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Geologic Influences on Sinkhole Morphometry in Siargao Island, Surigao del Norte, Philippines

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Abstract

The 2013 Bohol earthquake and other phenomenon has caused numerous sinkholes to emerge in several areas specially in karstic regions, leaving a significant gap in research concerning sinkholes, especially in the Philippines. In an island primarily composed of carbonate materials like Siargao Island in southern Philippines, it becomes imperative to understand the potential geological hazards that may arise in karstic regions. This study utilizes remote sensing techniques, including IfSAR-DEM, processed in GIS platform, to evaluate sinkhole hazards. It involved detailed geological and geomorphological assessments, considering factors like sinkhole distribution, lineaments, streams, elevation, and formational units. The methodology includes using sinkhole inventory from Mines and Geosciences Bureau - Region XIII in locating high-risk areas. The resulting maps depict regions prone to subsidence, particularly where sinkholes can form unexpectedly. The study shows four key factors influencing sinkhole occurrence in the island such as lineaments, elevation, slope, and karstic bedrock. Majority of sinkholes are found in low elevation, gentle slope, and proximal to lineaments (200-400m). The findings of this investigation will not only contribute to a deeper comprehension of the geological forces influencing the island's topography but also provide valuable insights for better land-use planning and risk mitigation in this region, where such geological phenomena can have significant implications for local communities and infrastructure.

1. Introduction

Siargao Island, located in Surigao del Norte, Philippines has a diverse geologic background. The island is also declared as one of the largest protected areas in the country with 283,974.77 hectares of protected landscape and seascape based on the National Integrated Protected Areas System (NIPAS). The island is predominantly composed of karst formations, mainly Siargao Limestone (Mines and Geosciences Bureau, 2010).

Sinkholes, one of the most common features that occur in karstic environments, are developed from the dissolution of soluble rocks (Benson and Yuhr, 2016). Carbonate rocks when subjected to dissolution fluid weathers the rocks over time. This will result in the formation of voids and cavities in the subsurface. This increases the risk of the residents within the island communities not only in terms of infrastructure but also in overall environment.

This study investigates the physical characteristics of sinkholes, by classifying the parameters of sinkhole morphometry, such as area, perimeter, compactness, eccentricity, and circularity index. These classifications impart insights on the process behind sinkhole formation and its potential for future changes. Factors that contribute to sinkhole formation are rock type, underlying geological features like faults and fractures, and the area's hydrology. Other factors that can also contribute to these formation are anthropogenic processes (or human activities), such as groundwater pumping, agriculture, and excavations. Understanding these factors enables local government units to utilize these findings to identify sinkhole prone areas. This will be beneficial in developing preparedness plans, mitigation strategies, and land use planning related to sinkhole hazards.

2. Geology and Topography of the Study Area

The island is composed of different lithologies and formations such as the Dinagat Ophiolite, Sapao Formation, and Siargao Limestone (Figure 1). The Dinagat Ophiolite is the basement unit of Siargao Island that consists of Late Cretaceous volcanic member spilitic basalt and diabase, with minor ash flow and welded tuff as exposed in the island. This unit is mainly found in the Dinagat Islands (and neighboring areas in the mainland Surigao peninsula), just west of the Siargao Island (Dimalanta et al., 2019). Overlying the basement rocks is the Sapao Formation, which consists of Paleocene tuffaceous shale and sandstone, and volcanic wackes. This rock formation is mainly located on the southern portion of the main Siargao Island.
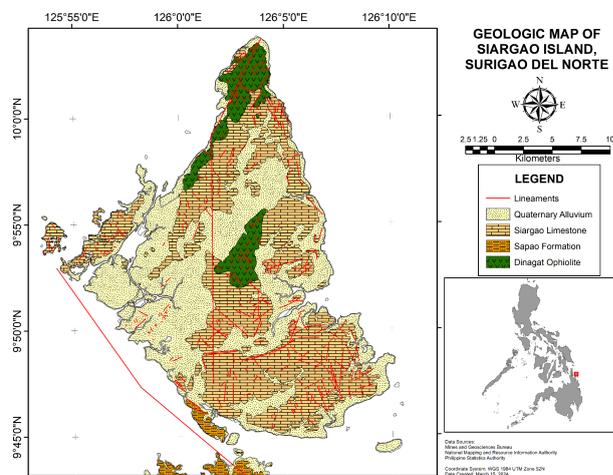

Figure 1. Geologic Map of Siargao Island, Surigao Del Norte, Philippines.

