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GIS Modelling of Karstification Potential of Samal Island, Davao Del Norte

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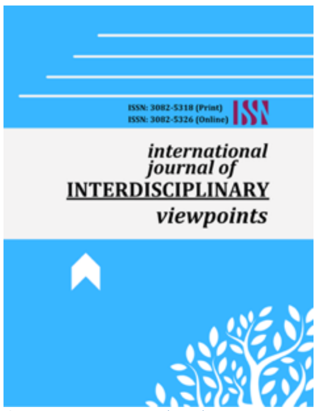
Research Article



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ABSTRACT

In the Philippines, Samal Island is a karst environment that has undergone significant changes due to human activity over the last few years. At this rate of growth, it may be challenging to recognize that karstification is still being caused by natural processes, which may not be fully evident on current karst sinking risk maps. The goal of this study is to determine the different levels of karstification (or karstification potential) on the island by categorizing areas into high, moderate, and low karstification using a GIS-based analysis guided by the Analytical Hierarchy Process (AHP). To make a new geologic map, detailed geologic mapping was done. Other related datasets were rasterized, reclassified, and weighted using a pairwise comparison matrix. The central part of Samal Island exhibits a high level of karstification, as confirmed by accuracy tests and an inventory of caves, sinkholes, and other karst features. On the other hand, there is moderate karstification in the edges of coastal places, especially where sedimentary rocks with limestone are present. The study revealed that rock and rainfall are the primary factors that cause karstification. After creating a map that identifies areas that may become karst, local governments can utilize it as a guide when developing long-term land use plans and mitigating risks on Samal Island.

Keywords: AHP, Geohazard, GIS, Karstification Potential, Philippines

INTRODUCTION

Some of the most unstable and changing types of land on Earth are karst areas. Rocks that can break down, like dolomite and limestone, make them up. Caves, sinkholes, and underground drainage networks are some of the unique features that karstification turns the land into overtime (Ford & Williams, 2013). Approximately 15% of the world's land area comprises these types of landscapes, which are crucial for maintaining ecosystem balance, replenishing groundwater, and protecting biodiversity. People can harm karst environments, despite their importance to the ecosystem. The increasing number of people living in cities, increased factory activity, and changes in farming methods are all contributing to the acceleration of soil erosion and underlying soil instability. To manage properties in a way that is beneficial for the environment and reduces the risk of disasters, it is now crucial to understand how to measure karstification and its location.

Karst landscapes comprise approximately 10% of the Philippines' land area. Numerous of them reside in areas with a lot of limestone, such as Bohol, Cebu, Samar, Davao Oriental, and Davao del Norte (Wagner, 2013). It is essential for the ecosystem that these places exist. They also contribute to the economy by growing crops and attracting tourists. Sinkholes and ground subsidence are just as likely to occur when the delicate balance between geological processes and human activities is disrupted. The tropical karst environment on Samal Island in the Davao Gulf is characterized by porous coral limestone and extensive subsurface drainage (Restificar et al., 2006). The island has experienced rapid growth in the past few years, thanks to improved housing, increased tourism, and enhanced infrastructure. Geohazards are more likely to harm people due to pressures caused by human activities. These pressures can either accelerate or slow down natural karstification processes. Karst subsidence is one of the most unexpected geohazards in the country, according to the Mines and Geosciences Bureau (MGB, 2019). However, most current hazard maps only show how things are now, not how the landscape is changing over time.

People have tried to describe and record the Philippines' karst landscapes, but most of the studies being conducted now are merely descriptive and aimed at identifying dangers. They do not have any prediction models that incorporate the changing features of karst processes influenced by geological, hydrological, and human factors (Lumongsod et al., 2022). Therefore, we still do not fully understand how karstification operates in terms of both time and space. GIS-based methods, such as the Analytical Hierarchy Process (AHP) and multi-criteria decision analysis, have been successfully applied worldwide to identify and define areas that are likely to develop into karst (Moradi et al., 2016). These methods cannot be used very much in the rocky areas of the Philippines, however. A significant gap in our understanding of how karsts form and evolve on tropical islands is the lack of high-resolution, data-driven spatial models. These models would show how natural and human-made forces interact with each other.

