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Comparative Evaluation of Index-Based Techniques for Seawater Intrusion Vulnerability Analysis

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Abstract

Groundwater contamination is becoming a major concern worldwide, especially in the coastal regions, due to the threat of seawater intrusion. Keeping in mind growing freshwater contamination problems, especially in eastern India, the current study was conducted to assess the hydrogeological and geochemical characteristics and critically analyze the aquifer vulnerability to seawater intrusion in a coastal alluvial 'leaky confined aquifer' of West Bengal and Odisha. The seasonal (Pre-Monsoon and Post-Monsoon) groundwater-level and quality (EC, Cl^- and HCO_3^-) data of the 'leaky confined aquifer' in 2021 and well logs data were used in this study. Two overlay-and-index-based methods were applied, namely, 'Original GALDIT' and 'Modified GALDIT' (GALDIT-AHP) methods. The five GALDIT model parameters/themes considered are: 'Aquifer Hydraulic Conductivity (A)', 'Groundwater Elevation (L)', 'Distance from the Coastline (D)', 'Extent of Seawater Intrusion (I)', and 'Aquifer Thickness (T)'. The weights of the themes and their features were modified using the Analytic Hierarchy Process (AHP) method, and the raster layers of themes were integrated in ArcGIS v10.8.2 using the 'Weighted Overlay' tool. Results reveal that the 'Original GALDIT' method delineated 50–64% lesser, 47–61% higher and 3–4% higher areas under 'Low', 'Moderate' and 'High' vulnerability classes, respectively, compared to the three corresponding EC classes. Results further indicate that the 'Modified GALDIT' (GALDIT-AHP) method predicted 32–45% lesser, 14–24% higher and 17–21% higher areas under 'Low', 'Moderate' and 'High' vulnerability classes, respectively, than the EC classes. The spatial validation method and correlation analysis results suggest that the 'GALDIT-AHP' (r=0.712–0.742) method performed much better than the 'Original GALDIT' (r=0.518–0.589) method in delineating aquifer vulnerable zones. Therefore, the combined application of geospatial technologies (Remote Sensing/GIS) and multi-criteria decision making techniques (like AHP) provides a reliable approach for seawater intrusion vulnerability assessment. The outcomes of this study will aid in formulating efficient plans for the sustainable management of groundwater resources.

Keywords: Groundwater contamination, Coastal alluvial aquifer, Seawater intrusion vulnerability, GALDIT index, Analytic Hierarchy Process.

1. INTRODUCTION

Groundwater plays a pivotal role in the socio-economic development of a nation as well as in sustaining ecosystem health. Its importance as a precious natural resource in the Indian context can be judged from the fact that more than 85% of India's domestic water requirement and 60% of irrigation requirements are met from groundwater supplies (World Bank, 2012; Ghosh and Jha, 2024). However, unplanned and non-scientific development of groundwater resources leads to over-exploitation and quality deterioration, especially in coastal regions. Out of 6881 blocks (administrative units) investigated across India, a total of 1186 blocks (~17.2% of total) in various states were identified as 'over-exploited', 313 (~4.5%) as 'critical', and 972 (~14.1%) as 'semi-critical' (CGWB, 2019). In addition, groundwater in 100 coastal blocks (~1.4%) of the country is affected by seawater intrusion. Saline water causes detrimental impacts on freshwater resources, aquatic ecosystems and human health. Therefore, it is essential to analyze the spatio-temporal pattern of groundwater contamination due to seawater intrusion. The overall groundwater quality condition is challenging to demonstrate because of the spatial variation of various groundwater-quality parameters (Babiker et al., 2007). The water quality index gives a single dimensionless quantity expressing the overall quality of a water source depending on the existence of various crucial elements (Abbasi and Abbasi, 2012). It also serves as a useful tool to compare different water samples on the basis of the estimated index of each water sample. Furthermore, the theory of aquifer vulnerability deals with the assessment of the susceptibility of an aquifer to being harmfully affected by a forced pollutant load from the ground surface as well as seawater intrusion. Groundwater vulnerability explains the possibility/sensitivity of groundwater contamination under natural/anthropogenic factors. Aquifer vulnerability assessment is a standard tool that can aid in identifying the areas that are more susceptible to pollution than others. The GALDIT method is a widely used overlay-and-index-based technique to assess aquifer vulnerability to seawater intrusion worldwide (e.g., Chachadi and Lobo-Ferreira, 2001; Chachadi et al., 2003; Recinos et al., 2015; Das et al., 2022). The major limitation of the original GALDIT method lies in the fact that the weights of the themes/parameters and their features are fixed irrespective of any heterogeneity and dissimilarity of study regions (Bordbar et al., 2019). It also uses a fixed number of feature classes and class values. Very few researchers in the past have improved the performance of the GALDIT method by modifying the theme weights and its feature classes (e.g., Gontara et al., 2016; Gorgij and Moghaddam, 2016; Kazakis et al., 2019; Bordbar et al., 2022).

