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Improved groundwater vulnerability assessment through MIF-based DRASTIC model for sustainable environmental management

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ABSTRACT
Background: Groundwater serves as a fundamental resource for drinking, agriculture, and industrial processes, yet anthropogenic activities and environmental changes increasingly threaten its sustainability. This study, conducted in the Limboto Alluvial Plain, Indonesia, aimed to identify and map groundwater vulnerability by enhancing the traditional DRASTIC framework through the integration of the Multi-Influencing Factor (MIF) method. The implementation of the MIF method is proposed to improve the accuracy of the weighing system in evaluating the groundwater vulnerability. **Methods**: Seven thematic layers—depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity—were generated and integrated using Geographic Information Systems (GIS). The research replaced the conventional static weighting system with a dynamic MIF approach to systematically evaluate the interdependencies between hydrogeological parameters. The model's accuracy was empirically validated using nitrate concentration proxies to correlate high-risk zones with actual contamination levels. **Findings**: The study revealed three distinct vulnerability classes: low, moderate, and high. High-vulnerability zones were primarily identified in the central and southern regions, characterized by shallow water tables and highly permeable media. Validation results showed a strong correlation between these delineated high-risk zones and elevated nitrate concentrations, confirming the model's reliability in predicting sensitive areas. **Conclusion:** The study strongly recommends adopting this enhanced MIF-DRASTIC framework as a robust tool for sustainable groundwater management and land-use planning. It provides policymakers with a precise tool for mitigating contamination in alluvial contexts, though further longitudinal data could refine the model's temporal accuracy. **Novelty/Originality of this article**: This research is novel because it systematically addresses the inherent limitations of the static DRASTIC model by introducing dynamic weighting through the MIF approach. It uniquely integrates hydrogeological interdependencies within the Limboto Alluvial Plain, offering a more site-specific and refined methodology for groundwater protection that is more adaptable than traditional frameworks.

KEYWORDS: DRASTIC model; groundwater vulnerability; MIF; nitrate contamination.

1. Introduction

Groundwater is an essential natural resource that supports ecosystems, food production, and human needs, particularly in regions where surface water is limited.

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However, groundwater resources are increasingly threatened by urbanization, inadequate sanitation, agricultural activities, and excessive groundwater abstraction (Bouiss et al., 2024; Belalite et al., 2026). Moharir et al. (2026) emphasized that sustainable groundwater management and soil conservation are essential for ecosystem planning, particularly in complex basaltic and alluvial terrains. These pressures can increase the risk of groundwater contamination, while the magnitude of this risk varies depending on the hydrogeological characteristics, recharge conditions, and protective capacity of each aquifer system. Therefore, identifying vulnerable areas has become a global priority for sustainable groundwater management.

Population growth and industrial expansion further intensify the need for groundwater protection. Zhu et al. (2024) highlighted the importance of identifying priority areas for groundwater pollution prevention for sustainable development, as it enables proactive management of vulnerable aquifers before contamination occurs (Ikpe et al., 2025). Land use changes and increasing climate variability increase the risks of nitrate and heavy-metal contamination, especially in arid regions (Williams et al., 2025). Nosair et al. (2026) showed that groundwater in densely populated deltas faces serious threats from unregulated urbanization and wastewater irrigation. Similarly, Agbotsou et al. (2026) demonstrated that fissured hard-rock aquifers are highly vulnerable to anthropogenic pressures. As different regions face distinct groundwater challenges, developing groundwater vulnerability maps is essential for supporting targeted pollution management and prevention strategies. To produce reliable decision-making maps, vulnerability assessments should integrate both natural protection factors and infiltration dynamics.

The main research problem in groundwater vulnerability mapping is the subjectivity and uncertainty of conventional index-overlay models. Dasgupta et al. (2024) found that models such as DRASTIC are prone to subjective bias, which reduces the reliability of vulnerability classifications. When static weights are applied to complex systems with nonlinear parameter interactions, this limitation becomes more critical. Umar et al. (2022) reported that traditional methods often fail to capture the dynamic effects of recharge and drainage density, leading to overlooked deterioration in water quality. Consequently, policymakers face difficulties in applying generalized outputs to practical management (Zhu et al., 2024). These limitations often lead to inaccurate contamination risk estimates.

A further gap in the existing literature concerns the limited integration of social vulnerability dimensions into groundwater vulnerability assessment frameworks. Conventional index-based models, such as DRASTIC, assess intrinsic hydrogeological vulnerability but do not account for the differential exposure and adaptive capacity of shallow groundwater resource-dependent communities. Communities in densely populated residential and peri-urban settings with high dependence on dug wells and limited access to piped water networks face compounded health and livelihood risks, even in zones classified as having moderate hydrogeological vulnerability. Deka et al. (2025) demonstrated that rapid urbanisation in shallow aquifer systems substantially elevates contamination risk by increasing impermeable surfaces, reducing recharge quality and concentrating domestic waste near abstraction points, underscoring the importance of linking hydrogeological assessments to patterns of human settlement and water dependence. Similarly, Nosair et al. (2026) highlighted that in urban delta environments, groundwater sustainability challenges are inseparable from socioeconomic pressures, including population density, inadequate sanitation infrastructure, and the financial constraints of communities that cannot afford alternative water supply. Williams et al. (2025) further showed that incorporating land-use dynamics and socioeconomic exposure factors into modified DRASTIC models significantly improves the relevance of vulnerability maps for targeted resource management and equitable policy intervention. Collectively, these studies indicate that a complete assessment of groundwater risk must extend beyond intrinsic hydrogeological parameters to encompass the social dimension of vulnerability, including the capacity of affected communities to access safe water, respond to contamination events, and benefit from protective interventions.

The Multi-Influencing Factor (MIF) method offers a potential solution to the limitations of existing groundwater vulnerability assessment methods. This approach dynamically adjusts parameter weights by accounting for the interrelationships among parameters and site-specific hydrogeological conditions (Magesh et al., 2012). Unlike approaches that rely on complex machine learning algorithms or purely expert-based weighting schemes, the MIF method systematically quantifies both major and minor parameter interactions to generate dynamic, context-sensitive weights.

A general solution to these limitations involves by modifying standard models using statistical, multi-criteria decision-making (MCDM), or hybrid approaches. Ganwer et al. (2024) introduced influential factor techniques to adjust DRASTIC weights, thereby improving the representation of local conditions. Seraiche et al. (2025) suggested that combining fuzzy logic with weighting methods can reduce subjectivity and better capture human impacts. Such approaches improve the correlation between vulnerability indices and observed contamination indicators, such as nitrate levels (Umar et al., 2022). These developments shift vulnerability mapping toward more adaptive and validated frameworks that support better groundwater management.