This study employs a GIS-based Analytical Hierarchy Process (AHP) model to assess the karstification potential of Samal Island, Davao del Norte, thereby filling the existing knowledge gap. To identify and categorize areas with high, moderate, and low karstification, the study integrates geological, topographic, meteorological, and land cover data. The local government unit (LGU) of the Island Garden City of Samal utilizes the karstification potential map to inform science-based decisions regarding zoning, infrastructure planning, and disaster risk mitigation techniques. Additionally, the results can help the Department of Environment and Natural Resources–Mines and Geosciences Bureau (DENR–MGB) enhance its efforts to identify and mitigate geohazards. This study has local effects in the area where it was conducted and also contributes to the broader conversation about tropical karst geomorphology by demonstrating how GIS-based decision-making models can aid in planning land use and environmental protection in rapidly growing island ecosystems.

Problem Statement

Karst landscapes are among the most complex and dynamic geological systems, as they continually break down and become unstable below the surface. On Samal Island, an increasing number of human-made activities, such as building infrastructure, boosting tourism, and altering land use, make it harder to understand how karstification occurs naturally. Although the Mines and Geosciences Bureau (MGB) has geohazard maps, these only depict the current state of affairs and do not account for how the karstification process evolves or changes across space. Because of this, we need a study that examines the entire area and identifies locations with varying levels of karstification potential, as well as the factors that cause these changes. This study examines these problems, employing the Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) models to investigate how Samal Island may become karstified. To be more specific, it wants to answer the following study questions:

1. Where on the mainland of Samal Island is there a high, average, or low chance of karst formation?
2. What natural and environmental factors are most important for the karstification process on Samal Island?

By answering these questions, the study aims to establish a scientific foundation for identifying areas that are likely to experience karst, thereby enhancing the accuracy of hazard mapping and supporting land-use planning and environmental management in the island's karst environment.

Literature Review

Karst Landscapes Worldwide

Karst landscapes are among the most diverse on Earth. Sinkholes, caves, and subsurface drainage systems emerge when slow-dissolving materials like limestone, dolomite, and gypsum wear away (Ford & Williams, 2013). Karst habitats, which make approximately 15% of the planet, protect groundwater and support many species (Cahalan & Milewski, 2018). These systems are sensitive to environmental and human changes. Alsharhan and Kendall (2003) suggested climate and sea level change coastal carbonate systems. Tropical strong rainfall and biological activity accelerate karstification, according to Veress (2020). Although karst landscapes are environmentally friendly, they are prone to sinkholes and ground sinking. Rock type, water flow, and land use often define these dangers, according to studies from Europe, the Middle East, and Asia (Farrant & Cooper, 2008; Santo et al., 2007; Seif & Ebrahimi, 2014). Green (2015) and Kaufmann (2007) have noted that even slight environmental changes, such as groundwater levels, can lower the surface. This makes geospatial technologies for karst process tracking and modeling more vital. Perrin et al. (2015) and Moreno-Gómez et al. (2019) found that utilizing GIS and statistical modeling can identify karst-hazardous areas.

Regional and tropical karst studies

Karst processes accelerate and intensify in tropical and subtropical regions due to high temperatures, copious rainfall, and dense vegetation. Water flow and rainfall are crucial to the formation and evolution of caves and other karst features, according to Vietnamese and Thai researchers (Hung et al., 2002; Nguyen Van Hoang, 2021). Veress (2020) suggested tropical karst systems are more difficult than temperate ones. They have thicker soil, deeper dissolution zones, and more surface formations.Alsharhan and Kendall (2003) discussed how temperature and sea level affect coastal karst systems in the Middle East. In the Italian Apennines, karst processes and groundwater flow produce slope instability, according to Santo et al. (2007). Calzar et al. (2018) showed that UAVs and GIS can track geomorphology and mining-related changes. These works demonstrate how technology has improved karst landscape research by predicting risky locations and detecting subtle form changes.

Philippine karst landscapes

Karst landscapes cover 10% of the Philippines. These are common in Bohol, Cebu, Samar, Davao Oriental, and Davao del Norte (Wagner, 2013). Under these regions, thick limestone strata have broken down, forming sinkholes, caves, and underground streams. Restificar, Day, and Urich (2006) claimed Philippine karst systems are ecologically rich but fragile. They warned that unchecked land use and quarrying threaten hydrologic balance. Recent MGB Region XI (2022) and Borromeo (2017) research discovered over 100 sinkholes on Samal Island. Many of them are in fast-growing tourist and residential areas, they cautioned. Highly permeable limestone strata in humid regions tumble more often worldwide (Farrant & Cooper, 2008). In another study, Lumongsod, Ramos, and Dimalanta (2022) used GIS to map Cebu's karstification potential and showed that geological, hydrological, and climatic elements can be combined to identify sensitive locations. Cabrera and Lee (2019) mapped Davao Oriental flood risk using multi-criteria decision analysis. We may apply the same GIS-based scoring technique for karst hazard evaluations.

