Karst Groundwater Risk Assessment in Siargao Island, Philippines Towards Sustainable Groundwater Resource Management

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Abstract

The Philippines is known for its karst landscapes, comprising about 10% of the total land area. Due to the inherent characteristics of karst, groundwater quality is easily degraded by natural and anthropogenic factors. This research addresses a critical need for sustainable groundwater management in Siargao Island, a region facing escalating threats to its groundwater resources. More so, the methodologies generally consist of data collection, data analysis and interpretation, and formulation of a groundwater resource framework. The Pearson correlation, principal component analysis, and chi-square statistics were performed using open-source software for statistical computation. Study revealed that the risk to the Karst groundwater system is influenced by natural processes, geological features and land use infl,uence groundwater quality. Groundwater resources in karst are highly vulnerable to anthropogenic contamination and saltwater intrusion due to numerous fractures and a network of cavities in the limestone.

Keywords: karst, risk assessment, groundwater resource framework, aquifer management plan, sustainability, Siargao Island

Introduction

The Philippines is known for its scenic karst landscapes that majorly contribute to the country's economic performance in tourism. These types of rock commonly develop distinct karst features that often become centers of tourist attraction in many parts of the country. Examples of these are the leading tourist destinations such as the Masungi Reserves of Rizal, the Chocolate Hills of Bohol, Puerto Princesa Subterranean River of Palawan, Sumaguing Cave of Sagada, and the islands of Boracay and Siargao in the provinces of Aklan and Surigao del Norte, respectively.

The karst system is one of the most fragile environments in the world because of its inherent characteristics and is highly susceptible to global climate change (Brinkman and Parise, 2012; Mammola *et al,* 2019). With about ten percent (10%) of the Philippine land area underlain by limestone and other carbonate rocks (Restificar *et al,* 2006; Wagner, 2013), tourist areas classified as karst systems are more vulnerable due to their geological and hydrological characteristics (Watson, 1997). Recent studies have explored how irresponsible human activities and natural processes negatively impact karst environments and how these ultimately give rise to various socio-economic problems (Williams, 1993; Goldscheider, 2012).

Tropical island karst is an important asset of the tourism industry in the Philippines. However, without a sustainable development plan, this beautiful landscape is vulnerable to degradation. In most contexts, declining environmental status is an increasing global concern, according to the United Nations. Alarming issues include pollution of the environment, loss of habitat and biodiversity, coastal erosion and siltation, and man-made land subsidence. This is common in a place or an area that has experienced rapid urbanization and commercialization, and the island of Siargao is not immune to this threat. The continuing rise of tourists and development could lead to greater problems that may occur in the future. These include the growing concerns about water security. In addition, a large influx of migrants and tourists may put the island's carrying capacity at risk, particularly regarding its natural resource system, resource use and conservation, and environmental state (Hüttche *et al,* 2002; Graymore, 2005). Likewise, the direct impacts of any ecotourism project would be (1) competition over water use; (2) possible contamination from sewage, wastewater, and solid waste; and (3) possible saltwater intrusion.

Furthermore, some of the noteworthy issues on the island include a surge in solid waste, groundwater saltwater intrusion, deterioration of water quality, and a limited freshwater supply (Serrona *et al,* 2022). These threats are becoming more relevant and necessitate the development of environmental management plans; if not addressed properly, they may lead to complex ecological problems in the future.

Objectives of the Study

In the Philippines, the relationship between surface and subsurface processes in this fragile system is still under study. This study aims to describe the influence of natural and anthropogenic factors on karst groundwater resources in Siargao Island. This can be achieved through the following specific objectives: (1) to assess the current status of karst groundwater vulnerability in Siargao Island using hydrogeological and geochemical data; (2) to evaluate the groundwater pollution potential that is susceptible to exploitation and contamination; (3) to identify potential sources of contamination and quantify their impact on groundwater quality; and (4) to propose effective mitigation strategies and management measures to safeguard groundwater resources in Siargao Island. This is in line with the United Nations Sustainable Development Goals for 2030, which highlight the importance of access to clean water, sanitation, and hygiene (SDG 6) and environmental protection (SDG 14 and 15).

