

Hydrogeological Evaluation of Groundwater Vulnerability Assessment Using the DRASTIC and Pesticide DRASTIC Model: A Case Study from the Qushtapa and Shamamik Area, within Erbil Basin, Kurdistan Region, Iraq

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Abstract

Groundwater is a vital freshwater resource. Evaluating its vulnerability to contamination has emerged as a powerful tool for preventing and managing groundwater pollution. This study applied GIS-based standard DRASTIC and Pesticide DRASTIC models to the Qushtapa and Shamamik area to evaluate and delineate groundwater sensitivity zones. The DRASTIC index ranges from 74 to 130, while the Pesticide DRASTIC index ranges from 96 to 168. According to both methods, the examined area is classified into four classes: very low, low, moderate, and high vulnerability zones. The results show that the low vulnerability class for both models occupy the largest area, which is approximately 45.92% and 53.47% of the total area. Additionally, sensitivity analysis for a single parameter has shown that for DRASTIC, the vadose zone is the most effective impact parameter of the vulnerability index, while for Pesticide, the DRASTIC soil media parameter has the most impact on the vulnerability index. The models are validated with NO_3 concentration that ranges between 12-43 mg/l in Qushtapa area and 18-44 mg/l in Shamamik area. The findings show that Pesticide DRASTIC has a higher coefficient of determination R^2 of about 0.62 than DRASTIC, which is about 0.58, indicating that Pesticide DRASTIC is a more precise model for evaluating aquifer vulnerability in the study area.

Keywords:

Hydraulic Conductivity, Sensitivity Analysis, Soil Media, Nitrate.

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1. Introduction

Groundwater is a crucial naturally occurring freshwater resource that is vital for human well-being, economic growth, and ecological processes (Arya et al., 2020; Paul and Das, 2021). Groundwater pollution is a significant and escalating issue in many large urban and agricultural regions, as aquifers are naturally vulnerable to contamination from land use and human activities (Saidi et al., 2011). Erbil Basin, as part of Iraq, is similar to other arid and semi-arid areas because of its limited surface water supplies, or its unsuitability renders groundwater the sole

water supply; however, groundwater contamination has emerged as a progressively severe issue, especially in regions where fertilizers are extensively used in agriculture. Groundwater is directly threatened by numerous human activities, including overexploitation, population growth, rapid urbanization, intensive agriculture, increased food production, and alteration in land use, while indirect threats arise from seawater intrusion, global warming, and climate change (Haritash et al., 2017; Ncibi et al., 2020). Moreover, the widespread use of chemical fertilizers exacerbates the critical issue of nitrate contamination in aquifers. According to Haritash et al. (2016), Houria et al. (2020), and Kirlas et al.

(2022), the Environmental Protection Agency (EPA) of the United States uses nitrate content as an index for assessing groundwater quality degradation and defining susceptible regions. Currently, assessment of aquifer vulnerability is conducted in nearly all developed countries in regions where water resources face difficulties resulting from urbanization, industrial, and agricultural activities. The remediation of contaminated aquifers is excessively expensive and sometimes unfeasible. In this context, acknowledging the necessity for effective methods to safeguard groundwater resources against prospective contamination, resource managers and researchers have attempted to establish aquifer vulnerability evaluation methods to predict which areas are more susceptible to contamination due to surface activities. Groundwater vulnerability mapping is crucial for effectively mitigating groundwater pollution (Oke, 2020). It assesses the likelihood of groundwater contamination across various sizes and administrative tiers. DRASTIC (Aller et al., 1987) is one of the most prevalent subjective techniques employed in porous aquifers, recognized for its popularity, reliability, and extensive application as an empirical rank-based index approach. It serves as a model to spatially and comparatively illustrate areas of high vulnerability to low vulnerability concerning groundwater pollution potential (Dixon, 2005). The primary benefit of the model lies in its simplicity and adaptability across many hydrogeological contexts and pollution sources, including agricultural, urban, and industrial influences (Ahmed et al., 2015). To validate the precision of a vulnerability approach for a particular aquifer, a relationship between groundwater vulnerability values and chemical parameters is frequently employed. The predominant chemical measure utilized for validation is nitrate content since it is strongly linked to several human activities, including agricultural activities (Khosravi et al., 2018). Pesticide DRASTIC is a specialized variation of the classic DRASTIC that assesses groundwater sensitivity to a particular contaminant. In contrast to the classic DRASTIC, it employs specific parameter weight values for the factors, while the factor ratings remain the same. Saha and Alam (2014), Saida et al. (2017), and Kirlas et al. (2022) all assert that P-DRASTIC has a superior correlation coefficient, signifying its greater

