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Evaluation of Groundwater Vulnerability and Risk Mapping Using LULC and the Modified DRASTIC Model: A Case Study from Puducherry, India

Reshma Susan Jacob[1], **Joji Vasantha Sukumaran**[1*], **Dipankar Saha**[2]

[1]Department of Marine Geology and Geophysics, School of Marine Sciences, Cochin University of Science and Technology, Lakeside Campus, Fine Arts Avenue, Cochin, India
[2]Chair Professor, CAWTM, MRIIRS, Faridabad, India

Abstract

Introduction: Groundwater is a vital resource for agricultural, industrial, and domestic needs, especially in coastal regions where alternative water sources are limited. Assessing groundwater vulnerability is crucial to ensuring sustainable water management and mitigating contamination risks.

Methods: This study evaluates groundwater vulnerability in the Puducherry region using the DRASTIC model, which incorporates hydrogeological parameters such as depth to the water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. Geographic information system (GIS) techniques were employed to generate vulnerability maps, categorizing the region into low-, moderate-, and high-susceptibility zones. Additionally, land use and land cover (LULC) data were integrated with the traditional DRASTIC model to develop a modified risk assessment layer. The model was validated using nitrate and chloride concentration data.

Results: The findings indicate that integrating LULC data with the conventional DRASTIC model provides a more comprehensive assessment of groundwater vulnerability. The modified analysis revealed that high-risk areas account for 26.64% of the study region, highlighting the significant impact of human activities on groundwater contamination.

Conclusion: This research presents a robust framework for assessing groundwater vulnerability in coastal regions. The results underscore the need for targeted groundwater management strategies to protect water resources. The study provides policymakers with valuable insights for developing sustainable water management practices.

Keywords: Water resources, Geographic information systems, Nitrates, Chlorides

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***Correspondence to:**
Joji Vasantha Sukumaran, Email: jojivsdeepam@gmail.com

Introduction

Groundwater vulnerability refers to the properties of groundwater that determine its susceptibility to adverse impacts from pollutant loads. Human and agricultural activities largely drive the degradation of groundwater levels, increasing vulnerability. Sustainable development strategies are essential to protecting these vital resources, particularly regarding the declining depth of the water table (DTW) (1). In regions where alternative water sources are limited, groundwater is important for agriculture, industry, potable water supply, and other municipal applications. Establishing clear policies and guidelines for groundwater quality regulation and monitoring is vital to ensure a reliable supply and mitigate negative impacts (2). Unlike surface water, the groundwater in aquifers is difficult to purify and, in some cases, may be irrecoverable (3).

Assessing vulnerability is a critical component of management strategies aimed at preserving groundwater quality, as it evaluates an aquifer's sensitivity and risk to pollution (4,5). The definition of groundwater vulnerability does not account for pollutant attenuation; it focuses solely on hydrogeological conditions (6).

The DRASTIC MODEL is an extensively recognized technique for evaluating groundwater vulnerability to contaminants (7). This technique, introduced by Aller (7) in collaboration with the US Environmental Protection Agency and the National Water Well Association, provides a methodology for assessing contamination risk. Geographic information systems (GIS) have been highly effective in managing and analysing extensive datasets (8,9). The DRASTIC model evaluates seven parameters, each rated on a scale of 1 to 10 and assigned a weight of 1 to 5 reflecting its significance (7). These ratings and weights are combined to calculate a vulnerability index, which is then used with GIS tools to create maps that highlight pollution risks associated with activities such as pesticide application and chemical fertilizer use (10).

This study focuses on the Puducherry region, situated along the Coromandel Coast of India. The agricultural, industrial, and municipal needs of the area are mostly met by groundwater. However, the region is increasingly impacted by over-extraction, contamination, and changes in land use. While the DRASTIC model has been widely applied across settings, integrating it with LULC data provides a more comprehensive perspective on the combined effects of natural and human factors on groundwater vulnerability. The study mainly focused on (a) evaluating groundwater vulnerability using the DRASTIC model, (b) incorporating LULC data to develop a modified risk layer, and (c) validating the results through nitrate and chloride concentration measurements in groundwater. By enhancing the traditional DRASTIC model, this research aimed to deliver actionable insights for the sustainable management of groundwater resources in Puducherry and similar coastal regions.

