

Remote Sensing-Based Assessment of Exorheic Siltation in Homonhon Island, Philippines Using Hyperspectral Imagery

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DOI : <https://doi.org/10.51583/IJLTEMAS.2025.140500041>

Received: 28 May 2025; Accepted: 31 May 2025; Published: 09 June 2025

Abstract: Mining activities on Homonhon Island, Philippines, have increasingly contributed to coastal water pollution and siltation, particularly during extreme weather events. This study investigates the influence of climatological factors—specifically precipitation—on mining-induced siltation using satellite-based remote sensing. Sentinel-2A imagery was employed to monitor and quantify changes in water turbidity and sediment deposition before and after typhoon events. Two spectral indices, the Normalized Difference Water Index (NDWI) and Normalized Difference Turbidity Index (NDTI), were applied to assess the extent of siltation across different time periods. Results revealed a notable increase in siltation areas following typhoons, with the year 2023 showing a surge of approximately 11 million square meters of affected areas, despite receiving only 23.9 mm of rainfall. This indicates that cumulative land degradation from mining operations may have heightened siltation susceptibility even under moderate precipitation. These findings highlight the critical role of satellite-based monitoring in supporting sustainable land use and coastal resource management in mining-affected regions.

Keywords— Remote Sensing; Hyperspectral Imagery; coastal management; Siltation;

I. INTRODUCTION

Mining activities, particularly small-scale gold mining, have significant impacts on water quality through siltation. In the Amazon, gold mining has led to increased turbidity in previously clear rivers, with sediment plumes traveling hundreds of kilometers downstream (Lobo et al., 2018). Similar effects have been observed in the Philippines, where nickel laterite mining has contributed to coastal water siltation, with total suspended solids reaching up to 1000 mg/L during heavy runoff (Apodaca et al., 2018). The expansion of artisanal and small-scale gold mining in the Tapajós River Basin over 40 years has been linked to increased water siltation, with periods of mining intensification corresponding to higher total suspended solids concentrations (Lobo et al., 2016). Factors contributing to siltation in mining operations include high settling velocity of particles, inefficient milling and classification, poor slurry agitation, and particle flocculation. Mitigation measures such as increased milling residence time and particle deflocculation have shown promise in reducing siltation (Osei et al., 2016).

With these global concern regarding the effects of mining operations on the aquatic environment and water quality of streams and coastal areas, the same have been expressed in Homonhon Island in Guiuan, Eastern Samar.

Siltation, the accumulation of fine sediment particles in water bodies, is a critical environmental concern, particularly in coastal areas. In recent years, the rise in siltation rates has been increasingly attributed to human activities, such as deforestation, agriculture, and mining (Lee et al., 2019). Among these, mining is recognized as a significant driver of siltation, especially in island ecosystems where large-scale mining operations expose large areas of soil to erosion. Homonhon Island, Philippines, a site of both historical and ongoing mining activities, serves as a case in point. This island, rich in mineral resources, has experienced heightened environmental degradation, with mining-induced siltation being exacerbated by climatological factors such as typhoons. The island's exorheic (outward draining) nature, where sediment is carried from land to the surrounding sea, amplifies the impact of mining on coastal siltation (Baloloy et al., 2018).

Mining, as a key contributor to sedimentation, accelerates soil erosion due to the removal of vegetation and surface soil disturbance. Without vegetation to hold the soil together, exposed areas are more prone to erosion during heavy rains, a common phenomenon in the typhoon-prone region of Homonhon Island (Cruz et al., 2021). Typhoons, which bring intense rainfall and strong winds, significantly increase the rate at which eroded soil is carried into rivers and ultimately deposited into the coastal waters. In the case of Homonhon, mining activities have left vast tracts of land bare and vulnerable to erosion. As the storm waters rush downhill, they carry sediment from these disturbed mining sites, leading to a sharp rise in siltation levels in the adjacent coastal areas following each typhoon event (Lal et al., 2020).

While this Island could not be easily reached particularly in some months where rainy season starts and high tide is observed, actual data gathering is not an option. A method to do so is by taking water samples and running them through the chemistry lab. The problem with this methodology is that it can be time and labor expensive. Fortunately, there are satellites that take images from outer space for Earth's observation and monitoring, including its water bodies. While different satellite image sources provide

different image quality altogether, they can be harmonized through a model (Nguyen et al., 2020). Studies have demonstrated the effectiveness of Sentinel-2 satellite imagery for monitoring siltation and water quality in various aquatic environments. Alves e Santos et al. (2024) developed a method to assess sediment transport in an Amazonian hydropower dam using Sentinel-2 data, revealing significant sedimentation processes and mapping eroding and silting reaches. In agricultural settings, Al-Gaadi et al. (2021) successfully used Sentinel-2 data to predict soil salinity, achieving high correlations with field measurements. Tripathi et al. (2020) employed Sentinel-2 imagery to analyze turbidity changes in the Ganga River during the COVID-19 lockdown, observing improvements in water quality. Similarly, Prasetyo et al. (2019) utilized Sentinel-2 data to map total suspended solids distribution in the Wulan River estuary, finding that regression-based algorithms performed best for this application. These studies highlight the versatility of Sentinel-2 data for monitoring siltation and related water quality parameters across diverse aquatic ecosystems.