Geographical and analytical frameworks

Modern mapping technology makes studying and charting karst terrains easier. The Environmental Systems Research Institute (2016)'s ArcGIS software combines geology, climate, and topography data into a single model. High-resolution global datasets like WorldClim 2 allow researchers to study how temperature and rainfall affect karst processes at various scales (Fick & Hijmans, 2017).The Analytical Hierarchy Process (AHP), developed by Saaty, is still a popular geoscience decision-making tool since it helps researchers assess external factors' importance. Moradi, Kalantari, and Charchi (2016) mapped Iran's karst potential using AHP and fuzzy logic. Their model and field data matched nicely. Lumongsod et al. (2022) in the Philippines applied the AHP approach, proving its suitability for tropical climates. Perrin et al. (2015) and Seif and Ebrahimi (2014) also showed that ranking geological and hydrological parameters can improve karst susceptibility maps. Satellite-based technologies like InSAR (U.S. Geological Survey, n.d.) and LiDAR (Moreno-Gómez et al., 2019) make karst ground movement easier to detect. These tools can detect even modest Earth surface changes, enabling early warning and preparation. GIS, AHP, and remote sensing improve karst investigations.

Karst Risks and Environmental Protection

Karst landscapes make land use planning, technical work, and environmental protection difficult. The U.S. Geological Survey (Kaufmann, 2007) and WaterMatters.org (n.d.) state sinkholes are one of the most unpredictable natural disasters since they develop suddenly. Farrant and Cooper (2008) suggested utilizing digital hazard mapping to monitor sinking areas, while Perrin et al. (2015) showed that multi-criteria spatial models may accurately anticipate hazard zones and aid decision-making. In the Philippines, entities like MGB have employed geographic risk assessment methods (MGB ROXIII, 2021). Calzar et al. (2018) suggest using UAV-based mapping to get real-time high-resolution photos of karst landforms. These tools assist track land use changes, especially in rapidly developing infrastructure and tourist destinations.

MATERIALS AND METHODS

Study Area

The study was done on Samal Island, which is in Davao Gulf, Davao del Norte, Philippines. It is officially called the Island Garden City of Samal (IGACOS). The island is about 30,130 hectares big, and the Pakiputan Strait separates it from mainland Mindanao. Geologically, Samal is part of the Agusan–Davao Basin. It is mostly made up of porous coral limestone and coral breccia from the Bunawan Limestone Formation. This formation sits unevenly on top of the Pleistocene-aged Mandog Sandstone (Casasola, 1956; Peña, 2008). Its eastern edge has broken slopes that run north to south and show that it has been lifted and folded. A description by PAGASA says that the island has a Type IV climate, which means that it rains evenly throughout the year. The stable weather and mostly limestone terrain of Samal support active dissolution processes that are always changing the karst landscape.

Research Design

Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) were used together in a quantitative geographic analysis for the study. This framework let the researcher look at many natural and geological factors that affect karstification and give each factor a weight based on how important it was. Based on the work of Moradi et al. (2016) and Lumongsod et al. (2022), the AHP was used to group and rate factors like rock, rainfall, temperature, slope, drainage density, elevation, lineament density, and land cover. There were four main steps in the workflow:

1. Getting information from secondary sources and field studies,
2. Standardization and pre-processing of data,
3. GIS-based AHP for spatial research and model creation, and
4. Validation and testing of data with statistics.

Data Gathering

The information for this study came from both first-hand observations and data gathered from other sources, like national mapping and environmental agencies.

Data from the field

Karst features like caves, sinkholes, and limestone hills were checked out in the field to make sure they were there and to find out how big they were. Geological mapping using standard traverse methods and writing down rock types, lithologic boundaries, and surface features linked to dissolution were all part of the fieldwork. To record locations and structure orientations, a GPS receiver and Brunton compass were used. Mobile devices were also used to geotag photos and field notes. These notes made on-site were very important for checking and improving geological maps that were already out there.