Study area

Puducherry, located on the Coromandel coast between 11° 45' and 12° 03' North Lat. and 79° 37' and 79° 53' East Long., spans an area of 294 km^2 (Figure S1). It is part of the Pambai Watershed. It has 164 populated communities and is divided into five communes. The South Arcot district of Tamil Nadu borders this region on three sides, while the Bay of Bengal borders it on the fourth. It is situated 162 kilometres south of Chennai. Dispersed throughout this region are the South Arcot Taluks of Cuddalore, Villupuram, and Tindivanam. The overwhelming majority of Puducherry lies on a peneplain at an elevation of 15 m above mean sea level. Typically, there are three significant physiographic units: upland, alluvial, and littoral plains. The coastal plain is a thin tract that stretches for approximately 22 km along the eastern shore of the Bay of Bengal, with widths varying from 60 to 400 m. The two primary drainage basins are characterized by the dispersion of lakes and reservoirs throughout the deltaic channels of the Rivers Gingee and Pennaiyar, as well as other streams. The monsoon season in Puducherry is markedly different from that of the rest of the country. The Region experiences typical precipitation from July to September and from November to January. Coastal regions, including Puducherry, are characterized by high humidity. According to precipitation data, the annual mean precipitation in the Puducherry Region is 1383 mm. Puducherry falls under the over-exploited category based on the stage of groundwater extraction. The sole groundwater abstraction structures in the Region are tube wells. The Regional geological setting of the Puducherry Region has been compiled (Table S1).

Materials and Methods

The DRASTIC model is widely used in Europe and Latin America and was developed to assess the potential for groundwater pollution at regional scales (11,12). Its primary aim is to identify areas that require heightened protection or management. Sixty-two samples were collected in May 2022 (Premonsoon/PRM) at depths of 2–100 mgbl, and analyses were carried out following the APHA 2022 standard guidelines. The variables analyzed are categorized into three key components: the aquifer or saturated zone, the land surface, and the unsaturated zone, which are fundamental to the DRASTIC methodology (13). Developed by Aller (7), the DRASTIC approach assesses groundwater vulnerability using seven parameters, including depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). Each parameter is weighted based on its importance, and specific classifications are assigned specific ratings. The method relies on several assumptions for estimating vertical groundwater vulnerability: (a) the pollutant originates at the ground surface, (b) it moves through the unsaturated zone by percolation or infiltration, (c) the pollutant's mobility is equivalent to that of water, and (d) the area of interest exceeds 0.4 km^2. The DRASTIC index (DI) is computed to approximate the likelihood that a contaminant will reach the depth of the water (DTW). A higher DI score signifies a greater vulnerability to pollution and is presented by

$$\text{DRASTIC Index (DI)} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$$

The steps followed in the DRASTIC model are explained in Figure 1 using mainly the Arc GIS 10.2 and the weight of the parameters compiled (Table S2).

Results

Based on field and secondary data, various layers were created to represent each parameter in the GIS platform.

Depth to the water table, DTW

The DTW establishes the uppermost surface of the saturation zone because it determines the length a pollutant must travel before it reaches the DTW. As shown in Figure 2, there are three DTW categories: 1–38, 38–54, and 54–100 mbgl. The extent of time the percolating water is in contact with components in the vadose zone controls the spread of dispersion, oxidation, and sorption of pollutants, which result in natural attenuation—the probability of contaminants attenuating increases with increasing water depth. Borehole records, direct measurements from shallow boreholes, and well drilling are all methods used to collect groundwater depth