appropriateness for regions characterized by agricultural practices and significant chemical fertilizer application. The study area is the Qushtapa and Shamamik area, which is part of the Erbil plain, characterized by intensive agricultural and industrial activities. It's the area within the Erbil Basin that faces the greatest water shortage and groundwater decline due to over-exploitation and land-use change, in addition to climate change. The escalating contamination of freshwater from agricultural, industrial, and urban sources in the region is causing water pollution issues in water resources to reach alarming levels. Smail and Dişli (2023) applied the original and two modified DRASTIC models to the central Erbil sub-basin. Their results showed that the depth to groundwater (D) parameter and vadose zone (I) have the most impact on groundwater vulnerability. Later, Hamed et al. (2024) applied the standard DRASTIC model focusing on a dumpsite, which is part of the central sub-basin. Their findings revealed that vadose zone (I) and aquifer media (A) parameters are the most influential factors in groundwater vulnerability. Although previous studies applied the model to significant areas within the Erbil Basin, there is still a clear gap in assessing the groundwater vulnerability in areas that practice intensive agriculture and industry and are directly influenced by the remnants of human activities.

2. Aim of Study

This study aims to assess the vulnerability of the aquifer in Qushtapa and Shamamik areas using standard DRASTIC and Pesticide DRASTIC, and to identify the effect of each factor or applied parameter on the aquifer vulnerability. To accomplish these aims, many GIS analysis and mapping frameworks are employed using the ArcMap 10.8 version to create a vulnerability map of the region. These vulnerability maps serve as key instruments to attract the attention of authorities. Groundwater pollution vulnerability maps are among the most effective tools for notifying policymakers about potential future polluting activities.

3. Materials and Methods

Study Area

The study area is situated in the Erbil basin, Iraqi Kurdistan Region. Geographically located to the south of Erbil City between latitudes (35° 43'

50° to 36° 14' 01" N) and longitudes (43° 40' 42" to 44° 17' 55" E) as shown in Fig. (1). It encompasses an area of about 1,302 km². Its climate is categorized as dry to semi-arid. The topographical variability of the Erbil Basin influences the depth of the water table (Gardi, 2017). Consequently, it exhibits fluctuating water table levels over short distances. The major geological formation outcrop units in the study area are Recent alluvium, Lower Bakhtiari (Mukdadiya), and Upper Bakhtiari (Bai Hassan) formations (Fig. 2). According to Shekhmamundy and Surdashy (2022) and Mohammed et al. (2013), the alluvium and Upper Bakhtiari (Bai Hassan) Formation are composed of conglomerate, gravel, sand and clay, while the Lower Bakhtiari (Mukdadiya) Formation is composed of thin layers of gravelly sandstone, siltstone and claystone.

DRASTIC Parameters Data

DRASTIC is an acronym representing seven important hydrogeological parameters, including: (D) depth to groundwater, (R) net recharge, (A) aquifer media, (S) soil media, (T) topography, (I) impact of vadose zone, and finally (C) hydraulic conductivity. Each parameter is allocated a weight between 1 and 5 based on its significance. The least significant parameter is assigned a weight of 1, whilst the most significant parameter is assigned a weight of 5 (Salih and Al-Manmi, 2021).

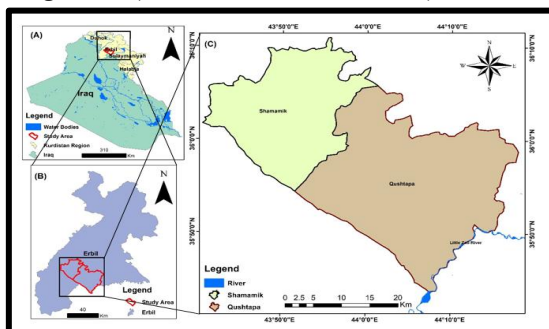


Fig. 1. Location map of the study area in Erbil Governorate.

