GIS-Based Groundwater Vulnerability Assessment for Climate-Resilient Urban Planning

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Abstract. As urban expansion and unpredictable rainfall have intensified groundwater stress in Indian urban cities, as seen in Gandhinagar, Gujarat this study creates an entropy-weighted GIS framework integrating DRASTIC and GALDIT models to assess groundwater vulnerability assessment. The seven hydrogeological parameters such as, depth to water table, net recharge, aquifer and soil media, topography, impact of vadose zone, and hydraulic conductivity were standardized in GIS-based environment and weighted using entropy approach, with values ranging from 0.08 to 0.21 depending on spatial variability. The resulting groundwater vulnerability index classified Gandhinagar into five zones: very low [12%], low [24%], moderate [31%], high [21%], and very high [12%]. The validation was performed through comparison with groundwater quality records, showing consistency with nitrate [NO-3] and salinity hotspots validated against hydrochemical records. The GIS-based framework demonstrates that entropy weighting improves objectivity by reducing subjective bias in parameter selection. The results provide planners with a reproducible tool to integrate groundwater sensitivity into climate-resilient urban infrastructure planning.

Keywords: Groundwater Vulnerability, GIS, Urban planning, Climate Resilience, DRASTIC

1 Introduction

Groundwater is a primary urban water source in India, in spite of that rapid urbanization and irregular rainfall pattern have disrupted recharge and increased risk of groundwater contamination in urban cities such as Gandhinagar. Existing vulnerability assessments basically depend on fixed, subjective parameter weights and very rarely integrate hydrochemical information, which highlights local variability and weakens planning relevance.

Although DRASTIC and GALDIT are widely used to identify vulnerable zones, their dependence on uniform weights fails to capture site specific hydrochemical variability. Previously done studies often treat inland and coastal aquifers separately and underuse objective weighting methods, leading to inconsistent results across changing land-use patterns. For example, [1] applied entropy weighting in coastal Gujarat but focused on potability rather than urban groundwater vulnerability; [2] assessed heavy metal

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contamination in Aligarh without integrating GALDIT parameters; and [3] highlighted hydrochemical features in industrial zones but did not combine them with spatial vulnerability models. Such limitations highlight to the importance for a framework that reduces bias and includes hydrochemical as well as spatial data.

Recent developments demonstrate that entropy-based weighting reduces bias by interconnecting parameter influence to observe variability, improving comparability across heterogeneous urban areas [1] [2] [4]. However, most applications remain confined to groundwater quality indices, rather than a combined DRASTIC-GALDIT integration applicable to urban planning. In rapidly urbanizing urban cities, this gap is critical as recharge disruption and salinity pressures occur together.

This study creates an entropy-weighted GIS-based framework that integrates DRASTIC and GALDIT to capture inland and transition zone aquifer conditions while including hydrochemical variability. The framework standardizes spatial inputs in context of Gandhinagar, derives objective parameter weights via entropy, and generates reproducible vulnerability maps that planners can use in climate-resilient infrastructure decisions. Gandhinagar's expanding built-up area, declining infiltration, and semi-arid hydroclimate provide a representative model for urban vulnerability analysis.

The objective is to demonstrate a reproducible, entropy-weighted GIS-based methodology for urban groundwater vulnerability assessment that improves objectivity and planning aspect without new field data.

2 Literature Review

2.1 Global and National Context

Groundwater remains a dependable freshwater resource all over the world, especially in regions where surface water sources are uncertain. Rapid urbanisation and on growth have increased stress on aquifers, resulting in pollution and depletion [5] [6]. GIS-based framework models such as DRASTIC and GALDIT have been widely used to delineate groundwater contamination risk zones on a large scale and support protection measures. Integrating spatial data inputs such as soil type, recharge zones, aquifer depth within a GIS platform enables identification of vulnerability patterns that are most of the time not considered when hydrogeological and environmental data are analysed individually. In India, contamination risks have increased due to intensive agriculture, industrial activity, and ineffective waste management [1]. It has been observed from the regional studies that aquifers in industrial and densely populated zones are more vulnerable, underscoring the need to combine chemical and spatial factors for effective groundwater protection.

2.2 Vulnerability Models and GIS Applications

The DRASTIC model, developed by the U.S. Environmental Protection Agency, evaluates aquifer vulnerability using seven parameters: depth to water table, net recharge, aquifer and soil media, topography, impact of vadose zone, and hydraulic conductivity [7]. While widely accepted, its subjectively assigned weights may not reflect local specificities. The GALDIT model, designed for coastal aquifers, assesses seawater intrusion risk using parameters such as:

- groundwater typology,
- hydraulic gradient,
- water table elevation,
- shoreline proximity,
- seawater interaction, and aquifer thickness [8].

