributors. (2023, September 15). OpenStreetMap. https://www.openstreetmap.org

Stumpf, R. P., Holderied, K., & Sinclair, M. (2003). Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnology and Oceanography, 48(1part2), 547–556. https://doi.org/10.4319/lo.2003.48.1_part_2.0547

Wethey, D. S., Woodin, S. A., Hilbish, T. J., Jones, S. J., Lima, F. P., & Brannock, P. M. (2011). Response of intertidal populations to climate: Effects of extreme events versus long term change. Journal of Experimental Marine Biology and Ecology, 400(1–2), 132–144. https://doi.org/10.1016/j.jembe.2011.02.008