Keeping in mind the research gaps, the present study aimed at a broad objective of analyzing the aquifer vulnerability to seawater intrusion in a coastal alluvial 'leaky confined aquifer' of West Bengal and Odisha, eastern India. Two overlay-and-index-based methods, namely, 'Original GALDIT' and 'Modified GALDIT' (GALDIT-AHP), were used to achieve this goal. The performances of these two methods were evaluated using a suitable spatial validation technique and correlation analysis. The outcomes of this study will aid water managers, planners and decision-makers in adopting efficient management strategies to mitigate groundwater pollution, create awareness among people about the risk of groundwater contamination and take necessary steps for the sustainable management of groundwater resources.

2. MATERIALS AND METHODS

2.1 Study Area

The present study was conducted within the inter-basin of the Haldi-Kansabati-Subarnarekha Rivers in eastern India, covering 6358.70 km^2 area over the coasts of West Bengal (parts of 'Purba Medinipur', 'Paschim Medinipur' and 'Jhargram' districts) and Odisha (part of 'Baleshwar' district). It is bounded within 21°32′–22°30′ North latitudes and 87°00′−88°03′ East longitudes (Figure 1). The study area is characterized by alluvium (older and newer), laterites and coastal flat alluvium geological traits, with agriculture being the dominant land-use type. Groundwater pumped using shallow dug wells and deeper tubewells is the primary source of domestic and irrigation water supplies (Ghosh and Jha, 2024). Water shortage under the changing climate is a major worry, which further increases the risk of seawater intrusion in the coastal zones of West Bengal and Odisha.

2.2 Data Collection

Groundwater-level and groundwater-quality (EC, Cl^- and HCO_3^-) data of Pre-Monsoon (April) and Post-Monsoon (November) seasons were collected from 108 observation wells tapping the 'leaky confined aquifer' (20–120 m bgl depth) for the year 2021. Furthermore, well logs (lithology log) data of 122 borehole logs were also acquired across the study area. All these data were procured from: (i) Central Ground Water Board (CGWB), Kolkata and Bhubaneswar, (ii) Ground Water Survey and Investigation (GWS&I), Bhubaneswar, and (iii) Water Resources Investigation & Development

Department (WRIDD), Kolkata.