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The Siargao Limestone, covering over half of the island's area, consists mainly of limestone. These carbonate rocks are mostly massive, oolitic, porous reef limestone that extends from Santa Monica to Dapa municipalities. Limestone is a porous and soluble rock that is easily dissolved by rainwater or groundwater. As water passes through the limestone, it dissolves the rock, creating cavities, sinkholes, and underground rivers. These rocks can also contribute to the island's water supply by serving as an aquifer (Pavlopoulos et al., 2010). Rainwater seeps into the limestone and fills the underground reservoirs, providing a reliable source of water for the island's residents and tourists (Chalikakis et al., 2011). Overlying the Siargao Limestone is the Quaternary Alluvium unit composed of Holocene detrital deposits, mainly carbonates in composition. These unconsolidated sediments are predominantly sand, silt, and gravel size, distributed along the shorelines and river systems of the island. These geological formations shape the island's landscape and contribute to its complex hydrological dynamics.
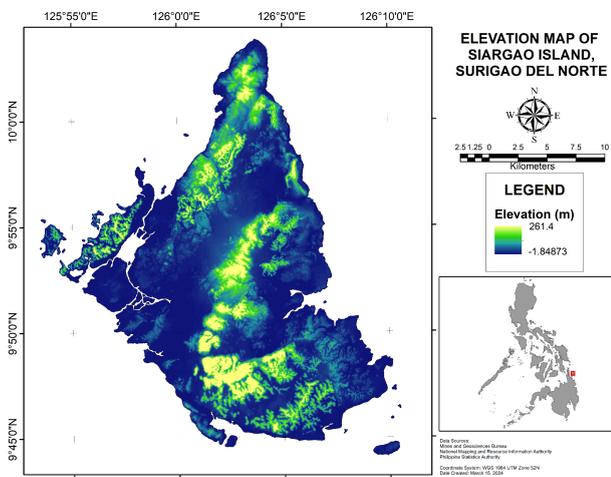

Figure 2. Elevation Map of Siargao Island, Surigao Del Norte, Philippines.

Siargao Island's topography is generally characterized by low-lying areas with a maximum elevation of around 261 meters above sea level (Figure 2). These low elevation areas also coincide with the Quaternary Alluvium unit.

3. Methodology

Existing ground-validated sinkhole data from MGB-RXIII were utilized. This was followed by field surveys to document sinkhole features, which were later digitized. Sinkholes were then treated as centroids, and their frequency and proximity to several factors (i.e., geological formational units, elevation, slope, stream, and lineaments) were also noted (Figure 3). These were digitized from various sources like topographic maps and remote sensing data (Lumongsod et al., 2020).

This study also utilizes sinkhole polygons to measure their geometric properties, such as area, compactness, eccentricity and circularity index shown below:

$$C = 4\pi \cdot A/P^2 \qquad \text{Eq. (1)}$$

where C = compactness
A = area
P = perimeter

$$e = \sqrt{1 - \frac{b^2}{a^2}} \qquad \text{Eq. (2)}$$

where e = eccentricity
a = semi major axis
b = semi minor axis

$$Pe = 2\pi \left(\frac{\sqrt{A}}{\pi}\right) \qquad \text{Eq. (3)}$$

where P_e = expected perimeter for a perfect circle polygon
A = area

$$Circ_i = \left(\frac{Po - Pe}{Pe}\right) \qquad \text{Eq. (4)}$$

where $Circ_i$ = circularity index of the polygon
P_o = observed perimeter
P_e = expected perimeter for a perfect circle polygon

Additionally, Pearson Correlation method was also used to measure the relationship between these factors and the sinkhole frequency.
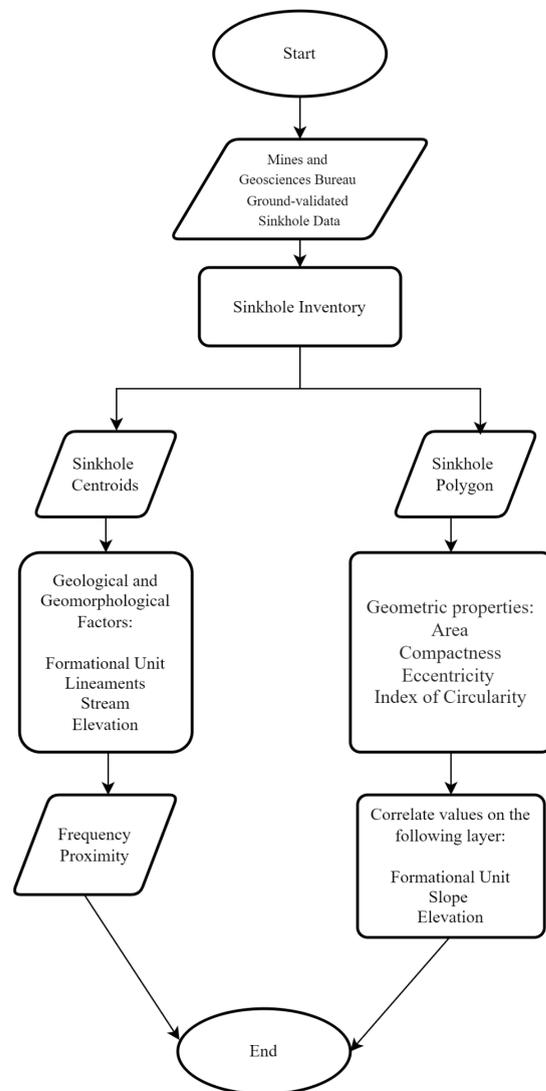