Satellite-based monitoring has become an essential tool for studying the environmental impacts of siltation, particularly in remote regions like Homonhon Island. Remote sensing technologies, such as Sentinel satellites, allow for the continuous observation of land and water changes, providing critical data for understanding the spatial and temporal patterns of siltation (Mouchel et al., 2019). However, consistent and accurate satellite imagery can be difficult to obtain, especially when cloud cover obscures the area during key observation periods. Initially, this study considered a long-term analysis using data from 2017 to 2023 to track siltation trends over several years. However, due to the inconsistency of good-quality satellite images across all months, the decision was made to focus on pre- and post-typhoon analysis instead. This approach offers a more precise understanding of how mining, combined with climatological drivers like typhoons, influences exoreic siltation in Homonhon Island.

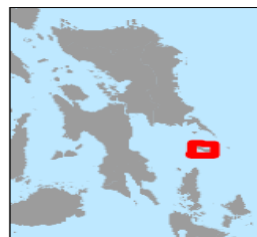
By integrating satellite imagery and climatological data, this research aims to quantify the extent of mining induced siltation on Homonhon Island and assess how typhoon events exacerbate these processes. Understanding these dynamics is critical for developing effective environmental management strategies that mitigate the impact of mining on coastal ecosystems, especially in areas prone to extreme weather events (Jenkins et al., 2020). This study contributes to the growing body of knowledge on human-induced environmental degradation and the importance of satellite-based monitoring in addressing these global challenges.

The objective of this study is to analyze and map exoreic siltation in Homonhon Island, Guianan, Eastern Samar by utilizing hyperspectral imagery, with the aim of identifying sediment concentration patterns and assessing their environmental impact on surrounding coastal ecosystems.

II. Methods

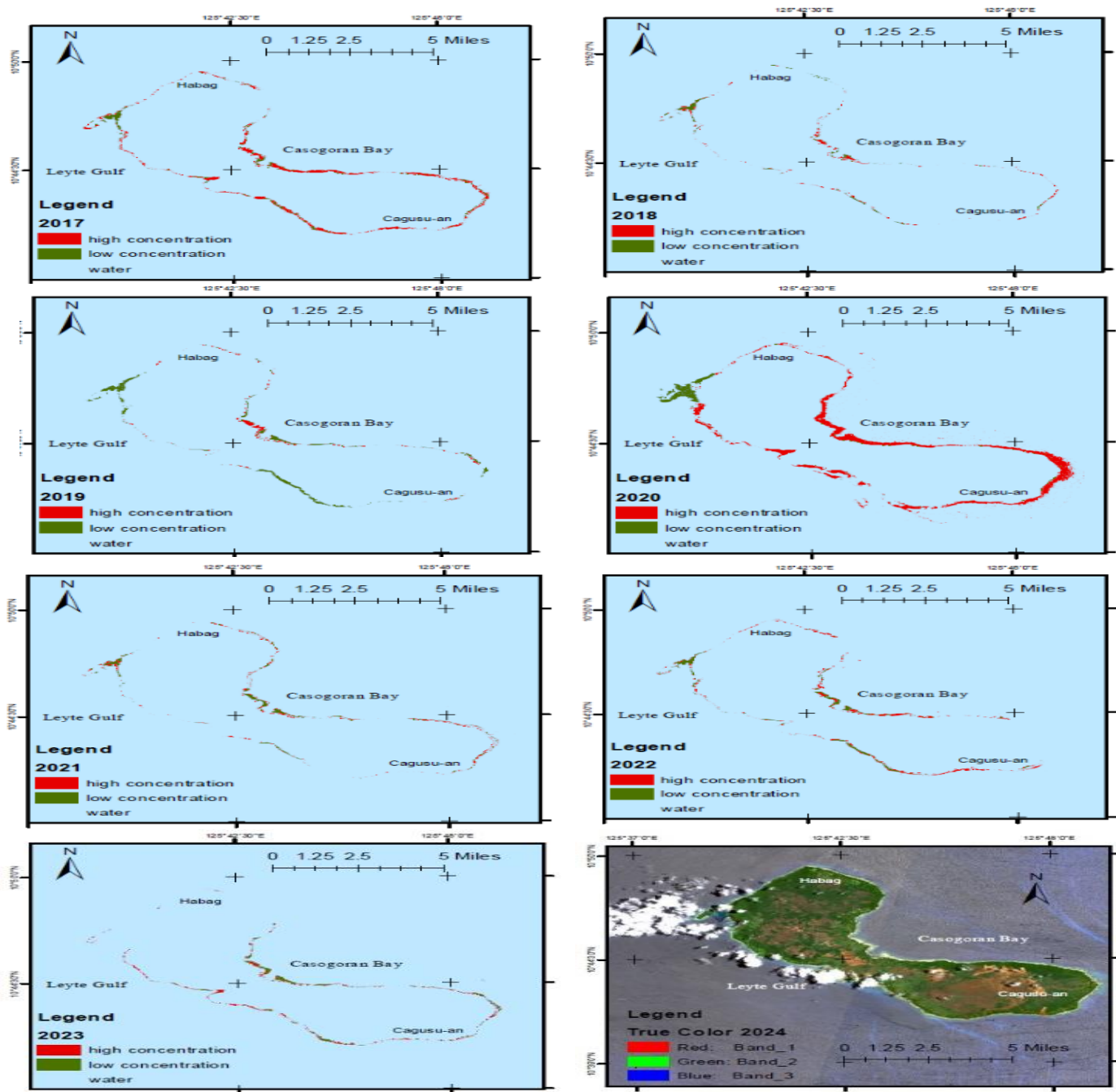
Study Area

Homonhon Island in Eastern Samar, Philippines, has experienced significant environmental degradation due to decades of mining activities, which have led to widespread habitat destruction, water pollution, and a decline in marine resources. These mining-induced changes have exacerbated coastal siltation, disrupting local ecosystems and impacting the livelihoods of residents, particularly in fishing communities. Despite ongoing opposition from local and environmental groups, the expansion of mining continues, making Homonhon Island a critical area for studying the climatological factors, such as precipitation, that drive exoreic siltation in mining-affected regions.