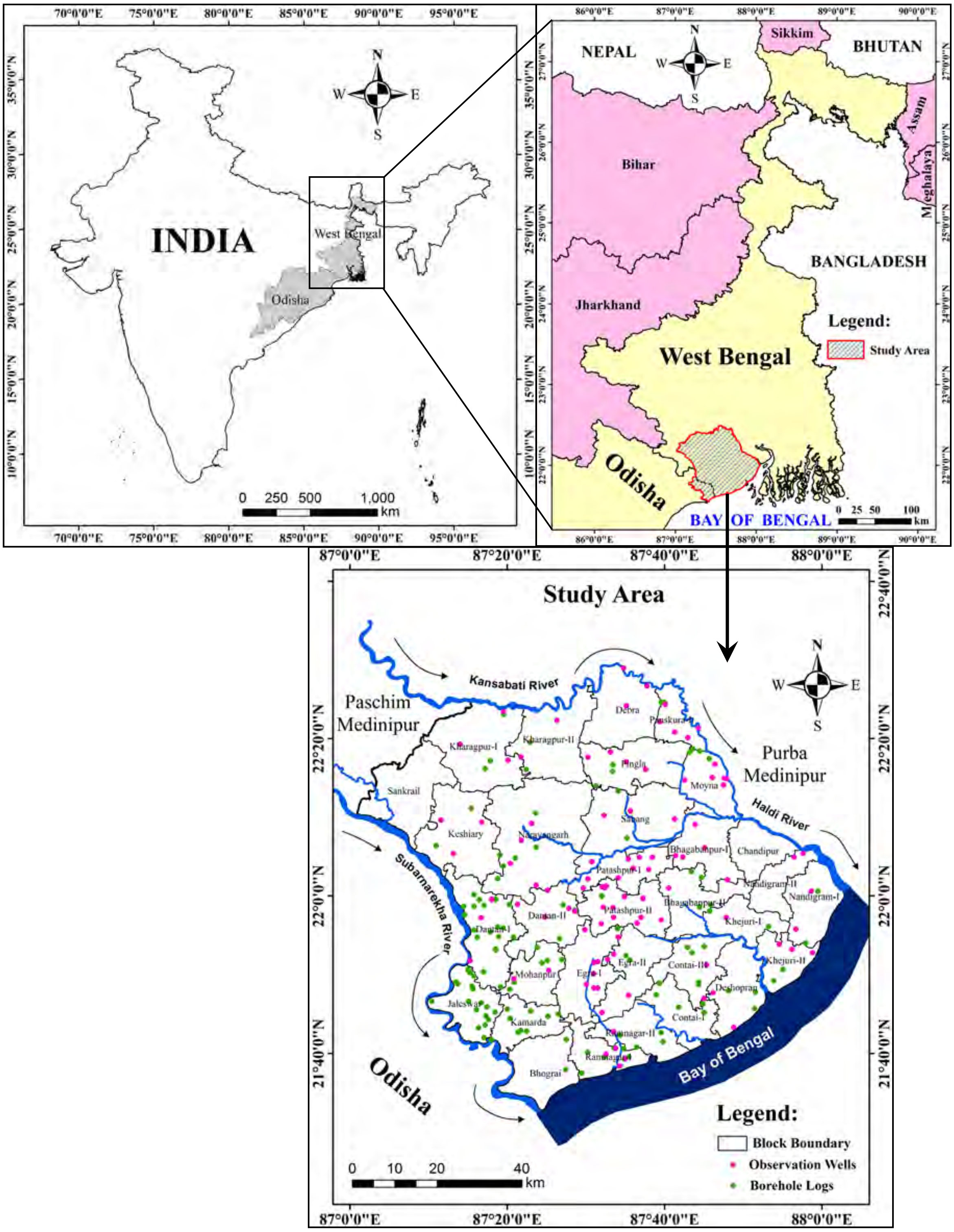


Figure 1. Map of the study area.

2.3 Vulnerability Analysis Using the Original GALDIT Method

In this study, five parameters/thematic layers of the 'Original GALDIT' method were considered for assessing aquifer vulnerability to seawater intrusion, which are depicted in Figure 2. The parameters are: (i) Aquifer Hydraulic Conductivity (A), (ii) Groundwater Elevation (L), (iii) Distance from the

Coastline (D), (iv) Extent of Seawater Intrusion (I), and (v) Aquifer Thickness (T). The parameter 'I' was estimated as the Chloride-Bicarbonate ratio (Cl^-/HCO_3^-). The raster layers of these five themes were prepared in ArcGIS v10.8.2 using the Inverse Distance Weighted (IDW) interpolation method. The raster layers of these five themes were integrated using the 'Weighted Overlay' tool available in ArcGIS v10.8.2. The weights and ratings were taken from Chachadi and Lobo-Ferreira (2001) and Chachadi et al. (2003). The final vulnerability maps were prepared using Eqn. (1), and the vulnerability index is termed as the 'Original GALDIT Vulnerability Index (OGVI)'.

