

# **ASSESSMENT OF METRO CEBU'S GROUNDWATER VULNERABILITY TO SEAWATER INTRUSION USING THE GALDIT INDEX**

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## ABSTRACT

Groundwater is an important source of freshwater in the Philippines. However, this resource is vulnerable to deterioration if not properly managed due to both natural and anthropogenic forces. To address this issue, this study identified and located areas that exhibit higher tendencies of seawater intrusions using publicly available datasets. These outputs help direct attention to areas that show higher vulnerabilities. In this study, Metro Cebu, one of the country's major economic centers, was chosen as the study area as large amounts of groundwater extraction and existing seawater intrusions have been observed in the region. For this study, the GALDIT index was employed to highlight which areas exhibit higher vulnerabilities to seawater intrusions based on several parameters being considered by the method. By pairing with geographic information system (GIS) strategies, the GALDIT method provides a well-established framework for assessing the seawater intrusion vulnerability of an area. Additionally, several alterations of the original GALDIT method, GALDIT-AHP, and GALDIT-SUSI, were also implemented to provide insights into how the investigated parameters influence the vulnerability classification of an area. The results of this study have emphasized the sensitivity of the vulnerability assessment to its investigated parameters and their corresponding weights. This has led to differences among the investigated indices when classifying highly vulnerable areas of Metro Cebu by up to 6%. The outputs of this study will be used as decision support tools by different stakeholders and water resource managers.

**Keywords:** *groundwater; vulnerability; GIS, GALDIT; Cebu*



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## INTRODUCTION

Groundwater plays an essential role in meeting the rising global demand for freshwater. Estimates reveal that around 30% of the world's freshwater resources are located underground and are not readily accessible for use (Amanambu et al., 2020). Currently, the total volumetric estimates of global groundwater range from 16 to 30 million cubic kilometers. However, the resource is unevenly distributed throughout the globe, with some countries having short amounts of groundwater (Gleeson, Befus, Jasechko, Luijendijk, & Cardenas, 2016). As the population continues to increase at an alarming pace, excessive extraction is expected to sustain the growth of municipal, industrial, and agricultural sectors. This rapid increase in the rate of consumption may not allow enough time for sufficient recharge of groundwater aquifers which may lead to premature depletion of the natural resource. This emphasizes the urgent need for monitoring systems that can aid in the proper assessment and management of both local and regional groundwater resources (Green et al., 2011). While the actual quantity and status of global subsurface freshwater remain uncertain, it is clear that this resource will play a significant part in addressing the need for clean water, especially in water-stressed regions worldwide.

Around 40% of the world's population is clustered within or near coastal areas. The coastal aquifers in these areas that supply the communities and cities are considered susceptible to contamination by seawater which may render the groundwater unusable or require additional measures before it may be regarded as usable (Prusty & Farooq, 2020). The Philippines, an archipelago with one of the longest coastlines, houses a significant portion of its cities' population near its coasts. The islets and large island groups that comprise the country are surrounded by several straits, seas, and an open ocean (Licuanan, Cabreira, & Aliño, 2018). Depending on the region, the groundwater produced via deep wells is used for various purposes across different agricultural, municipal, and industrial sectors. Excessive and unmonitored groundwater extraction may potentially harm a number of the country's most important hydrogeologic systems due to hastened seawater intrusions.

The country currently has three metropolitan areas: agglomerations of highly-urbanized municipalities and cities. These metropolitan centers are areas of high economic growth and are central to both local and international commerce and logistics (NEDA, 2017). In one of these densely populated areas, Metropolitan Cebu, groundwater extraction has far exceeded the prescribed limits for sustainable production (Cristina, Arlene, Roberto, Ramon, & Guillermo, 2001). Furthermore, the country's coastal aquifers are more exposed to the effects of climate change as the country frequently encounters typhoons, experiences storm surges, and has sea level rises greater than the global average (Licuanan et al., 2018).

To monitor this anticipated influence of both human and environmental factors on the overall quality of groundwater supply, consistent sampling and data gathering from monitoring wells are being conducted. This establishes a baseline statistic and identifies possible trends in groundwater quality (Uddin, Nash, & Olbert, 2021). However, identifying priority areas for monitoring provides a difficult challenge for groundwater management planners due to (a) the significant costs associated with establishing monitoring wells, (b) a scarcity of information about the locations of existing wells, and (c) the lack of a system that identifies the optimal locations for monitoring groundwater quality. This work aids in selecting the priority areas for monitoring the coastal aquifers of Cebu based on their vulnerability to seawater intrusions.