Furthermore, as groundwater vulnerability and risk assessment is a broad aspect, this study will only concentrate on the geophysical survey and hydrogeochemical characterization of groundwater in Siargao Island. The profile of the study area was mainly focused on the municipalities of General Luna and Del Carmen, where both permanent establishments and high tourism activities are present. Additionally, limitations in data availability and potential biases in the study should also be considered. Ultimately, this study seeks to uncover the hidden dynamics that govern the quality and sustainability of karst groundwater in one of the country's most rapidly developing island destinations.

Methodology

The methodologies generally consist of data collection, data analysis and interpretation, and formulation of a groundwater resource framework. In data collection, secondary data from the literature review was used for this study. Water quality was assessed according to the acceptable parameters defined in DENR Administrative Order 2021–19, the updated Water Quality Guidelines and General Effluent

Standard of 2021, the Department of Health (DOH) Administrative Order No. 2017-0010 Philippine National Standards for Drinking Water (PNSDW) of 2017, and the World Health Organization (WHO) Guidelines for Drinking Water Quality of 2011.

Meanwhile, for data analysis, regression analysis was performed using the data analysis built-in plugin in Microsoft Excel. Scatter plot graphs were then generated, incorporating linear trendlines, equations, and R-squared values. The Pearson correlation analysis and chi-square statistics were performed using open-source software for statistical computation.

Results and Discussion

1. Siargao's Groundwater Quality Parameters

Table 1
Descriptive Statistics of Siargao's Groundwater Quality Parameters

Parameter	Unit	Mean	Median	SD	Min.	Max.	DOH-AO 2017-10	DENR-AO 2021-19*	WHO Limit
pH	-	6.99	7.05	0.41	6.30	8.00	6.5 - 8.5	6.5 - 8.5	6.5 - 8.5
Temperature	°C	28.6	28.3	2.79	24.5	36.1	-	26 - 30	-
Conductivity	mS/cm	1.68	0.58	2.71	0.03	8.88	-	-	<1500
Salinity	g/L	0.88	0.26	1.54	0.01	5.02	-	-	-
Alkalinity	mg/L	310	325	94.7	60.0	431	<300	-	<500
TDS	mg/L	679	398	632	52.0	2000	<600	-	<500
TSS	mg/L	1.60	1.40	1.13	0.30	4.40	-	<50	-
Nitrates	mg/L	2.35	1.00	4.44	<0.50	19.0	<50	<7	<50
Phosphates	mg/L	7.35	7.00	2.91	5.00	19.0	-	<5^	-
Sulfates	mg/L	25.5	8.50	44.9	<1.00	188	<250	<275	<250
Chlorides	mg/L	158	30.5	371	5.00	1615	<250	<250	<250
Bicarbonates	mg/L	378	396	115	73.0	526	-	-	<500
Sodium	mg/L	68.0	19.0	137	4.00	594	<200	-	<50
Potassium	mg/L	4.80	2.50	6.53	<0.05	25.0	-	-	<12
Calcium	mg/L	90.1	89.0	30.4	7.00	133	-	-	<300
Magnesium	mg/L	9.70	5.50	14.3	1.00	64.0	-	-	<50
Total Coliform	MPN	559	240	632	1.8	1600	<1.1	-	(n.d.)
Fecal Coliform	MPN	391	49	539	1.8	1600	<1.1	<50	(n.d.)

Water Quality Guidelines for "Class A" Water Body Classification
^Phosphate limit reported as PO_4-P (Total Phosphorus)
MPN – Most Probable Number reported per 100mL

The DENR Administrative Order 2021–19 Water Quality Guidelines applies to all water bodies in the country. Water quality parameters classify and maintain those water bodies according to their intended beneficial usage. The General Effluent Standard, on the other hand, applies to all point sources of pollution regardless of the volume discharged to the receiving bodies of water. Meanwhile, the PNSDW prescribes standards and procedures for drinking water quality to protect the public's health. The descriptive statistics calculated for the groundwater quality parameters of Siargao are presented in the above Table.