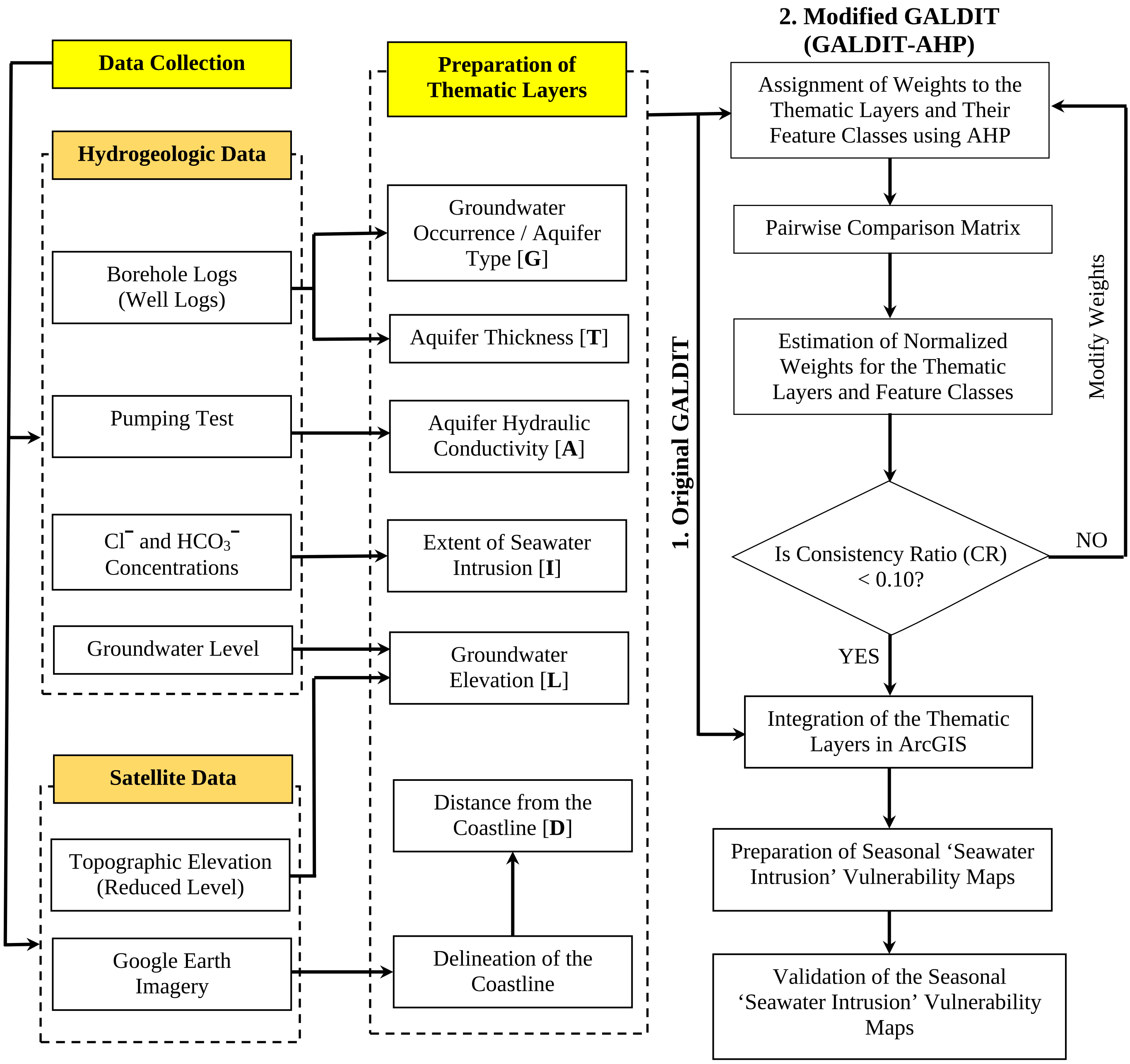


Figure 2. Flowchart for 'Original GALDIT' and 'Modified GALDIT' methods.

$$OGVI = \frac{\sum_{T,F} W_T \times R_F}{\sum_{T,F} W_T} \quad (1)$$

where, OGVI = Vulnerability index estimated using the 'Original GALDIT' method; W_T = Weights of the themes/parameters; W_F = Ratings of the themes' features; t = Number of themes; and f = Number of features under corresponding themes. The OGVI values were classified into three vulnerability categories, namely (i) Low Vulnerability (2.5–5.0), (ii) Moderate Vulnerability (5.0–7.5), and (iii) High Vulnerability (>7.5).

2.4 Vulnerability Analysis Using the Modified GALDIT Method

In the 'Modified GALDIT' or 'GALDIT-AHP' method, the same parameters/themes of the 'Original GALDIT' method were considered; however, the weights and ratings were modified using the Analytic Hierarchy Process (AHP) method considering local areal heterogeneities and expert's opinion (Saaty, 1980; Saaty, 1994). The normalized weights of the themes and their features are shown in Table 1. The vulnerability index was calculated using Eqn. (2), and is termed as 'Modified GALDIT Vulnerability Index (MGVI)'.

$$MGVI = \sum_{T,F} \omega_T \times \omega_F \quad (2)$$

where, MGVI = Vulnerability index estimated using the 'Modified GALDIT' method; ω_T = Normalized weights of the themes; ω_F = Normalized weights of the features. The MGVI values were categorized into three vulnerability classes, namely (i) Low Vulnerability (<0.14), (ii) Moderate Vulnerability (0.14–0.28), and (iii) High Vulnerability (>0.28).

Table 1. Normalized weights of the 'Modified GALDIT' or 'GALDIT-AHP' method

Sl. No.	Theme/ Parameter	Weight	Normalized Weight (ω_T)	Feature Class	Weight	Normalized Weight (ω_F)
1	**A** (Aquifer Hydraulic Conductivity, m/day)	6	0.104	<25	1	0.023
				25–50	3	0.043
				50–75	4	0.062
				75–100	5	0.089
				100–125	7	0.174
				125–150	8	0.249
				>150	9	0.360
2	**L** (Groundwater Elevation, m MSL)	8	0.264	<(–13)	9	0.426
				(–13)–0	8	0.303
				0–13	5	0.130
				13–26	3	0.066
				26–39	2	0.044
				>39	1	0.031
3	**D** (Distance from the Coastline, km)	9	0.418	<15	9	0.546
				15–30	6	0.229
				30–45	4	0.113
				45–60	3	0.075
				>60	1	0.037
4	**I** (Extent of Seawater Intrusion)	7	0.165	<1.00	1	0.050
				1.00–2.00	3	0.104
				2.00–3.00	6	0.279
				>3.00	8	0.567

5	**T** (Aquifer Thickness, m)	4	0.049	<20	1	0.032
				20–40	4	0.077
				40–60	6	0.149
				60–80	8	0.297
				>80	9	0.445

3. RESULTS AND DISCUSSION

3.1 Spatial Variation of GALDIT Parameters

Sand, gravel, clay, silt and sandstone constitute the 'leaky confined aquifer' of the study area. Depending upon the presence of these materials, the hydraulic conductivity of the 'leaky confined aquifer' was calculated (Todd and Mays, 2004), and its value varies from 3.25–165.00 m/day over the study area [Figure 3(a)]. Hydraulic conductivity (A) values are found to be <25, 25–50, 50–75, 75–100, 100–125, 125–150 and >150 m/day in 792.3 km^2 (12.46% of total), 3665.1 km^2 (57.65%), 1777.8 km^2 (27.96%), 91.3 km^2 (1.44%), 17.8 km^2 (0.28%), 9.7 km^2 (0.15%) and 3.58 km^2 (0.06%) areas of the study region, respectively.