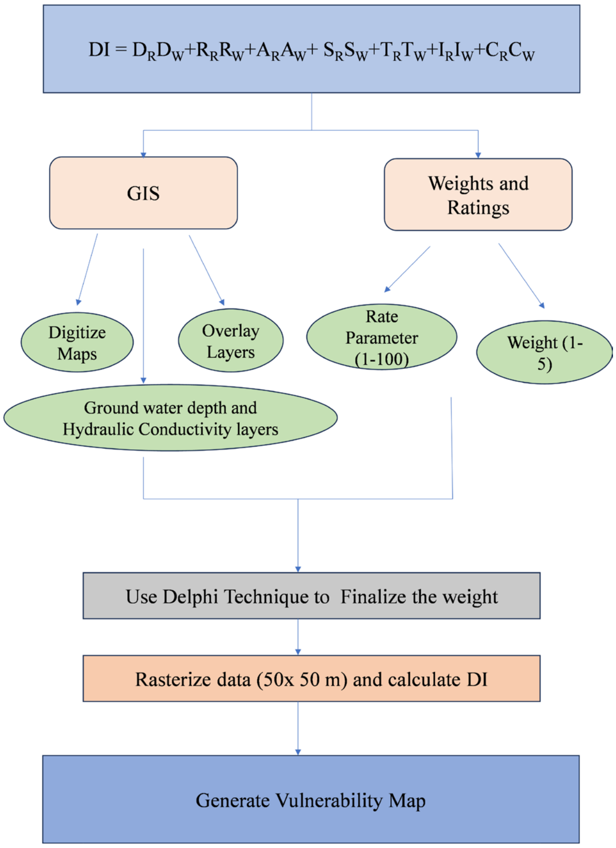

Figure 1. Steps in DRASTIC vulnerability

information. To generate a seamless representation of groundwater depth, an interpolation technique known as inverse distance weighting is used. This method employs a straightforward inverse-power approach and integrates a large number of input points with measured data points.

Net recharge

The vulnerability of groundwater reservoirs increases as the net recharge volume increases. The amount of groundwater recharge is influenced by the amount of water that percolates into the DTW, LULC, soil permeability, slope, and rainfall. A high recharge rate suggests a high risk of contamination. As shown in Figure 2, the net recharge ranges from 136 to 272 mm/year. The basin's shallow aquifer has a high recharge rate, while the deep aquifer receives limited recharge due to an impervious clay layer; the net recharge is shown below.

Net recharge = (Rainfall – Evaporation) × Coefficient of Thiessen

Aquifer media

The flow properties of the aquifer material are significantly influenced by particle and void dimensions, which, in turn, affect contaminant dispersion rates and, consequently, the vulnerability of groundwater. In general, water permeability increases with the presence of larger particles and cavities (7). This increased permeability enables the migration and diffusion of pollutants with greater ease, resulting in a broader range of pollution and, consequently, greater vulnerability. Hydraulic conductivity, or the rate and type of discharge in a reservoir, is regulated by the media or supporting material of an aquifer. As shown in Figure 2, the aquifer media present here are Cuddalore sandstone and alluvium.

Soil media

The size and composition of soil particles are critical components of these factors. Groundwater vulnerability is correlated with increased particle size and heightened swell-shrink characteristics. In essence, the susceptibility to pollution is increased by larger particulates and pronounced swell-shrink attributes. The infiltration rate is influenced by soil properties, which in turn regulate filtration, volatilization, biodegradation, and sorption during percolation (7). Soil permeability and contamination burden are effectively reduced by clay, silt, peat, and other fine-grained materials, as well as by organic matter. The soil layer is composed of deposits of silty loam, non-shrinking and non-aggregated clay, gravel, sand, loam, sandy loam, and clay loam (Figure 2). The highest rate was observed in gravel, sand, and granular loam. The sand exhibited a high degree of permeability.

Topography

Pollutants infiltrating groundwater are reduced by steeper ground slopes, which promote more efficient surface discharge. As the slope increases, groundwater vulnerability decreases due to reduced potential for pollutant infiltration. The DEM of the area is used to determine its topography. Contaminants will subsequently reach the DTW by settling into the ground or exiting the area as discharge (14). Additionally, topography provides clues about where impurities will accumulate. Figure 2 shows that Pondicherry has a lower slope. The lower slopes are more susceptible to pollution because runoff from agricultural lands at higher elevations channels to lower ones.

Effect of the vadose zone

This is the manner in which the vadose zone influences the percolation of water. The pollution warning properties, including dispersion, sorption, mechanical filtration, volatilization, and biodegradation, are influenced by the nature of the material in this zone (7). Its impact is the same as that of the aquifer, primarily because its permeability affects groundwater vulnerability. Incomparable scenarios: increased permeability increases groundwater vulnerability, enabling more efficient movement of contaminants. The Puducherry Region is mainly composed of gravel and grit, with silt and clay (Figure 2).