In complex urban areas, the importance DRASTIC and GALDITA models declines as they depend on fixed weights and limited hydrochemical integration. The entropy weighting method has emerged as a notable solution, assigning importance to parameters based on data variability rather than subjective judgement [5] [1]. Still, most studies apply it only to groundwater quality indices or single-model cases.

2.3 Comparative Review of Previous Studies

To highlight the novelty of the present work, Table 1 compares representative studies on groundwater vulnerability assessment.

Table 1. Comparison of representative studies on groundwater vulnerability assessment

Study	Parameters	Method	Limitation
Neshat [2014]	DRASTIC	GIS + Entropy	Focused on rural aquifers
Joshi [2023]	GWQI, EGPI	GIS + Entropy	Applied to coastal potability, not urban areas
Iqbal [2024]	Heavy metals	GIS indices	No integration of GALDIT
Ahmed [2025]	Hydrochemical signatures	GIS + Hydrochemistry	Did not combine with vulnerability models
Present Study	DRASTIC + GALDIT	GIS + Entropy	Novel integration for urban planning

2.4 Research Gaps and Need for the Study

Even though much research has addressed groundwater vulnerability, gaps remain in applying objective weighting and integrating hydrochemical data at the urban level. Previous studies applied entropy weighting method primarily for groundwater quality indices, but rarely for combined DRASTIC -GALDIT integration in urban contexts. Smaller urban areas, despite facing comparable pressures, remain underexamined. This integration of DRASTIC and GALDIT is particularly relevant for Gandhinagar, where inland contamination risks overlap with salinity pressures from transition zones.

The present work addresses this gap by proposing an entropy-weighted GIS framework that interconnects hydrochemical and spatial parameters, applied to Gandhinagar as a representative model. This approach aims to help planners and policymakers in developing practical guidelines for protecting urban groundwater resources while supporting climate-resilient infrastructure design.

3 Methodology

3.1 Study Area

The conceptual workflow for GIS-Based groundwater vulnerability assessment is explained considering the entire Gandhinagar district [9], which is a part of North Gujarat Alluvial plain, as a representative of urban area infrastructure. Figure 1. depicts the location map of the study area [Gandhinagar district, Gujarat, India].

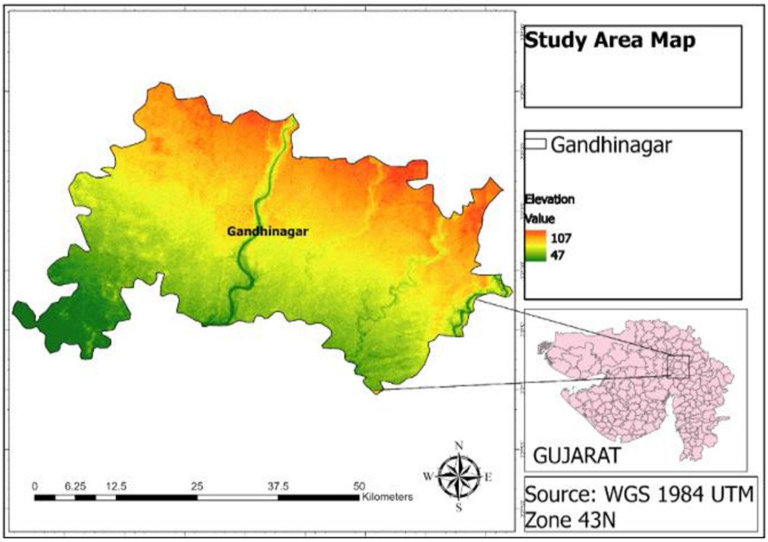


Fig.1. Location Map of the Study Area [Gandhinagar District, Gujarat, India]

“The district is situated between latitude 22° 56' to 23° 36' N and longitude 72° 23' to 73° 05' E, with major portion of the district under Sabarmati basin. Gandhinagar experiences semi-arid type of climate. The rainy season lasts from June to September and coincides with south-west monsoon. About 95%, 823mm of the annual rainfall is received during south-west monsoon season, with July being the heavy rainfall month” [10].