Initial Process

Prior to finalizing the methodology and data gathering approach, various options were considered to enhance the accuracy of siltation observations. One such option involved using satellite data spanning seven years (2017-2023) to track siltation changes over time. However, this approach was ultimately not pursued due to the inconsistency and low accuracy of Sentinel imagery during key observation months across multiple years. The inconsistent availability of high-quality images during these periods hindered reliable analysis. Consequently, a different data collection method was adopted, focusing on pre- and post-typhoon imagery to ensure a more accurate and consistent assessment of siltation changes as shown in Figure 2.



Process Flow

Figure 3 shows the methods used in the study. The methodology depicted in the process flow involves the use of multi-spectral imagery to assess water characteristics. First, two indices are calculated: The Normalized Difference Water Index (NDWI) to extract the water boundary and the Normalized Difference Turbidity Index (NDTI) to detect turbidity, from which the highest values are extracted based on a 75% threshold. The detected water areas are then clipped, followed by uniform random sampling.

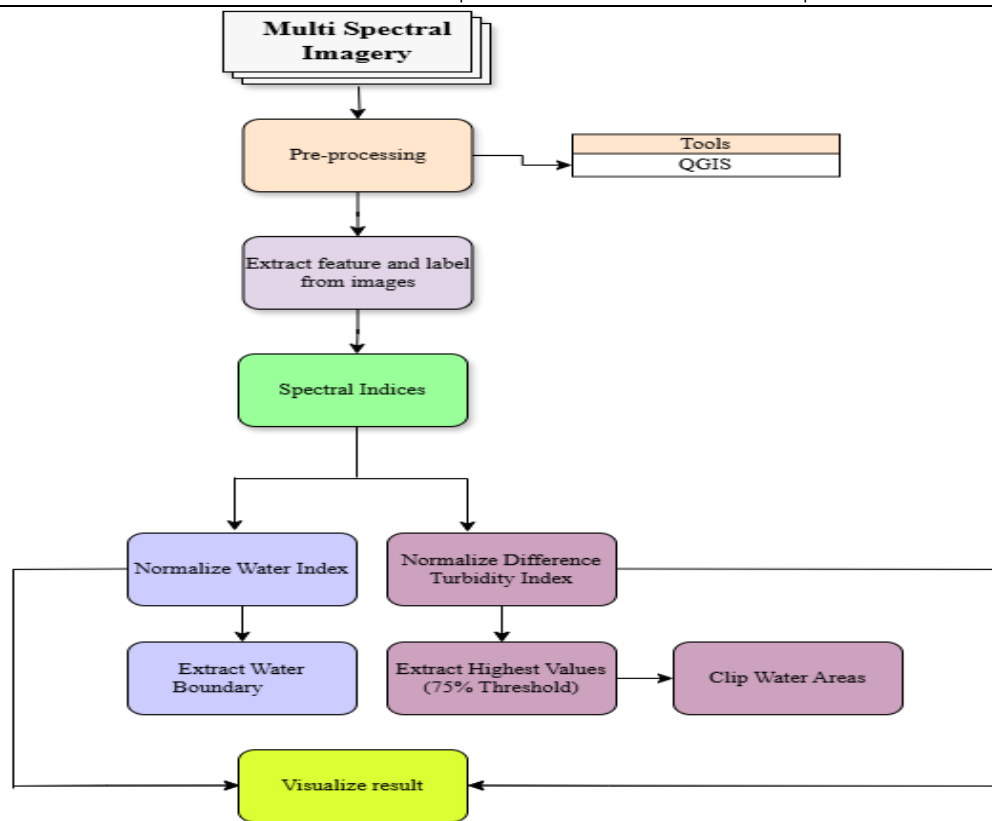


Fig. 1 Process Flow

Sentinel-2 Satellite Data

Sentinel-2A image was downloaded from the USGS Earth Explorer (<https://earthexplorer.usgs.gov>) coinciding with the field samples. Sentinel Application Platform (SNAP) developed by the European Space Agency (<https://step.esa.int/main/download/snap-download/>) was used for image analysis. The SNAP is a free software program especially designed for the analysis of Sentinel images. The images were geo-rectified to the Universal Transverse Mercator (UTM) coordinate system using the World Geodetic System (WGS) 1984 datum assigned to the north UTM zone 38. The region of interest (ROI), pertaining to the experimental field was extracted for further analysis. The raw image was processed in ArcGIS software for bottom-of-reflectance, clipped to the study area and was subsequently used in conjunction with a set of spectral bands.

