COMPARATIVE GROUNDWATER VULNERABILITY ANALYSIS BY MODIFIED DRASTIC AND GALDIT MODELS: A CASE STUDY IN BAGERHAT SADAR UPAZILLA

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ABSTRACT

In Bagerhat Sadar, groundwater as a resource is not scarce, but usable groundwater, considering the quality, is highly vulnerable. The quality of water is under threat due to salinity intrusion into the inland caused by both natural and anthropogenic activities. Reasons like the increase of mean sea level, reduced upstream flow from the Ganges basin and brackish aquaculture pose significant effects on the water quality of the study area. To address this concern and also to observe the temporal variation in vulnerability index, a comparative study of GIS-based groundwater vulnerability models: DRASTIC, modified DRASTIC and GALDIT models were carried out for 2013 and 2019. GALDIT model is preferable for coastal areas due to its parameters like distance from shore and seawater intrusion. As the DRASTIC model cannot incorporate seawater intrusion and only gives generalized aquifer vulnerability, so water quality was incorporated in DRASTIC model to assess how vulnerability changes due to water quality. Morever, both DRASTIC and GALDIT model parameters were modified to take care of the local geo-hydrology. A total of six maps were generated for each of the years 2013 and 2019, which are the traditional DRASTIC model, modified weightaged DRASTIC model, traditional and modified weightaged DRASTIC model with water quality (DRASTIC-Q), traditional GALDIT model and modified weightaged GALDIT model. This study shows a temporal variation in the vulnerability between 2013 and 2019 for different models. In 2013, according to DRASTIC model about 20.61% of the area is highly vulnerable, 79.4% is moderately vulnerable to groundwater contamination. On the other hand, modified weightage DRASTIC model shows about 24.47% is low vulnerable, and 75.53% is moderately vulnerable. In 2019, about 1.7% is highly vulnerable, and 98.3% is moderately vulnerable to groundwater contamination. But modified weightage DRASTIC about 61.32% is low vulnerable, and 38.66% is moderately vulnerable. So overall condition becomes better in 2019 compared to 2013. But when water quality indicator Cl-/HCO3- incorporated with the DRASTIC model, a much more vulnerable condition showed. In 2013, the DRASTIC-Q map shows about 28.45% is very highly vulnerable, and 71.55% is highly vulnerable. But the modified weightage DRASTIC-Q map shows about 75.54% is highly vulnerable, and 75.54% is moderately vulnerable to groundwater contamination. In 2019, the DRASTIC-Q map shows about 4.04% is very highly vulnerable, and 95.96% is highly vulnerable. However, the modified weightage DRASTIC-Q map shows about 62.46% is highly vulnerable, and 37.54% moderately vulnerable to groundwater contamination. Lastly, in 2013, the GALDIT model shows entire area is susceptible to highly vulnerability. However, modified weightage GALDIT model shows about 94.56% is highly vulnerable and 5.44% is moderately vulnerable. But in 2019, the whole study area is highly vulnerable for both conventional and modified GALDIT models. The comparison of DRASTIC, DRASTIC-Q, and GALDIT models reveals differing trends in groundwater vulnerability due to their distinct focus areas. While DRASTIC shows overall improvement and DRASTIC-Q reflects slight progress despite high vulnerability from pollution and salinity, the GALDIT model indicates worsening conditions due to increased risk of seawater intrusion. This underscores the need for model-specific approaches in assessing and managing groundwater vulnerability, especially in coastal regions. Thus, these methods can provide comprehensive insights to adopt sustainable measures and policies for better water management in coastal regions of Bangladesh.

Keywords: *Groundwater Vulnerability, Modified DRASTIC, GALDIT, Salinity Intrusion, Coastal Aquifer*

1. INTRODUCTION

1.1 Background of the study

Water plays a vital role in biological, social and industrial aspects of life. Water as an available resource is not a main concern in coastal regions. But the potable water in coastal areas like Bagerhat Sadar is really a pressing issue reflecting the impact of natural and anthropogenic reasons. Because Deep aquifer Groundwater in coastal areas plays an indispensable role as a primary freshwater resource for human consumption, agriculture and economy. In case of Shallow aquifer of coastal region, it mainly recharged through Local precipitation and surface water infiltration are the main sources of shallow aquifer recharge. Hence, due to some climate change effects like sea water rise and change in seasonal precipitation causes reduction in net recharge, depth of water along with changes in other parameters and threatens to degrade water quality by increasing sea water intrusion in the mainland, which ultimately reduces the freshwater availability and increases salinization (Gumuła-Kawęcka et al., 2024). One of the main issues of water quality in the selected study area is saline water intrusion (Abedin et al., 2019; Jaydhar et al., 2022; Nahin et al., 2020; Zaman et al., 2017). Shrimp farming in Bagerhat Sadar is done by flooding lands with brackish water for prolonged period causing salt accumulation in soil and ground water eventually degrading shallow aquifer condition. This study enables the identification of risk zones in Bagerhat Sadar arising from both surface contamination and seawater intrusion. The findings can support decision-makers in formulating appropriate structural interventions and policy measures to mitigate groundwater vulnerability. Also, this study will give scopes to adopt mitigation measures and identify risk zones using different models.