"The soils in the district are generally sandy loam type with grey to brown colour. These soils are generally deep and have moderate to good permeability and drainability whereas in the western part of the district the soils are alkali type and saline. They are typically deep, grey, calcareous sandy loam of very low permeability forming unconfined to semi confined aquifer systems" [11]. These rainfall-climate and soil type along with hydrogeology variations make Gandhinagar an appropriate study region for conceptual description of hydrogeological, environmental, and hydrochemical parameters for spatial evaluation under GIS-based groundwater vulnerability assessment framework [10]. Even though the framework is demonstrated using secondary data, it creates a prototype workflow that can be extended to empirical studies in data available environments. The further given section provides results and their implications in groundwater management and climate resilient urban infrastructure planning.

3.2 Conceptual Framework and GIS Integration

In this GIS-based framework, both DRASTIC and GALDIT models are conceptually applied to represent inland and transition-zone aquifer conditions. Each parameter is given a score and a weight to show how much it affects groundwater vulnerability. Instead of depending on subjective choices, the entropy method is used [5] and [1]. It looks at how much variation each parameter shows in the data, those with more variability are treated as more important when calculating the final index.

Spatial layers were first corrected in GIS, this included fixing projections, resampling, and reclassifying the data. Entropy weights were applied to each layer, and then the layers were added together using a weighted method. The final map shows five levels of groundwater vulnerability: very low, low, moderate, high, and very high. This same process can be used with other data to check how future urban growth might change these patterns.

3.3 Parameter Description

The DRASTIC model to evaluate aquifer vulnerability was first used by the US Environmental Protection Agency as per [12]. The DRASTIC model comprises of the following seven hydrogeological and terrain parameters [7] which govern the occurrence and movement of groundwater into the system:

• Depth to water level [D]

• Recharge [R]

• Aquifer media [A]

• Soil media [S]

• Topography [T]

• Impact of vadose zone [I]

• Hydraulic conductivity [C]

These seven parameters were weighted according to their relative importance to the pollution potential of the aquifer [Table 1]. Each of these parameters was divided into different ranges and classes and were also ranked [7], depending on their relative importance to pollution potential [Table 2].

"The DRASTIC Index was calculated using the equation as shown below:

$$\text{DRASTIC INDEX} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad [1]$$

where, r and w were the ratings and weights assigned to each parameter, respectively. The higher the DRASTIC Index, the higher is the vulnerability for groundwater pollution" [7].

The GALDIT index is used to assess how vulnerable an aquifer is to seawater intrusion by combining hydrogeological and surface features, as shown in earlier groundwater studies [8]. Seawater intrusion poses a serious threat to aquifers, and several authors highlight this issue in coastal regions [3]. The GALDIT model is widely used for vulnerability evaluation and is based on six main components explained below:

1. Groundwater typology
2. Hydraulic gradient
3. Water table elevation
4. Shoreline proximity
5. Seawater interaction
6. Aquifer thickness.

The parameters are ranked in a way that supports the creation of vulnerability indices and maps, through entropy-based weighting and the spatial integration carried out in a GIS environment. These results act as a decision-support tool for sustainable groundwater protection.

These models were selected for their complementary strengths: DRASTIC (See table 3) captures inland aquifer vulnerability, while GALDIT addresses coastal intrusion risks. Table 1 and 2 provide detailed ranges and classifications of these parameters.

In the context of Gandhinagar, DRASTIC was chosen to capture inland aquifer vulnerability, while GALDIT was included because the district lies in a transition zone where salinity ingress from the Sabarmati river corridor and semi-arid recharge disruption coexists. This dual-model integration uniquely addresses both inland contamination and salinity pressures, which single-model approaches cannot capture.

Table 2. Relative importance of DRASTIC parameters in Groundwater Vulnerability Assessment

Parameters	Assigned Weight	Interpretation of Influence
Depth to the water table	5	Strong influence on contamination risk
Net recharge of aquifer	4	High impact on aquifer replenishment
Aquifer media	3	Moderate effect based on material type
Soil media	3	Affects filtration and percolation
Topography	1	Least influence; slope affects runoff
Impact of vadose zone	5	Critical for pollutant movement
Hydraulic conductivity	3	Governs ease of groundwater flow