In this study, the climatological drivers of exshore siltation on Homonhon Island caused by mining were examined using Sentinel-2 satellite data. Sentinel-2's multispectral imaging, which records high-resolution spatial and spectral data, was very helpful in evaluating how water quality and siltation patterns changed over time. The study tracked the relationship between increases in coastal siltation and precipitation events, as well as the monitoring of sediment plumes, by utilizing satellite-based tools for visualizing water quality. The information made it easier to spot patterns in the geographical accumulation of silt and enabled a more accurate examination of the ways in which the intensity of rainfall affects the movement of sediment from mining sites into coastal seas. This method of remote sensing provides a thorough, time-based view of how mining operations affect the environment. The band specifications according to are as shown in Table 1.

Band	Name	Central wavelength (nm)	Spatial resolution (m)
B1	Coastal	443	60
B2	Blue	490	10
B3	Green	560	10
B4	Red	665	10
B5	Red Edge 1	705	20
B6	Red Edge 2	740	20

B7	Red Edge 3	783	20
B8	NIR	842	10
B8a	NIR-narrow	865	20
B9	Water vapor	940	60
B10	Cirrus	1375	60
B11	SWIR-1	1610	20
B12	SWIR-2	2190	20

Table I. Sentinel-2 Multispectral Imager Instrument (MSI) band specifications

Normalized Difference Water Index

The Normalized Difference Water Index (NDWI), based on the formula introduced by McFeeters in 1996, is used to distinguish water bodies from other land cover types. The NDWI makes use of reflected near-infrared radiation and visible green light to enhance the presence of such features while eliminating the presence of soil and terrestrial vegetation features. It is suggested that the NDWI may also provide researchers with turbidity estimations of water bodies using remotely-sensed digital data. It is calculated using the following formula:

$$NDWI = \frac{R_G - R_{NIR}}{R_G + R_{NIR}}$$

Where R_g and R_{nir} are reflectance in green and near infrared (NIR) bands. These wavelengths were selected to maximize the typical reflectance of water features by using green light wavelength, to minimize the low reflectance of NIR by water features and to take advantage of the high reflectance of NIR by terrestrial vegetation and soil features.

NDWI used to differentiate water from dry land or more suitable for mapping water bodies. The body of water has low radiation and strong absorption in the visible infrared wavelength range. NDWI uses the near infrared and green bands of remote sensing imagery based on their occurrence. It can improve water information efficiently in most of the cases. It is smooth on built-up ground and often ends up in overly high bodies of water.

Figure 2. NDWI (McFeeters, 1996)

Normalized Difference Turbidity Index

$$NDTI = \frac{R_R - R_G}{R_R + R_G}$$

Where R_r is reflectance in the red band. The reflectance of pure water is more in green than the red wavelength region. However, the water pixels were identified as mentioned above, the Equation (2) was applied using these two bands to map NDTI. High NDTI values indicate higher turbidity levels due to suspended particles in the water, which affect the reflection of red and green bands (Bustamante et al., 2009). The use of green and red band reflectance to estimate variable suspended sediment concentration in the stratified water column.

Therefore, later the results were validated through mapping of NDTI, which is a normalized ratio of red and green band reflectance (S. Tassan, 1997). It was noticed that red and NIR bands are more sensitive towards turbidity estimation (R Foteh et al., 2018). These bands are very useful to quantitatively estimate the turbidity in the absence of field observed data for optically deep water. Based on the finding, it can be deduced that in the absence of ground observed data, remote sensing approach can be used for preliminary estimates on water quality.

Elhag M. (2019) was successful in utilizing remote sensing data acquired from Sentinel-2 to estimate chlorophyll, nitrogen content and water turbidity. The mean values of raster data showed a high correlation with the actual data from the conducted laboratory examination.

III. Meteorological and hydrologic Data

Typhoon Dates and Duration

Typhoons trigger localized heavy rainfall patterns due to interactions with topography, leading to high sediment discharge in rivers (Galewsky et al., 2006). Seismic monitoring of riverbeds during typhoons reveals hysteresis in sediment transport and detects landslides, providing insights into bedload flux and erosion processes (Chao et al., 2015). The typhoon tracking data was taken mostly from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) public reports following its intensity, affected land areas and coastal waters. The considerations for choosing the typhoon/ tropical depression was

that Homonhon Island is part of the affected areas. Table 2 shows the full list for the selected year and duration.

Year	Duration of Typhoon/ Tropical Depression
2018	Nov11-15,2018
2019	Dec13-17,2019
2020	May12-May16, 2020
2022	April 1-5, 2022
2023	July21-25,2023

Table II. List of Typhoon/ Tropical Depression used in this study

Rainfall Measurement

The Global Satellite Mapping of Precipitation (GSMaP) system, developed by JAXA, provides hourly global rainfall data with 0.1-degree resolution (Kachi et al., 2011). GSMaP combines microwave and infrared radiometer data from multiple satellites to produce near-real-time precipitation estimates (Kubota et al., 2020). Validation studies have shown that GSMaP data correlates well with ground-based observations, particularly during rainy seasons, though it tends to underestimate rainfall amounts (Kachi et al., 2011; Syaifullah, 2014).