Second-hand Data

Reliable institutions were used to get high-quality location datasets:

NAMRIA gave a Digital Elevation Model (DEM) with a precision of 5 meters that was based on Interferometric Synthetic Aperture Radar (IFSAR); The geologic map, karst subsidence danger map, and sinkhole inventory were all provided by MGB Region XI. DENR Region XI and the LGU of Samal gave information on land use and cover. The weather information, like the amount of rain and temps, came from Fick and Hijmans (2017). To make sure that the research was consistent and correct, all datasets were set to the UTM Zone 51N, WGS 84 projection.

Working with Data

ArcGIS Pro 3.0.2 was used to do pre-processing on spatial data. Standard tools for terrain analysis were used to make slope, elevation, and stream density maps from the DEM at their base. We got the lineament density by making hillshade models from the DEM at three different lighting angles (310°/60°, 210°/90°, and 270°/60°), following the steps outlined by Moradi et al. (2016). To make sure that all datasets had the same precision, vector layers like geology and land cover were changed to raster format. Using the Raster Calculator tool, monthly rasters of temperature and precipitation were averaged to make mean annual layers. Each dataset was reclassified using a five-point scale, where higher scores meant that karst growth was more likely to happen. The method for classifying things used the ideas from Farrant and Cooper (2008), Green (2015), and Lumongsod et al. (2022).

Analysis Based on GIS

The Analytical Hierarchy Process (AHP) was used to figure out how much each factor affected karstification. Using Saaty's (1980) nine-point scale, each factor was judged in relation to the others by comparing them pairwise. The pairwise matrix that was made was checked for internal consistency and found to have a Consistency Ratio (CR) of 0.058, which is well below the acceptable range of 0.1. This showed that the weighting method was sound. With these weights, an ArcGIS Weighted Overlay Analysis was done to find the karstification potential score.

Checking for errors and using statistics

We checked how reliable the model was by putting it on top of the karstification potential map and looking at sinkhole and cave survey data from MGB and DENR. To check for precision, the Confusion Matrix and the Kappa Statistic were used. The model got a Kappa coefficient of 0.82, which means that the predicted and actual karst features were very similar. Then, a Generalized Linear Regression (GLR) analysis was done to find the factors that had the biggest effect on karstification. The karstification potential was the dependent variable in the regression model, and the eight environmental factors were the drivers. Geology and precipitation were found to be the most important factors, with both having high statistical importance ($p < 0.01$). The model gave a modified R^2 value of 0.88, which means that the factors were very good at explaining things and had a strong connection with each other.

An Outline of the Methodology

Field observations, GIS-based spatial analysis, and statistical models were all used in this study to map and understand Samal Island's potential to become karst. It was easier to see how natural and environmental factors affect karst landscapes when thorough field data and analytical modeling were used together. The structure created in this study can be used in other tropical karst areas. It is a useful tool for planning the environment, figuring out risks, and managing land use in a way that doesn't harm the environment.

RESULTS AND DISCUSSION

Possible Karstification Mapping

Based on AHP analysis and GIS, a karstification potential plan of Samal Island was made. The island is split on the map into five areas, each with a different chance of becoming karst: very high, high, moderate, low, and very low. The regional spread shows that the island is karstified all over, but mostly in the middle and southern parts. About 69% of the land area on this island has a high chance of becoming karst, and the other 30% has a medium chance. Only about 1% of the island was low promise, and most of it was around the edges. Most of the places that are high or very high are made up of pure limestone rocks. These rocks are more likely to dissolve because of their chemical make-up and high porosity. In these places, there are also gentle hills, good draining systems, and a lot of rain, all of which speed up the karst process. These are not as easy to break down, so they are usually found near clastic sedimentary units or mixed sedimentary-limestone lithologies. The possibility for karstification is spread out so that it fits the shape of the island. This shows that the type of rock is the most important thing that controls the karstification process. GIS-based karst studies in other tropical areas have found that karst forms faster in places with a lot of carbonate rocks, a lot of rain, and lots of plants (Moradi et al., 2016; Lumongsod et al., 2022). The wet tropical climate in Samal means that water keeps seeping in and chemicals keep breaking down, which speeds up the process of the land becoming karst.