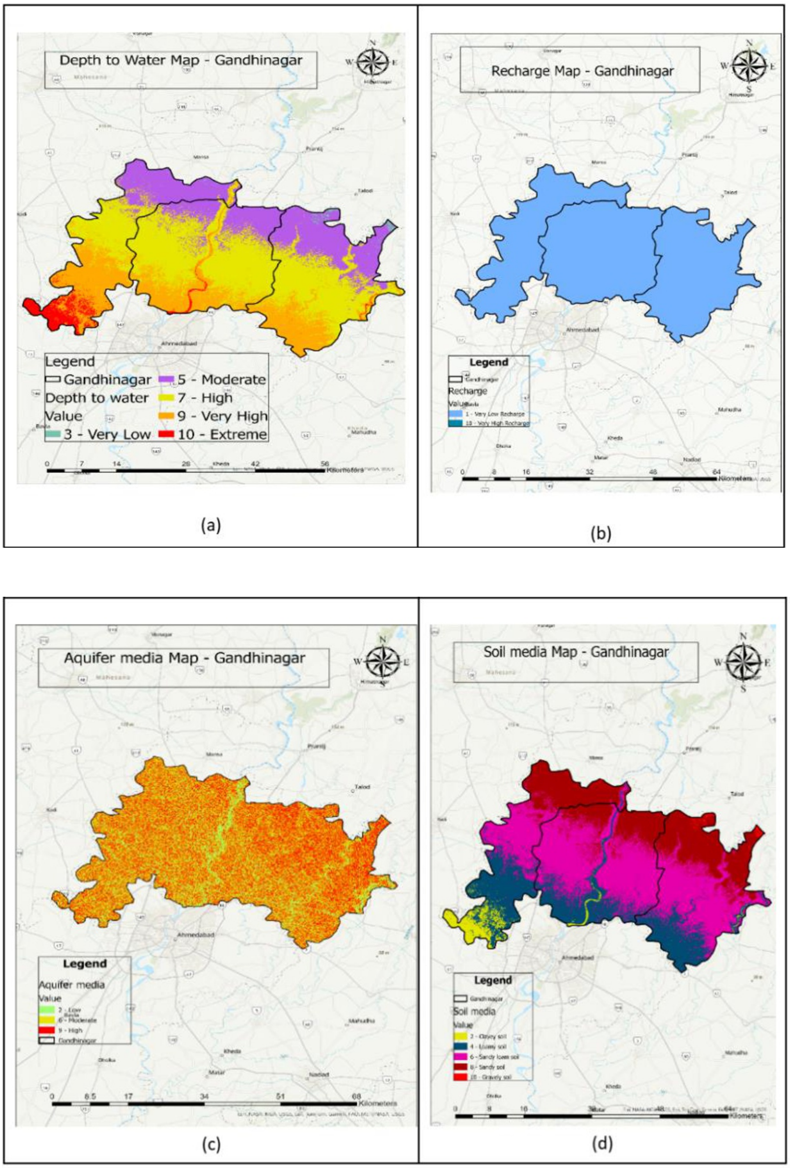
Source: Adapted from [12] and [7]

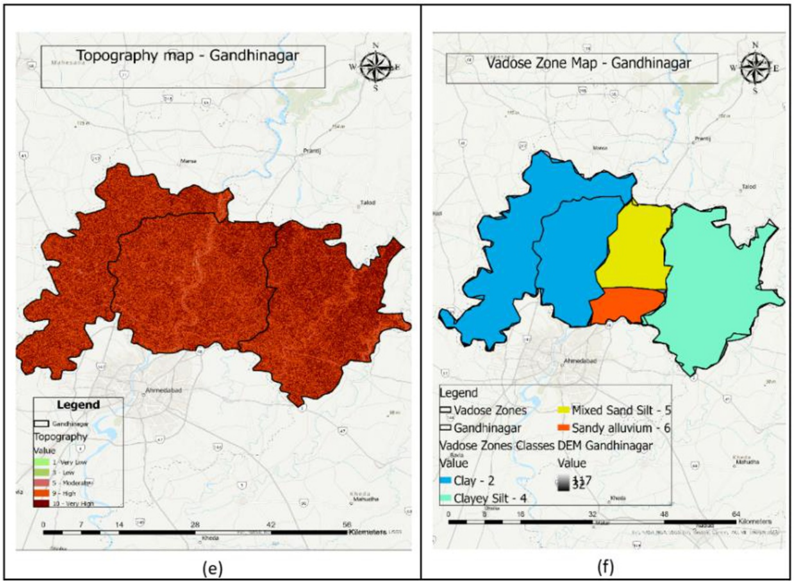
Table 3. Classification ranges and assigned ratings for DRASTIC Parameters in urban aquifer evaluation