The vulnerability of an aquifer refers to its likelihood of contamination due to either anthropogenic or natural forces. It is considered an intrinsic property of the aquifer, which depends on several contributing factors that highly depend on the identified possible sources of contamination for the groundwater system. Because contamination might come from different and multiple sources, several methodologies have been developed specifically targeting the aquifer's vulnerability to certain contaminants. In most vulnerability studies, popular index-based methods such as DRASTIC, GOD, and SINTACS were implemented to classify areas of the aquifer with different vulnerabilities (Machiwal, Jha, Singh, & Mohan, 2018). However, these methods do not mainly address the aquifer's vulnerability to seawater intrusions but rather focus on the tendency of contamination from other sources. In coastal aquifers, such as those found in this study, the concept of an index-based groundwater vulnerability method called GALDIT and some of its derivative hybrid methodologies were used to identify the vulnerability of the aquifer to seawater intrusion (Parizi, Hosseini, Ataie-Ashtiani, & Simmons, 2019). For this work, methods such as GALDIT-AHP and GALDIT-SUSI were tested against the classic method to determine the differences in their classification of vulnerable areas.

In summary, this study applied several index-based methods to geographically assess the groundwater vulnerability in the Metro Cebu area. The geographical assessment utilizes geospatial information systems (GIS) techniques to visualize the spatial variation of the index as maps. The maps were constructed using publicly available datasets and open-source tools for GIS. These outputs have highlighted areas, which are highly vulnerable to seawater intrusion, that should be prioritized in groundwater monitoring and management plans. The results of this study will be used as decision support tools for local authorities to protect and monitor the region's groundwater resources and for future research and development work.

## METHODOLOGY

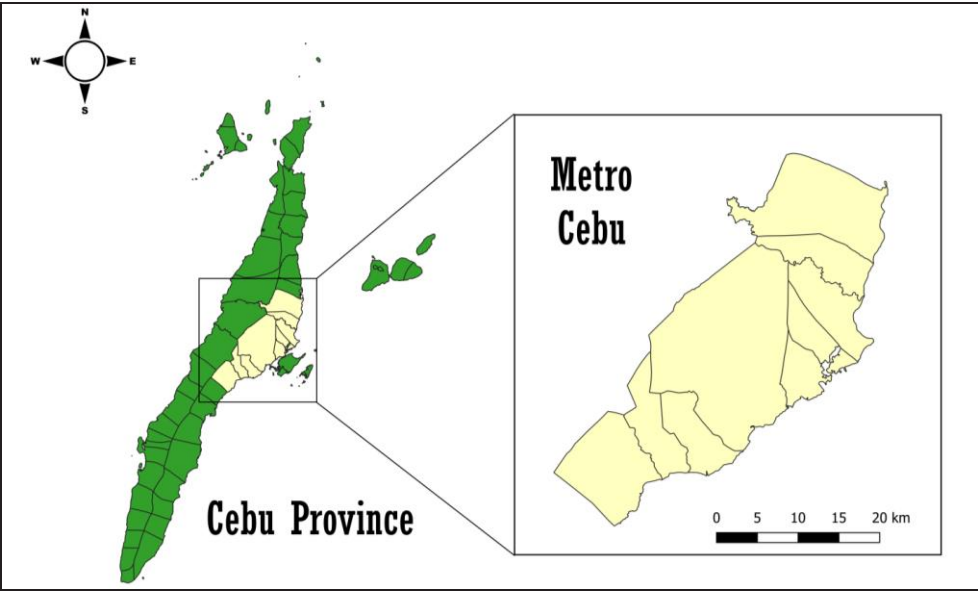
### Study Area

Metropolitan Cebu refers to a collection of nine urbanized cities and municipalities in the island province of Cebu, Philippines. Cebu is composed of 11 geological formations: Talavera group, Naga group, quartz diorite, largely intra-Miocene quartz diorite, Mananga group, Carcar Limestone, keratophyre and andesite flows, Barili formation, basement complex, ultramafic and mafic plutonic rocks, and quaternary alluvium.

The metropolitan area extends from longitudes 123.5° to 124.6° E and latitudes 9.9° and 10.8° N and has an area of approximately 786 km<sup>2</sup>. It is considered the second largest urbanized metro in the country. The different municipalities and cities comprising the study area stretch along the eastern coastline of the island province. These include Danao, Compostela, Liloan, Consolacion, Mandaue City, Cebu City, Minglanilla, Talisay City, and Naga City. Figure 1 shows the location and extent of the study area. The latest reports project the population of Metro Cebu to reach 3.8 million by 2030. The aquifers, which provide the needed groundwater supply for the growing region, are classified as coastal aquifers and may be considered vulnerable to saltwater intrusions if not adequately monitored and managed.