Physicochemical

The water quality assessment represents the seasonal variations in the water's physical, chemical, and biological characteristics (Winter et al., 1998). It is also affected by both anthropogenic activities and natural factors (Nitasha and Sanjiv, 2015), such as the extent of interaction that may have occurred between the lithology under investigation and the sampled water. Hence, the water quality classification determines its usefulness for various purposes, which are integral to groundwater resource management. The hydrochemistry demonstrated the concentration trends of major anions were $HCO_3^- > CO_3^- > Cl^- > SO_4^{2-} > NO_3^- >> PO_4^{3-}$ while cations $Na^+ > Ca^{2+} > Mg^{2+} >> K^+$ *(Fig. 1)*. The water chemistry revealed calcium and sodium are the predominant cations in the karst water of two municipalities, with concentrations varying from (7 – 133 mg/L) and (4 – 594 mg/L), respectively. Meanwhile, the predominant anions are characterized by chlorides (5 – 1615 mg/L) and bicarbonates (73 – 526 mg/L). Chlorides, sulfates, and bicarbonates occur naturally in all types of water. The mean concentrations of the major constituent cations in the aquifers meet the acceptable WHO (2011) limits, except for sodium.

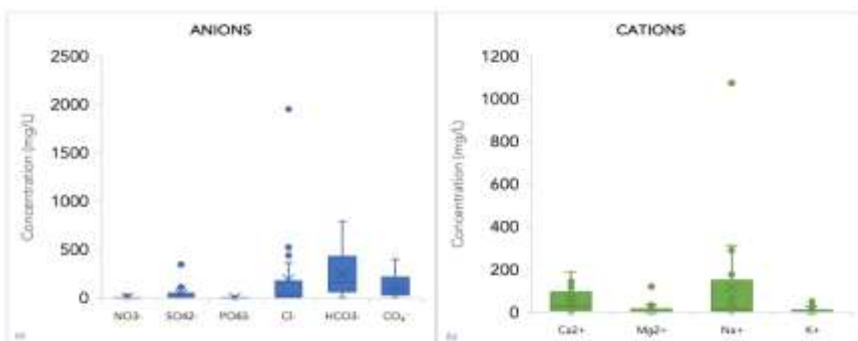


Figure 1. Box Plot of Physicochemical Parameters (a) anions, (b) cations

Trace Metals

Table 2
Summary: Trace Metals Analysis Results

	Trace Metals				
	Copper (mg/L)	Manganese (mg/L)	Chromium (mg/L)	Cadmium (mg/L)	Cobalt (mg/L)
PNSDW, 2017	≤1.00	≤0.40	≤0.05	≤0.03	≤0.05
Min	<0.05	<0.05	<0.05	<0.01	<0.05
Max	<0.05	0.07	<0.05	0.03	<0.05
Mean	<0.05	<0.05	<0.05	<0.01	<0.05

	Trace Metals					
	Iron (mg/L)	Nickel (mg/L)	Lead (mg/L)	Zinc (mg/L)	Mercury (mg/L)	Arsenic (mg/L)
PNSDW, 2017	≤1.00	≤0.07	≤0.01	≤5.00	≤0.001	≤0.05
Min	<0.05	<0.05	<0.05	<0.05	<0.001	<0.05
Max	<0.05	0.06	<0.05	0.06	<0.001	<0.05
Mean	<0.05	<0.05	<0.05	<0.05	<0.001	<0.05

The analysis data for the trace metals *(Tab. 2)* conform to values below the maximum allowable level for the following parameters: zinc (<5 mg/L), iron (<1 mg/L), copper (<1 mg/L), manganese (<0.4 mg/L), nickel (<0.07 mg/L), cobalt (<0.05 mg/L), arsenic (<0.05 mg/L) total chromium (<0.05 mg/L), and mercury (<0.001 mg/L). Meanwhile, the reported concentrations for cadmium and lead were 0.01 ± 0.0042 mg/L and 0.05 ± 0.0095 mg/L, respectively. The most common heavy metal pollutants in groundwater are lead, cadmium, chromium, iron, zinc, arsenic, and mercury, with possible sources of contamination from sewage sludge, industrial waste, and mining activities.