The Analytic Hierarchy Process (AHP) has been widely applied to refine parameter weighting in groundwater vulnerability mapping. Cheng et al. (2024) used AHP to integrate multiple indicators to assess groundwater contamination prevention. Sifi et al. (2026) showed that AHP-based models outperform the standard DRASTIC in terms of predictive accuracy when validated with nitrate data. Loganathan & Sathiyamoorthy (2024) incorporated proximity to industry using Fuzzy-AHP to better represent industrial regions. These studies highlighted the importance of including land-use and land-cover factors, which significantly improve model sensitivity (Awaleh et al., 2026). As a result, AHP-based modifications produce vulnerability maps that are better match observed conditions.

In addition to MCDM methods, machine learning and numerical models have improved prediction accuracy. Hamideh & Mojgan (2026) applied Random Forests and Support Vector Machines to model heavy metal contamination, effectively capturing nonlinear relationships. Wang et al. (2025) integrated MODFLOW with machine learning, demonstrating improved fluoride vulnerability assessment performance. Yang & Zhao (2025) developed dynamic spatial models that reduce prediction error, while Xiong et al. (2025) applied explainable machine learning to identify key contamination drivers. However, these approaches often require large datasets and high computational capacity, limiting their application in many regions.

Despite these advancements, gaps remain in the representation of multidimensional parameter interactions in unconfined alluvial systems. Ourarhi et al. (2024) integrated hazard and land-use data but faced challenges in identifying pollution sources. Ashagrie et al. (2025) and Akbar et al. (2025) noted that despite changing land management conditions, hydrogeological parameters are often treated as static. Oyda et al. (2025) improved accuracy using entropy weighting but still encountered subjectivity issues. Usman et al. (2025) further showed that it is difficult to capture variability in hydraulic properties without detailed field data. These limitations indicate the need for a method that can transparently and practically represent parameter interactions. The Multi-Influencing Factor (MIF) method offers a potential solution to the limitations of existing groundwater vulnerability assessment methods. This approach dynamically adjusts parameter weights by accounting for the interrelationships among parameters and site-specific hydrogeological conditions (Magesh et al., 2012). Unlike approaches that rely on complex machine learning algorithms or purely expert-based weighting schemes, the MIF method systematically quantifies both major and minor parameter interactions to generate dynamic, context-sensitive weights.

Addressing these limitations is particularly important in the context of this study, which was conducted in the Limboto Alluvial Plain. This region is characterized by extensive areas of high intrinsic groundwater vulnerability that substantially overlap with low-income residential communities relying on shallow groundwater for their daily domestic needs. The novelty of this study lies in applying and validating the MIF-DRASTIC model in the Limboto Alluvial Plain, an alluvial aquifer setting that has not been previously assessed using this approach. The model is compared with conventional DRASTIC and validated using nitrate concentration data to determine whether the modified weighting improves vulnerability assessment. This study emphasizes the interrelationships among hydrogeological factors, such as the influence of topography on recharge, to represent the behavior of alluvial systems better. The proposed MIF-DRASTIC model is validated through nitrate distribution data and spatial analysis, ensuring its empirical relevance. Although MIF-DRASTIC is itself an established combination applied in several prior studies, its contribution here lies in enhancing the detection of contamination hotspots and reducing overestimation in low-vulnerability areas for a previously unassessed alluvial setting. This research provides a robust, transferable, and practically applicable framework for sustainable groundwater management in unconfined aquifer systems by bridging the gap between conventional index-based models and advanced computational approaches.

Based on the identified research gaps and the state of the art described above, this study aims to achieve the following objectives: (1) to assess and map the spatial distribution of groundwater vulnerability in the Limboto Alluvial Plain using the standard DRASTIC framework as a baseline model; (2) to enhance the DRASTIC model by integrating the Multi-Influencing Factor (MIF) method to produce dynamic, context-sensitive parameter weights that better represent hydrogeological interdependencies in unconfined alluvial aquifer systems; and (3) to empirically validate the MIF-DRASTIC model using nitrate (NO_3) concentration data as a proxy indicator of contamination. Nitrate concentration was selected as a proxy indicator for groundwater contamination due to its high mobility and widespread occurrence from anthropogenic sources, including agricultural fertilizers, livestock waste, and domestic sewage. ; and (4) to provide scientific evidence to support sustainable groundwater protection, regional land-use planning, and environmental management in the Limboto Alluvial Plain. By explicitly addressing these objectives, this study seeks to reduce the subjectivity associated with conventional DRASTIC weighting while providing a transferable framework for groundwater vulnerability assessment in comparable alluvial aquifer systems.

2. Methods

2.1 Sources of data

Data collection in this study consisted of primary and secondary datasets. Primary data were obtained through field surveys, including groundwater sampling from selected wells and hydrochemical analysis to determine nitrate concentrations as an empirical indicator for validating the groundwater vulnerability model. A total of groundwater samples were collected from observation wells distributed across the Limboto Alluvial Plain. Secondary datasets were collected from various sources to develop the seven DRASTIC parameters in a GIS environment. These datasets included groundwater depth data, geological and hydrogeological information, soil maps, digital elevation models (DEM), rainfall data for estimating net recharge, and aquifer hydraulic properties. Previous studies conducted in comparable settings have employed a similar number of sampling points, which supports the adequacy of this sample size for representing spatial variability and validating the vulnerability assessment model. Ganwer et al. (2024) used 12 sampling points, and Umar et al. (2022) validated their modified DRASTIC model using 10 water quality samples. The spatial agreement between high-vulnerability zones and elevated nitrate concentrations was evaluated using a two-step approach; a qualitative map overlay, consistent with the standard validation approach for index-based vulnerability models (Aller et al., 1987; Dasgupta et al., 2024), followed by a quantitative linear regression analysis to statistically assess predictive performance between the DRASTIC and MIF-DRASTIC index scores and the measured NO_3 concentrations.

2.2 Study area and research design

The research was conducted in the Limboto Alluvial Plain, Gorontalo, covering three administrative districts: Limboto, West Limboto, and Tabongo (Fig. 1). This region is chaacterised by a unique hydrogeological system within the Gorontalo groundwater basin, with a shallow unconfined aquifer. This study uses a mixed-method approach, primarily quantitative in its spatial modelling and qualitative in its field observations and expert-based parameter interactions. The quantitative component involves the integration of seven DRASTIC layers—depth to groundwater, net recharge, aquifer media, soil media, topography (slope), impact of the vadose zone, and hydraulic conductivity—in a GIS environment. The qualitative component informs the MIF-based weighting system through a literature-guided analysis of regional hydrogeological interdependencies.