The administrative boundaries of Metro Cebu are further delegated into smaller government units called barangays. To streamline the government's efforts, the barangays have been entrusted with administering their constituents. These include responsibilities such as health services, public security, and in some cases, environmental and natural resources protection (Bañas, Subade, Salaum, & Posa, 2020). The administrative boundaries of the 270 barangays comprising Metro Cebu were used to divide the study area into smaller units of interest which will be used throughout the study to determine the prioritized areas based on the GALDIT index.

**Figure 1**  
*Location map of the study area*



**GALDIT Methodology**

The GALDIT method is a groundwater management tool that uses a numerical ranking system to assess groundwater vulnerability to seawater intrusion (Ferreira, Chachadi, Diamantino, & Henriques, 2007). The method considers six parameters which include groundwater occurrence (G), aquifer hydraulic conductivity (A), the height of groundwater above sea level (L), distance from the shore (D), the impact of the existing status of seawater intrusion (I), and thickness of aquifer (T). To calculate the GALDIT index, the values and classifications associated with the aforementioned indicators must be identified together with their corresponding rating (Chachadi & Ferreira, 2007).

Eq. (1) 
$$G_i = \frac{\sum_{i=1}^6 W_i R_i}{\sum_{i=1}^6 W_i}$$

Eq. (1) shows the formula for calculating the GALDIT index ( $G_i$ ), where  $W_i$  and  $R_i$  correspond to the weight and rating of the  $i^{th}$  parameter, respectively. Table 1 shows the different ranges of the parameters with their corresponding weights and rating scores. Using the datasets collected from different sources, several thematic maps were generated which represent the geospatial distribution of the vulnerability ratings for each parameter. Groundwater quality data was collected from the country’s National Water Resources Board. Maps for Cebu’s geology were sourced from the region’s Mines and Geosciences Bureau. Digital elevation models and administrative boundaries were provided by the different mapping agencies in the area.

**Table 1***GALDIT parameters, weights, ranges, and rating*

Parameter	GALDIT - SUSI Weights	GALDIT - AHP Weights	GALDIT Weight	Indicator Ranges	Importance Rating
Groundwater Occurrence (aquifer type)	0.134	0.024	1	Confined	10
				Unconfined	7.5
				Leaky	5
				Bounded	2.5
Aquifer hydraulic conductivity (m/day)	0.041	0.145	3	>40	10
				10 to 40	7.5
				5 to 10	5
				<5	2.5
Groundwater level above sea level (m)	0.258	0.253	4	<1	10
				1 to 1.5	7.5
				1.5 to 2.0	5
				>2.0	2.5
Distance from the shore (m)	0.101	0.448	4	<500	10
				500 to 750	7.5
				750 to 1000	5
				>1000	2.5
Impact of the existing status of seawater intrusion (uS/m)	0.015	0.08	1	>3000	10
				2000 to 3000	7.5
				1000 to 2000	5
				<1000	2.5
Thickness of the aquifer (m)	0.032	0.044	2	>10	10
				7.5 to 10	7.5
				5 to 7.5	5
				<5	2.5
Vadose zone hydraulic conductivity (m/day)	0.101			>40	10
				10 to 40	7.5
				5 to 10	5
				<5	2.5
Elevation (m)	0.165			<2	10
				2 to 4	7.5
				4 to 10	5
				>10	2.5
Torrent (m)	0.012			<75	10
				75 to 150	7.5
				150 to 300	5
				>300	2.5

**Table 1** (continuation)

Parameter	GALDIT - SUSI Weights	GALDIT - AHP Weights	GALDIT Weight	Indicator Ranges	Importance Rating
River (m)	0.014			<75	10
				75 to 150	7.5
				150 to 300	5
				>300	2.5
Wetland (m)	0.035			<75	10
				75 to 150	7.5
				150 to 300	5
				>300	2.5
Lagoon (m)	0.092			<75	10
				75 to 150	7.5
				150 to 300	5
				>300	2.5

The individual layers for each criterion were generated. Groundwater occurrence (G) refers to the type or types of aquifers located in the study area. The four types of aquifers classified for the GALDIT method include confined, unconfined, leaky, and bounded. The coastal aquifers of Metro Cebu are composed of unconfined and semi-confined aquifers where limestone is overlain by unconsolidated and alternating sediments near the coast. According to a report from the Mines and Geosciences Bureau (David & Larano, n.d.), the aquifer exhibits a transmissivity of 2,000 to 3,000 m<sup>2</sup>/d, a storage coefficient of 0.01 and 0.05, a specific yield of 3% to 27%, and a resistivity of 360 to 640 ohm-m.