Groundwater elevation (L) in the 'leaky confined aquifer' during Pre-Monsoon and Post-Monsoon seasons vary between (–25.04)–32.86 and (–13.99)–46.81 m MSL, respectively [Figures 4(a,b)]. Groundwater elevation in the Pre-Monsoon season is found to be <(–13), (–13)–0, 0–13, 13–26 and 26–39 m MSL in 1203.6 km^2 (18.93% of total), 3563.3 km^2 (56.04%), 929.7 km^2 (14.62%), 587.7 km^2 (9.24%) and 74.3 km^2 (1.17%) areas, respectively. On the other hand, groundwater elevation in the Post-Monsoon season is (–13)–0, 0–13, 13–26, 26–39 and >39 m MSL in 3104.5 km^2 (48.83% of total), 2305.6 km^2 (36.26%), 543.9 km^2 (8.56%), 356.6 km^2 (5.61%) and 47.2 km^2 (0.74%) areas, respectively.

Distance from the coastline (D) defines the proximity of the land area towards the sea. It is evident from Figure 3(b) that about 1321.9 km^2 (20.79% of total), 1192.9 km^2 (18.77%), 1099.1 km^2 (17.29%), 950.6 km^2 (14.95%) and 1792.7 km^2 (28.20%) land areas are situated at a distance of <15, 15–30, 30–45, 45–60 and >60 km away from the Bay of Bengal coastline, respectively.

The Chloride-Bicarbonate ratio (I) in the 'leaky confined aquifer' during both seasons varies between 0.04–4.16 [Figures 4(c,d)]. The ratio in the Pre-Monsoon season is found to be <1.00, 1.00–2.00, 2.00–3.00 and >3.00 in 5866.9 km^2 (92.26% of total), 370.0 km^2 (5.82%), 82.4 km^2 (1.3%) and 39.5 km^2 (0.62%) areas, respectively. In addition to that, the ratio in the Post-Monsoon season is <1.00, 1.00–2.00, 2.00–3.00 and >3.00 in 5763 km^2 (90.63% of total), 452.5 km^2 (7.12%), 96.9 km^2 (1.52%) and 46.4 km^2 (0.73%) areas, respectively.

The thickness (T) of the 'leaky confined aquifer' varies from 1.52–88.39 m over the study region [Figure 3(c)]. The thickness of the aquifer is <20, 20–40, 40–60, 60–80 and >80 m in 147.6 km^2 (2.32% of total), 4599.4 km^2 (72.34%), 1508.5 km^2 (23.72%), 97.1 km^2 (1.53%) and 5.9 km^2 (0.09%) areas, respectively.

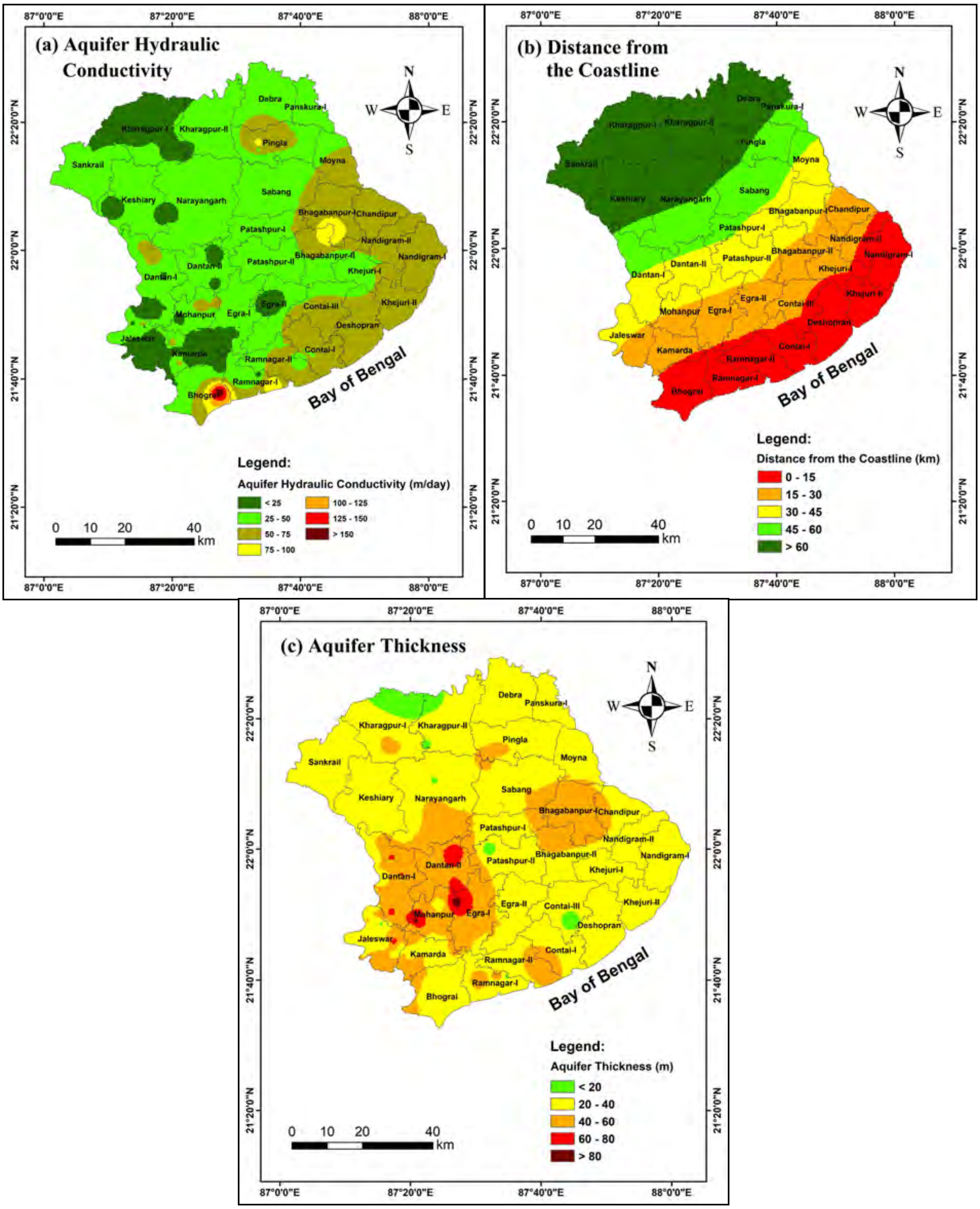
3.2 Results of Vulnerability Analysis Using the Original GALDIT Method