1.2 Importance of the study

Groundwater in Bagerhat Sadar is highly saline, making vulnerability mapping essential for agriculture, shrimp farming, industry, and domestic use. Limited studies have applied DRASTIC, DRASTIC-Q, and GALDIT models in this area, though DRASTIC has been used recently for pollution risk mapping. Given the critical threat of salinity intrusion in coastal shallow aquifers, the DRASTIC model was modified to include local water quality, improving accuracy in identifying vulnerable zones. This study aims to fill research gaps among different assessment approaches, supporting sustainable water management and safe water use with limited resources. Vulnerability risk zones are mapped using DRASTIC and GALDIT models, while the integration of water quality into DRASTIC evaluates its effect on the vulnerability index. The GALDIT model specifically assesses seawater intrusion, highlighting mitigation strategies such as reducing upstream water withdrawals. Combining DRASTIC, DRASTIC-Q, and GALDIT allows comprehensive identification of risk zones, and comparative analysis helps reveal area-specific vulnerabilities according to contamination sources. This integrated approach provides a robust framework for managing groundwater resources and addressing both pollution and salinity risks in coastal regions.

1.3 Objectives of the study

1. To develop groundwater vulnerability risk zone maps generated by DRASTIC, modified DRASTIC, DRASTIC incorporating water quality, GALDIT and modified GALDIT models.
2. To observe the change in vulnerability of the models due to adopting modified weights relevant to local conditions and incorporating water quality, and
3. To observe the temporal changes of groundwater vulnerability in the study area.

1.4 Possible Outcomes of the study

1. The study would identify groundwater vulnerable zones of the Upazila.
2. The study would also determine the change in vulnerability with time.
3. The importance of changing the standardized weights of the models to suit to the local condition and importance of incorporating water quality in the model would also be ascertained from the study.

2. LITERATURE REVIEW

2.1 Review on previous study with the DRASTIC method

The DRASTIC method is widely used worldwide to assess groundwater vulnerability due to its simplicity and reliance on accessible data. Shirazi et al. (2013) applied a GIS-based DRASTIC model in Melaka, Malaysia, using precipitation for recharge estimation and borehole tests for hydraulic conductivity. Their map showed 11% of the area as less vulnerable, 61% moderately vulnerable, and 27% very vulnerable. A risk map indicated that over 11% of the region, mostly agricultural land, was highly susceptible. Shekhar et al. (2015) assessed groundwater vulnerability in Jharkhand, India, finding DRASTIC index values between 79–160, with 54% of the area classified as highly to extremely vulnerable. In Jordan's Azraq basin, Al-Adamat et al. (2003) found low to moderate vulnerability (DRASTIC index 123–139), with 84% of the area moderately vulnerable despite excluding hydraulic conductivity due to data gaps. Sener et al. (2009) mapped vulnerability in Turkey's Senirkent-Uluborlu Basin identifying 20.8% as high, 27.3% as average, and 51.9% as low vulnerability. Nitrate validation confirmed that high-risk agricultural zones matched elevated nitrate levels. Adhikary et al. (2013) found DRASTIC values of 99–173 in Bangladesh's Barind Tract, where low-lying areas were more vulnerable than elevated regions. Sresto et al. (2013) enhanced the method with a fuzzy AHP-based DRASTIC-L model in Khulna, finding 10% of the area with low, 29% moderate, and 19% high vulnerability. Built-up zones correlated with higher chlorine and electrical conductivity, confirming pollution potential.

2.2 Review on previous study with the GALDIT method

The GALDIT method, designed to evaluate seawater intrusion risks, has become a key tool for coastal groundwater studies. Barzegar et al. (2021) enhanced GALDIT's accuracy by integrating resampling and machine learning, reducing subjectivity in parameter weighting and improving predictive power for coastal aquifers. Sujitha et al. (2020) used GALDIT along the North Goa coast, India, finding 58% of wells moderately and 42% low vulnerable. The study emphasized the importance of sea distance and aquifer thickness in determining risk. Hu et al. (2018) compared AHP-DRASTIC and GALDIT in China's Weibei Plain. GALDIT identified high vulnerability within 2.5 km of the coast and validated its accuracy with hydrochemical data, though AHP-DRASTIC performed better for inherent vulnerability. Tasnim & Tahsin (2016) applied GALDIT in South Florida, showing its adaptability and usefulness for identifying critical zones of saltwater intrusion linked to excessive pumping. Fatema (2020) assessed Cox's Bazar's coastal aquifers using hydrochemical tools with GALDIT, finding large areas moderately to highly vulnerable due to groundwater overuse and tidal effects. A 0.5 m sea-level rise could expand vulnerable zones by 22%, stressing the need for sustainable groundwater management. Hossain et al. (2025) evaluated southwestern Bangladesh (Satkhira, Khulna, Bagerhat), finding 40.8% of the region highly and 58.7% moderately vulnerable. Vulnerability correlated with land use changes, shrimp farming, and irrigation expansion, highlighting how groundwater overuse accelerates seawater intrusion.