The aquifer hydraulic conductivity (A) is estimated from the geology of the study area, as further explained by Basilan and Dayao (2019) The important geological formations in Metro Cebu are Carcar limestone, quaternary alluvium, Barili formation, Mananga group, and largely intra-Miocene quartz diorite.

The data for the static water level were retrieved from the Philippine National Water Resource Board database and interpolated through inverse distance weighing. A total of 94 data points were used to generate the water level map. The static water level raster layer was then deducted from a digital elevation model map of Metro Cebu to create a contour map representing the height of the water table relative to the mean sea level (L).

The distance from the shore layer (D) was generated using a proximity analysis of Metro Cebu’s natural coastline.



Originally, the metric used to rate the impacts of existing seawater intrusions (I) was based on the chloride and carbonate components of the sampled groundwater in the study area. However, it has been found that the groundwater's electrical conductivity can also be used as an alternative to estimate seawater intrusions in groundwater aquifers (Chang, Chung, Kim, Tolera, & Koh, 2019).

This concept was applied to this study and showed that seawater intrusions are apparent in some areas near the coasts.

Lastly, the rating for aquifer thickness (T) was based on information gathered from previous investigations of the island's coastal aquifers.

After the maps for each layer were created, the overall GALDIT index map was constructed using Eq. (1). After establishing a GALDIT index map, a zonal statistics analysis for each barangay was conducted using the GALDIT as the parameter of interest. The mean GALDIT index values were then used to classify which barangays showed low, moderate, and high vulnerability to seawater intrusions. Next, the mean GALDIT scores were calculated using Eq. (2), where  $G_{mean}$  is the mean GALDIT score per barangay,  $G_i$  is the GALDIT score of pixel  $i$ , and  $n$  is the total number of pixels in a barangay.

$$\text{Eq. (2)} \quad \bar{G} = \frac{\sum_{i=1}^n G_i}{n}$$

A GALDIT score greater than 7.5 is considered highly vulnerable to seawater intrusion; scores between 7.5 and 5.0 are considered moderately vulnerable; and values less than 5.0 exhibit low vulnerability. Shapefiles of the administrative boundary for the 270 barangays were retrieved from the country's mapping agency, NAMRIA. The steps in generating the GALDIT index map were repeated with minor alterations to produce the GALDIT-AHP and GALDIT-SUSI index maps. In the case of the GALDIT-SUSI index, the production of additional layers was required as it considers factors such as rivers, torrents, lagoons, and wetlands in its computation.

## RESULTS AND DISCUSSION

As shown in Figure 2a, around 60% of the study area has an unconfined aquifer, while the remaining area is considered a leaky or semi-confined aquifer. The leaky aquifer nearest the coastline stretches from 1.3 to 10 km inland.

The quaternary alluvium and Carcar limestone, which lie nearest the coasts, exhibit moderate to high hydraulic conductivities, suggesting saltwater vulnerability. Moving further inland, the rest of the formations show low conductivity and, therefore, lower vulnerability to seawater intrusions. Figure 2b shows the geospatial distribution of the hydraulic conductivity rating for the study area.

The majority of the aquifer (57%) located within the Metro Cebu area show low vulnerability; however, 18% of the total land area shows a GALDIT rating of 10, which is attributed to the Carcar limestone located near the coastline.

**Figure 2**  
*GALDIT rating spatial distribution maps for a) groundwater occurrence, b) aquifer hydraulic conductivity, c) height of water above sea level, d) distance from the shore, e) impact of existing seawater intrusion, and f) aquifer thickness*