It is apparent from Figure 5(a) that the 'Original GALDIT' method in the Pre-Monsoon season of 2021 indicated around 1226.7 km^2 (19.42% of total), 4893.6 km^2 (77.46%) and 197.1 km^2 (3.12%) areas under 'Low', 'Moderate' and 'High' vulnerability classes. In the Post-Monsoon season of 2021, it was found that about 1910.2 km^2 (30.24% of total), 4191.7 km^2 (66.36%) and 215.2 km^2 (3.41%) areas are under 'Low', 'Moderate' and 'High' vulnerability classes [Figure 5(b)].

3.3 Results of Vulnerability Analysis Using the Modified GALDIT Method

It is evident from Figure 5(c) that the 'Modified GALDIT' (GALDIT-AHP) method in the Pre-

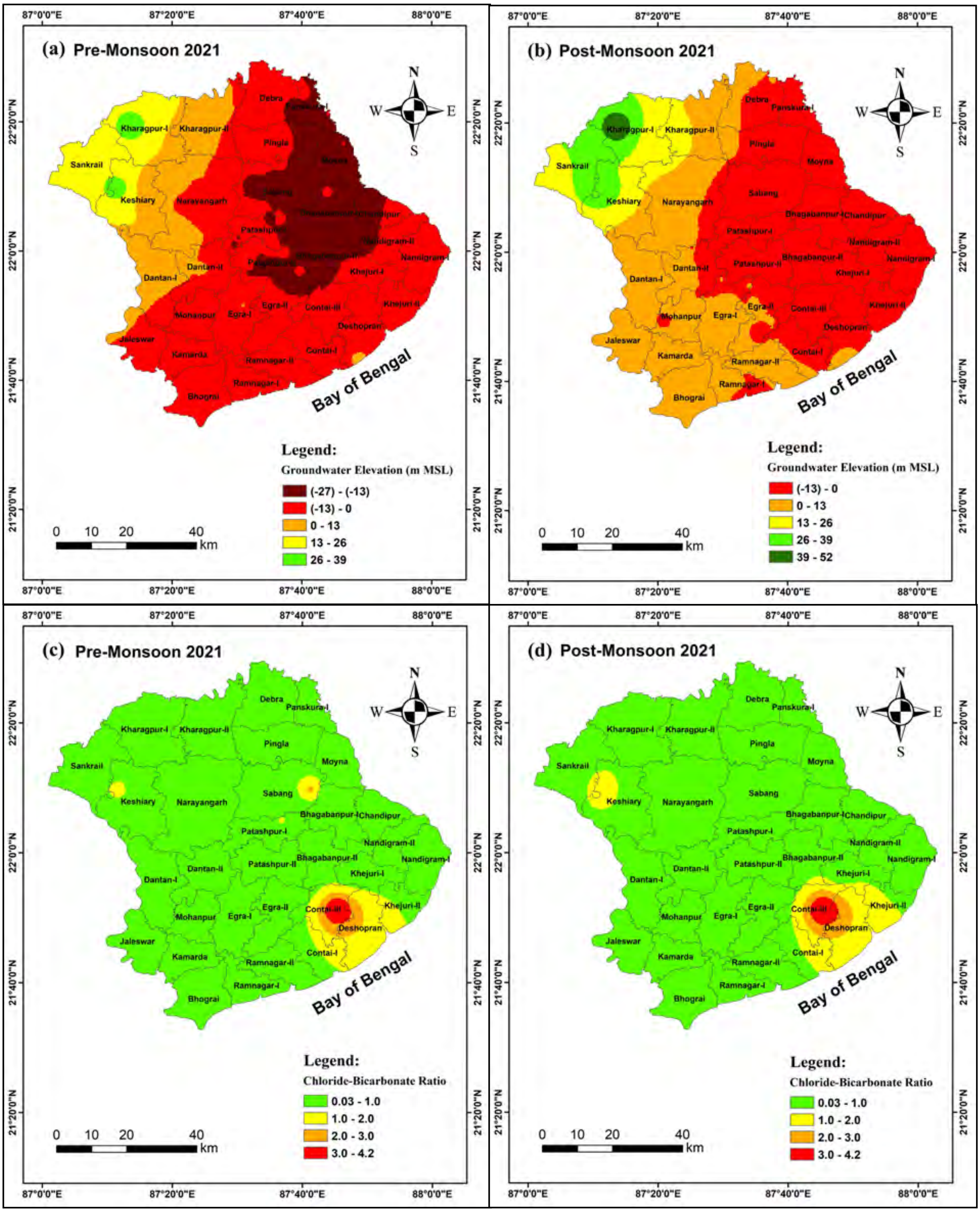
Monsoon season of 2021 revealed around 2470.0 km^2 (39.05% of total), 2542.7 km^2 (40.19%) and 1313.3 km^2 (20.76%) areas under 'Low', 'Moderate' and 'High' vulnerability classes. In the Post-Monsoon season of 2021, it was found that about 3096.6 km^2 (48.95% of total), 2119.8 km^2 (33.51%) and 1109.8 km^2 (17.54%) areas are under 'Low', 'Moderate' and 'High' vulnerability classes [Figure 5(d)].