3. MODEL DESCRIPTION

3.1 DRASTIC Model

The DRASTIC model, developed by the U.S. Environmental Protection Agency (EPA), is a widely used method for assessing groundwater vulnerability due to its simplicity, low cost, and accessible data requirements. It evaluates vulnerability based on seven hydrogeological parameters which are Depth to water (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic conductivity (C) (Aller et al., 1987). Each parameter is assigned a weight and rating to calculate the DRASTIC Index, a dimensionless value ranging typically from 45 to 200, where higher values indicate greater pollution susceptibility.

The model performs best for areas larger than 100 acres and is often integrated with GIS for spatial mapping. However, it applies generalized weights and assumes pollutants originate at the surface and move vertically, limiting accuracy in smaller or heterogeneous regions (Patel et al., 2022). Despite these limitations, DRASTIC remains an essential tool for groundwater management and planning. By integrating these factors within GIS, the DRASTIC model produces spatial vulnerability maps, helping decision-makers identify high-risk zones and implement effective groundwater protection strategies.

Among its parameters, Depth to Water (D) is often the most influential where greater depths indicate lower vulnerability. Net Recharge (R) reflects the amount of water reaching the aquifer, where higher recharge increases contamination potential. Aquifer Media (A) and Soil Media (S) describe subsurface and surface materials where coarse, sandy textures heighten vulnerability. Topography (T) affects infiltration like flatter terrain raises risk. The Vadose Zone (I) influences pollutant filtration and attenuation, while Hydraulic Conductivity (C) determines how easily water and contaminants move through the aquifer.

3.2 DRASTIC-Q Model

The water quality is not directly shown by the drastic model. The ratio of Chloride to Bicarbonate is employed in the Drastic-Q model. This model creates two Drastic-Q vulnerability map and incorporates water quality with the traditional and modified weightage DRASTIC model. Quality is included as a separate indicator alongside DRASTIC, ranges and ratings are assigned to the Quality indicator, reflecting its pollution potential or impact on groundwater

3.3 GALDIT Model

The GALDIT method is a numerical ranking system developed to assess groundwater vulnerability to seawater intrusion in coastal aquifers (Chachadi & Lobo-ferreira, 2001). It evaluates six key parameters: Groundwater occurrence (G), Aquifer hydraulic conductivity (A), Level of groundwater above sea level (L), Distance from the shoreline (D), Impact of existing seawater intrusion (I), and Thickness of the aquifer (T). Each is rated and weighted to calculate the GALDIT Vulnerability Index (GVI), which typically ranges from 2.5 to 10, classifying areas as low, moderate, high or very high vulnerability.

The method, often used with GIS, helps create spatial maps that identify high-risk zones and guide coastal aquifer protection. While effective and widely applied across coastal regions, its reliance on subjective weighting can introduce bias, leading researchers to develop modified or data-driven versions for improved precision under sea-level rise and over-extraction pressures. By integrating these six parameters, the GALDIT method provides a clear, spatially based understanding of coastal aquifer vulnerability, supporting sustainable groundwater management and mitigation of seawater intrusion.

Among its parameters, Groundwater Occurrence (G) identifies aquifer type, where unconfined aquifers being most vulnerable. Aquifer Hydraulic Conductivity (A) measures water movement, where higher values increase intrusion risk. Level of Groundwater Above Sea Level (L) reflects hydraulic resistance, where lower levels imply higher vulnerability. Distance from Shoreline (D) shows that closer proximity heightens risk. Impact of Existing Seawater Intrusion (I) is assessed using electrical conductivity or salinity data to represent current intrusion intensity. Thickness of Aquifer (T) affects the extent of seawater movement, with thicker aquifers typically allowing greater intrusion volumes.

4. METHODOLOGY

4.1 Study Area

The study was conducted in Bagerhat Sadar, which is one of the 19 coastal districts of Bangladesh. It is situated in southwestern part of Bangladesh. It is located in between 22°35' and 22°50' north latitudes and in between 89°38' and 89°53' east longitudes encompassing a 272.7 square kilometer area. The topography of the location is mainly flat. This region has mainly fine sand, silt or silty clay soil texture.