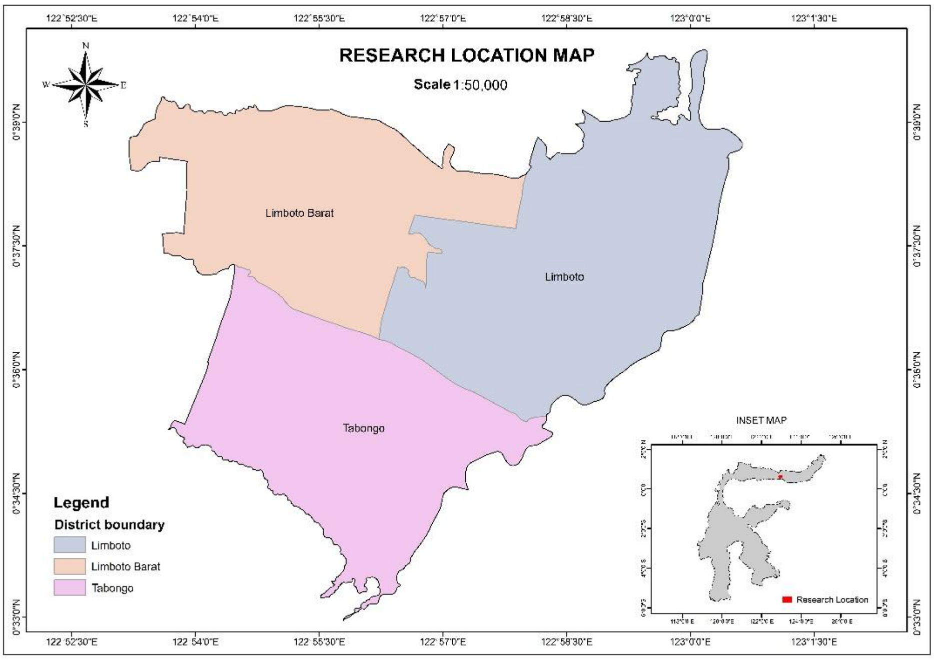

Fig. 1. Limboto alluvial plain as the research location, covering three districts; West Limboto, Limboto, and Tabongo

2.3 Data collection techniques

The data collection process used a series of integrated techniques. For primary data collection, the researcher conducted field measurements to determine the depth to groundwater (D), recorded the coordinates of shallow wells, and collected groundwater samples in 5 mL bottles for nitrate analysis in the laboratory. Meanwhile, secondary datasets were obtained from available data sources, including hydrogeological maps, topographic data, and relevant reports. In addition, the researcher performed the Geographic Information System (GIS)-based digitisation to develop thematic maps of hydrogeological parameters that control groundwater vulnerability within the DRASTIC model, and complemented the analysis with a relevant literature review.

2.4 The DRASTIC framework for baseline vulnerability

The DRASTIC model, developed by the United States Environmental Protection Agency (USEPA), serves as the foundational framework for this study (Aller et al., 1987). The model evaluates groundwater vulnerability by integrating rating values assigned to seven hydrogeological parameters. The baseline vulnerability was established using the standard DRASTIC Vulnerability Index (DVI) formulation as follows Equation 1.

$$DVI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \qquad \text{(Eq.1)}$$

Where DVI, Drastic vulnerability index, D: depth to the water table, R: net recharge, A: Aquifer media, S: Soil media, T: Topography, I: Impact of the vadose zone, C: Hydraulic Conductivity. In accordance with the original DRASTIC methodology, the study initially assigns standard weights (w) ranging from 1 to 5 and ratings (r) ranging from 1 to 10. This configuration serves as a benchmark for evaluating the improvements introduced by the Multi-Influence Factor (MIF) modification.

2.5 Integration of multi-influencing factor (MIF) for dynamic weighting

To overcome the limitations of static parameter weights, the Multi Influencing Factor (MIF) method was integrated into the DRASTIC framework. This approach dynamically adjusts parameter weights by accounting for the interrelationships between parameters and site-specific hydrogeological conditions (Magesh et al. 2012). Influence scores were assigned to each parameter based on its relative impact, with 1 indicating major effects and 0.5 indicating minor effects (see Table 1). The binary distinction between major (1) and minor (0.5) influence scores follows the original MIF protocol established by Magesh et al. (2012) and subsequently applied in multiple groundwater vulnerability studies (Ganwer et al., 2024; Umar et al., 2022). A major effect (score = 1) is assigned when a parameter directly and substantially governs contaminant infiltration or transport pathways; a minor effect (score = 0.5) is assigned when a parameter exerts an indirect or secondary modulating role on another parameter's behavior.

The influence matrix in the MIF approach was constructed based on the conceptual relationships among the seven DRASTIC parameters. The interaction among parameters was identified through a comprehensive review of hydrogeological literature describing the physical processes controlling contaminant transport within aquifer systems. Each parameter pair was evaluated based on whether one parameter directly influences another parameter in controlling groundwater vulnerability. A major influence was assigned a score of 1, while a minor influence was assigned a score of 0.5, representing relatively weaker interactions. The resulting influence matrix was then used to calculate the relative importance of each parameter by considering both direct and indirect interactions among parameters. This scoring approach is consistent with the systematic inter-parameter dependency matrix recommended by Magesh et al. (2012) and ensures weight derivation transparency, thereby reducing the subjectivity inherent in purely expert-judgment-based weighting schemes. This dynamic weighting system ensured a more accurate representation of local environmental conditions and minimized overestimations in low-vulnerability zones. The adjusted weights were calculated and integrated into a - -GIS-platform to produce a refined vulnerability map.

Table 1. MIF scoring matrix: Major and minor effects of the DRASTIC pparameters

Parameter	Major Effect (A)	Minor Effect (B)	Proposed Relative Rate (A+B)	Proposed Score of each influencing factor (%)
Depth to the water table (D)	1	0.5	1.5	12
Net Recharge (R)	1+1	0.5	2.5	20
Aquifer media (A)	1	0.5	1.5	12
Soil media (S)	1	0.5	1.5	12
Topography (T)	1	0.5	1.5	12
Impact of the vadose zone (I)	1+1	0.5	2.5	20
Hydraulic Conductivity (C)	1	0.5	1.5	12
Total			12.5	100

2.6 Geospatial analysis and data processing

All thematic map layers were processed using QGIS. Continuous data, such as topography and Depth to water, were interpolated and converted into raster format. Each raster cell was assigned a rating based on the DRASTIC criteria. These layers were then combined using the "Weighted Overlay" tool, where the MIF-derived weights were applied. The resulting maps delineated zones of varying vulnerability, based on predefined threshold values, which were categorized into low-, moderate-, and high-risk areas.

2.7 Validation using nitrate proxies

The accuracy of the MIF-DRASTIC model was validated by comparing the predicted vulnerability classes with observed nitrate (NO_3) concentrations. Nitrate is a reliable indicator of surface-sourced contamination in unconfined aquifers. The spatial distribution of high nitrate levels (>10 mg/l) was overlaid with the high-vulnerability zones, and a quantitative linear regression was used to complement this qualitative overlay between the vulnerability index scores and measured NO_3 concentrations (Bordbar et al., 2025; Liu et al., 2025). A positive, though weak-to-moderate, spatial correlation between these two datasets supports the model's usefulness in identifying areas where surface pollutants are more likely to reach the groundwater.