Figure 3. Conceptual Framework of the study adapted from Lumongsod et al. (2020).

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4. Results and Discussion

4.1 Frequency and Proximity

The data reveals correlations between sinkhole frequency in Siargao Island and to these factors: proximity to lineaments, streams, slope angle, and elevation. The increased frequency of sinkholes near lineaments suggests that these weaknesses play a role in sinkhole development (Figure 4). Groundwater flow is often channeled along these fractures, which can accelerate the dissolution of soluble rocks like limestone and create cavities that eventually collapse to form sinkholes.
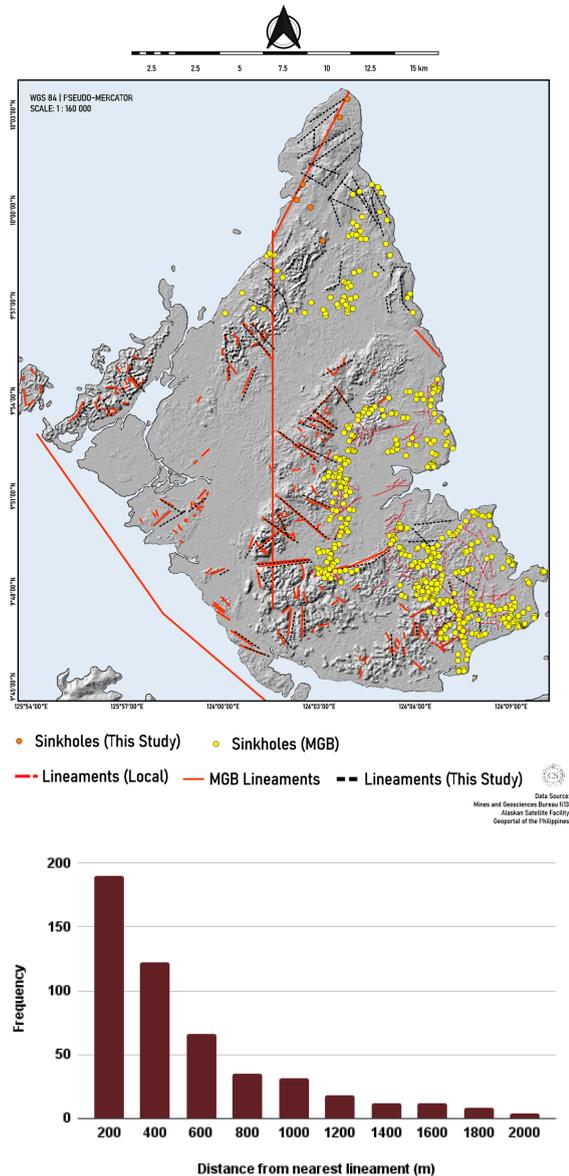

Figure 4. Sinkhole centroid distribution map of Siargao Island with the identified lineaments (top), with sinkholes primarily occurring in close proximity (bottom) to these linear features.

However, no clear correlation was found between sinkholes and proximity to streams (Figure 5). The correlation of two variables has an r value of -0.02496 which indicates that there is less to no correlation between stream and sinkhole frequency. This could be due to the delineation of only major streams in Siargao. Identifying the water accumulation areas can be a