4.2 DRASTIC Index Model

Drastic index is calculated by using the following equation-

$$DRASTIC\ Index = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad (1)$$

Here, Subscript r and w denote rating and weight respectively
A DRASTIC Simplified map of Bagherhat Sadar was created using ArcGIS 10.8's Weighted Sum tool. displays the DRASTIC index Simplified classification provided by Aller et al. (1987)

Table 4.1: Vulnerability assessment criteria using the DRASTIC approach

Class Vulnerability	Low	Moderate	High	Very High
DRASTIC Index Value	47–92	93–136	137–184	>184

Source: (Aller et al., 1987)

4.2.1 Relative Weights DRASTIC Indicators

On a scale from one to five, each extreme component has a corresponding weight. This weighting shows how significant that aspect is in comparison to the others. A weight of five is given to the most significant parameter, while the least important element is given a weight of one. In Table 4.2, we can see how the seven extreme parameters worked out (Aller et al., 1987).

Table 4.2: Assigned weights for DRASTIC parameters (Aller et al., 1987).

Parameter	"Depth to Water"	"Net Recharge"	"Aquifer Media"	"Soil Media"	"Topography"
Weight	5	4	3	2	1
Parameter	"Impact of Vadose Zone Media"		"Hydraulic Conductivity of the Aquifer"		
Weight	5		3		

4.2.2 Modified weight DRASTIC Indicators

The DRASTIC model was developed by the EPA for the US. The weightage given for each DRASTIC parameter is mainly for the US. These parameters vary for individual regions. In this study, the c of the DRASTIC parameters is modified, considering the study area's meteorology and topography. For coastal are, depth of water is not very important because extraction of shallow aquifer water is not a problem and water availability is great because of sea, so it reduced to 2. Net recharge is extremely important for coastal region because if net recharge increased then salinity is reduced. As coastal region is mainly flat area so topography reduced to 1. Again, as aquifer media and vadose zone is similar so vadose zone weightage reduce and taken 2. Hydraulic conductivity is very important because hydraulic conductivity proportional to salinity. Considering this fact, the weightage of hydraulic conductivity was taken as 4. The modified weightage is shown in Table 4.3.

Table 4.3: Modified Assigned weights for DRASTIC parameters

Parameter	"Depth to Water"	"Net Recharge"	"Aquifer Media"	"Soil Media"	"Topography"
Weight	2	5	3	3	1
Parameter	"Impact of Vadose Zone Media"		"Hydraulic Conductivity of the Aquifer"		
Weight	2		4		

4.2.3 Ranges and Ratings DRASTIC Indicators

The required ranges have been defined for every Drastic parameter. Based on the degree to which every range has been rated. Range and rating for different drastic variable are demonstrated in Table 4.4.

Table 4.4: Ranges and Ratings for Depth to water (Patel et al., 2022)

"Depth to Water" (m)		**"Net Recharge" (mm/yr)**		**"Aquifer Media"**	
Ranges	**Ratings**	**Ranges(mm/yr)**	**Ratings**	**Ranges**	**Ratings**
"0-1.5"	10	"0-51"	1	"Massive Shale"	2
"1.5-4.5"	9	"51-102"	3	"Metamorphic/Igneous"	3
"4.5-9"	7	"102-178"	6	"Weathered Metamorphic/Igneous"	4
"9-15"	5	"178-254"	8	"Glacial Till"	5
"15-22.5"	3	"254+"	9	"Bedded Sandstone, Limestone, Shale"	6
"22.5-30"	2	**"Topography" (%Slope)**		"Massive Sandstone"	6
"30+"	1	**Ranges**	**Rating**	"Sand and Gravel"	8
"Soil Media"		"0-2"	10	"Basalt"	9
Range	**Rating**	"2-6"	9	"Karst Limestone"	10
"Thin or absent"	10	"6-12"	5	**"Impact of Vadose Zone Media"**	
"Gravel"	10	"12-18"	3	**Range**	**Rating**
"Sand"	9	"18+"	1	"Confining Layer"	1
"Peat"	8	**"Hydraulic Conductivity" (m/day)**		"Silt/Clay"	3
"Aggregated clay"	7	**Range**	**Rating**	"Shale"	3
"Sandy Loam"	6	">4"	1	"Limestone"	6
"Loam"	5	"4-12"	2	"Sandstone"	6
"Silty Loam"	4	"12-29"	4	"Metamorphic/Igneous"	4
"Clay Loam"	3	"29-41"	6	"Sand and Gravel"	8
"Muck"	2	"41-82"	8	"Basalt"	9
"Non aggregated Clay"	1	"82+"	10	"Karst Limestone"	10

Depth to the Aquifer: Water table data for Bagerhat Sadar were estimated using IDW interpolation in ArcGIS 10.8 based on six nearby BWDB sites. In 2013, levels ranged 1–2.37 m, and in 2019, 1.57–3.07 m. Due to narrow fluctuations, a single rating was assigned for the entire area in both years.