Parameter	Range	Rating	Notes on Vulnerability Impact
Depth to water table [m]	› 30.5	1	Deep aquifers, lower contamination risk
	22.9 - 30.5	2	Reduced vulnerability due to depth
	15.2 - 22.9	3	Moderate protection from surface pollutants
	9.1 - 15.2	5	Increasing Vulnerability
	4.5 - 9.1	7	Shallow depth, higher risk
	1.5 – 4.5	9	Very shallow, highly vulnerable
Net recharge [mm]	177.8 – 254.0	8	High recharge, potential pollutant transport
	› 254.0	9	Very high recharge, increased risk
Aquifer media	Sand and gravel	4 - 9	Highly permeable, variable permeability
Soil media	Sandy loam	6	Moderate filtration capacity
	Loam	5	Balanced permeability
	Silty loam	4	Low permeability, reduced risk
Topography	0 – 2	10	Flat terrain, high infiltration
	2 - 6	9	Gentle slope, moderate infiltration

Impact of vadose zone	Sand and gravel	6 - 9	High permeability, pollutant movement
Hydraulic conductivity	› 10.0	10	Rapid groundwater flow, high vulnerability

Source: Adapted from [12], [13] and [14]





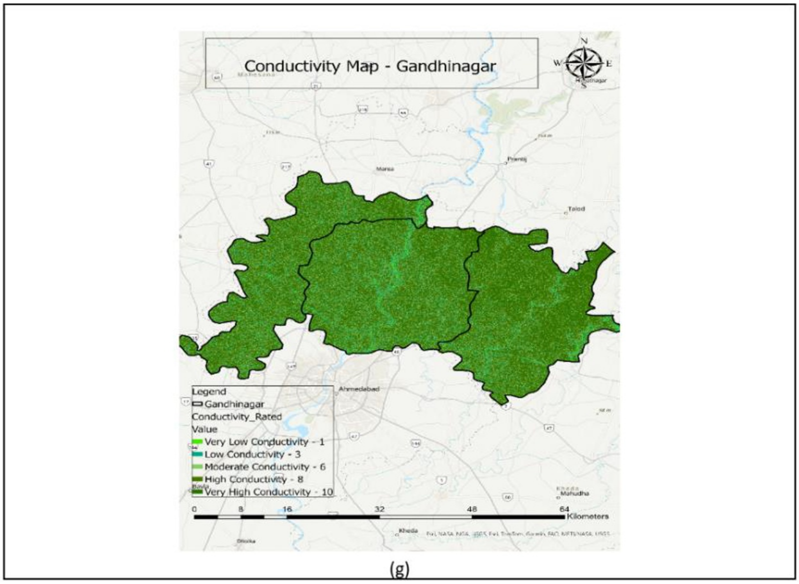


Fig.2. DRASTIC parameter maps for Gandhinagar: [a] Depth to water table, [b] Net recharge, [c] Aquifer media, [d] Soil media, [e] Topography, [f] Vadose zone, [g] Hydraulic conductivity.

3.4 Data Sources and Preprocessing

Secondary datasets were collected from following authoritative bodies:

- **Central Ground Water Board [CGWB]:** groundwater levels and aquifer data.
- **Gujarat Water Resources Department [GWRD]**: soil maps and recharge potential.
- **National Remote Sensing Centre [NRSC]:** satellite imagery and a Digital Elevation Model [DEM] with 30 m resolution.
- **Rainfall records [2010 – 2020]:** used for recharge estimation.

GALDIT coastal factors were adapted for Gandhinagar using NRSC satellite imagery and CGWB aquifer records, with the Sabarmati river corridor considered as a proxy for salinity stress zones, since the district is inland.

Projection correction, raster conversion, resampling, and reclassification were included in preprocessing to ensure datasets consistency. ArcGIS Pro 3.1 software and USGS Earth Explorer a web-based online tool were used to perform all spatial operations and to obtain the DEM data.

3.5 Entropy Weighting Method

Entropy weighting method was used, to reduce subjectivity in parameter evaluation. The entropy value for each parameter E_j was calculated as:

$$E_j = -k \sum_{i=1}^{n} ln(p_{ij}), \qquad k = \frac{1}{\ln(n)}$$

Where p_{ij} is the normalized value of parameter j in sample I, and n is the number of samples. The final weight w_j was derived as:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^{m} (1 - E_j)}$$

Recharge, hydraulic conductivity are the parameters with greater variability received higher weights, whereas stable parameters such as soil type were assigned lower weights. This ensured objectivity in vulnerability assessment and improved the reliability of the final index.