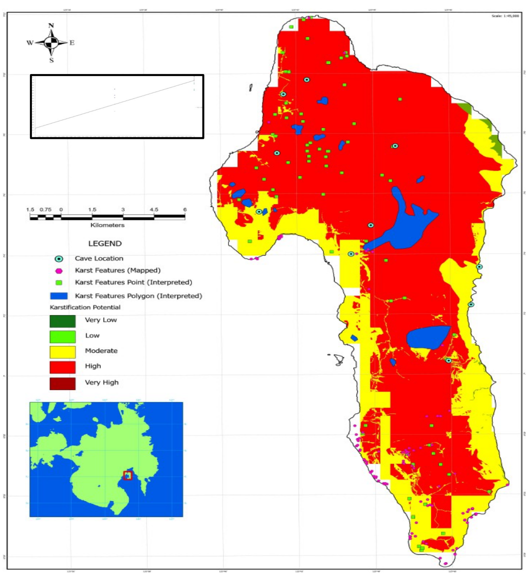

Fig. 1 Validation of the Karstification Potential Map of Samal Island

Making sure the model for how karst forms works

It was checked to see how accurate the model was by comparing it to field-based data from MGB and DENR studies that showed sinkholes, caves, and other karst features. The data show that there is a strong spatial relationship between areas that are predicted to have a high potential and places where known karst traits are found. In fact, 59 of the 69 sinkholes shown on the current karst sinking danger map are in areas with a lot of stress. Seven out of ten marked caves (70%) and the hundred karst features that have been looked at are in high-potential places. The moderate-potential zones cover the other 64 features, or 64%. In places that were rated as having low or very low promise, no karst traits were found. The accuracy test adds to the strength of these conclusions. With a Kappa value of 0.82, the confusion matrix showed that the expected model and the real field conditions agreed on many points. They said in 1977 that a Kappa number above 0.80 means that there is almost perfect agreement. So, the model does a good job of showing how karstification changes on Samal Island over time and space. This proof not only proves that the AHP-based GIS method works, but it also shows that predictive modeling can make regular geohazard mapping methods work a lot better. The model shows how karst changes over time better than static maps that only use field readings because it combines geomorphic, climate, and lithologic data.

Karstification Zones: Where to Find Them and How They Look

The central plateau and south-central parts of the island have the most high-karst places, as we can see from the space trends. Over here, there is a lot of limestone bedrock and not much dirt, so water can soak in and break down calcium carbonate more easily when it rains. There are still karst processes going on in these places because there are a lot of sinkholes, uvalas, and fields. Not far from the coast, on the other hand, there are small karstification zones with mixed sedimentary units and limestone interbeds. Karstification isn't as strong here, but you can still see it in the form of small depressions and other signs of breaking down. The change between rocks that are mostly carbonate and rocks that are mostly clastic can be seen in these middle zones. The northeastern coast has a lot of low karstification zones. The limestone bedrock speeds up the process. The same kinds of interactions have been seen in tropical karst areas in Southeast Asia and the Middle East, where rain and carbonate rock types mix. In terms of shape, these places change quickly (Veress, 2020; Green, 2015).

A detailed look at the things that lead to karstification

We used the GLR method to find the geological and natural causes that have a big impact on the formation of karsts on Samal Island. Weather and geology were found to be the two most important factors based on statistics. The fact that both had p-values less than 0.01 means that they are strongly linked to the chance of karstification. When you change the R^2 number to 0.88, these two things seem to explain nearly 88% of the differences in the island's karst levels. It turned out that geology was the most important thing. Karst processes were most likely to happen where the ground was made of pure limestone. This finding is similar to what Farrant and Cooper (2008) and Moradi et al. (2016) found, which was that lithology was the main thing that shaped how karst formed. Different from dissolution, precipitation is a small but important force that gives them the water they need.

What this means for running the environment and land use

In this study, a karstification potential map was made. This map can be used to help with emergency planning, local government, and land use. Finding places that are likely to become karst can help the Island Garden City of Samal (IGACOS) and other groups make smart decisions about where to put infrastructure, how to boost tourism, and how to set rules for zoning. For instance, limiting heavy building in places where karst is likely to happen can lower the chances of land sinking and ground falling. The tests also help the Department of Environment and Natural Resources – Mines and Geosciences Bureau (DENR–MGB) figure out how to better assess geohazards. AHP and other GIS-based prediction models can be used in national hazard mapping systems to help scientists and planners learn more about how karsts change over time. This will help them learn more about how karsts change over time in a way that is more dynamic and based on processes. This study also shows how important it is to use both geospatial technology and local geological data when taking care of karst settings in tropical places. It also adds to what is known about tropical geomorphology by showing that the connection between geology and rainfall is still the most important thing in karstification, even when weather or plant life changes from one area to another.