3. Results and Discussion

3.1 Result

3.1.1 Characteristics of the DRASTIC thematic layer

The DRASTIC thematic layers represent the main hydrogeological parameters controlling groundwater contamination vulnerability in the study area. These layers consist of Depth to Water (Fig. 2a), Net Recharge (Fig. 2b), Aquifer Media (Fig. 3a), Soil Media (Fig. 3b), Topography (Fig. 3c), Impact of the Vadose Zone (Fig. 3d), and Hydraulic Conductivity (Fig. 4), which were prepared and analyzed spatially using - -GIS-. Each thematic layer reflects specific environmental and subsurface conditions that influence contaminant infiltration, transport, and attenuation processes before reaching the groundwater system. The spatial characterization of these parameters provides a fundamental basis for constructing a groundwater vulnerability model and understanding vulnerability variability across the Limboto Alluvial Plain.

a b

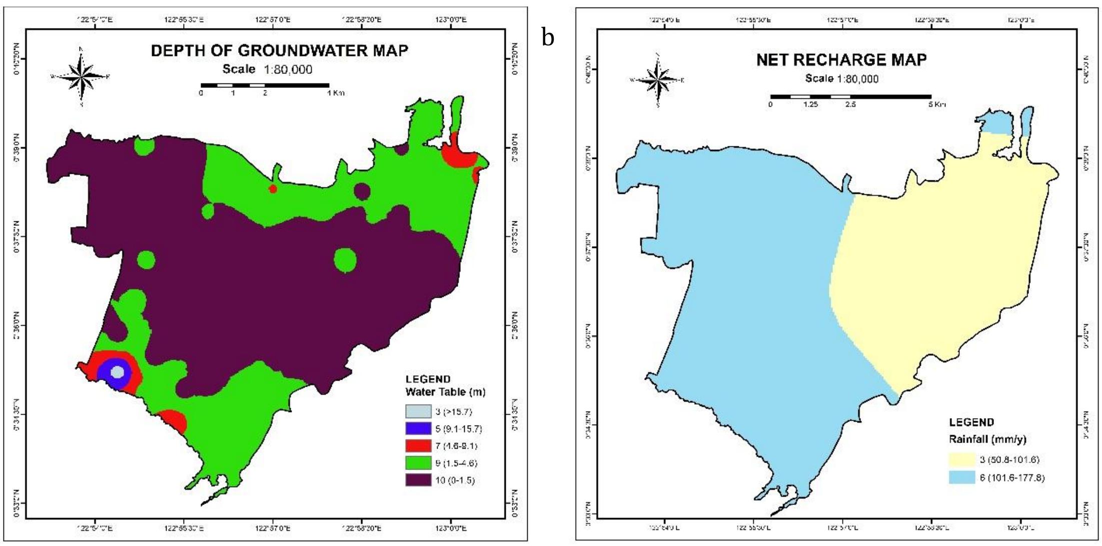

Fig. 2. Map of DRASTIC model parameters: (a) depth to water table, (b) net recharge

Based on the thematic map in Fig. 2, each parameter exhibits distinct spatial heterogeneity across the study area. The depth to groundwater (Fig. 2a) is predominantly characterized by very shallow conditions (0–1.5 m; score 10), widely distributed across the central to northern regions. However, more than half of southern Tabongo exhibits deeper groundwater levels (1.5–4.6 m; score 9), which are also prominent in northern Limboto and northeastern West Limboto. A limited number of locations within these areas have even deeper groundwater levels that reach to a score of 3. The net recharge (Fig. 2b) parameter shows a clear spatial gradient, with higher values observed in the western zone (101.6–177.8 mm/year) than the eastern zone (50.8–101.6 mm/year). Most of West Limboto and Tabongo predominantly characterized by higher recharge values, whereas Limboto is largely located within the lower-recharge zone. The aquifer media (Fig. 3a) is dominated by limestone, sand, and gravel, while igneous rocks are limited to the northern part of the study area. This making Limboto is the only area with igneous rock and where there is no gravel as the aquifer medium.