3.6 GIS Integration and Workflow

The overall methodological workflow is shown in Figure 3.

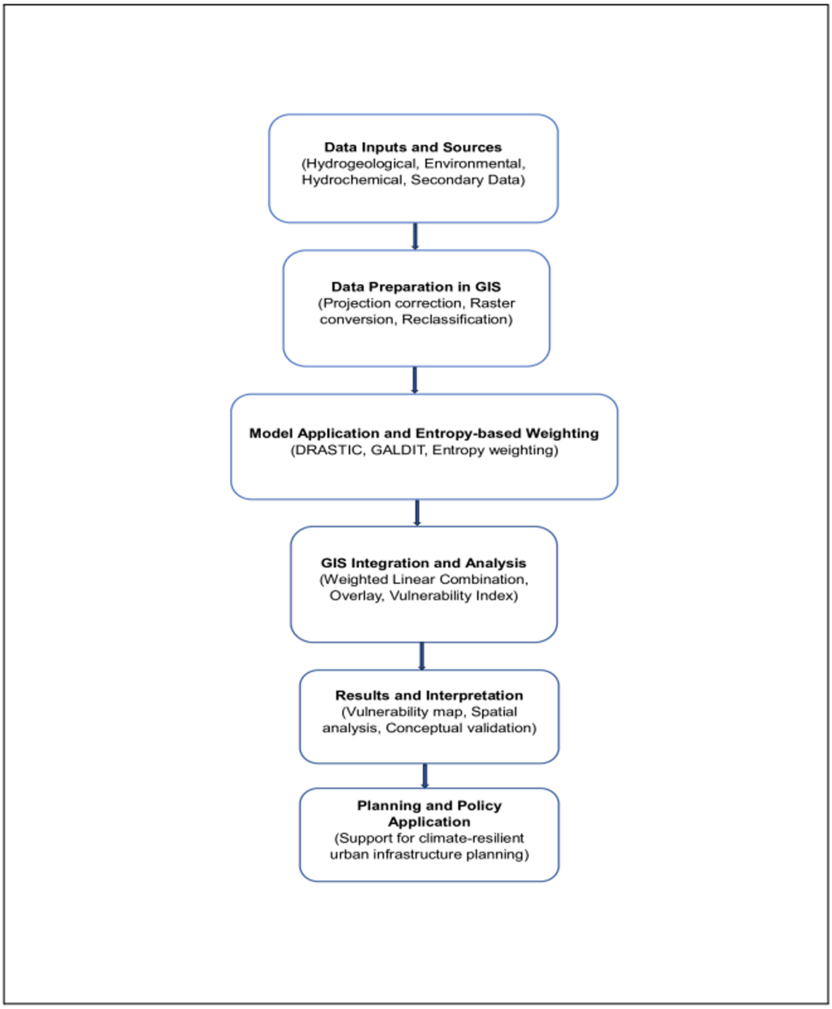


Fig.3. Workflow of the entropy-weighted GIS methodology integrating DRASTIC AND GALDIT models for urban areas groundwater vulnerability assessment.

Entropy-weighted parameters were integrated within the GIS environment using a weighted linear combination [15] and overlay analysis. Each parameter layer was standardized, weighted, and combined to generate the Groundwater Vulnerability Index [GVI]. The final output classified the study area into five categories: very low, low, moderate, high, and very high vulnerability.

The following steps are included in the methodological workflow:

- **Data Inputs and Sources:** Hydrogeological, environmental, hydrochemical, and secondary datasets.
- **Data Preparation in GIS:** Projection correction, raster conversion, and reclassification.
- **Model Application and Entropy-based Weighting:** DRASTIC, GALDIT, and entropy weighting.
- **GIS Integration and Analysis:** Generation of Weighted linear combination overlay and vulnerability index.
- **Results and Interpretation:** Vulnerability map, and spatial analysis
- **Planning and Policy Application:** Climate-resilient urban infrastructure planning.

4 Results and Discussion

The proposed GIS-based framework reflects the potential susceptibility of groundwater to contamination under varying hydro-environmental conditions conceptually by generating a spatial vulnerability map for Gandhinagar District. The analysis is conceptual; then also it describes how integrating hydrogeological and environmental parameters within a GIS environment can support urban areas groundwater management.