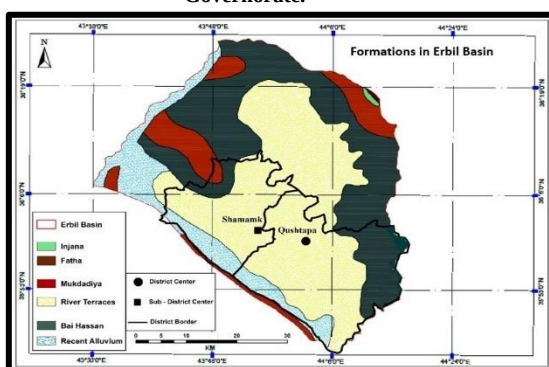


Fig. 2: Geological map of the Erbil Basin showing the study area boundary (modified after Mustafa and Mawlood, 2024).

The classic DRASTIC is applicable for regular settings, whereas the Pesticide DRASTIC is utilized in agricultural regions characterized by significant pesticide and fertilizer application, resulting in distinct weight categorization (Aller et al. 1987). Additionally, the rating of the parameters is dependent upon their relative importance for pollution potential, with ratings ranging from 1 to 10 (Table 1), where 10 indicates the greatest pollution potential, and 1 signifies the smallest pollution potential. Most parameters are assigned a single rating per range; however, some factors, such as impact of vadose zone (I), soil media (S), and aquifer media (A), get ratings informed by location-specific knowledge (Pórcel et al., 2014).

Table 1: Range/type, weight, and ratings of parameters in DRASTIC and Pesticide DRASTIC (modified from Aller et al., 1987).

Parameters	Range or Type	Rating	Standard Weight	Pesticide Weight
D	17-20	9	5	5
	20-30	8		
	30-40	7		
	40-50	6		
	50-60	5		
	60-70	4		
	70-80	3		
	80-90	2		
R	90-131	1	4	4
	3-5	1		
	5-7	3		
	7-9	5		
	9-11	8		
A	11-13	10	3	3
	Massive Shale	2		
	Metamorphic/Igneous	3		
	Weather Metamorphic/Igneous, clay with sand	4		
	Glacial till, clay with gravel	5		
	Bedded sandstone, shale sequence, massive sandstone, massive limestone	6		
	Sand	7		
	Sand and Gravel	8		

	Basalt	9		
	Karst limestone	10		
	No Shrinking Clay	1		
	Muck	2		
	Clay loam	3		
	Silty loam	4		
	Loam	5		
S	Sandy loam	6	2	5
	Shrinking Clay	7		
	Peat	8		
	Sand	9		
	Gravel	10		
	0-2	10		
	2-6	9		
T %	6-12	5	1	3
	12-18	3		
	>18	1		
	Confining layer	1		
	Silt/Clay	2		
	Shale	3		
	Limestone	4		
	Sandy Clay	5		
I	Sandstone	6	5	4
	Sand, gravel, and silt	7		
	Sand and gravel	8		
	Basalt	9		
	Karst limestone	10		
	0.04074-4.074	1		
	4.074-12.222	2		
	12.222-28.518	4	3	2
	28.518-40.74	6		
	40.74-81.48	8		
	>81.48	10		

The DRASTIC and Pesticide DRASTIC models have been implemented based on transdisciplinary data. This study utilizes a methodology consisting of the following steps:

1. Collection of raw data.
2. All DRASTIC parameters are converted into a raster layer using ArcGIS 10.8 with IDW spatial analysis interpolation. According to previous research, IDW is one of the simplest and most commonly applied techniques, and it has been effectively used in hydrogeological assessments (Chakraborty et al., 2022; Kirlas et al., 2022; Hamed et al., 2024).
3. Construction of a rating map for each parameter by reclassifying each raster based on the

rating criteria developed by Aller et al. (1987), which correspond to local conditions.

4. Preparation of vulnerability maps for each model by applying the DRASTIC standard weights, and the final index is calculated with the weighted overlay approach.