A karstification potential map has been generated via GIS-based analysis (Figure 26), ranging from Very High, High, Moderate, Low, Very Low. Very High to High ratings indicate areas underlain by carbonate rocks with limited surface runoff, receiving high precipitation rates, and have considerable land cover, while Moderate ratings denote areas with impure carbonate rocks, receiving lesser precipitation and sparse land cover. Low to Very Low are areas underlain by lithologies other than carbonate rocks. The map indicates that around 69% of the total Samal Island land area falls under High degree of karstification, 30% are under the Moderate degree of karstification, and only 1% under the Low degree of karstification. It can be noted that areas falling under the High classification are underlain by Limestone, Moderate by both Limestone and Sedimentary Rocks with Limestone, while areas classified as Low are underlain by Clastic Sedimentary Rocks only. The resulting map shows gaps or missing cell data in the peripheral area. This is attributed to the way the Temperature and Precipitation datasets are obtained. However, this has not affected the analysis and the missing cell values around the peripheral area of the datasets are ignored. Upon validation, fifty-nine (59) out of the sixty-nine (69) or 85.5% of the delineated sinkholes present in the existing karst subsidence hazard map occur in areas falling under the

High classification. Moreover, seven (7) out of ten (10) or 70% of identified caves likewise occur in High karstification potential areas. The sinkhole mapping inventory proves to be somewhat limited, as the recorded features are concentrated on the southwestern part of the island. However, it is noted that all of these mapped karst features occur on areas with High to Moderate karstification potential. To be precise, 36% (36 out of 100) mapped features are under High, while 64% (64 out of 100) are in moderate. All identified sinkholes, caves, and other karst features do not occur on areas under Low to Very Low classification.

Table 1. Features in High, Moderate, and Low Karstification potential areas

Source / Rating	Very High	High	Moderate	Low	Very Low
Sinkholes (Karst Subsidence Hazard Map)	0	59	10	0	0
Karst Features (Karst Inventory / Report)	0	36	64	0	0
Caves (Cave Inventory)	0	7	3	0	0
Total	0	102	77	0	0

To further validate the generated map, a confusion matrix accuracy test was performed in the GIS space in order to obtain the Kappa statistics. This value (Kappa > 0.8) denotes how accurate the karstification map is compared to ground truth conditions. A kappa value of 0.82 was derived from this analysis, thereby validating the accuracy of the produced map.

Table 2. Distribution of different rock types in Samal Island

Class	C_1	C_2	C_3	C_4	Total	U_Accuracy	Kappa
C_1	0	0	0	0	0	0	0
C_2	7	0	3	0	10	0	0
C_3	0	0	105	16	121	0.8678	0
C_4	0	0	9	367	376	0.9761	0
Total	7	0	117	383	507	0	0
U_Accuracy	0	0	0.8974	0.9582	0	0.9310	0
Kappa	0	0	0	0	0	0	0.8205

The distribution of karstification potential in terms of area coincides strongly with the distribution of carbonate to non-carbonate rocks in the island (Figures 28 and 29). This indicates that geology, or the kind of rock which underlies the area, is the primary factor in karstification, as what have been previously linked (Moradi et al., 2016; Green, 2015; and Farrant and Cooper, 2008). In order to validate and quantify this observation, a linear regression analysis was performed among the layers, or factors, involved in the karstification potential analysis. The following table shows the results of the analysis. The Generalized Linear Regression (GLR) tool available in the GIS software was utilized in order to perform a regression analysis to the eight (8) factors, which are unified in the classification scale based on literature (5 as higher positive effect to karstification and 1 as lower positive effect to karstification). GLR is a tool unique in the newer versions of GIS platforms, which generates or creates models and/or predictions of a dependent variable relative to its explanatory or independent variables. Likewise, this tool incorporates the functionality of Ordinary Least Squares (OLS) analysis, as well as three different kinds of regression models, namely, Continuous (Gaussian), Binary (Logistic), and Count (Poisson). In practice, the input (dependent and independent variables) should be in numeric forms.