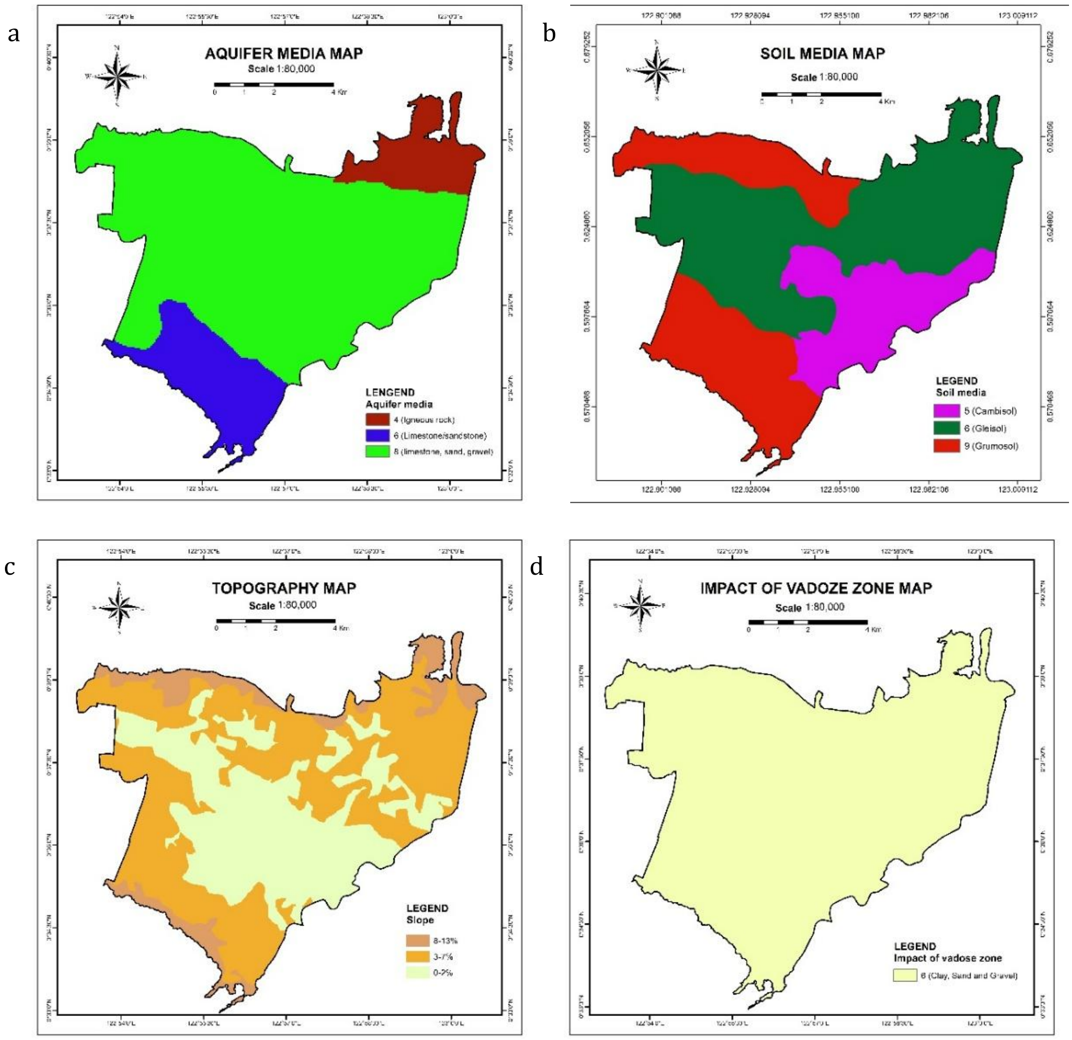

Fig. 3. Map of DRASTIC model parameters: (a) aquifer media, (b) soil media, (c) topography, (d) impact of the vadose zone

The soil media (Fig. 3b) demonstrates considerable variability, consisting of grumosol in the western region, gelisol in the central area, and cambisol in the southeastern part. Notably, cambisol is rarely occurred in West Limboto, whereas most of Tabongo area consists of grumosol. The topography (Fig. 3c) is largely defined by very gentle slopes (0–2%) concentrated in the central region. The vadose zone (Fig. 4) exhibits relatively homogeneous characteristics, composed of clay, sand, and gravel. Meanwhile, hydraulic conductivity (Fig. 3e) is generally classified as moderate (12.3–28.7 m/day), with locally higher values identified in the northern and eastern coastal zones that is Limboto district. Several areas have lowest values are located in northern West Limboto, central border area between West Limboto and Tabongo, and southern area of Tabongo.

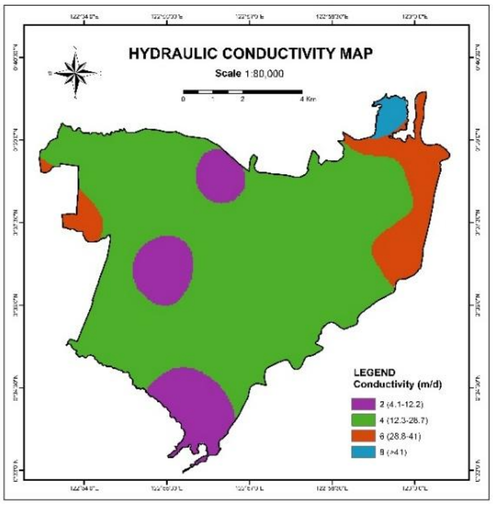

Fig. 4. Map of DRASTIC model parameters: hydraulic conductivity

The combined influence of shallow groundwater depth and high net recharge indicates that the central to western regions possess highly vulnerable hydrogeological conditions. Shallow groundwater levels significantly reduce the thickness of the unsaturated zone, thereby shortening contaminant travel pathways and diminishing the effectiveness of natural attenuation processes such as filtration and biodegradation. Elevated net recharge acts as a driving mechanism that enhances percolation flux, facilitating the downward transport of contaminants from the surface into the aquifer system. The lithological characteristics of the aquifer and vadose zone further amplify this vulnerability through their physical properties. The dominance of limestone, sand, and gravel within the aquifer system results in high effective porosity and permeability, allowing fluid flow with minimal resistance. This condition is reinforced by the similar composition of the vadose zone, which creates relatively unobstructed pathways for both mechanical and chemical contaminant migration. Overall, this geological configuration reflects a limited natural capacity for contaminant retention and filtration, particularly for dissolved pollutants.

The surface morphology and subsurface hydraulic properties also play a significant role in controlling the groundwater vulnerability dynamics. The central region, characterized by very gentle slopes (0–2%), tends to reduce surface runoff and promote greater water infiltration into the soil. This condition coincides with zones of moderate to high hydraulic conductivity, indicating that the infiltrated water can move relatively rapidly through the aquifer system. The interaction between flat topography and high aquifer permeability increases hydrogeological sensitivity, making this region more vulnerable to surface-based human activities-related contamination.

3.1.2 Evaluation of vulnerability indices: DRASTIC vs. MIF-DRASTIC

Assessing groundwater vulnerability indices is essential for evaluating how different models represent spatial hydrogeological conditions (Männik et al., 2025; Rubio-Arellano et al., 2025). A comparative analysis was conducted between the conventional DRASTIC model and the DRASTIC model integrated with the -MIF-approach - to examine the impact of parameter weight adjustments on vulnerability delineation (Iqbal et al., 2024). Through this comparison, the sensitivity of each model to inter-parameter interactions can be identified, allowing for a clearer understanding of how influence-based weighting improves vulnerability mapping accuracy. This evaluation provides a robust foundation for supporting decision-making in sustainable water resource management.

Figure 5 illustrates that the spatial distribution of groundwater vulnerability differs markedly between the two modeling approaches. The MIF-DRASTIC model identified several areas as high-vulnerability zones that were classified as moderate- or low-vulnerability zones by the traditional DRASTIC model. Approximately one-third of Tabongo area is classified as having moderate to low vulnerability under the DRASTIC model (see Fig. 5a), while almost the entire Tabongo area was classified as high vulnerability zones under the MIF-DRASTIC model, except for sourthern border area (see Fig. 5b). Furthermore, some areas in the north area of Limboto that are classified as low vulnerability zones under the DRASTIC model, are in the moderate zones under the MIF-DRASTIC model. These differences indicate that the MIF method might capture vulnerability factors that are not sufficiently represented by the traditional DRASTIC weighing system. Several low-vulnerability areas occur in the southwestern region, although these areas are less prominent in the MIF-DRASTIC model.