Figures 3(a–c). Spatial variability maps of 'A', 'D' and 'T' parameters.

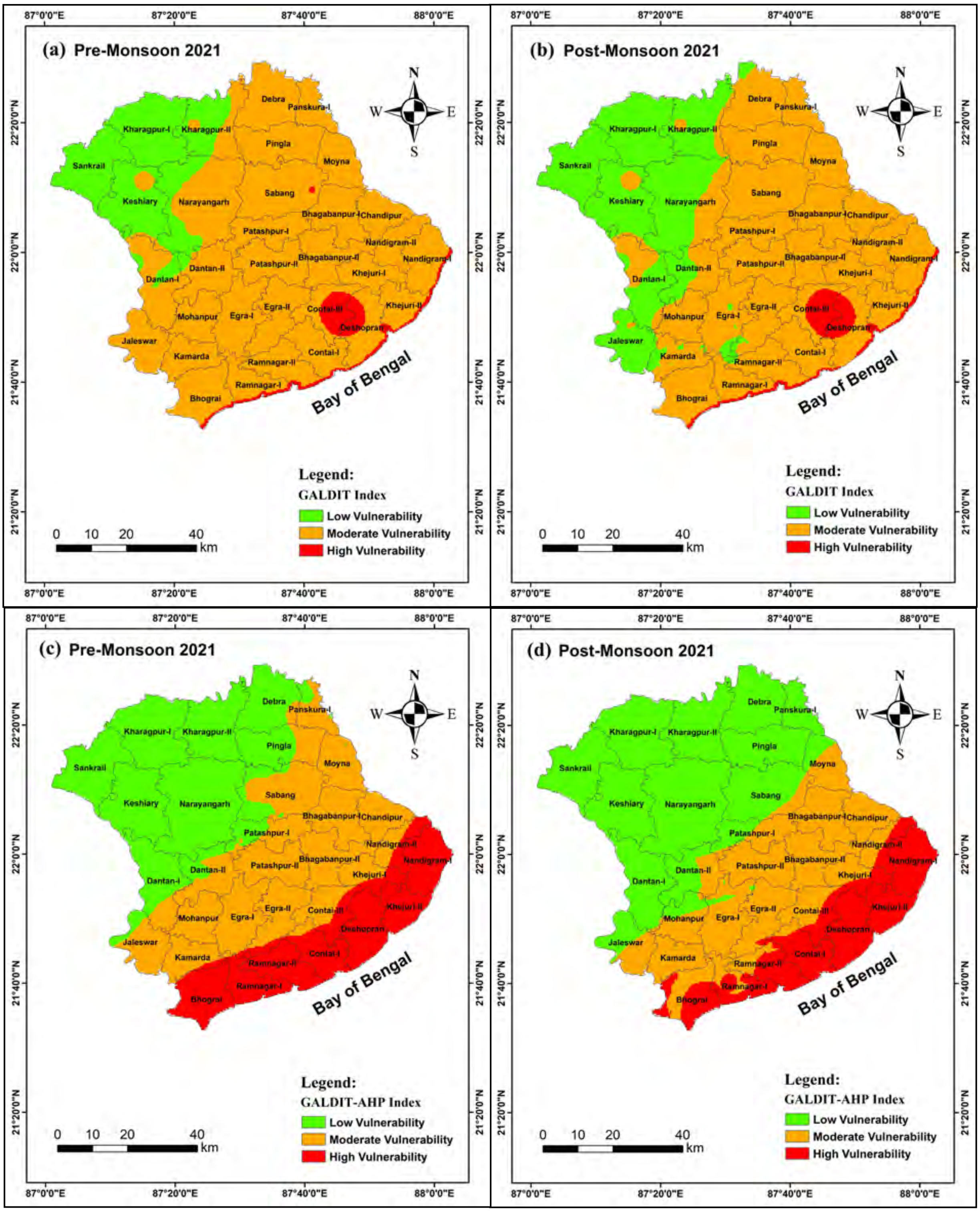
3.4 Validation of Vulnerability Analysis Results

The results produced by the two overlay-and-index-based methods were validated spatially using measured Electrical Conductivity (EC) values of the 'leaky confined aquifer'. According to the World Health Organization (WHO) standards, the EC values were classified as: (i) acceptable/low hazardous (<750 μS/cm), (ii) permissible/moderate hazardous (750–3000 μS/cm), and (iii) not suitable/high hazardous (>3000 μS/cm) for drinking and irrigation purposes (Ghosh and Jha, 2024).