Microbiological

The microbiological data *(Fig. 2)*, on the other hand, revealed that six (6) stations exceeded the fecal coliform limit (400 MPN/100mL) set in the DENR Administrative Order 2021-19. Similarly, regarding PNSDW and WHO standards, microbial analysis shows that all samples do not meet the allowable limit of 1.1 MPN/100mL. Coliform groups are used to assess the level of pollution and water quality. When present, it indicates that human or animal wastes from sewage discharges, stormwater runoff, and animal manure leaching have contaminated the water.

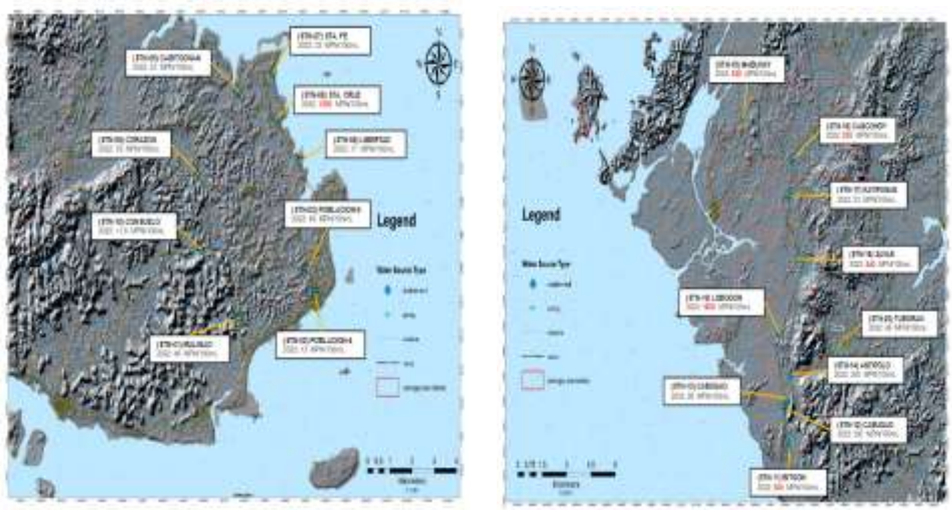


Figure 2. Microbiological Result: (left) General Luna; (right) Del Carmen

Current Risk Associated with Karst Groundwater System

Karst groundwater systems are highly dynamic and vulnerable due to their unique hydrogeological characteristics. In this study, the focus is on identifying and analyzing the major risks affecting these systems by integrating physicochemical and geophysical datasets from Siargao Island. Through this approach, it aims to understand the overall vulnerability.

Groundwater Pollution

Table 3
Summary: Pearson's Correlation Matrix

		Theoretical Depth		Nitrates		Phosphate
Nitrates	Pearson's r	0.664	**	—		
	p-value	0.010		—		
	95% CI Upper	0.883		—		
	95% CI Lower	0.206		—		
Phosphate	Pearson's r	0.780	***	0.832	***	—
	p-value	< .001		< .001		—
	95% CI Upper	0.927		0.945		—
	95% CI Lower	0.426		0.539		—

Note. * p < .05, ** p < .01, *** p < .001

Based on the hydrochemical data, the concentration of sulfate (2 – 188 mg/L) and nitrates (0.7 – 19.1 mg/L) satisfies the DENR permissible limit. However, the level of sulfate and nitrates was found to be relatively high in groundwater samples collected from urban and tourist areas that are underlain by limestone. Elevated nitrate concentration in water resources is associated with intense agricultural activities, septic systems, confined animal facilities, and wastewater treatment facilities (Wakejo et al., 2022). Meanwhile, total phosphate (5 – 19 mg/L) conforms with DENR guidelines except for the sample collected from the urban areas in General Luna. The results can be attributed to human activities primarily caused by domestic sewage. Also, the strong correlation between phosphate and nitrates can be associated with anthropogenic activities.