Comparisons between NASA's TRMM Microwave Imager (TMI) rainfall datasets and JAXA's GSMaP have been conducted, highlighting differences in their algorithms and outputs (You et al., 2020). GSMaP data has been applied in various fields, including flood warning systems, and serves as a prototype for the Global Precipitation Measurement (GPM) mission (Kachi et al., 2011). Monthly analyses of GSMaP data generally show better correlation with ground observations compared to daily analyses (Syaifullah, 2014). From the typhoon/ tropical depression dates identified to be used in this study, the rainfall derived data in mm has been downloaded and summarized as shown in Table 3.

Year	Duration of Typhoon/ Tropical Depression	Derived Rainfall (mm)
2018	Nov11-15,2018	104.6
2019	Dec13-17,2019	73.4
2020	May12-May16, 2020	47.40
2022	April 1-5, 2022	63.2
2023	July21-25,2023	23.90

Table III. List of Typhoon/ Tropical Depression used in this study with derived rainfall data

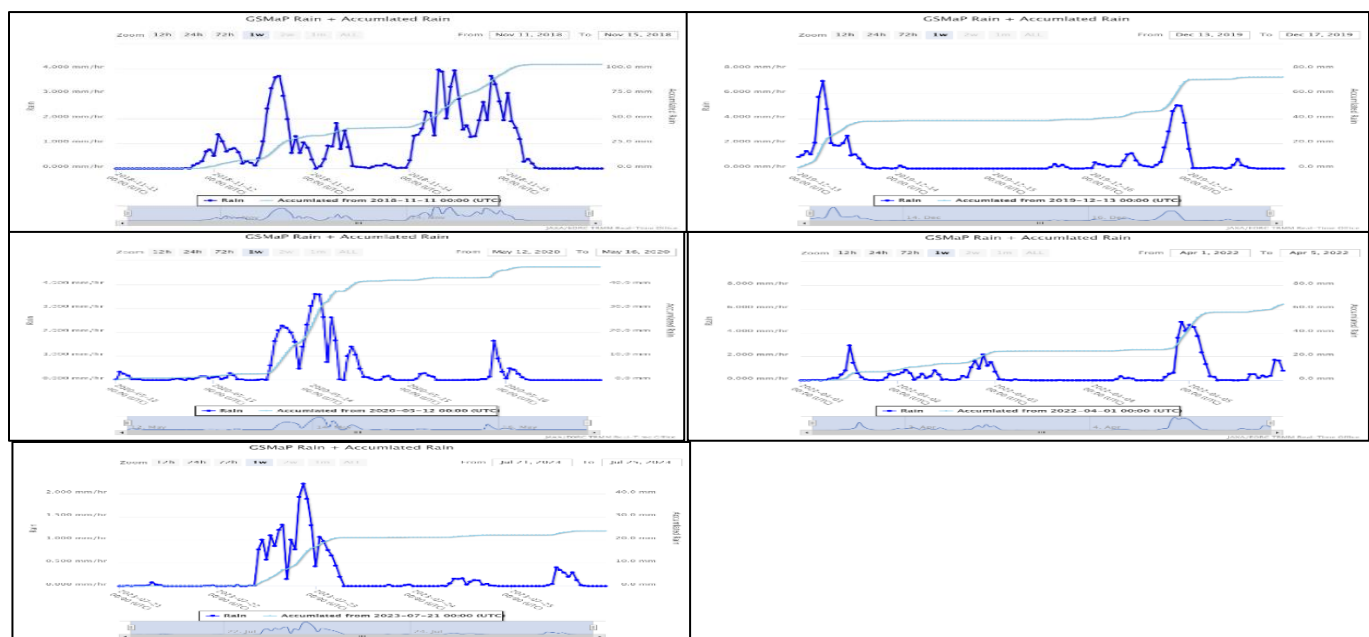


Figure 5. Rainfall Derived Data from JAXA

Pre and Post Typhoon Data (area)

Year	Pre-Typhoon Area (sqm)	Post-Typhoon Area (sqm)	Diff	rainfall (mm)
2018	7400849.203	14749704.90	7348855.692	104.6
2019	6829796.005	15115894.81	8286098.801	73.4
2020	1428360.953	13158692.12	11730331.17	47.40
2022	7065678.757	99610514.20	92544835.45	63.2
2023	1985465.256	13004926.66	11019461.41	23.90

Table IV. Comprehensive Data for pre and pos-typhoon area of siltation including the its rainfall in mm.

Data Processing

Data processing to investigate reservoir turbidity begins with determining the coordinates of the polygon area study. A computational function is derived from the polygon to facilitate clipping to the extent shapefile. Subsequently, the acquired Sentinel-2A image is imported. A consolidated image is then generated from this collection using the mosaic function, incorporating bands 3 (Green), 4 (Red), and 8 (VNIR). The Normalized Difference Water Index (NDWI) is computed, resulting in a binary raster. The Normalized Difference Turbidity Index (NDTI) is calculated, and the outcome is constrained by the water mask. Lastly, the map layer is incorporated into the analysis.