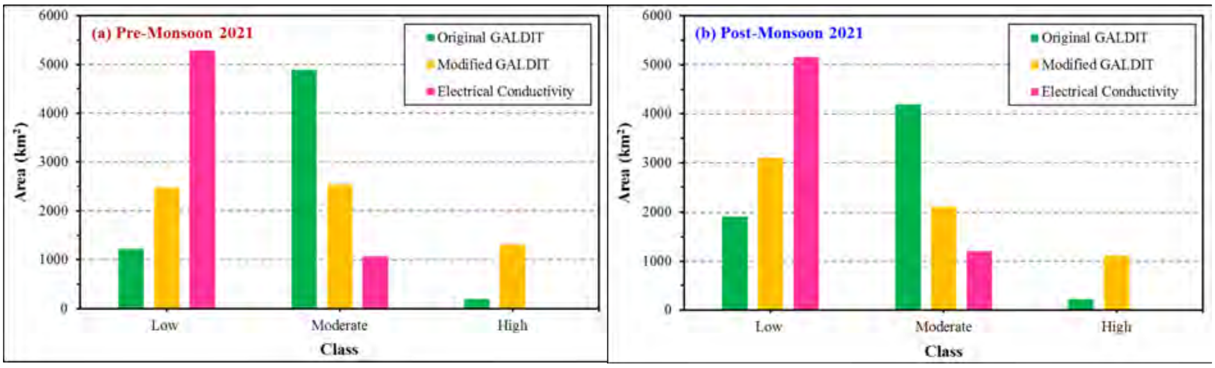


Figures 4(a–d). Spatial variability maps of 'L' and 'I' parameters.

The EC values in the Pre-Monsoon season are <750 and 750–3000 μS/cm in 5288.5 km^2 (83.17% of total) and 1070.0 km^2 (16.83%) areas, respectively. On the other hand, EC values in the Post-Monsoon season are <750 and 750–3000 µS/cm in 5156.7 km^2 (81.10% of total) and 1201.9 km^2 (18.90%) areas, respectively. Areas under each vulnerability class given by the two index-based methods were compared to the areas under each corresponding EC class, and the results are shown in Figures 6(a,b). Results reveal that the 'Original GALDIT' method delineated 50–64% lesser, 47–61% higher and 3–4% higher areas under 'Low', 'Moderate' and 'High' vulnerability classes, respectively, compared to the three corresponding EC classes.



Figures 5(a–d). Vulnerability maps prepared by 'Original GALDIT' and 'GALDIT-AHP' methods.



Figures 6(a,b). Spatial validation of vulnerability analysis results.

Results further indicate that the 'Modified GALDIT' (GALDIT-AHP) method predicted 32–45% lesser, 14–24% higher and 17–21% higher areas under 'Low', 'Moderate' and 'High' vulnerability classes, respectively, than the EC classes. Furthermore, moderate correlations were found between the OGVI and EC values in both Pre-Monsoon (r=0.518) and Post-Monsoon (r=0.589) seasons, whereas high correlation was found between MGVI and EC values in both Pre-Monsoon (r=0.712) and Post-Monsoon (r=0.742) seasons. Therefore, these results suggest that the GALDIT-AHP method performed much better than the 'Original GALDIT' method.

4. CONCLUSIONS

Keeping in mind growing freshwater contamination problems, especially in eastern India, the present study was undertaken to assess the hydrogeological and geochemical characteristics and critically analyze the aquifer vulnerability to seawater intrusion in a coastal alluvial 'leaky confined aquifer' of West Bengal and Odisha. Groundwater-level, groundwater-quality data and well logs procured in 2021 were used in this study. Two overlay-and-index-based methods were applied, namely, 'Original GALDIT' and 'Modified GALDIT' (GALDIT-AHP). The Analytic Hierarchy Process (AHP) method was used to modify the weights of the GALDIT model parameters/themes and its features. Results reveal that the 'Original GALDIT' and 'Modified GALDIT' (GALDIT-AHP) methods indicated 69–81% and 51–61% areas under 'Moderate-to-High' vulnerability classes, respectively. The spatial validation method and correlation analysis results suggest that the 'GALDIT-AHP' method performed much better than the 'Original GALDIT' method in delineating the seawater intrusion vulnerable zones. The overall results demonstrated that the combined application of geospatial technologies (Remote Sensing/GIS) and multi-criteria decision making techniques (like AHP) potentially provides an excellent platform for studying the aquifer vulnerability to seawater intrusion with reliable results. The vulnerability maps could be useful for various developmental activities, as well as for identifying the priority areas to implement groundwater management projects and programs.

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