Net Recharge: This study uses the "Water Table Fluctuation (WTF)" technique to compute net recharge. It is a simple and easy-to-use method and requires minimum data.The specific yield of earth stratum is required to calculate the recharge value by Equation 2, (Khan & Chakma, 2020):

$$R = S_y \frac{\Delta h}{\Delta t} \tag{2}$$

Where, Sy= specific yield (%); Δh/Δt= fluctuation of water table with time; R= groundwater recharge (m/year). Total Specific yield was determined by taking the weighted average of specific yield values of each stratum using Equation 3, (Khan & Chakma, 2020):

$$Sy = \frac{s_{y_1}.\text{thickness}_1 + s_{y_2}.\text{thickness}_2 + \ldots}{Total\ thickness\ of\ the\ aquifer} \tag{3}$$

After determining the specific yield for locations, net recharge was estimated, and the map was created using the "Inverse Distance Weighted (IDW)" approach in "ArcGIS 10.8's Spatial Analyst tool" shown in 6. The highest net recharge was 410 mm/year in the research area, and the lowest was 120 mm/year for the year 2013. The net recharge varies form 78 mm/year to 337 mm/year in the year

2019. Also, the IDW map is demonstrated where it can be observed that maximum study area had net recharge less than 254 millimeter per year.

Aquifer Media: The aquifer consists mainly of very fine sand, fine sand, and silty clay. Ratings (4–6) reflect the dominance of fine materials, with coarser materials rated higher. Borehole logs from 2013 and 2019 were used to assign these ratings.

Soil Media: Topsoil texture data from FAO were processed in ArcGIS 10.8. Soil types were classified and rated: clay soils offer more protection and receive low ratings, while loam allows easier contaminant movement and higher ratings.

Topography: The study area has a flatter terrain. The topography was downloaded from the USGS website and rearranged in accordance with the DRASTIC model's assessment.

Impact of Vadose Zone: The vadose zone in the area under investigation consists same soil types like soil media. Therefore, the rating was chosen according to the table. The data from the drill logs was used to derive the vadose zone media.

Hydraulic Conductivity: Each Location's hydraulic conductivity was determined using Equation 4 (DAS & BRAJA, 2010).

$$k_{v(eq)} = \frac{H}{\left(\frac{H_1}{k_{v1}}\right) + \left(\frac{H_2}{k_{v2}}\right) + \left(\frac{H_3}{k_{v3}}\right) + \cdots \left(\frac{H_n}{k_{vn}}\right)} \tag{4}$$

Here, $k_{V(eq)}$= equivalent hydraulic conductivity; H_1, H_2, H_3, H_n = Thickness of individual layers; H =Total thickness; k_{V1}, k_{V2}, k_{V3}, k_{Vn} = Hydraulic conductivities of the individual layers in the vertical direction

After determining hydraulic conductivity for different locations, utilising ArcGIS 10.8's IDW function, the hydraulic conductivity for the entire study area was extrapolated. Finally, the rating was given according to the range of hydraulic conductivity set by DRASTIC guidelines, and a map was obtained.

4.3 DRASTIC-Q Index Model

In DRASTIC-Q model, we incorporated one extra parameter which is water quality with seven parameters of DRASTIC model. We use Cl/HCO3 ration because for Bagerhat Sadar it is one of the most impacted water quality indicators for shallow water. So, ratings, weightage and procedure DRASTIC Analysis. The Groundwater quality map combined with both traditional and modified weightage DRASTIC model through weighted sum in ArcGIS 10.8.

4.4 GALDIT Index Model

GALDIT vulnerability Index is calculated by using the following equation-

$$GVI=(G_rG_w+A_rA_w+L_rL_w+D_rD_w+I_rI_w+T_rT_w)/(G_w+A_w+L_w+D_w+I_w+T_w) \tag{5}$$

Here, Subscript r and w denote rating and weight respectively

A GALDIT Simplified map of Bagherhat Sadar was created using ArcGIS 10.8's Weighted Sum tool. displays the GALDIT vulnerability Index classification provided by (Chachadi & Lobo-ferreira, 2001; Ferreira et al., 2007)

Table 4.5: Vulnerability assessment criteria using the GALDIT approach

Class Vulnerability	Low	Moderate	High	Very High
GALDIT vulnerability Index	<5	5-6	6.1-7.5	>7.5

Source: (Chachadi & Lobo-ferreira, 2001; Ferreira et al., 2007)

4.4.1 Relative Weights GALDIT Indicators

On a scale from one to four, each extreme component has a corresponding weight. This weighting shows how significant that aspect is in comparison to the others same as DRASTIC. A weight of four is given to the most significant parameter, while the least important element is given a weight of one. We can see how the six extreme parameters worked out (Chachadi & Lobo-ferreira, 2001).