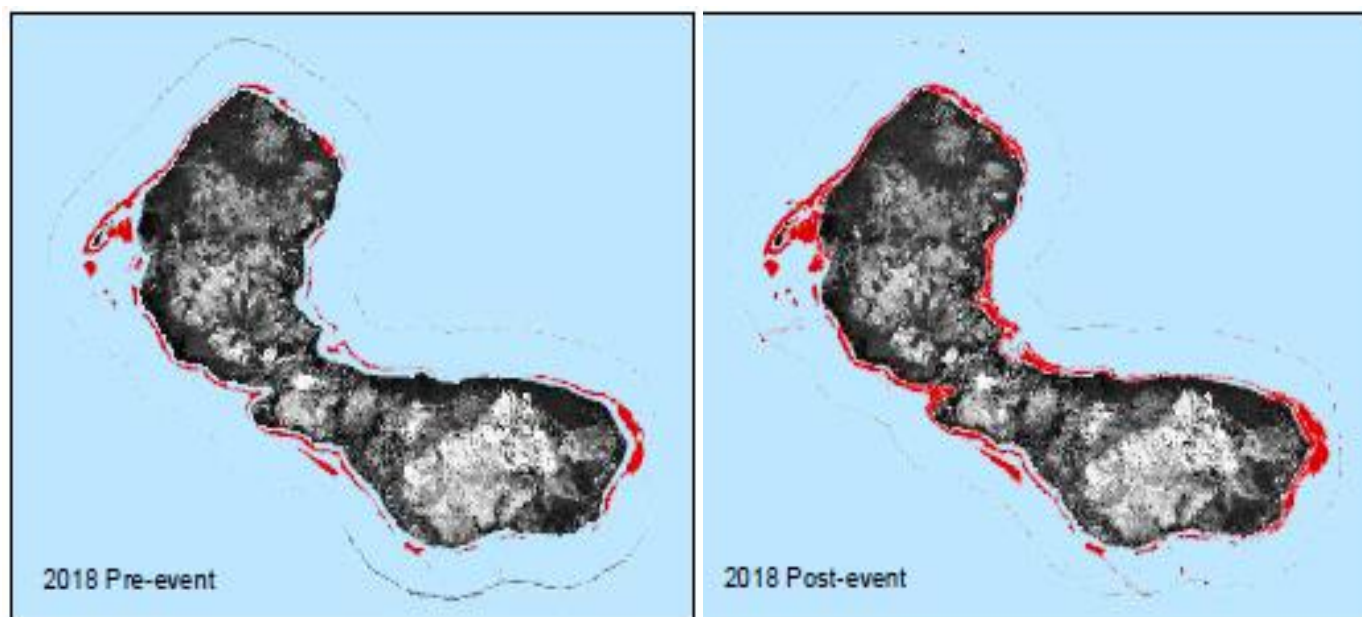
This study was carried out using a stack of many indexes. In addition to providing a brief summary of key landscape characteristics, this index stack illustrates the mathematical foundation for quantitative analysis

and image categorization utilizing index values; in this instance, both NDWI and NDTI were employed. The ability to alter and expand this kind of study is practically limitless due to the wide range of indices that are available.infinite.

Comparative Analysis of Pre- and Post-Typhoon Siltation Areas

The dataset shows marked differences in the siltation areas measured in square meters (sqm) before and after each typhoon event. In 2018, siltation increased by approximately 7.3 million sqm following the typhoon event in November, with high rainfall (104.6 mm) contributing to significant sediment transport. The largest increase was observed in 2023, with a post-typhoon rise of about 11 million sqm, despite relatively lower rainfall levels (23.9 mm). This suggests that by 2023, the cumulative impacts of ongoing mining had degraded the landscape to a point where even moderate rainfall could lead to severe siltation.

These changes indicate that typhoon-driven rainfall exacerbates siltation, but its impact is modulated by land conditions. The regression results, combined with these findings, imply that the degradation from mining activities has left the landscape more susceptible to erosion and runoff, amplifying the siltation response even with lower precipitation.