major improvement for the proper analysis of the influence of streams to the sinkhole formation. This is due to river networks can erode and expose soluble rocks like limestone (Lindsay et al., 2019). This process can create cavities that eventually collapse and form sinkholes. Additionally, streams can influence the groundwater table, promoting more advanced dissolution in areas closer to them.
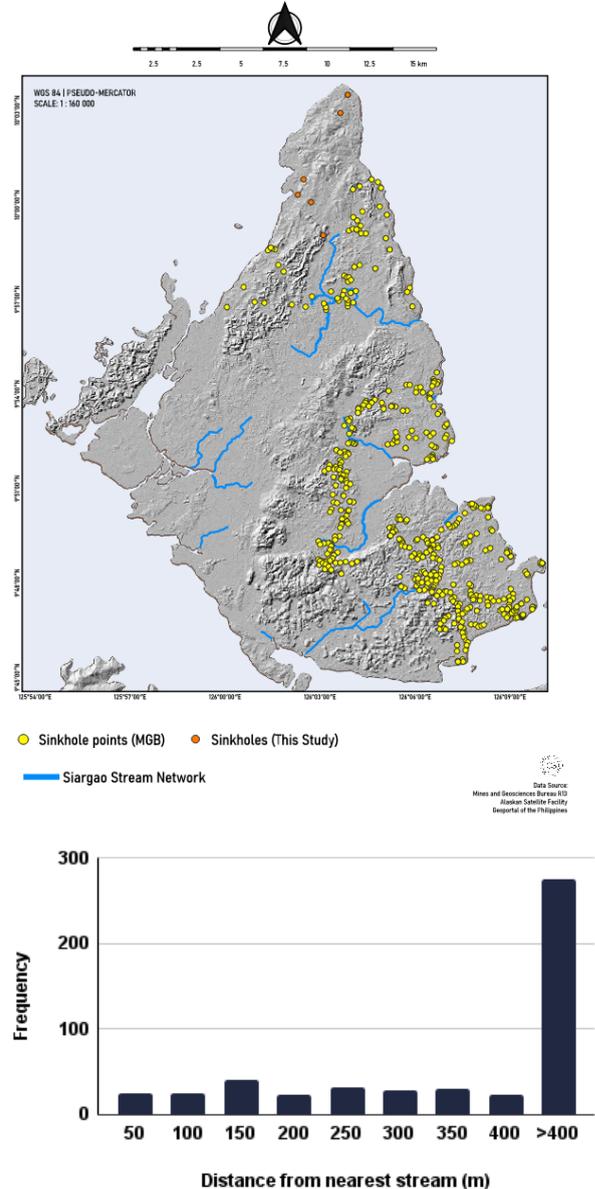

Figure 5. Sinkhole centroid distribution map of Siargao Island with the identified streams (top), showing the frequency of these sinkholes versus its distance with the nearest stream (bottom).

There is a visible reduction in the frequency of sinkholes as slope angle (Figure 6) and elevation (Figure 7) increases. While there isn't a consistent pattern observed, specifically concerning the elevation, the majority of the sinkholes are typically found at elevation below 50 meters above sea level (masl). This suggests a potential correlation between sinkhole distribution and certain terrain characteristics, where areas with gentle slopes and lower elevations tend to exhibit a higher incidence of sinkholes.

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Based on the Pearson correlation method, it was determined that the occurrence of sinkholes are moderately correlated to the elevation with an r value of -0.56. Whereas, the slope is highly correlated to the occurrence sinkholes with an r value of -0.71, well below the threshold of 1.

Island primarily consist of these older limestones which further increases its sinkhole formation potential. Only five sinkholes were plotted in the igneous Dinagat Ophiolite, while none were recorded in the other clastic unit, Sapao Formation.
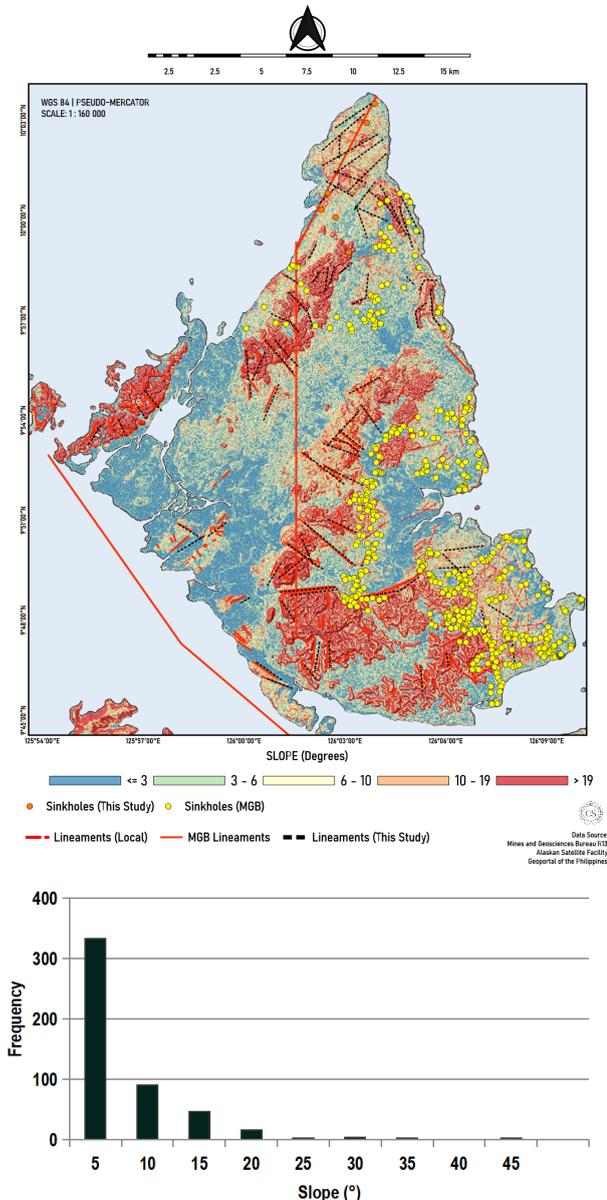