Hydraulic conductivity ©

The C value measures the capability of a groundwater reservoir to transport water, and groundwater is perpetually in motion. Therefore, this component regulates the rate at which contaminants traverse a groundwater reservoir (7).

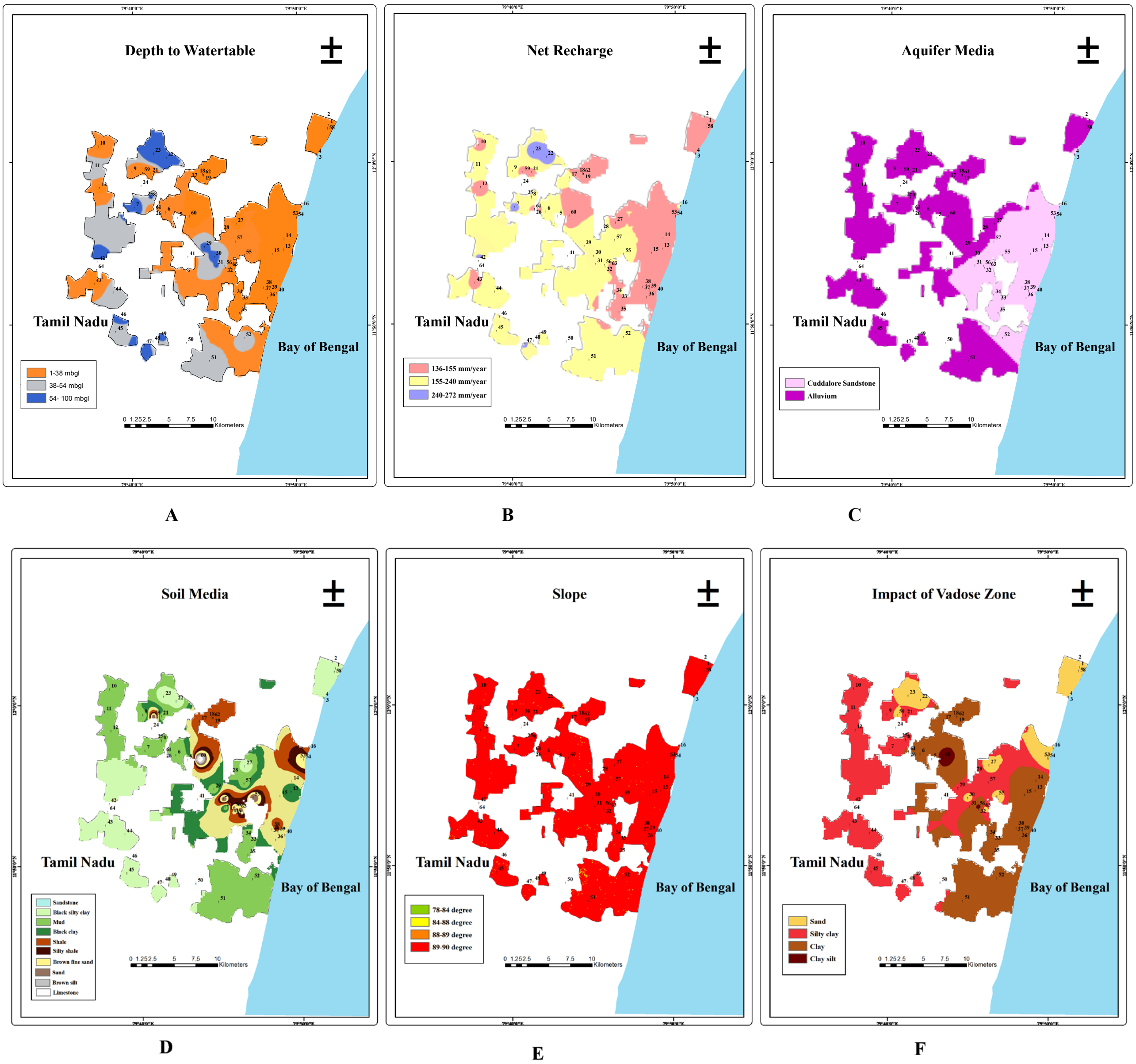

Figure 2. (A) depth to the water table, (B) net recharge layer, (C) aquifer media layer, (D) soil media layer, (E) topography layer, and (F) impact of vadose zone layer of Puducherry Region

C is determined by the interconnectivity and porosity of the intergranular void spaces. C decreases as the particle size decreases. Besides particle size, C is affected by the sphericity of grains and their packing.