Table 4.6: Assigned weights for GALDIT parameters

Parameter	"Groundwater occurrence" (aquifer type)	"Aquifer hydraulic conductivity"	"Level of groundwater above sea level"
Weight	1	3	4
Parameter	"Distance from the shoreline"	"Impact of existing seawater intrusion"	"Thickness of the aquifer"
Weight	4	1	2

4.4.2 Modified weight GALDIT Indicators

As Bangladesh is a Delta and Coastal regions, distance from shoreline is very important but Bagerghat Sadar has a long distance from shoreline so it taken 3. Most important is the intrusion of seawater because Bangladesh is a delta and that's why the weightage is taken 4. As water uses from shallow aquifer is not a concern for study area that's why its weightage reduce to 1.

Table 4.7: Assigned weights for GALDIT parameters

Parameter	"Groundwater occurrence" (aquifer type)	"Aquifer hydraulic conductivity"	"Level of groundwater above sea level"
Weight	2	3	4
Parameter	"Distance from the shoreline"	"Impact of existing seawater intrusion"	"Thickness of the aquifer"
Weight	3	4	1

4.4.3 Ranges and Ratings GALDIT Indicators

Table 4.8: GALDIT parameters and their ranks based on the range (Chachadi & Lobo-ferreira, 2001)

"Groundwater Occurrence"		**"Aquifer Hydraulic Conductivity" (m/day)**		**"Elevation of Groundwater Level" (m)**	
Aquifer Type	**Ranking**	**Range**	**Ranking**	**Range**	**Ranking**
"Unconfined"	10	">10"	10	"<2"	10
"Semi-confined"	7.5	"8.1-10"	7.5	"2.1-4"	7.5
"Leaky Confined"	5.0	"6.1-8"	5	"4.1-6"	5
"Confined"	2.5	"<6"	2.5	">6.1"	2.5
"Distance from the Shore" (Km)		**"Impact of Existing Status of Seawater Intrusion" (Cl/HCO_3)**		**"Thickness of the Aquifer" (m)**	
Range	**Ranking**	**Range**	**Ranking**	**Range**	**Ranking**
"<1"	10	">2.1"	10	">80"	10
"1.1-5"	7.5	"1.6-2.0"	7.5	"60.1-80"	7.5
"5.1-10"	5.0	"1.1-1.5"	5.0	"40.1-60"	5
">10.1"	2.5	"<1.0"	2.5	"<40"	2.5

Groundwater Occurrence: Bagerhat Sadar has a leaky confined aquifer, rated 5, as unconfined and semi-confined aquifers are more vulnerable to seawater intrusion.

Aquifer Hydraulic Conductivity: Same IDW mapping process as DRASTIC was used; ratings remained consistent for 2013 and 2019.

Groundwater Level Above MSL: In 2013, levels ranged from –1.58 to –0.54 m, and in 2019, –1.13 to –0.42 m. All values <2 m, so a single rating was applied using IDW interpolation.

Distance from Shore: Bagerhat Sadar is ~83 km from the sea; greater distance reduces seawater intrusion risk, assigned a rating of 2.5.

Impact of Existing Seawater Intrusion (Cl/HCO_3): Chloride-to-bicarbonate ratios ranged 1.26–4.48 in 2013 and 1.77–10.85 in 2019. Due to narrow ranges, a single rating was applied for each year using IDW.

Aquifer Thickness: The shallow aquifer is 85 km thick, providing significant storage and protection; thickness >20 km corresponds to a rating of 2.5.

5. RESULTS AND DISCUSSIONS

5.1 DRASTIC Vulnerability Maps

According to the DRASTIC model, groundwater vulnerability in the region improved from 2013 to 2019. In 2013, 20.6% of the area was highly vulnerable and 79.4% moderately vulnerable, while the modified map showed 24.47% low and 75.53% moderately vulnerable. By 2019, only 1.7% remained highly vulnerable, with 98.3% moderately vulnerable, and the modified map indicated 61.32% low and 38.68% moderately vulnerable. This reduction may result from improved recharge or groundwater table changes. The modified maps provide a more balanced and accurate representation by addressing potential over- or underestimations of the original model.