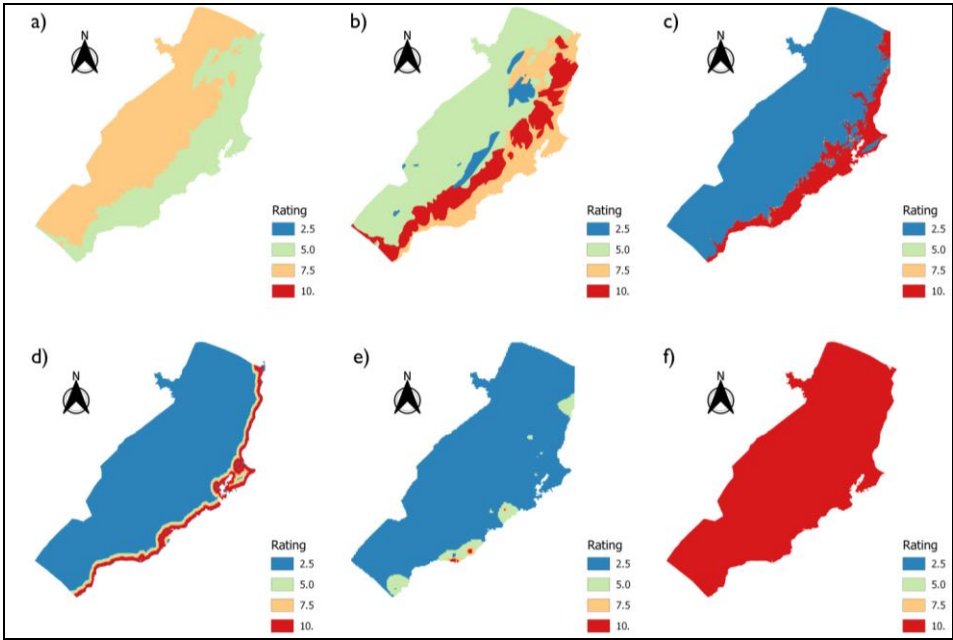


Figure 2c shows that in general, the height of the water above sea level is lower near the coasts and rises further inland. Some areas have depressions on their water table heights of up to -20 meters below sea level which indicate excessive extraction in its vicinity. These areas are considered highly vulnerable to saltwater intrusions. Areas with a height of groundwater level above the mean sea level of less than one meter represent 16% of the study area and are generally located at the lower elevations and closer to the coasts.

According to the GALDIT index ratings, areas nearer to the coasts exhibit greater vulnerability to seawater intrusions. The vulnerability to seawater intrusions decreases further inland. Around 88% of the area exhibits the lowest rating for vulnerability attributed to distance from the shoreline, as seen in Figure 2d. In the case of Cebu, the presence of large land reclamation projects has altered the coastline of the study area. Moreover, as the island province experiences higher rates of coastal sea-level rise, this may, in the future, change the distance from the shore data that will likely influence the groundwater vulnerability of the area (Ferreira et al., 2007).

A total of 186 locations with electrical conductivity data were used to produce the thematic layer (Figure 2e) for this parameter. Most of the area (95%) being investigated exhibited low scores for this parameter, with less than 1% of the area showing existing seawater intrusions.

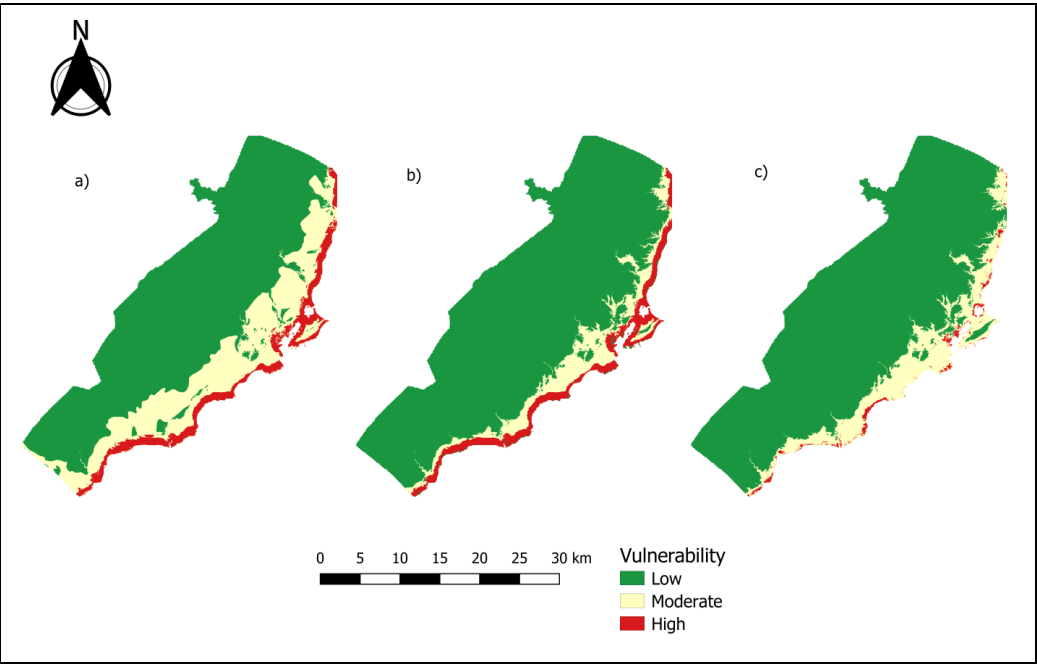
The entire study area was assigned a high vulnerability score of 10 for aquifer thickness. Several previous research efforts in the study area have reported the coastal aquifers of Metro Cebu to range from 20m to 80m. As seen in Figure 2f, the minimum thickness recorded for the coastal aquifers located within Metro Cebu is greater than 10m (Japan International Cooperation Agency & Metro Cebu Water District, 2010; Scholze, O, Hillmer G, Schneider, 2002).