Land use Land Cover, LULC

A region's vulnerability to pollution and its LULC patterns are significantly influenced by its geological context. For example, intensive agriculture is often practiced in regions with fertile soils, leading to nutrient runoff and soil erosion that affect local ecosystems and water bodies (15). Typically, urbanisation occurs on flat, stable terrain; however, this can disrupt natural infiltration of water and increase runoff, which can transport pollutants into adjacent rivers and lakes (16). Water quality is frequently adversely affected by mining activities in regions with abundant mineral deposits, which lead to acid mine drainage and heavy metal contamination (17). Industrial discharge and agricultural runoff exacerbate pollution in coastal and deltaic regions, which are affected by sedimentation and erosion (18). The LULC map of Pondicherry is shown in Figure S2.

Geological formations also determine the susceptibility of specific regions to pollution. The underground drainage systems of karst regions are extremely permeable and particularly susceptible to groundwater contamination, as they are characterized by soluble rocks such as limestone. The underground aquifers in these regions can be severely contaminated by inadequate sewage treatment and agricultural runoff (19). In mountainous and hilly regions, steep slopes and intense rainfall can result in rapid runoff and landslides, mobilising substantial quantities of sediment and pollutants into water bodies (20). By implementing sustainable resource extraction practices and geologically informed LULC planning, these impacts can be mitigated, thereby fostering environmental health and sustainability (21).

Creation of the DRASTIC layer

The production of the DRASTIC layer and risk layer considers crucial factors such as DTW, net recharge, aquifer media, soil media, topography, the impact of the vadose zone, and hydraulic conductivity. All GIS coverage is in raster format, and the values for each overlay are determined by multiplying the ratings by their corresponding DRASTIC weights and assigning the resulting pixel values to each location. The range is classified into four because of the minimum value. The minimum possible DI for utilizing these parameters is 23, and the maximum is 230 (7). This investigation yielded DI values ranging from 77 to 150. The DI is categorized into three groups: high (>113), moderate (105–113), and low (77–105). Table 1 illustrates the categorization of affected areas and the spectrum of classifications. The DRASTIC layer generated indicates that 17.73% of the Puducherry Region is classified as high, 43.45% as moderate, and 38.82% as low-vulnerability, as shown in Figure 3.

As per the DRASTIC layer, around 20% of the Region is extremely vulnerable, while 45% is moderately risky. In those places, either agricultural or urban areas are concentrated. There is a considerable risk, mostly in coastal areas. Because of the higher permeability and agricultural activities, which may have contributed to groundwater pollution, surface recharge is quite high.

Creation of a risk layer

The study assesses the potential groundwater hazard by considering LULC behavior in conjunction with the DRASTIC layer. The risk layer is created by adding an extra LULC element to the usual DRASTIC approach. The modified DRASTIC technique is the term used to describe this combination. The risk layer primarily emphasizes the impacts of agriculture, industry, and urbanization on groundwater vulnerability. To create the risk layer, the LULC layer is evaluated and assigned a value built on the norms provided by Saidi (22) and Secunda (23). These values are then weighted according to Tables S3 and S4. The LULC layer is transformed into a raster grid and then multiplied by the parameter's weight (Lw = 5). To determine the geospatial correlation between LULC and the DRASTIC layer, the LULC layer is superimposed on the traditional DRASTIC layer. The final grid coverage is augmented with the usual DRASTIC method. The risk layer delineates specific regions within the research area and identifies the types of human activity most likely to increase groundwater vulnerability. The risk layer is divided into three groups: low (93–143), moderate (143–153), and high (>153), as depicted in Figure 4. The analysis results indicate that 26.64% of the area exhibits high susceptibility, 33.35% displays moderate susceptibility, and 40.01% demonstrates low susceptibility. The risk layer indicates that the high-sensitivity area has expanded by more than 8.9% compared to the conventional DRASTIC layer (Table 1). This growth is due to agricultural, industrial, and urban interventions.