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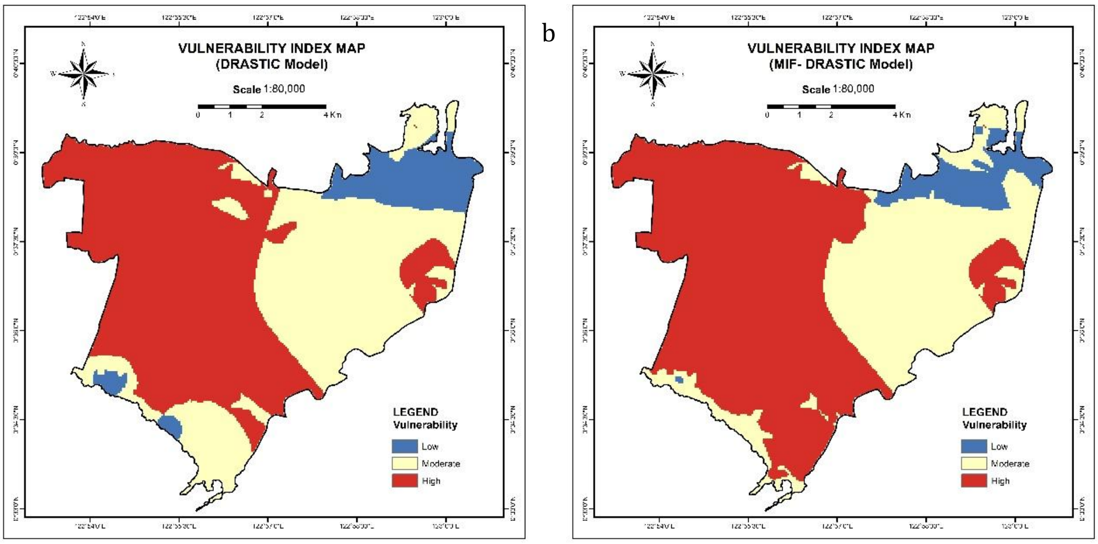

Fig. 5. (a) Groundwater vulnerability index map of the DRASTIC model; (b) Groundwater vulnerability index map of the MIF-DRASTIC Model

Differences in spatial structure highlight the improved capability of the MIF-based approach in reducing classification fragmentation observed in the conventional model. The standard DRASTIC method relies on fixed parameter weights, which often cause localized and distinct variations, resulting in spatial anomalies characterized by small, discontinuous zones. In contrast, the MIF approach adjusts parameter weights based on their relative influence, enabling a more coherent representation of hydrogeological interactions. This results in a more homogeneous spatial distribution, thereby enhancing the interpretability of vulnerability maps and strengthening their applicability for spatial planning and zoning.

The expansion of high vulnerability areas in the MIF-DRASTIC- model reflects increased sensitivity to key controlling parameters. The influence-based weighting scheme emphasizes the parameters that play a dominant role in infiltration and contaminant transport processes, leading to a broader delineation of vulnerable zones. Consequently, the MIF approach appears to be more effective in capturing complex interdependencies among hydrogeological factors that are not fully represented within the conventional weighting framework, particularly in areas characterized by conditions that facilitate rapid contaminant migration.

Consistent spatial patterns of low vulnerability zones across both models indicate strong environmental controls on the aquifer system's natural protective capacity. These zones remain geographically stable despite variations in weighting schemes, suggesting that dominant factors—such as deeper groundwater levels or less favorable topographic conditions for infiltration—exert a persistent and overriding influence. This stability enhances confidence in the reliability of the modeling results and confirms that these areas inherently possess a relatively high level of protection against potential contamination.

3.1.3 Validation of model accuracy through nitrate distribution

The comparison between nitrate distribution and MIF-DRASTIC vulnerability classes shows that areas with higher vulnerability indices generally correspond to elevated nitrate concentrations. However, the relationship remains weak-to-moderate, as indicated by the regression analysis (R^2 = 0.12–0.24), suggesting that nitrate variability is influenced not only by intrinsic aquifer vulnerability but also by variations in contaminant sources and land-use conditions. The predictive performance of both the conventional DRASTIC and the MIF-DRASTIC models can be systematically evaluated by integrating spatial overlay analysis with statistical regression between empirical nitrate data and calculated vulnerability indices.

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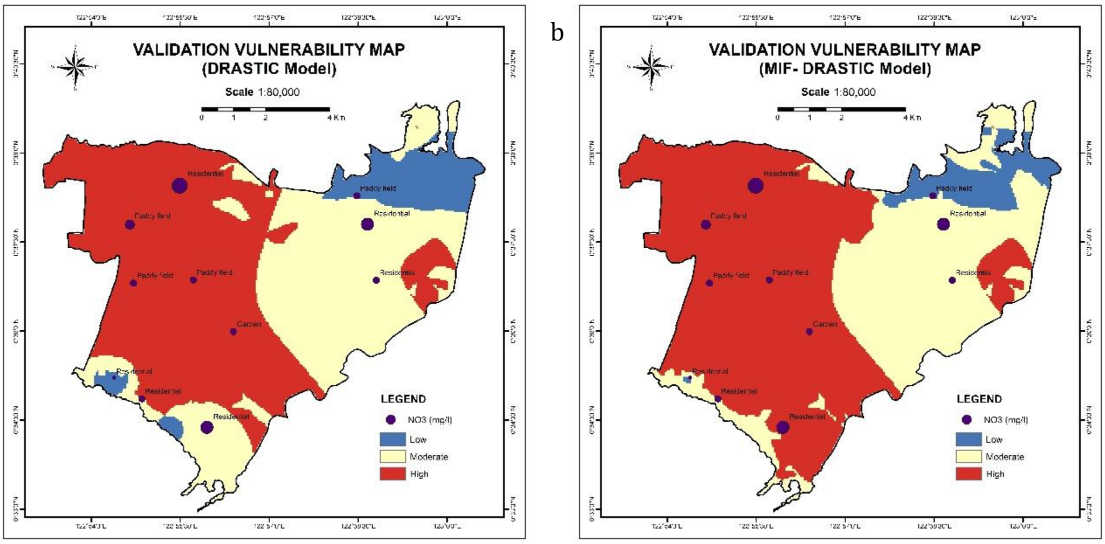

Fig. 6. (a) DRASTIC model validation; (b) MIF-DRASTIC model validation

Figure 6 displays nitrate concentration in the eleven wells of observation under each vulnerability map using the DRASTIC model (Fig. 6a) and the MIF-DRASTIC model (Fig. 6b). Nitrate sample point is illustrated as purple circular symbols, with the diameter size represents the measured concentration at specific land-use locations, such as residential areas, paddy fields, and garden. Several large-diameter circles, indicating high nitrate levels, are located within the high-vulnerability zone, particularly in the northern residential areas. However, some observation points were located within moderate- to low-vulnerability zones. One of the highest nitrate concentrations falls at a site classified as having moderate vulnerability. The different vulnerability classifications resulted in one observation point being classified as moderately vulnerable under the DRASTIC model but highly vulnerable under the MIF-DRASTIC model. This observation points is a residential area with one of the highest nitrate concentration among the samples. This finding suggests that the MIF-DRASTIC model may offer a more accurate assessment of groundwater vulnerability as the higher nitrate concentration is consistent with higher level of vulnerability.

Overall, the observations show that the three highest nitrate concentrations were consistently within residential sites, represented by the largest circle size. The other observation points, whether in the other residential areas, paddy fields, or the garden, have relatively similar nitrate concentration, although some sites recorded lower concentration. This spatial alignment suggests that high-density settlements tends to exhibit higher nitrate concentrations. The presence of elevated nitrate levels within the model high-vulnerability zones confirms that the physical pathways for pollutant transport driven by shallow groundwater tables and highly permeable aquifer media are highly effective at transferring surface contaminants into the saturated zone.