The use of geospatial techniques has aided in the evaluation and understanding of groundwater. These tools range from prospecting potential groundwater sources to mapping groundwater quality (Juanico, Cayson, & Patiño, 2020; Mosafari, Pourakbar, Shakerkhatibi, Fatehifar, & Belvasi, 2014). Some previous reports have demonstrated the viability of using overlain index methods using GIS to determine groundwater vulnerability in some parts of the Philippines. A vulnerability assessment known as DRASTIC has been frequently used due to its easily accessible data requirements. The layers or parameters considered for these mapping efforts include the depth to the water table, recharge, aquifer material, soil and vadose zone material, topography, and hydraulic conductivity (Basilan & Dayao, 2019; Linan, Ella, & Florece, 2013). While these parameters do exhibit the vulnerability of the area of interest to contamination from sources located on the surface, they are unable to estimate the tendency of horizontal movement of seawater moving inland (Barbulescu, 2020). To specifically look at potential seawater intrusions on coastal aquifers, a more adequate index such as GALDIT, together with its other variants, is being commonly implemented (Allouche et al., 2017).

The GALDIT method was applied for the entire extent of the study area to evaluate the vulnerability of the area's coastal aquifers to seawater intrusion. Figure 3a shows the geospatial distribution of vulnerability to seawater intrusions in Metro Cebu. The vulnerability of the areas was classified based on their calculated decision criteria or their GALDIT score. The results of this study suggest that areas lying near the coastlines exhibit very high vulnerabilities to groundwater contamination with GALDIT values greater than 7.5. Highly vulnerable areas extend as far as one (1) km inland and cover around 52 sq. km, which is 7% of the entire study area. The high index scores in these areas are attributed to their high ratings for the height of water above sea level and distance from shore criteria. Both the L and D layers have weights of 4 which are the highest among the different criteria covered by the GALDIT index.

Moving further inland, the vulnerability to seawater decreases to moderate levels. The areas lying immediately after the high vulnerability zones have higher aquifer hydraulic conductivity levels as they lie on Carcar limestone. Despite having high vulnerability scores for the A layer due to the innately high hydraulic conductivity of limestone, this middle area still lies farther from the coastlines and has elevated water levels relative to the mean sea level. Most areas in this region present GALDIT index values of around 5 to 7.5 which are considered moderate scores for seawater intrusion. The farthest points from the coastline received low scores for vulnerability. These areas are characterized by aquifers with low hydraulic conductivity, high levels of the water table, and have no signs of existing seawater intrusions.

**Figure 3**  
*a) GALDIT, b) GALDIT-AHP, and c) GALDIT-SUSI index for Metro Cebu*



Out of 270 barangays in Metro Cebu, only 257 barangays were covered by the final GALDIT index layer generated. Around 38% of the barangays presented low vulnerability to seawater intrusions; 41% showed moderate vulnerability scores; and 21% were classified as highly vulnerable. Barangay Central Poblacion in the City of Naga showed the highest GALDIT score of 8.78, while Barangay Tabla in the Municipality of Liloan had the lowest score of 3.88. These results can aid in the selection of specific barangays for locating possible monitoring wells by using prioritization frameworks (Amiri, Azadi, Javadpour, Naghavi, & Boczkaj, 2022). However, a noteworthy shortcoming of this prioritization process would be the uneven areas for barangays which would influence the distribution factor of the prioritization method.

While the classic GALDIT index does provide the needed insights to help manage groundwater sources based on their vulnerability using cheap and available data, the subjectiveness of the weights and ratings of these numerical ranking systems has always been a major downside. To overcome this obstacle, advancements and alterations of the classical GALDIT methodology have been achieved using techniques such as machine learning and more complex concepts (Barzegar et al., 2021; Bordbar, Neshat, Javadi, Pradhan, & Aghamohammadi, 2020). In this study, the weights of a GALDIT index improved using the analytical hierarchy process, GALDIT-AHP, which was also used to show the sensitivity of the assessment when parameter weights are changed (Mirzavand, Ghasemieh, Sadatinejad, Bagheri, & Clark, 2018).