Table 3. Regression analysis. Std E = Standard Error, t-stat = t statistics, Prob = Probability, Rob_SE = Robust standard errors, Rob_t = Robust t statistics, Rob_Pr = Robust probability, VIF = Variance Inflation Factor

Layer	Coefficient	Std E	t-stat	Prob	Rob_SE	Rob_t	Rob_Pr	VIF	Layer
Drainage Density	0.022211	0.055	0.408	0.686	0.046	0.488	0.63	1.10	Drainage Density
Elevation	-0.041673	0.067	-0.623	0.537	0.060	-0.693	0.49	6.39	Elevation
Geology	0.448515	0.042	10.702	0.000	0.032	13.834	0.00	2.16	Geology
Lineament Density	0.000407	0.054	0.008	0.994	0.025	0.016	0.99	1.25	Lineament Density
Precipitation	0.188151	0.047	4.049	0.000	0.073	2.588	0.01	2.63	Precipitation
Slope	0.060763	0.053	1.146	0.260	0.042	1.454	0.16	1.67	Slope
Temperature	0.016525	0.083	0.200	0.84	0.071	0.234	0.82	8.80	Temperature
Land Cover	0.086907	0.067	1.302	0.202	0.082	1.067	0.29	1.22	Land Cover

A single dependent variable can be related with several independent, or explanatory, variables, making this method appropriate in determining the relationship of the eight (8) factors and the resulting karstification potential map. Since the classification scheme in determining the karstification potential of the study area is in the scale of five (5) to one (1), a numeric value, which are the results of the analysis in the same unified scale, the GLR tool is directly performed with the Karstification Potential as the Dependent Variable, and the eight (8) factors, namely, Geology, Precipitation, Temperature, Land Cover, Elevation, Lineament Density, Drainage Density, and Slope, as the Explanatory Variables, using the Continuous (Gaussian) model as the datasets have a wide range value. Information derived from this analysis are the adjusted r-squared value and Akaike's Information Criterion (AICc), which measures the performance or fitness of the generated model. The regression analysis shows that two (2) factors have significance in the karstification potential analysis, namely, Geology and Precipitation. Geology has both Prob and Rob_Pr values of 0.00, while Precipitation has 0.00 and 0.01 of Prob and Rob_Pr values, respectively. This indicates that the two factors are the driving forces of the karstification process within Samal Island. Moreover, the relationships between the variables and resulting karstification potential yielded an Adjusted R2 = 0.88, and shows a positive correlation when plotted in and Actual vs Predicted line graph. The AICc value likewise shows a value of 1.22. However, since there is only one model involved, this parameter may not be significant in this study. Moreover, looking at the relationships between the karstification potential and its factors (Figure 31), it can be observed that Geology (R2 = 0.81) has positive correlations to the karstification. Meanwhile, Precipitation (R2 = 0.13), Slope (R2 = 0.12), Elevation (R2 = 0.07), Land Cover (R2 = 0.04) both Lineament Density and Drainage Density (R2 = 0.01) have a weak positive correlation, while Temperature has a negative correlation (R2 = 0.00). This supports the results of previous karstification potential studies that a more uniform carbonate rock area receiving higher precipitation experience more intense karstification (Lumongsod et al., 2022 and Moradi et al, 2016). Consequently, the higher precipitation an area receives, the lower the temperature gets.

Conclusion and Recommendations

This study was successful in developing a karstification potential map of Samal Island by using the Analytical Hierarchy Process (AHP) to eight key karstification criteria. The map was verified against previously mapped karst features to ensure that it appropriately reflects real-world conditions. The findings show that geology and precipitation are the primary sources of karstification on the island, highlighting their significance in Samal's hydrogeological behavior. Although the analysis provides important baseline information for development planning, it is constrained by the datasets' historical scope and the current concentration of karst inventories in the island's southern area.

To improve future assessments, researchers should use more diverse and current spatiotemporal datasets, as well as conduct extensive island-wide karst mapping to account for unrecorded features such as sinkholes, springs, caves, and caverns. The development of a strong geologic and hydrogeologic database, which includes lithological contacts, bedding orientations, faults, disappearing springs, and other indicators, is critical for long-term planning and ensuring that infrastructure projects include effective hydrogeological management plans. Finally, public participation should be encouraged by providing a mechanism for residents to report karst-related issues, enabling for both community knowledge and timely local government action to enhance sustainable landscape and development management.

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Conflict of Interest

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