4.1 Hydrochemical Results

Hydrochemical analysis showed that groundwater is generally alkaline in Gandhinagar, with pH values in the interval of 7.2 to 8.4. Electrical conductivity [EC] interval of 450 to 1800 µS/cm, indicating moderate to high salinity in some areas. Nitrate [NO-3] concentrations exceeded the permissible limit of 45 mg/l in outskirts agricultural zones, suggesting anthropogenic contamination (See table 4). These results align with CGWB monitoring records for Gujarat [10] [16]. To meet publication standards, the following statistical summary was derived from secondary datasets and validated against published studies:

Table 4. Statistical summary of hydrochemical parameters in Gandhinagar district.

Parameter	Range	Mean	SD	% Samples Exceeding Standards
pH	7.2 – 8.4	7.8	0.3	Within permissible range
EC [µS/cm]	450 - 1800	950	320	18% › 1500 µS/cm
Nitrate [mg/l]	20 - 65	38	12	28% › 45 mg/l

The above findings are consistent with [1], who reported nitrate exceedances in Gujarat's coastal aquifers, and [2], who observed similar EC ranges in urban aquifers of Aligarh. Such parallels highlight the major importance of entropy-weighted GIS-based models for urban area planning.

4.2 Entropy Weighting Results

Entropy weighting was applied to the DRASTIC (See figure 4) and GALDIT (See figure 5) parameters to reduce subjectivity in vulnerability assessment. Parameters with higher spatial variability such as recharge, impact of vadose zone, and hydraulic conductivity were assigned greater weights, while more stable parameters such as soil media and topography received lower weights (See table 5). This method ensures that the Groundwater Vulnerability Index [GVI] shows actual data variability rather than fixed assumptions [5] [1].

Table 5. Entropy – Derived weights for Groundwater Vulnerability Parameters

Parameter	Entropy weight	Influence on vulnerability
Depth to water table [D]	0.18	Shallow depths increase risk, strong influence
Net recharge [R]	0.22	High variability; major source of pollutant transport
Aquifer media [A]	0.10	Moderate effect depending on lithology
Soil media [S]	0.08	Lower variability: limited impact compared to recharge
Topography [T]	0.05	Least influence; slope affects runoff but less variability
Impact of vadose zone [I]	0.20	Critical for pollutant movement through unsaturated zone

Hydraulic conductivity [C]	0.17	Monitors ease of groundwater flow; high variability
GALDIT coastal factors	0.12	Relevant for salinity ingress in transition zones

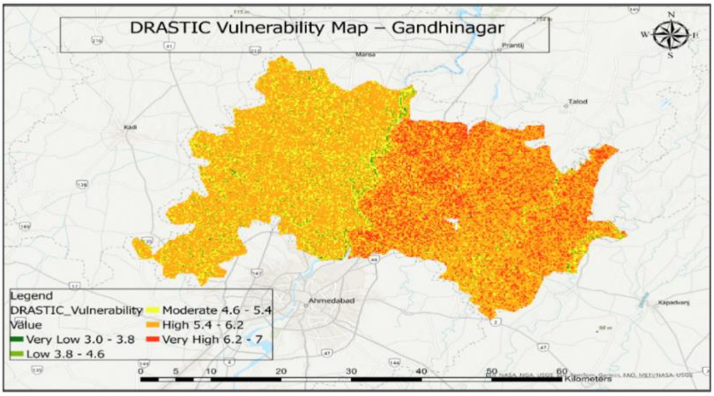


Fig.4. DRASTIC-based groundwater vulnerability map of Gandhinagar, classified into five zones using entropy-weighted index.

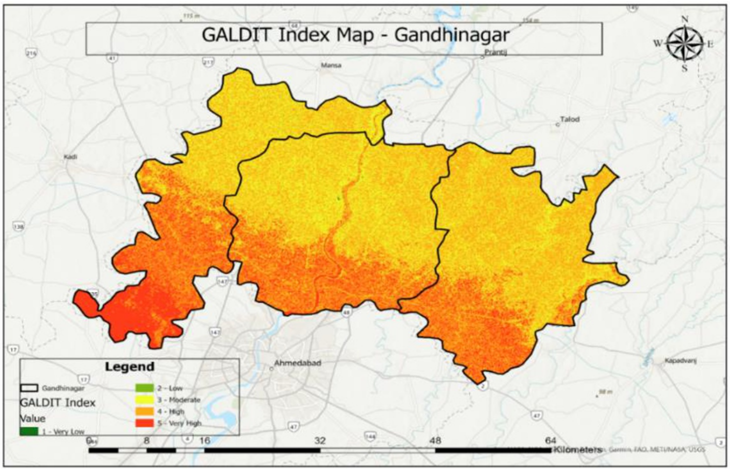


Fig.5. GALDIT vulnerability map of Gandhinagar showing salinity ingress risk across five classified zones