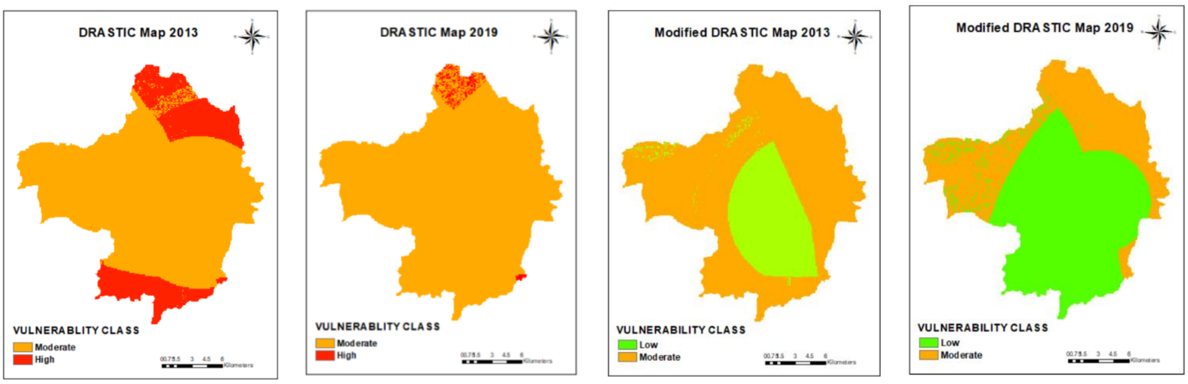

Figure 5.1: Traditional and Modified DRASTIC Vulnerability Classification Maps

5.2 DRASTIC-Q Vulnerability Maps

The DRASTIC-Q model, which adds a water quality (Q) component to account for pollution and salinity, showed higher groundwater vulnerability than the standard DRASTIC model. In 2013, the original map classified 28.45% of the area as very highly vulnerable and 71.55% as highly vulnerable, while the modified map adjusted this to 24.46% moderately and 75.54% highly vulnerable. By 2019, the original map showed 95.96% highly vulnerable and 4.04% very highly vulnerable; the modified map indicated 37.5% moderately and 62.46% highly vulnerable. Despite slight spatial improvements, vulnerability remains high due to salinity, emphasizing the area's sensitivity to water quality threats and the need for targeted groundwater management in coastal Bagerhat.

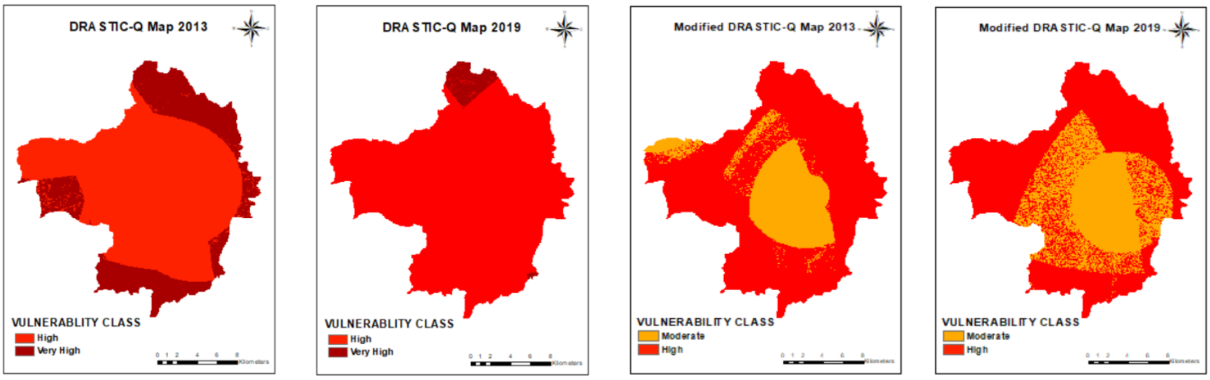

Figure 5.2: Traditional and Modified DRASTIC-Q Vulnerability Classification Maps

5.3 GALDIT Vulnerability Maps

According to the GALDIT model, the region exhibited consistently high levels of groundwater vulnerability, with increasing severity observed between 2013 and 2019. In 2013, both the original and modified vulnerability maps classified the entire region as highly vulnerable, with 94.55% of the area falling under the highly vulnerable category and the remaining 5.44% as moderately vulnerable. By 2019, this condition had further deteriorated, as 100% of the region was categorized as highly vulnerable on both map versions. The GALDIT model consistently indicates elevated sensitivity to saline water intrusion, particularly in 2019, reflecting a worsening hydrogeological situation. This trend aligns with known regional challenges in Bagerhat Sadar, where the proximity to the coast and the overexploitation of groundwater resources have intensified the risk of seawater intrusion.