Validation of the methods

Validation of the standard DRASTIC method and the modified DRASTIC approach is conducted using two water-quality measures: nitrate and chloride. Nitrate is not typically found in groundwater, in general. As a result, the presence of this substance in the groundwater system is a clear indication of groundwater contamination. This contamination occurs when contaminants infiltrate groundwater reservoirs. The values of nitrate and chloride concentrations are used to build relationships with those of the traditional DI and the modified DI. To investigate the relationship between two quantitative, continuous variables, a technique known as correlation is used. According to this investigation's findings, the highest DRASTIC index values are associated with the highest nitrate and chloride concentrations. As shown in Figure 5, both DI and MDI demonstrate significant positive correlations with nitrate and chloride concentrations, confirming the robustness of the models. The slightly higher correlation values for the modified DRASTIC index suggest that it better represents actual groundwater vulnerability than the standard method.

Discussion

The depth of the water table (DTW) plays a significant role in groundwater vulnerability (7). Greater depths generally correlate with lower vulnerability because they offer greater opportunities for interaction with the vadose zone, thereby promoting natural attenuation processes (24). Conversely, higher net recharge increases vulnerability as more water, potentially carrying pollutants, enters the aquifer (25). The nature of the aquifer media also influences vulnerability. Larger particles and cavities increase permeability, facilitating contaminant dispersion (3). Similarly, soil properties affect infiltration and pollutant attenuation. Fine-grained materials, such as clay, reduce permeability and thus the risk of contamination (14). Topography is another key factor; low-slope areas are more susceptible to pollution

Table 1. DRASTIC index for Puducherry Region

Vulnerability classification	Conventional DRASTIC		Modified DRASTIC	
	Index range	Percentage of area	Index range	Percentage of area
High	>113	17.73	>153	26.64
Moderate	105–113	43.45	143–153	33.35
Low	77–105	38.82	93–143	40.01