To determine the relationship between pollution source intensity (e.g., nitrate, phosphate concentration) and groundwater contamination, the use of Pearson (r) correlation is applied. A Pearson coefficient value of r close to 1.0 indicates a positive correlation. In contrast, a value close to 0 indicates no correlation between the two variables. Based on the computed results *(Tab. 3),* Pearson's correlation established a moderate linear correlation for Nitrates: ($r = 0.664$, $\alpha = 0.05$) and a strong linear correlation for Phosphates: ($r = 0.780$, $\alpha = 0.05$). A positive linear correlation suggests that pollutant concentration increases as the distance from the pollution source decreases. This also suggests that phosphate levels have a more pronounced effect than nitrates. Additionally, the computed p-value of 0.010 and <0.001 for nitrate and phosphate, respectively, is less than 0.05. In this regard, pollution sources significantly impact groundwater contamination in Siargao's karst systems.

Sources of Contaminants

Karst groundwater is an essential source of the domestic water supply in Siargao. Water sources serve more than 80% of Siargao's household population, piped from bore wells, shallow wells, and spring systems (PhilCCAP, 2015). The unconfined nature of the aquifer system translates to an inherent vulnerability to contamination from the surface. It is attributed to the direct linkage of surface and subsurface features. The absence of natural barriers above the karst aquifers and the potential for direct infiltration via dissolution openings leave the groundwater easily reachable by contaminants. The caves, sinkholes, and springs identified act as the entry and exit points or points of recharge and discharge of water, which acts as a medium for the pollutants. The geophysical survey from both municipalities indicate the presence of interconnected cave systems, lowering of the ground, and a potential aquifer (PhilKARST, 2022). These contaminants are commonly known to originate from residential houses, commercial establishments, agriculture (fertilizers and pesticides), and other wastes that surge as water gets transported directly to the mentioned karst pathways.

Saltwater Intrusion

To validate the occurrence of saltwater intrusion in Siargao, the use of base exchange indices (BEX) is applied for aquifer systems using the equation given as: BEX = Na + K + Mg – 1.0716 * Cl, where the concentration of all parameters is expressed in normality (Stuyfzand, 2008). The positive BEX indicates freshening, while the negative BEX suggests salinization. The plot of the BEX index vs. electrical conductivity *(Fig. 3)* indicates that the six (6) sampling stations in Siargao, particularly in Del Carmen, were undergoing salinization.

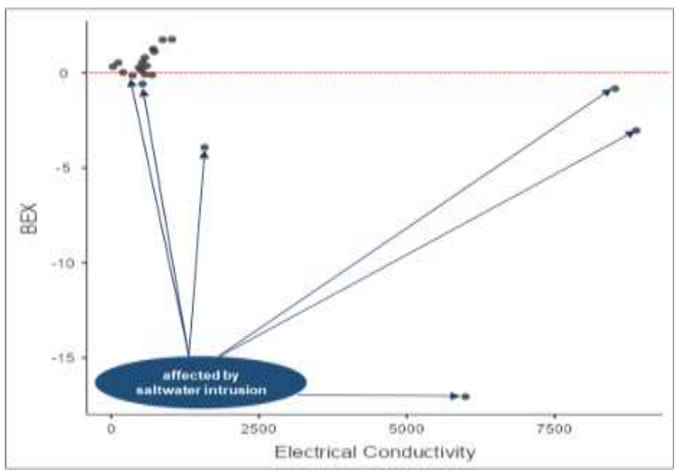


Figure 3. BEX vs Electrical Conductivity Plot

A major problem, especially on islands such as Siargao, is with limited freshwater sources. It may occur as an effect of both natural and anthropogenic factors, such as climate change or over-pumping of wells. Numerous locations in Siargao, particularly in Del Carmen, were now experiencing groundwater salinity or saltwater intrusion, complemented by high electrical conductivity and salinity readings. The values of chlorides yielded the DENR limit of 350 mg/L. Attendant to this, the station with the highest chloride concentration is located near the coastline; the excess chloride values can be attributed to seawater interference during tidal events.