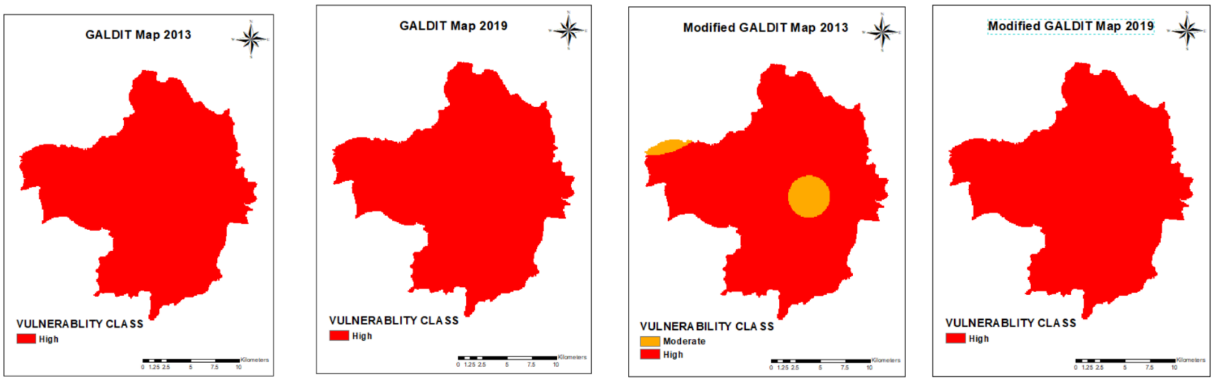

Figure 5.3: Traditional and Modified GALDIT Vulnerability Classification Maps

5.4 Comparison of Model results

A comparative analysis of DRASTIC, DRASTIC-Q, and GALDIT models highlights differing groundwater vulnerability trends between 2013 and 2019 due to their focus on distinct factors. The DRASTIC model, assessing vulnerability from surface contamination, showed a significant reduction: highly vulnerable areas dropped from 20.6% to 1.7%, and low vulnerable areas increased to 61.32% in the modified map. The DRASTIC-Q model, incorporating water quality, indicated persistently high vulnerability in coastal zones. While "very highly vulnerable" areas decreased from 28.45% to 4.04%, highly vulnerable zones remained substantial, reducing modestly from 75.54% to 62.46%. This underscores the impact of salinity and pollution on vulnerability. In contrast, the GALDIT model, focused on seawater intrusion, showed increasing risk: highly vulnerable areas rose from 94.55% in 2013 to 100% in 2019. This trend reflects intensified saline intrusion in Bagerhat, likely due to shrimp farming and proximity to the sea. Overall, DRASTIC and DRASTIC-Q suggest moderate improvement in contamination vulnerability, whereas GALDIT emphasizes a growing coastal-specific threat.

Table 5.1: Change in vulnerability due to temporal change and revised weightages

Year	Model	Map	Low Vulnerable	Moderately Vulnerable	Highly Vulnerable	Very Highly Vulnerable
2013	DRASTIC	Vulnerability Map		79.4%	20.6%	
		Modified Weightage Vulnerability Map	24.47%	75.53%		
	DRASTIC-Q	Vulnerability Map			71.55%	28.45%
		Modified Weightage Vulnerability Map		24.46%	75.54%	
	GALDIT	Vulnerability Map			100%	
		Modified Weightage Vulnerability Map		5.44%	94.55%	
2019	DRASTIC	Vulnerability Map		98.3%	1.7%	
		Modified Weightage Vulnerability Map	61.32%	38.68%		
	DRASTIC-Q	Vulnerability Map			95.96%	4.04%
		Modified Weightage Vulnerability Map		37.5%	62.46%	
	GALDIT	Vulnerability Map			100%	
		Modified Weightage Vulnerability Map			100%	

6. CONCLUSIONS

6.1 Conclusions

The study's key conclusions based on the analysis are as follows:

1. The study compares vulnerability changes between two years and finds that shallow aquifer vulnerability in Bagerhat Sadar increased in 2019.
2. Differences among models show that the modified DRASTIC model (including water quality) indicates higher vulnerability and more contamination-prone areas.
3. Locally adjusted DRASTIC and GALDIT models reveal that the modified weighted DRASTIC reduces vulnerability, while the modified GALDIT shows greater variability in seawater intrusion risk.
4. The DRASTIC index shows reduced highly vulnerable areas from 2013 to 2019, while the modified weighted model identifies 82.62% of the area as low vulnerable.
5. DRASTIC-Q results show shifting vulnerability levels, with the modified weighted version indicating more balanced classifications and reduced highly vulnerable zones.
6. The GALDIT model shows that nearly all areas are moderately to highly vulnerable in both years, suggesting limited potable groundwater and rainwater harvesting remains a viable alternative.
7. DRASTIC maps focus on vertical contamination, while GALDIT highlights horizontal seawater intrusion; incorporating salinity into DRASTIC improves overall vulnerability assessment accuracy.

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