Figure 6. Sinkhole centroid distribution map of Siargao Island with the slope map (top), showing a noticeable decrease in sinkhole frequency as slope angle increases (bottom).
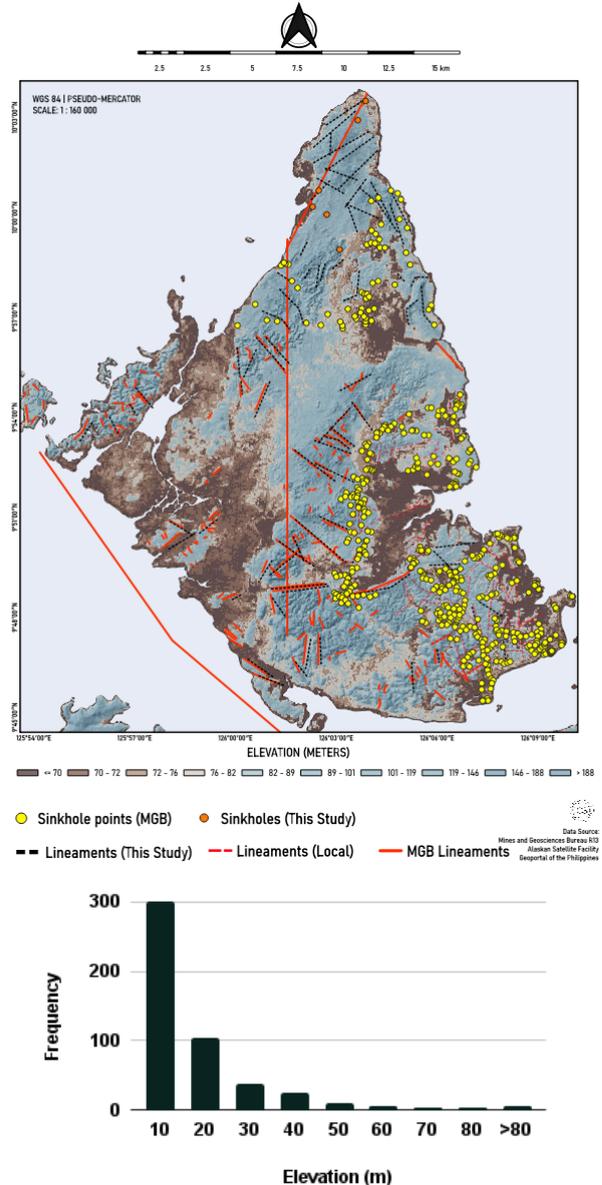

Figure 7. Elevation and sinkhole centroid distribution map of Siargao Island (top), showing a noticeable decrease in sinkhole frequency as elevation increases (bottom).

As expected, sinkhole formation tends to be more prevalent in carbonate materials, such as the Siargao Limestone. Among the total of 498 sinkholes, 297 sinkholes were located within the Siargao Limestone, underscoring its heightened vulnerability to sinkhole development (Figure 8). Additionally, 196 sinkholes were identified in Quaternary Alluvium, indicating a significant presence in this geological unit as well. This could be attributed to the possible underlying presence of Siargao Limestone beneath the recent alluvial deposits. Given that carbonate materials are known to be susceptible to sinkhole formation, the presence of Siargao Limestone beneath the Quaternary Alluvium increases the likelihood of subsidence or sinkhole development within this unit. The alluvium deposits of Siargao

The result of the comparison of frequency and proximity shows that the majority of the sinkholes occur in low elevation (i.e., -0.36 meters to 15.88 meters) (Figure 9) with gentle slopes (i.e., 0 to 8.34 degrees) (Figure 10). These sinkholes are located in Siargao Limestone and Quaternary Alluvium formational units (Figure 11). This could potentially address the limited data for the sinkhole inventory for the whole island (i.e., Dapa, Del Carmen, San Benito, and San Isidro).