Land Use Practices

The Water Quality Index (WQI) is an important metric for determining water quality and sustainability for consumption. It is used to evaluate the influence of natural and anthropogenic activities based on several key parameters of groundwater chemistry. WQI is an assessment technique that provides the composite influence of individual water quality parameters on the overall water quality (Brown *et al.,* 1972; Tyagi *et al.,* 2013). For this study, the WHO Guidelines for Drinking Water Quality (WHO, 2011) were used to calculate the water quality index based on Brown et al.'s weighted arithmetic index method. The weighted arithmetic method is in the following equation: $\text{WQI}_\text{A} = \sum_{i=1}^{n} \quad (wiqi\,)/\sum_{i=1}^{n} \quad (wi)$, where n is the number of variables or parameters, wi is the parameter's relative weight, and the ith parameter's water quality rating.

The computed water quality index *(Fig. 4)* using the weighted arithmetic index method by Brown et al. (1972) were classified based on the following criteria: (a) 0 - 25 Excellent; (b) 26 - 50 Good; (c) 51 - 75 Poor; (d) 76 - 100 Very Poor; and (e) 100+ Unsuitable for Drinking. Most stations fall within the 26 to 50 WQI classification, equivalent to "Good Quality Index" based on ten (10) physicochemical parameters using the WHO standard drinking water values. However, WQI from the two (2) stations in Del Carmen obtained an index score above 100, which is unsuitable for drinking purposes. The WQI map of Siargao Island using the land cover was generated using *Sentinel-2* imagery from the National Mapping and Resource Information Authority (NAMRIA). Based on its spatial analysis, areas underlain by karst and within built-up sites show a poor WQI score, indicating possible groundwater pollution. This justifies the vulnerability of karst areas to anthropogenic contamination.

STN	WATER QUALITY INDEX	
	Score	Classification
1	32.10	Good
2	87.68	Very Poor
3	38.84	Good
4	59.50	Poor
5	63.01	Poor
6	45.12	Good
7	50.20	Poor
8	49.18	Good
9	47.65	Good
10	39.75	Good
11	41.81	Good
12	100.40	Unfit
13	36.94	Good
14	36.63	Good
15	37.80	Good
16	71.71	Poor
17	44.24	Good
18	34.84	Good
19	192.59	Unfit
20	34.14	Good

Figure 4. Water Quality Index Map [Image: ESRI, ArcGIS, 2025]

Furthermore, the common land development practices in Siargao include land conversion for tourism, personal and commercial functions, and quarrying for road construction and embankments. If not regulated, construction related to urbanization, such as excavation and development of impervious surfaces, results in karst flooding in the area, disrupting the ground flow and reducing the natural water infiltration. Moreover, replacing natural land cover with a more impermeable layer increases surface runoff. It could further contribute to flooding events, which can overwhelm the capacity of the natural drainage systems. The community's land use also affects the area's groundwater quality.

To further evaluate the relationship of land use to karst terrain, the use of the chi-square (X^2) test or goodness-of-fit is used to determine whether an observed frequency distribution differs significantly from an expected distribution. In this case, the number of ground-validated sinkholes with land use type. Table 4 shows the calculated data of sinkhole events in different land uses using the formula: $X^2 = \sum_{i=1}^{n} (Oi - Ei)^2 / Ei$, where Oi is the observed frequency, and Ei is the expected frequency.

Meanwhile, the computed $X^2 = 1.386$ with two (2) degrees of freedom (df) corresponds to a p-value <0.05 based on the chi-square distribution table.

Table 4
Chi-Square Test Results
Proportions - Land Use

Level		Count	Proportion
Urban	Observed	149	0.226
	Expected	152	0.231
Rural	Observed	430	0.653
	Expected	405	0.615
Island	Observed	79	0.120
	Expected	101	0.154

χ^2 Goodness of Fit

χ^2	df	p
6.49	2	0.039

Since the computed chi-square value ($X^2 = 6.49$) exceeds the critical value ($X^2 = 1.386$), the null hypothesis (H_0) is rejected, indicating significant differences in sinkhole numbers across land use practices.