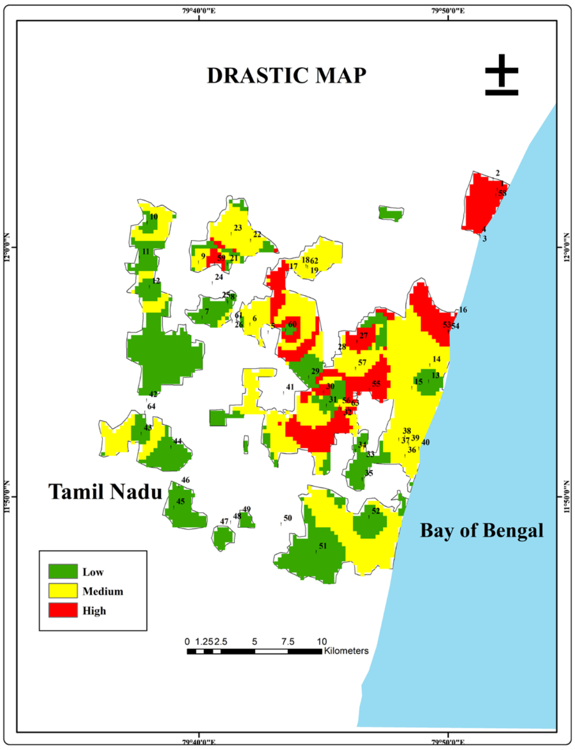

Figure 3. The DRASTIC aquifer vulnerability layer of Puducherry

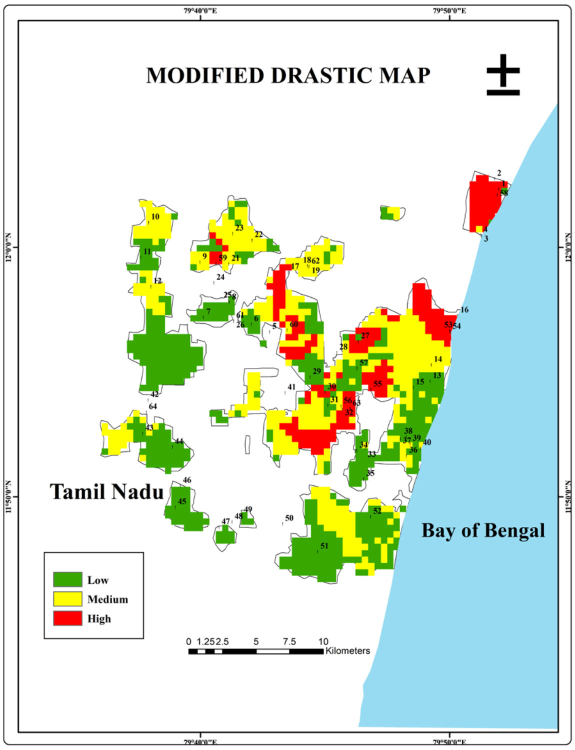

Figure 4. Modified DRASTIC aquifer vulnerability layer

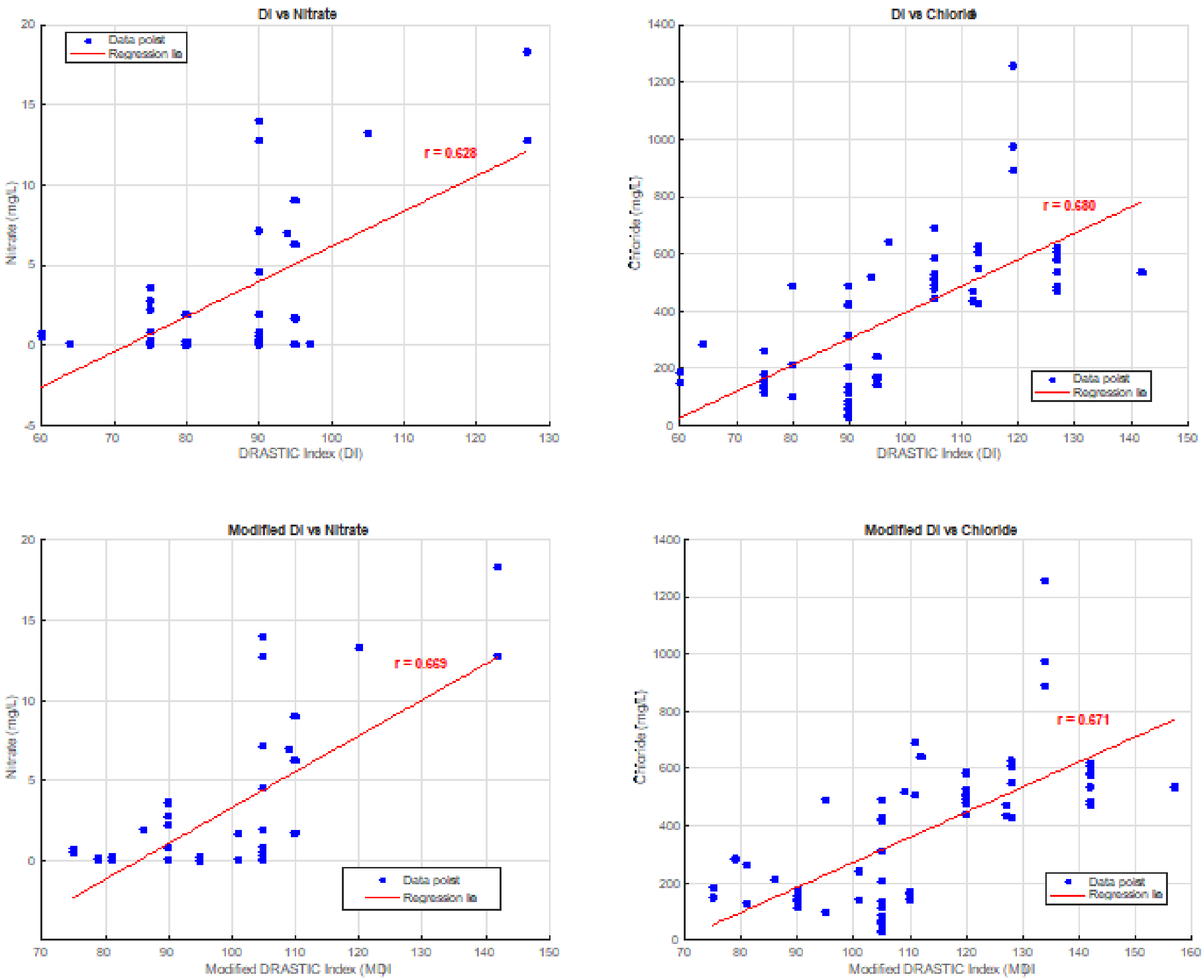

Figure 5. Correlation of DI and MDI with nitrate and chloride

due to increased water storage and infiltration (26). The vadose zone, much like the aquifer media, influences contaminant transport based on its permeability (7). Hydraulic conductivity governs the rate of contaminant movement within the aquifer (27). Land use and land cover (LULC) patterns significantly impact vulnerability (15).

Urbanization and agricultural practices, for instance, can contribute to increased pollution (28). The geological context also plays a role, with karst regions being particularly vulnerable (19). The DRASTIC method provides a framework for assessing vulnerability based on these parameters (7)., By incorporating LULC, the modified DRASTIC model highlights the influence of human activities on groundwater risk (29-32). The observed increase in the high vulnerability area in the modified DRASTIC model underscores the impact of agriculture, industry, and urbanisation (33,34). The modified DRASTIC model, when integrated with GIS, provides a more precise and reliable delineation of vulnerable zones compared to the standard DRASTIC approach, thereby strengthening groundwater management strategies (35). Finally, the validation of both the DRASTIC and modified DRASTIC methods using nitrate and chloride concentrations, with higher concentrations correlating with higher DRASTIC index values, suggests the effectiveness of these approaches in identifying areas of concern.

Conclusion

The study underscores the critical need to evaluate groundwater vulnerability using the DRASTIC method in the Puducherry Region, where groundwater is essential for agricultural, industrial, and municipal uses. The DRASTIC model employs GIS techniques to create a comprehensive vulnerability layer that identifies regions at high risk of pollution. This layer facilitates the effective planning and implementation of specific initiatives to conserve groundwater. The model's reliability was demonstrated through validation with data on nitrate and chloride concentrations. The results indicated that 17.73% of the area exhibited high risk, 43.45% moderate vulnerability, and 38.82% low vulnerability. Incorporating LULC data into the conventional DRASTIC model produced a more accurate