This can help local government units to establish restricted zones or designated for low-impact development. This would protect areas with sensitive geological conditions (i.e., low elevation, gentle slope, proximity to lineaments) from heavy development. These zones can be mapped to guide land use policies and construction activities.
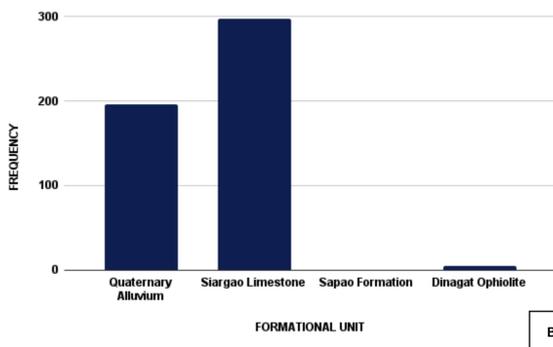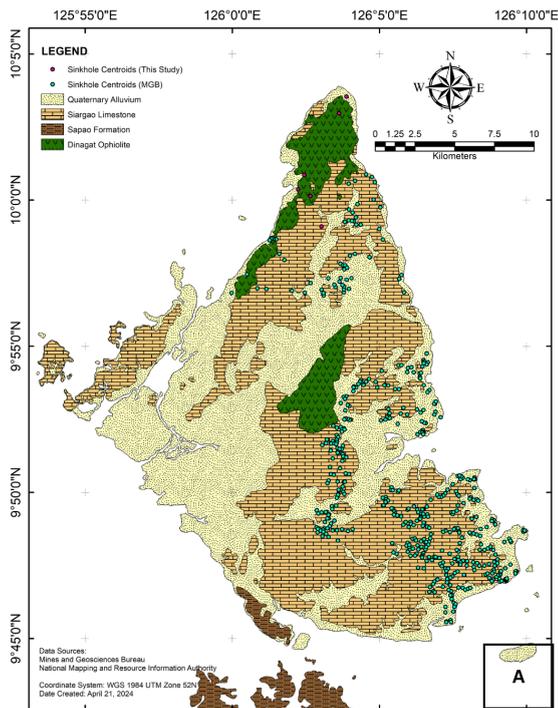
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Figure 10. Gentle slope areas with no sinkhole data in Siargao Island.

Figure 8. Geologic map of Siargao Island with an overlain sinkhole centroid feature (A). Sinkhole frequency in each formational unit (B).
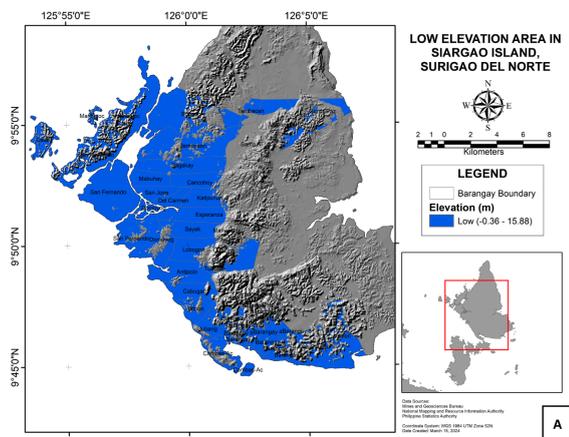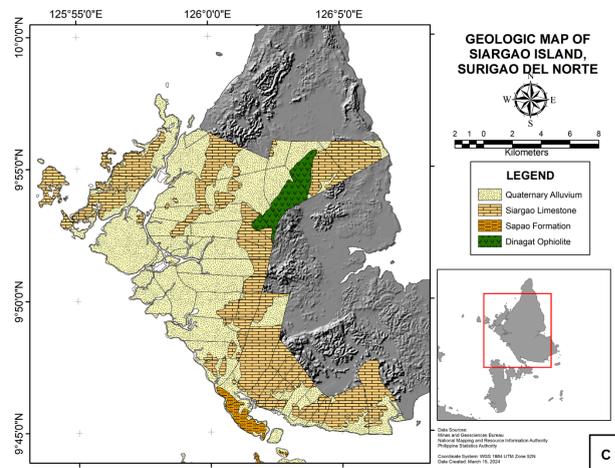

Figure 11. Karst areas associated with the Siargao Limestone and Quaternary Alluvium that are susceptible to sinkhole.

Establishing buffer zones where development is either designated as restricted or in places that require additional geotechnical assessments due to high risk of sinkhole hazards. Detailed geotechnical and hydrological surveys (e.g., water flow or infiltration modeling) must be done in these high risk areas considering that surface streams do not correlate with sinkhole occurrences but subterranean water movements do.