Summary of Findings

To summarize and simplify, Principal Component Analysis (PCA) was explored to identify the most influential factors contributing to groundwater risks. In the study of Siargao karst groundwater risks, the PCA group related hydrogeochemical variables to principal components. Varimax rotation was used for better interpretability. The PCA results *(Tab. 5)* present the summary of the variable that correlates with each component. The higher absolute values (close to ±1) mean that the variable heavily influences that component. The "Uniqueness" shows how much of each variable's variance is unexplained by the components. Meanwhile, eigenvalues explain how much variance each component captures. Eigenvalues greater than 1 using Kaiser's criterion confirmed their importance. Components 1, 2, and 3 together explain 95.5% of the total variance, while Components 4 and 5 are likely just noise.

Table 5
Summary: Principal Component Analysis

	1	2	3	Uniqueness
Sulfates	0.983			0.00868
Phosphates		0.943		0.08403
Chlorides	0.990			0.01223
Sodium	0.995			0.00629
Potassium	0.816	0.513		0.03904
Calcium			0.916	0.07936
Magnesium	0.989			0.02031
Bicarbonates			0.968	0.05994
Nitrates		0.948		0.09579

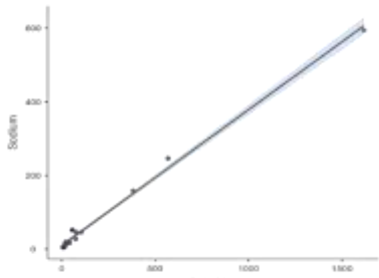
Summary: Component

SS Loadings	% of Variance	Cumulative %
4.63	51.4	51.4
2.12	23.5	75.0
1.85	20.5	95.5

Component 1: Sulfates, chlorides, sodium, magnesium, and potassium suggest a factor related to salinity intrusion or seawater contamination. This risk corresponds to a natural process.

Component 2: Phosphates and nitrates, which might indicate an anthropogenic factor. This includes possible contamination from sewage, wastewater, and solid waste discharge, and land use practices, among others.

Component 3: Calcium and bicarbonates are prominent, representing the geochemical process. This is due to the dissolution of carbonate minerals as the primary mechanism that controls the hydrochemistry of the karst groundwater system.



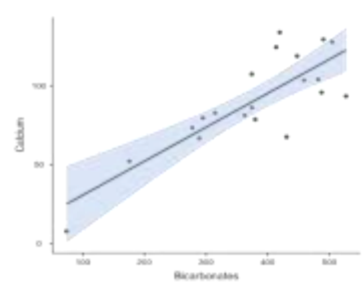


Figure 5. Scatter Plot of Hydrochemical Facies

Likewise, the scatter plot *(Fig. 5)* of sodium vs. chloride ($r = 1.00$, $\alpha = 0.05$) and calcium vs. bicarbonates ($r = 0.82$, $\alpha = 0.05$) depicts very strong and strong positive linear correlation, respectively.This will further substantiate the results of PCA and the regression analysis in identifying the most influential factors contributing to groundwater risks in Siargao Island.

Karst Groundwater Management Plan

Karst groundwater, in particular, is easily affected by natural and anthropogenic processes, which can lead to the degradation of groundwater resources and poor groundwater quality. In addition, the growing concerns about the island's water security are further exacerbated by the drying up of local springs during the summer months (ADB, 2019), and groundwater sources are now subject to salinity intrusion based on the findings of this study.

Karst Groundwater Management Plan is a multifaceted approach designed to ensure the sustainable management and protection of groundwater resources. It involves thoroughly assessing groundwater conditions, strategic planning for future use and protection, effective management practices, continuous monitoring, and developing supportive policies. The proposed karst groundwater management initiatives will be a combination of the following: (1) water resource conservation to protect and manage water production areas for water security, also to maintain the water consumptive activities at a minimum; and (2) water quality management to ensure that none of the effluent discharge from anthropogenic activities will contaminate the karst aquifer.