In general, the GALDIT-AHP index classified lesser areas as moderately vulnerable when compared to the classic GALDIT scores. The percentage of areas classified with moderate vulnerability by the GALDIT-AHP was 15% less than the original index method. However, the areas with high vulnerability scores were more or less the same with a difference of less than 1%. This disparity in labeling moderately vulnerable areas was due to the classic GALDIT method placing greater importance on the aquifer hydraulic conductivity factor in contrast to its GALDIT-AHP counterpart. This can be observed in the map generated using the GALDIT-AHP (Figure 3b) where there was an exclusion of the areas covered with Carcar limestone from the moderately vulnerable classified regions. It is important to note that the weights used for the GALDIT-AHP were adopted from reported literature. To further improve the analytical hierarchy process, the pairwise comparison step should be generated from engagements with local experts and stakeholders. This will ensure that the weights generated for each criterion would reflect the expert judgment of people who are most qualified to decide on the prioritization of parameters in the study area. Nevertheless, this step has provided insight as to how different criteria weights influence the overall vulnerability of Metro Cebu. Furthermore, this has opened opportunities to further investigate and improve the use of the analytical hierarchy process in complex problems such as seawater vulnerability.

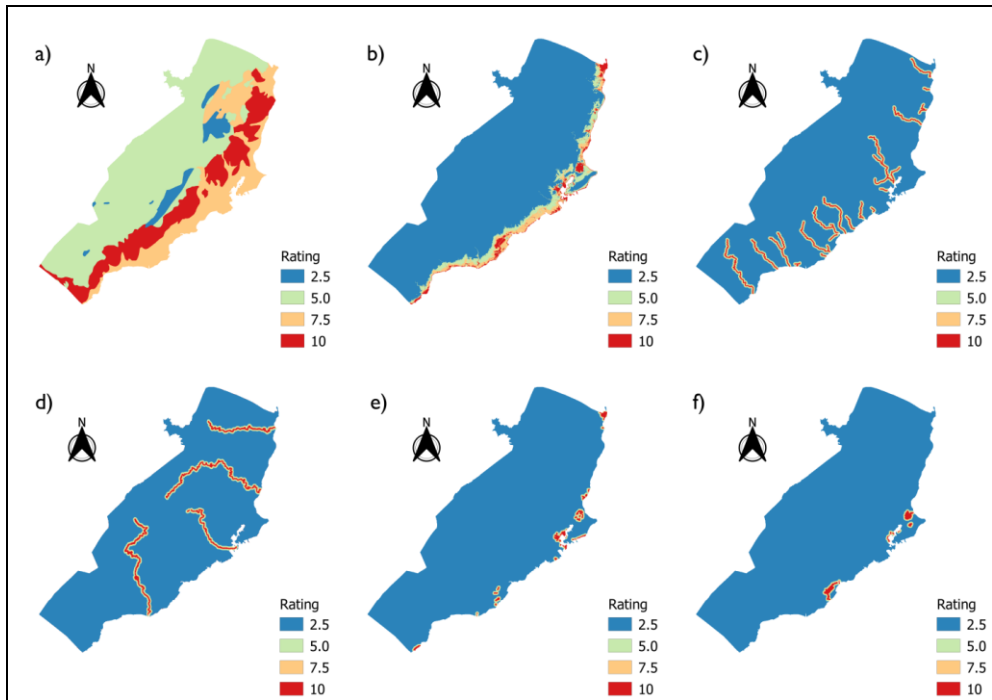
Recent improvements in the GALDIT scores have also leaned towards the inclusion of new parameters. The additional parameters that have been considered include natural features and built-up areas (Kazakis et al., 2019; Kazakis, Spiliotis, Voudouris, Pliakas, & Papadopoulos, 2018). For this work, a variation of the GALDIT index, the GALDIT-SUSI, that considers superficial seawater intrusion was also implemented. The GALDIT-SUSI method was originally introduced in the investigations of aquifers in Greece and Italy (Kazakis et al., 2019).

In the case of Metro Cebu where rivers, wetlands, lagoons, and streams are located, this procedure would provide a much-needed insight into how these features might influence the groundwater vulnerability of the area. Six new thematic layers were created for the computation of this index which represented elevation, vadose zone, rivers, torrents, lagoons, and wetlands. The additional maps are shown in Figure 4.