4. 2 Area, Compactness, Eccentricity, and Circularity Index

4.2.1 Formational Units: Siargao Limestone Quaternary Alluvium are similar rock units, which is in contrast to the Dinagat Ophiolite (Figure 12). It may be due to the frequency of the ground validated sinkholes in that formational unit: Siargao Limestone has over 297 sinkholes, Quaternary Alluvium has over 196 sinkholes, and Dinagat Ophiolite only 5 sinkholes. The sinkholes in Dinagat Ophiolite are few but they are bigger. Sinkholes in Quaternary Alluvium are fewer than Siargao Limestone but are similar in size. For Quaternary Alluvium, the sinkholes area is within the range of 4m², Siargao Limestone is between 3.5 - 4m², and Dinagat ophiolite is within the 4.5 - 5m² range.

Figure 9. Low elevation areas with no sinkhole data in Siargao Island

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Eccentricity looks into how close the sinkhole is to an ellipsoid. High eccentricity suggests that the small sinkholes over time would join together to form a bigger sinkhole ellipsoid, or most commonly known as an uvala (Lumongsod et al., 2020). Given the small availability of sinkhole data in the Dinagat Ophiolite unit, there was no conclusive interpretation on their sinkhole morphometry. Moreover, Dinagat Ophiolite units are not prone to dissolution due to its geologic characteristics- which are probably pseudosinkholes.
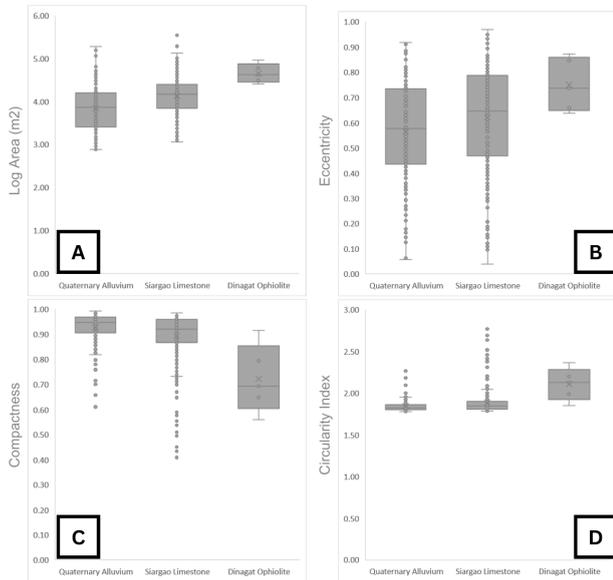

Figure 12. Box plot of sinkhole geometry against formational units. Plots showing area (A), eccentricity (B), compactness (C), and circularity index (D) with increasing relative age.

Siargao Limestone and Quaternary Alluvium sinkholes are similar in morphology (Figure 12). Whether the sinkhole occurs in the unconsolidated Quaternary Alluvium, or the more indurated Siargao Limestone, they have similar sinkhole geometry possibly attributing to their carbonate source.

4.2.2 Slope: The investigation of the correlation between sinkhole morphometry and slope, revealed that there was no notable effect on sinkhole geometry in terms of eccentricity, compactness, and circularity index (Figure 13). Most of the box plots were in similar ranges regardless of the distinguished slope angle- whether it is located at gentle, moderate, or high slopes, it has no effect on the sinkholes' geometry. In contrast to the areas observed, sinkholes have a bigger area in steeper slopes compared to low and moderate slopes which are almost similar in range. However, sinkholes located in moderate slopes have a slightly bigger area compared to gentle slopes. Thus, it was concluded that the slope angle only determines the frequency of the sinkhole, not the morphometry.

4.2.3 Elevation: Similar to slope, elevation has no influence on sinkhole geometry (Figure 14). Compactness, eccentricity, and circularity index are almost the same for the identified sinkholes. Moderate slope and moderate elevation yields bigger sinkholes in terms of area compared to sinkholes in gentler slope and lower elevation, and those in steeper slopes and higher elevations. A possible explanation of the influence of moderate slopes and elevation in the sinkhole area is that the sinkhole area has a balance of water infiltration and runoff. In instances where the infiltration rate is greater than the precipitation rate, the infiltrated water is able to dissolve the