The groundwater resource management plan starts with capacity building among stakeholders, including government (local and national), business establishments, agricultural sectors, and local communities, to better understand the environmental concepts and existing policies on water resource management.

In proposing a groundwater resource management plan, learning can be obtained from the management strategies adopted from the Siargao Islands Protected Landscape and Seascape Management Plan and the Lake Mainit Development Alliance Management Plan. This plan is essential for ensuring long-term water security, minimizing environmental damage, and maintaining the integrity of karst aquifers for future generations.

Goal 1: Effective management of ecotourism in Siargao Island as a strategy toward biodiversity conservation

- Prioritizing zoning of the area/land use and defining the allowable activities in a different zone following the established Comprehensive Land Use Plan (CLUP), which controls and regulates the growth and development of public and private lands.
- Conducting a technical study on the carrying capacity of Siargao Island. This can provide LGUs with guidance on managing their resources with the trend of growing tourists and human activities.
- Establishment of a visitor management plan for ecotourism activities.

- The collection of environmental fees should be collected per ecotourism destination, which will proceed to the ecotourism fund.

Goal 2: Strengthen groundwater resource management and development through an integrated and holistic approach.

- Establishing a common groundwater resource database for planning and environmental impact assessment.
- Enforcement of environmental legislation and regulations on waste disposal, water pollution, resource utilization, and other critical concerns.
- Develop systems to coordinate policy development, planning, and enforcement. This will ensure consistency between policies, programs, and overall goals and objectives.

Goal 3: Encourage participation by stakeholders in the management of groundwater resources.

- Capacity building of eco-tour guides, operators, and business establishments to influence tourist behavior.
- Information, Education and Communication (IEC) Program on water resource management should be communicated to all concerned stakeholders.
- Educating the general public on environmental concerns and establishing systems and structures for the participation of concerned stakeholders in the planning and implementation of environmental programs.
- Ongoing campaigns for public awareness to promote and maintain sustainable tourism on the island.

Conclusion

This study assessed and characterized karst groundwater quality in Siargao Island, Surigao del Norte, Philippines, to describe the effect of natural and anthropogenic factors on karst groundwater resources. Geochemical data from the top tourist spots in Siargao, General Luna, and Del Carmen municipalities revealed that geological features and anthropogenic activities (i.e., land use practices) influence groundwater quality. The groundwater resources in karst areas are highly vulnerable to anthropogenic contamination and saltwater intrusion due to numerous fractures and a network of cavities in the limestone. These findings are validated by the geophysical survey, indicating the presence of tabular cave systems, tension cracks, sinkholes, and spalling.

Further, based on the Philippines' health and environmental guidelines, the groundwater generally shows acceptable levels of physicochemical constituents. The concentrations of phosphates, sulfates, nitrates, and faecal coliform were relatively high in groundwater collected from urban and tourist areas under limestone. Elevated chloride levels, electrical conductivity, and total dissolved solids are indicators of saltwater intrusion into the groundwater aquifer. Currently, the overall assessment of the groundwater quality is categorized as "Class A" or "Public Water Supply Class II" under the revised DENR Administrative Order on the Water Quality Guidelines and General Effluent Standards. Conventional treatment will be required to meet the PNSDW criteria.

Meanwhile, in terms of water quality index using a weighted arithmetic index method developed by Brown et al, most aquifers were classified as good quality. However, areas underlain by karst and within built-up sites show a poor WQI score, indicating possible groundwater pollution.

Recommendations

The proposed karst groundwater management plan was formulated as a mitigation strategy to safeguard groundwater resources on the island. The groundwater resource management is a shared responsibility of the national and local government, the private sector, and communities benefiting from karst landscapes. Agencies with the technical capability to monitor the status of these areas should be able to provide the necessary inputs for policymaking by the national and local governments and the education and awareness of the public. In turn, engagement with local communities and private sectors through the national and local government units, and conducting Information, Education, and Communication (IEC) campaigns in communities, would provide a holistic approach to managing the karst environment.

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