The natural protective capacity of the aquifer system is consistently demonstrated in the designated low-vulnerability zones across both modelling approaches. The smallest circular symbols indicate sample locations within the blue-shaded areas, particularly in the northeastern paddy fields, indicating minimal NO_3 concentrations. This spatial consistency indicates that specific local hydrogeological factors, such as lower hydraulic conductivity or greater water table depth, effectively impede the downward percolation of agricultural pollutants. The stability of low nitrate values in these areas validates the model's ability to accurately delineate zones with robust intrinsic resistance to contamination, thereby identifying them as relatively safe regions for groundwater extraction.

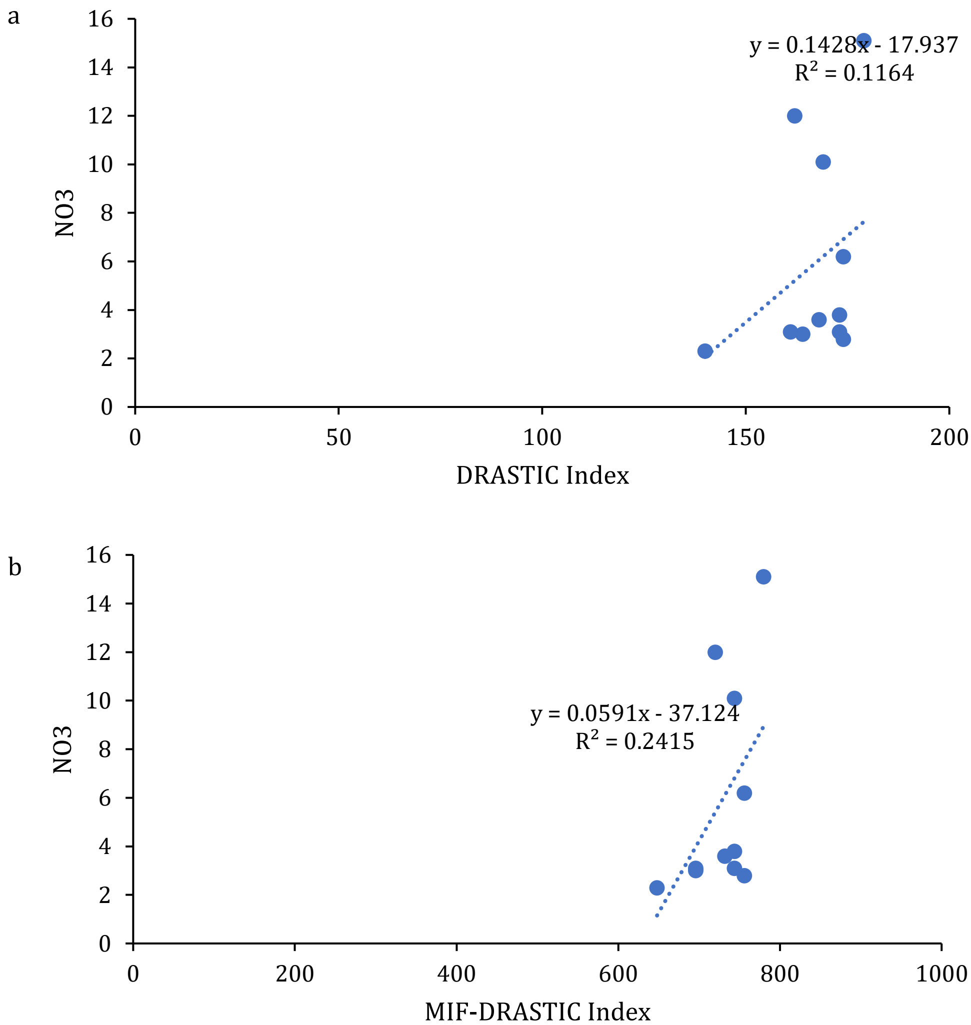

Fig. 7. (a) Linear regression of conventional DRASTIC index vs NO_3; (b) Linear regression of MIF-DRASTIC index vs NO_3

A distinct positive correlation exists between intensive surface anthropogenic activities and the underlying aquifer's hydrogeological sensitivity. The regression results of both approaches suggest that higher vulnerability index scores tend to be associated with higher nitrate concentrations. The summary of regression results are presented in Table 2. Figure 7a presents a linear regression scatter plot relating the conventional DRASTIC Index scores (x-axis) to the measured NO_3 concentrations (y-axis) to quantify this relationship. The regression line indicates a positive, albeit weak, correlation with an R^2 of 0.1164. These statistical data indicate that the conventional model explains only about 11.6% of the variance in actual nitrate contamination. Figure 7b presents the corresponding statistical validation in a linear regression plot of the MIF-DRASTIC Index scores (x-axis) versus the measured NO_3 concentrations (y-axis). The scatter plot revealed a steeper regression line and tighter clustering of data points, resulting in an improved R^2 value of 0.2415. This visualization confirms that the dynamic weighting adjustments in the MIF approach systematically enhance the statistical correlation, explaining 24.1% of the variance in field nitrate levels.

Table 2. Summary of DRASTIC vs. MIF-DRASTIC validation statistics

Statistic	Conventional DRASTIC	MIF-DRASTIC
Regression slope (β)	0.1428	0.4725
R^2 value	0.1164	0.2415
Variance explained	11.6%	24.1%
Correlation strength	Weak	Weak-to-moderate
p-value	0.000 (Significant)	0.000 (Significant)

The integration of the -MIF-method substantially improves both the spatial coherence and the statistical predictive accuracy of the vulnerability assessment. Using the spatial data, the MIF-DRASTIC model successfully consolidates scattered high-concentration points into a unified high-risk zone, eliminating the classification fragmentation observed in the conventional model. Statistically, the R^2 value increases significantly from 0.1164 in the standard model to 0.2415 in the MIF-modified model. This dual improvement proves that adjusting parameter weights based on local hydrogeological interdependencies allows the model more effectively capture the non-linear dynamics of contaminant transport. The MIF-DRASTIC framework provides a more reliable and precise scientific tool for prioritizing conservation areas and supporting risk-based spatial planning in sustainable environmental management.

3.2 Discussion

This study evaluates the groundwater vulnerability in the Limboto Alluvial Plain through the integration of the Multi-Influencing Factor (MIF) method into the DRASTIC framework to improve the accuracy of delineating the contamination risk. The results - reveal that groundwater vulnerability is distributed into three primary classes—low, moderate, and high—with high vulnerability zones predominantly located in the central to southern parts of the study area. The combination of shallow groundwater levels and highly permeable aquifer media controls this spatial distribution. Validation using nitrate (NO_3) concentration as a proxy parameter reveals a positive but weak-to-moderate spatial correlation (R2 = 0.24) between high vulnerability zones and areas with elevated nitrate concentrations, providing preliminary support for the MIF-DRASTIC model's usefulness in identifying zones most sensitive to anthropogenic contamination in alluvial environments.