underlying rock before sinkhole collapse or subsidence occurs. Due to the moderate slope and elevation, water does not rapidly flow compared to steeper slopes and higher elevations. These runoff waters pond in gentler slopes and low elevations thus explains the high frequency of sinkholes in these areas (Figure 6). This can also be observed from the sinkholes in Pajares Tunnels, Spain (Valenzuela et al., 2015), where a rainfall-runoff model using GIS software was used to validate these claims.
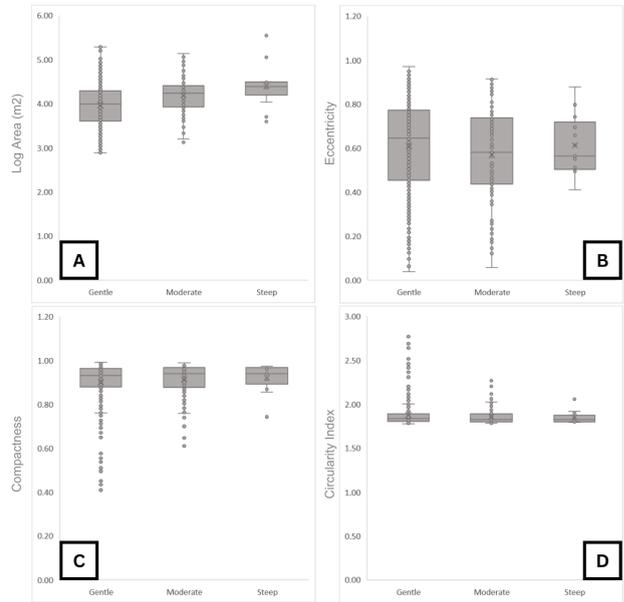

Figure 13. Box plot of sinkhole geometry against slope. Plots showing area (A), eccentricity (B), compactness (C), and circularity index (D) with increasing slope angle.
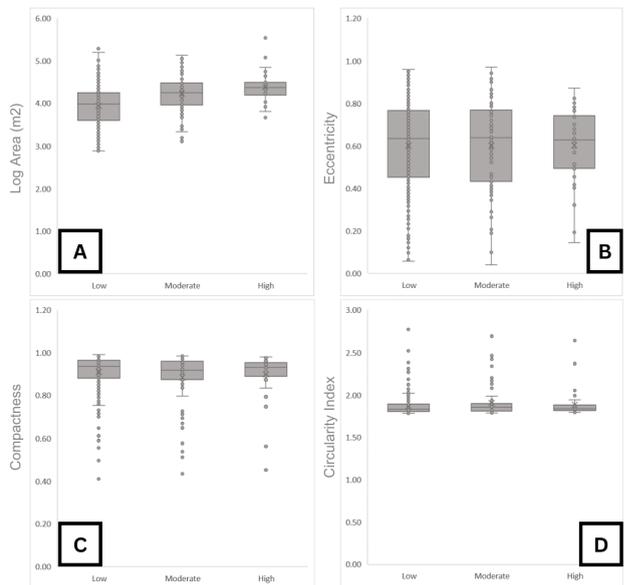

Figure 14. Box plot of sinkhole geometry against elevation. Plots showing area (A), eccentricity (B), compactness (C), and circularity index (D) with increasing elevation.

5. Conclusions and Recommendations

The sinkhole frequency and proximity analysis identified four key factors influencing sinkhole occurrence in Siargao Island: lineaments, elevation, slope, and karstic bedrock. Water plays a significant role in sinkhole formation, though surface streams showed no correlation with sinkhole occurrence, likely due to the inability of the generated stream network to detect subterranean water flow. Most sinkholes were found in areas with low elevations (0.36m to 15.88m), and gentle slopes (1° to 8.34°). Morphometric analyses showed that sinkhole size is more influenced by a balance of water infiltration and runoff in moderate slopes and elevations, rather than the type or age of the underlying rock. This supports findings from other studies, such as in the carbonate terrain in central Cebu, Philippines (Lumongsod et al., 2022), which show little correlation between slope and karstification potential. Most sinkholes in Siargao are located in low elevation and gentle slopes, likely due to focused dissolution from surface runoff in karstic bedrock (Valenzuela et al., 2015).

It is recommended to incorporate missing data for the municipalities of Dapa, Del Carmen, and Sta. Monica (Figures 9-11) to enhance the understanding of sinkhole formation and distribution across Siargao Island. This would improve local hazard awareness and preparedness for karst-related disasters. Encouraging citizen initiatives to consolidate community-observed sinkhole reports with official surveys from MGB is also suggested, along with the use of geophysical surveys to map sinkhole geometry and occurrences. Developing a sinkhole susceptibility model using Multi-Criteria Evaluation (MCE) or logistic regression would also help local government units (LGUs) determine high-risk areas based on the already identified factors (e.g., elevation, slope, and karstic bedrock). This can guide land-use development plans and the possible designation of restricted zones or areas for low-impact development, especially around lineaments. Establishing buffer zones (e.g., 200-400 meters from lineaments) with geotechnical investigations and risk assessments before developing tourism infrastructure will be beneficial to the community.

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