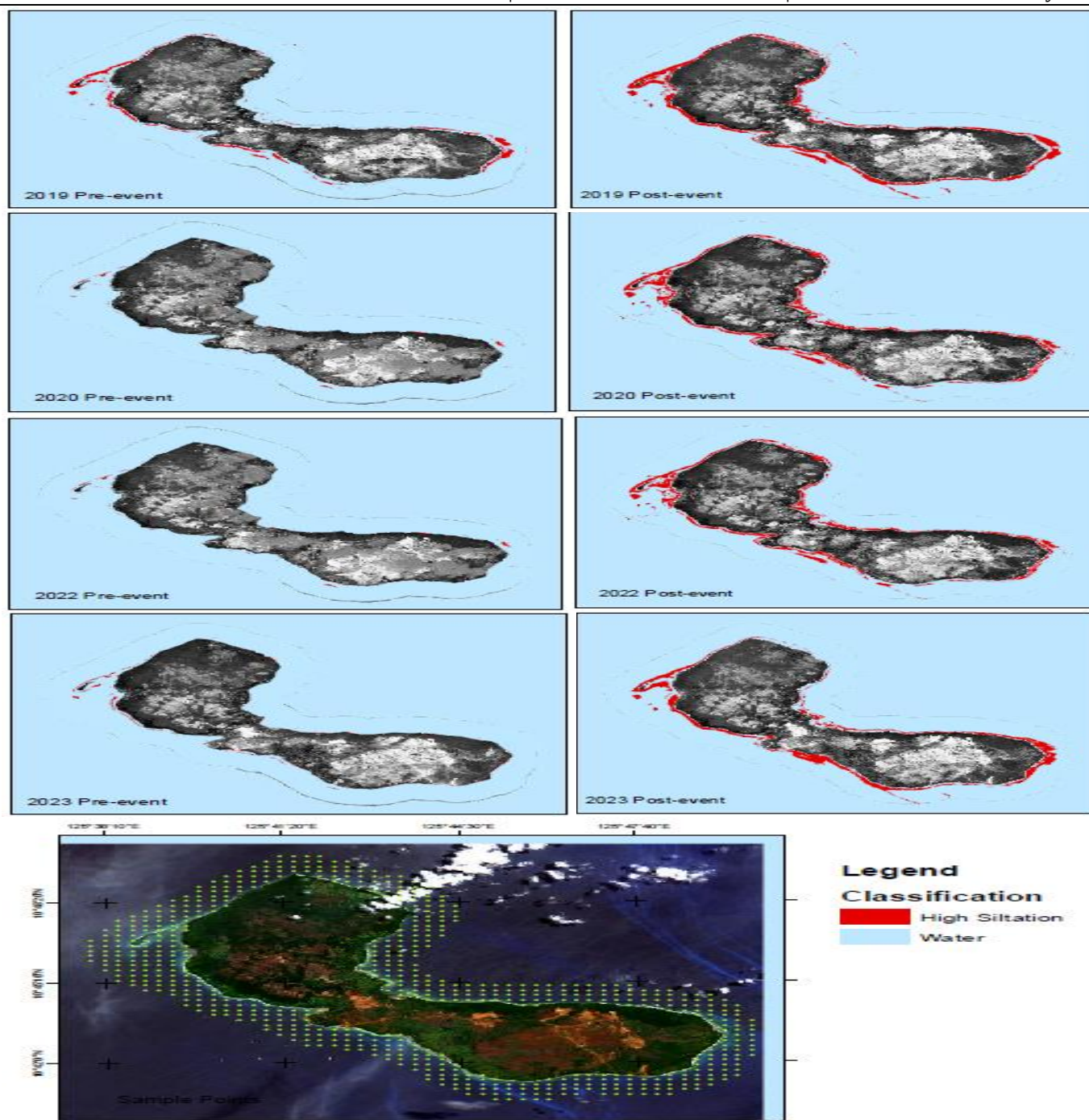
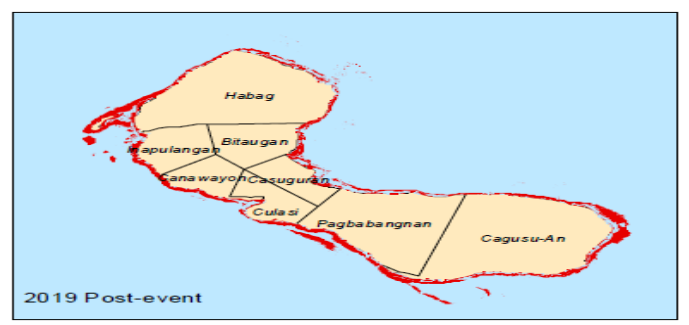
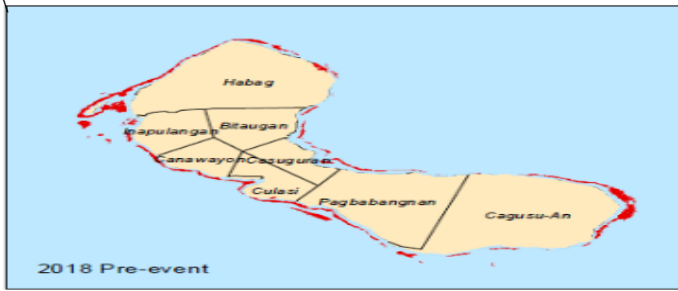


Fig. 6 Raster Map of Temporal Comparison of Siltation Levels and Water Classification in Homonhon Island (2018–2023).

Figure 6 illustrates temporal changes in siltation levels on Homonhon Island over multiple years, specifically for Figure 6 shows map of 2018, 2019, 2022, and 2023. Each set of pre- and post-event maps provides a visual comparison of siltation before and after specific climatological events, such as typhoons, which contributed to the increase in sediment deposition in surrounding water bodies. Each pair of maps (pre- and post-event) shows siltation areas identified using satellite imagery. The "pre-event" maps represent conditions before major rainfall or typhoon events, while the "post-event" maps illustrate changes in sediment levels after these events.

For each year, there is a notable increase in siltation following the event, indicated by highlighted areas in red, especially near the island's coastal and mining zones. This increase in sediment is indicative of runoff and erosion likely exacerbated by the heavy rainfall associated with typhoons.

The final map provides an overall view of Homonhon Island, with a focus on high-siltation zones (marked in red), water bodies (marked in blue), and the distribution of sampling points used in the study.