risk layer that better reflects the effects of human activities on vulnerability. The updated DRASTIC technique indicated that 26.64% of the area had high risk, 33.35% moderate vulnerability, and 40.01% low exposure. This signifies an 8.91% increase in the percentage of highly sensitive locations relative to the conventional layer. These findings emphasise the importance of implementing specific measures to conserve and sustain groundwater in the Puducherry Region. To translate the insights into practice, management strategies should include stricter regulation and monitoring of fertilizer use in agriculture, installation of groundwater recharge structures such as percolation ponds and check dams to enhance aquifer replenishment, and the designation of zoning regulations that restrict intensive land use in high-risk areas. Furthermore, establishing a network of monitoring wells in vulnerable zones can provide early warning of contamination. These measures will enhance the efficiency of groundwater management strategies and guarantee the long-term viability and safety of essential groundwater resources in the Puducherry region.

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Authors' Contribution

Conceptualization: Reshma Susan Jacob
Data curation: Reshma Susan Jacob
Formal Analysis: Reshma Susan Jacob
Investigation: Reshma Susan Jacob
Methodology: Reshma Susan Jacob
Project administration: Joji Vasantha Sukumaran
Resources: Joji Vasantha Sukumaran
Software: Reshma Susan Jacob
Supervision: Joji Vasantha Sukumaran
Validation: Dipankar Saha
Visualization: Joji Vasantha Sukumaran and Dipankar Saha
Writing – original draft: Reshma Susan Jacob
Writing – review & editing: Joji Vasantha Sukumaranand Dipankar Saha

Competing Interests

The authors have no competing interests, including financial or personal relationships with any third party whose interests could be positively or negatively influenced by the article's content. All data used in the study were collected by the first author as part of the research program.

Ethical Approval

The manuscript has not been submitted to any other journal and is not under consideration for publication elsewhere. The field data collected as part of the first author's research can be shared with the publisher upon acceptance for publication.

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Supplementary Files

Supplementary File 1 contains Tables S1–S4 and Figures S1 and S2.

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