The scores for the GALDIT-SUSI method reveal that only 1% of the entire study area is classified as highly vulnerable. This is a noticeable decrease from the GALDIT and GALDIT-AHP scores, which are 7% and 6% of the study area, respectively. The generally lower scores returned from the GALDIT-SUSI method are attributed to the greater number of parameters that are considered by this index. Only a small portion of the study area showed high vulnerability caused by the new parameters introduced using this method. As shown in Figure 3c, the most highly vulnerable areas labeled by this methodology are clustered around the wetlands and lagoons, which are parameters not considered by the previous GALDIT variations studied in this work. The addition of new parameters to the classic GALDIT index shows how the vulnerability changes depending on the parameters considered. In this case, the introduction of river systems, wetlands, and inland waters has significantly altered the vulnerability assessment of Metro Cebu. The researchers identified these additional parameters as crucial to the assessment of their local aquifers. This further emphasizes the need to investigate the improvement of seawater vulnerability assessments by considering unique local factors that may influence seawater intrusions. In Metro Cebu, this would mean factoring in the presence of fish ponds, reclaimed areas, storm surges, and sea level rises in assessing vulnerability.

**Figure 4**

*GALDIT-SUSI rating spatial distribution maps for a) vadose zone hydraulic conductivity, b) elevation, c) torrents, d) river, e) wetlands, and f) lagoons*



The assessment of Metro Cebu’s intrinsic vulnerability to seawater intrusion through the use of the classic GALDIT, GALDIT-AHP, and GALDIT-SUSI methods has provided enough insight into how the different criteria influence the vulnerability of an area. The classic GALDIT method provided the most conservative estimates among the investigated indices. This is observed when the classic GALDIT has classified a greater portion of the study area as moderately to highly vulnerable compared to its variants. Table 2 shows the summary of vulnerable areas when using the GALDIT, GALDIT-AHP, and GALDIT-SUSI. Thus, the results of the classic GALDIT method would be better used as a basis for a more comprehensive prioritization of which areas should be monitored. However, this also comes with a tradeoff as a larger monitoring area would incur more expenses. In cases where a more targeted and compact monitoring network is preferred, the results of the GALDIT-AHP and GALDIT-SUSI methods might be more suitable as both have identified lesser areas as vulnerable to seawater intrusion.

The generated maps of this study are crucial in understanding which areas are more vulnerable to seawater intrusion. This would help local environment planners to prioritize which areas require immediate attention to mitigate adverse effects. For example, the lowering of the water table might have been caused by the over-extraction of groundwater.

This would lead to a faster horizontal encroachment of seawater in the area (Raymund Albert, Ventura, & Guerra, 2018). The local authorities can then decide the best plan of action to prevent further degradation of its groundwater resources. Another possible use of these maps is for determining priority areas for groundwater quality monitoring. As some areas show higher vulnerability than others, more attention and resources should be allocated to these areas, such as the construction of a network of monitoring wells for long-term groundwater quality data collection.

**Table 2**  
*Summary of results when using GALDIT, GALDIT-AHP, and GALDI-SUSI*

	GALDIT		GALDIT-AHP		GALDIT-SUSI	
Vulnerability	Area (km²)	%	Area (km²)	%	Area (km²)	%
LOW	533.79	69%	652.22	84%	656.94	85%
MODERATE	190.60	25%	75.05	10%	110.04	14%
HIGH	52.49	7%	49.60	6%	9.67	1%

While the classic GALDIT provides a well-established framework for classifying the seawater intrusion vulnerability of aquifers, improvements on these estimations can be made by factoring in crucial parameters that are present locally yet are unaccounted for by the classic method. This study has also emphasized how crucial the corresponding weight for each parameter is in the vulnerability assessment. Thus, while the classic GALDIT method has its own established weights for each of its key parameters, decision-making techniques such as the analytical hierarchy process may provide a better prioritization of parameters. Lastly, the investigation of groundwater vulnerability is severely limited to the available data on coastal aquifers. In this study, easily accessible water and geological data were used to establish a vulnerability map. Additional investigations on the current state of groundwater quality will be required to further validate the results of this study.



## CONCLUSION

Areas that show high vulnerabilities to seawater intrusion have been identified in this study through the use of the GALDIT method and its variations. In addition, the study has successfully identified the different parameters that are considered important in estimating the likelihood of seawater intrusion into the groundwater resources of Metro Cebu. The application of different variations of the index has revealed important insights into the robustness of this method, as the classification of vulnerable areas relies heavily on the parameters and their corresponding weights. This study has shed light on the need to investigate vulnerability assessments further to include unique local conditions that might influence seawater intrusions. The information generated by this study is also essential in designing a groundwater monitoring network for coastal aquifers. Ultimately, the results of this study can serve as important tools for decision-makers to effectively protect and conserve Metro Cebu's groundwater resources.

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