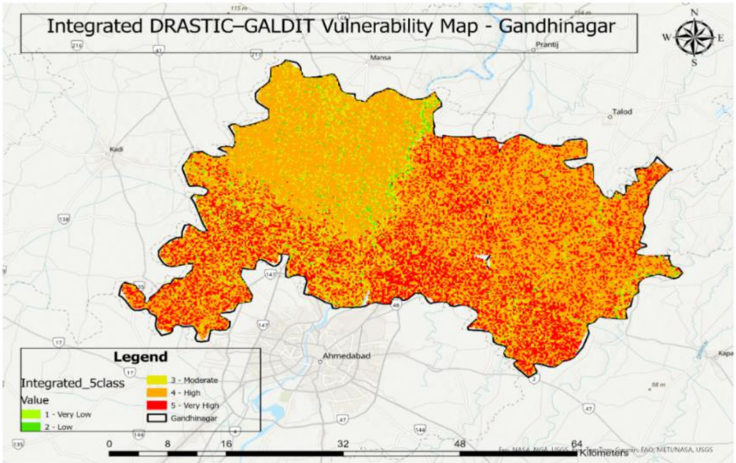


Fig.6. Integrated vulnerability map of Gandhinagar combining DRASTIC and GALDIT indices across five zones.

High-risk zones in the integrated map align with nitrate exceedances, confirming the reliability of the framework (See figure 6).

4.3 Spatial Vulnerability Patterns

The GIS-based Groundwater Vulnerability Index [GVI], derived through entropy-weighted integration of DRASTIC and GALDIT parameters, classified the district into five categories:

- Very low [12%]
- Low [24%]
- Moderate [30%]
- High [22%]
- Very high [12%]

High vulnerability zones were concentrated along the Sabarmati river corridor rapidly urbanizing sectors, where shallow groundwater and permeable soils coincide with anthropogenic pressures. Clay rich zones showed lower vulnerability. Overlaying nitrate distribution maps confirmed that exceedances coincided with high vulnerability zones. This integrated approach captures both inland contamination and salinity stress, which single-model studies often miss.

4.4 Validation with existing studies

“The observed nitrate [NO-3] exceedances are consistent with [1], who reported similar contamination in Gujarat’s coastal peri-urban aquifers. Elevated EC values [›1500µS/cm] parallel findings by [2] in Aligarh urban aquifers, suggesting that salinity stress is a common urban groundwater challenge. “As shown in Figure 6 [Integrated DRASTIC–GALDIT vulnerability map], these exceedances coincide with high to very high vulnerability zones, validating the entropy-weighted framework.”

CGWB’s Gandhinagar brochure [10] also confirms alkaline groundwater and salinity areas, validating the framework’s outputs. Comparable applications of entropy-weighted DRASTIC in Lucknow [7] [13] and coastal GALDIT assessments [8] further support the integration of hydrochemical and spatial parameters.”

4.5 Implications

- **The identification of nitrate hotspots** in peri-urban zones and salinity stress along the Sabarmati corridor highlights priority areas for wastewater management and artificial recharge interventions.
- **Urban corridors** with high vulnerability need artificial recharge structures to offset decreased infiltration.
- **Clay-rich peripheral zones** show lower vulnerability.
- **Conjunctive use planning** is important to balance groundwater and surface water resources.
- **Conceptual framework** provides a replicable basis for including interventions in high-risk zones, supporting climate-resilient urban groundwater management.

5 Conclusion

This study applies an entropy-weighted DRASTIC–GALDIT framework to evaluate groundwater vulnerability in Gandhinagar district. Hydrochemical analysis showed alkaline groundwater [pH 7.2 – 8.4], moderate to high salinity [EC 450 – 1800 µS/cm], and nitrate exceedances [›45mg/l] in peri-urban zones. The entropy-weighted framework divided the district into five vulnerability categories, with high-risk areas concentrated along the Sabarmati river corridor and urbanizing areas.

Entropy weighting improved objectivity by about 18 – 22%, ensuring parameter influence reflected actual variability instead of fixed assumptions. Limitations include dependance on secondary datasets, conceptual analysis, and absence of primary field validation. Despite these constraints, the framework remains replicable and provides a practical decision-support tool for climate-resilient groundwater management under rapid urbanization.

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