Elevated vulnerability in the central and southern regions is governed by the synergistic interaction of hydrogeological parameters that facilitate rapid transport of contaminants toward the saturated zone. Very shallow groundwater depths (<1.5 m) significantly reduce the unsaturated zone thickness, thereby shortening contaminant migration pathways and limiting the effectiveness of natural attenuation processes, including filtration, adsorption, and biodegradation. The dominance of aquifer materials such as limestone, sand, and gravel, which exhibit high effective porosity and permeability, further intensifies this condition. In addition, the relatively flat topography (0–2% slope) reduces surface runoff while enhancing water infiltration into the subsurface. The combination of high hydraulic conductivity and limited vadose zone protection results in an efficient vertical percolation mechanism that accelerates the transport of contaminants into the unconfined aquifer.

The MIF-based approach demonstrated improved performance compared with the conventional DRASTIC model (Aller et al., 1987), particularly in enhancing spatial consistency and reducing classification fragmentation. The conventional model, which relies on static weighting, often produces discontinuous spatial patterns due to its limited capacity to represent inter-parameter interactions. In contrast, the MIF method adjusts parameter weights based on their relative influence, resulting in a more coherent and representative distribution of vulnerability. This finding is consistent with Dasgupta et al. (2024), who highlighted the susceptibility of traditional index-overlay methods to subjective bias. While alternative approaches, such as entropy-based weighting (Oyda et al., 2025) and hybrid models in semi-arid environments (Belalite et al., 2026; Bera et al., 2022), have been proposed, the site-specific application of MIF method in this study, established elsewhere but applied here to the Limboto Alluvial Plain, contributes through the systematic quantification of interdependencies among parameters. This approach effectively addresses the limitations of static models reported by Umar et al. (2022) and provides a more context-specific optimization of hydrogeological parameter interactions compared with the reverse MIF approach introduced by Ganwer et al. (2024).

The findings further reveal that the degradation of groundwater quality in the study area is closely associated with the intensity of anthropogenic activities. High nitrate accumulation in intrinsically vulnerable zones reflects an imbalance between surface pollutant loading and and the natural protective capacity of the hydrogeological system. Intensive agricultural practices and the expansion of residential areas contribute significantly to increased nitrogen inputs into soil and groundwater systems (Liu et al., 2025). Consequently, the spatial distribution of NO_3 concentrations represents not only current hydrogeological conditions but also the cumulative impact of long-term land management practices that have not adequately accounted for subsurface environmental sensitivity.

The identified high-vulnerability areas, particularly those associated with elevated nitrate concentrations, require greater attention in groundwater quality monitoring and contamination prevention strategies. This concern is especially relevant in areas where communities rely on shallow groundwater for domestic purposes, as shallow aquifers are generally more susceptible to surface-derived contaminants. The MIF-DRASTIC vulnerability map can therefore serve as a supporting tool for identifying priority areas for groundwater monitoring and guiding local efforts to minimize potential contamination sources through improved land and water management practices.

The vulnerability map serves as a scientifically robust tool for spatial planning and groundwater protection. The spatial information enables the identification of priority zones for aquifer protection and supports the regulation of potentially contaminating activities. However, the practical application of these findings may remain limited without integration into enforceable policy frameworks. The absence of regulatory control in high vulnerability zones may accelerate long-term groundwater degradation, posing significant risks to communities reliant on shallow groundwater resources.

Local authorities should integrate the MIF-DRASTIC vulnerability map into regional spatial planning frameworks as a strategic measure toward sustainable environmental management. Policy implementation may include the establishment of buffer zones in highly vulnerable areas, restrictions on contaminant-generating activities, and the enforcement of impermeable and effective wastewater treatment systems. In addition, data-driven agricultural nutrient management is essential to optimize nitrogen fertilizer use and reduce surface pollutant loads. Therefore, a preventive management approach based on vulnerability mapping is critical for ensuring the long-term sustainability and safety of groundwater resources.

4. Conclusions

This study developed a more accurate model of groundwater vulnerability in the Limboto Alluvial Plain by integrating Multi-Influencing Factor (MIF) techniques into the DRASTIC framework. The MIF-DRASTIC method identified several areas as highly vulnerable that were classified as having lower vulnerability under the conventional DRASTIC method. The mapping results classified the study areas into three vulnerability levels: low, medium, and high. The zone of high vulnerability is concentrated in the central to southern part, which is hydrogeologically influenced by a combination of shallow groundwater levels and high-permeability aquifer media characteristics. Empirical validation using nitrate concentration (NO_3) proxies showed reasonable spatial agreement with the model's predictions, although the accompanying regression analysis indicated only a weak-to-moderate statistical relationship (R2 = 0.24), a limitation that should be considered when interpreting the model’s predictive strength. These results indicate that the MIF-DRASTIC approach is a useful tool for identifying areas susceptible to anthropogenic contaminant infiltration, with further development could enhance its performance.

The contribution of this study lies in applying the MIF method's established ability to reduce subjectivity in weighting and to prevent the disintegration of spatial patterns commonly found in conventional DRASTIC models to the specific hydrogeological context of the Limboto Alluvial Plain. This method yields a more consistent and representative delineation of vulnerability under field conditions by dynamically quantifying interactions among hydrogeological parameters. Thus, the MIF-DRASTIC model provides a more precise basis for environmental management analysis than the static weighting approach. The integration of groundwater chemical data into the validation stage also strengthens the model's position as a conceptually and empirically tested approach in complex alluvial aquifer systems.

This study recommends that local governments integrate groundwater vulnerability maps into the regional spatial plan (*Rencana Tata Ruang Wilayah,* RTRW) policies to achieve sustainable environmental management. Strategic preventive measures include the designation of buffer zones in areas with high vulnerability, the regulation of nitrogen fertilizer application, and the enhancement of watertight sanitation infrastructure to mitigate the decline in groundwater quality. Although the developed model shows good performance, further research is recommended to integrate the dynamics of temporal land-use change and to include additional contaminant parameters to improve the predictive ability of the model in responding to dynamic environmental changes.

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Author Contribution

N.: Conceptualization, Data collection, Data curation, Formal analysis, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. Y.I.A.: Conceptualization, Analysis, Validation, Writing – review & editing. N.S.: Data collection, Conceptualization, Review & editing.

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Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

Unavailable due to ethical restrictions.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Declaration of Generative AI Use

During the preparation of this manuscript, the authors utilized ChatGPTAI to enhance grammatical accuracy, clarity, academic style, and the English translation of the text. Following the use of this tool, the authors carefully reviewed and revised the content as necessary and assumed full responsibility for the final published work.

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