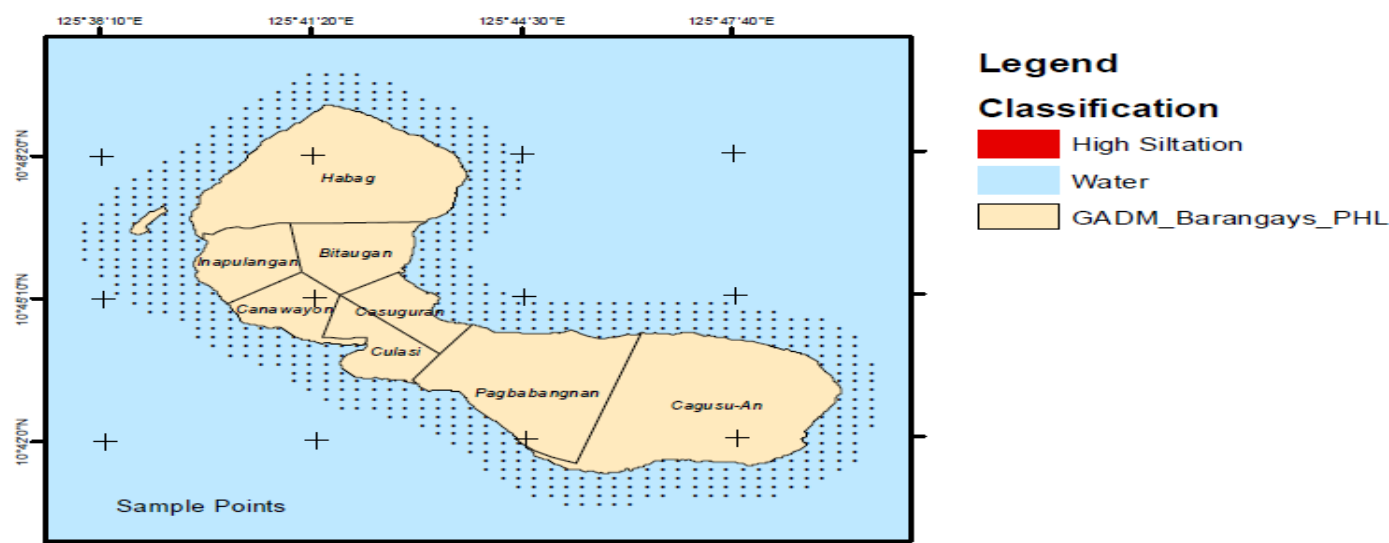


Fig. 7 Vector Map Layout of Temporal and Spatial Comparison of Siltation Levels and Water Classification in Homonhon Island (2018–2023).

Figure 7 illustrate the pre- and post-event siltation areas, marked with classifications such as high siltation (often in red) and water bodies (in blue). This color-coding helps visualize the spread and intensity of siltation immediately after typhoon events, providing insight into how each year's storm impacts sediment distribution.

By comparing these maps year-to-year, the study was able to assess the cumulative impact of repeated typhoons on sediment buildup. For instance, year 2018 and 2019 show siltation expansion following each event, indicating that successive typhoons further exacerbate sediment deposition in high-siltation zones, especially near mining sites.

The vector maps highlight specific zones that consistently experience high siltation after each typhoon. These high-risk zones are generally located near areas of active mining, as shown by the clustering of red zones along key mining regions in areas like Canawayon and Bitaugan.

The inclusion of sampling points on the maps (marked as discrete locations) shows where data was collected for validation, providing a spatial reference for ground-truthing the satellite-based siltation classifications. This is essential for verifying the accuracy of remote sensing data and enhancing the reliability of the study's findings. By linking these sampling points to high-siltation areas, the maps illustrate the study's methodology in selecting locations that represent both extreme and moderate siltation conditions. This approach strengthens the study's capacity to capture a wide range of siltation intensities across Homonhon Island.

The maps visually underscore the combined effect of mining and typhoon events on siltation. High siltation levels consistently occur downstream or adjacent to mining areas, showing how these disturbed lands contribute to sediment transport, especially during heavy rainfall. The progression of high-siltation zones over the years reflects the island's increasing environmental vulnerability. Each typhoon deposits more sediment into surrounding waters, amplifying the impact of mining-induced land degradation. This visual progression suggests a declining resilience of the landscape, where mining intensifies siltation effects beyond what would be observed in non-disturbed areas.

Siltation Patterns and Climatic Influences on Homonhon Island

The results reveal distinct changes in the siltation levels on Homonhon Island over multiple years, with substantial increases observed following typhoon events. The analysis focuses on the correlation between rainfall data derived from typhoon occurrences and the difference in siltation areas, particularly around the mining-impacted zones of the island. This approach highlights the combined effects of natural climatological events such as typhoons and human-induced mining activities on coastal and aquatic ecosystems.

IV. Conclusion and Future Work

Relationship Between Rainfall and Siltation

The study finds that while rainfall contributes to siltation, mining activities likely play a more substantial role in accelerating the runoff and sediment deposition in Homonhon Island. The presence of extensive mining areas can increase soil erosion, making it easier for rain, even in smaller amounts, to mobilize sediments and lead to significant siltation in water bodies.

Future research should consider a more comprehensive multivariable model that includes additional factors such as wind speed, storm surge, topography, and infrastructure resilience to better understand the impact of typhoons on damage levels. Additionally,

conducting a temporal analysis to observe how rainfall impacts damage in the weeks and months surrounding a typhoon event might reveal more nuanced relationships. Gathering more data across multiple typhoon events could also enhance the robustness of the analysis.

V. Acknowledgment

The authors would like to express their sincere gratitude to everyone who made this research possible. We also extend our thanks to the Copernicus Sentinel Open Access Hub sharing invaluable satellite data, which played a crucial role in our analysis. Special appreciation goes to the Local Government Unit of Guiuan (LGU-Guiuan) for their assistance and cooperation in facilitating data collection on the ground. Finally, we are deeply grateful to the Department of Environment and Natural Resources (DENR) for their guidance and access to environmental resources, which significantly enriched our study. This research would not have been possible without the collective efforts and contributions of these esteemed institutions.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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