5. Conducting a sensitivity analysis to compare effective and theoretical parameter weights.

6. Validation of vulnerability maps against nitrate concentration.

The parameters are outlined as follows:

Depth to water (D)

This denotes the distance between the ground surface and the groundwater level (Witczak et al., 2014). It is determined by measuring the static water level during October 2024 from 20 wells in cooperation with the Erbil Groundwater Directorate. It is classified into 9 classes, rated from 9 to 1, from shallow to deep (Table 1 and Fig. 3). A shallow water level indicates a higher chance of pollution. The rating is conducted based on rating criteria developed by Aller et al. (1987) to reflect the local hydrogeological condition, following Sener et al. (2009), Khan and Jhariya (2019), Kirlas et al. (2022), and Hamed et al. (2024).

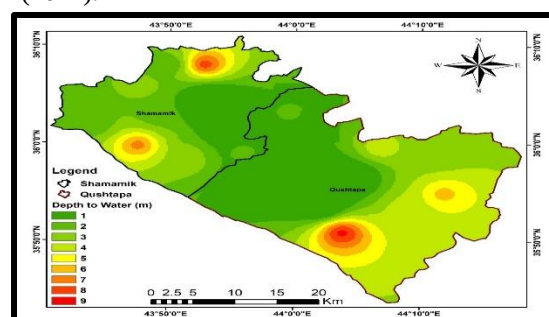


Fig. 3: Depth to groundwater rating map.

Net Recharge (R)

This denotes the volume of surface water that permeates through soil into the subsurface, ultimately reaching the aquifer system. Infiltration is crucial for the transfer of surface contaminants into groundwater. Consequently, elevated infiltration values enhance pollution potential (Aller et al., 1987). The map of this parameter is prepared by applying the Piscopo (2001) method as shown in Equation (1), which incorporates three different interpolated maps for soil permeability, rainfall, and slope.

$$\text{Recharge Value} = \text{Slope} + \text{Rainfall} + \text{Soil permeability} \dots \dots \dots (1)$$

The slope is derived from the digital elevation model (DEM) of the study area; rainfall data are estimated from a previous study for the Erbil Basin, which has an average rainfall of 467 mm/year from 2000-2020 (Hamad, 2022); and the soil permeability is determined by conducting infiltration capacity tests in 20 sites, which is moderate to high. Table 2 shows the standard values for the Piscopo method (Piscopo, 2001), whose weights are integrated with the previous interpolated maps to produce the recharge value index. The method has been applied by other researchers, including Awawdeh et al. (2015), Yankey et al. (2021), and Kirlas et al. (2022). The net recharge value for eastern and eastern-south was 6-7, and the rest was 7-9, which explains why the recharge rate was 3 and 5, respectively (Fig. 4).

Table 2: Net Recharge rating (Piscopo, 2001).

	Range	Factor
Slope %	<2	4
	2-10	3
	10-33	2
	>33	1
Rainfall mm/year	>850	4
	700-850	3
	500-700	2
	<500	1
Soil Permeability	High	5
	Moderate-High	4
	Moderate	3
	Slow	2
	Very low	1
Recharge Value	11-13	10
	9-11	8
	7-9	5
	5-7	3
	3-5	1

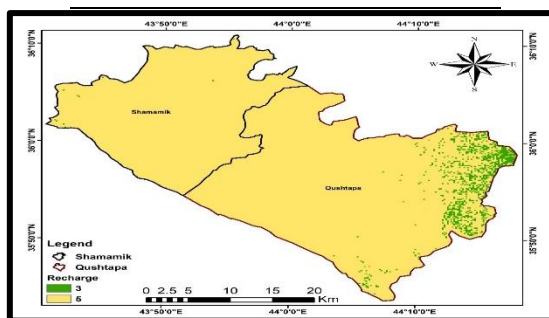


Fig. 4: Recharge rating map.

Aquifer Media (A)

This relates to the characteristics of the geological formation, including consolidated rocks and non-consolidated materials, whereby groundwater is retained inside its pores (Saha and

Alam, 2014; Zghibi et al., 2016). According to the geological profile of the wells obtained from the Erbil surrounding water directorate, the lithology of the aquifers varied from conglomerate to clay. Generally, larger grain size leads to higher vulnerability due to its higher permeability, which means gravel has higher effectiveness in groundwater vulnerability; therefore, rated 8 compared to sandy clay rated 4 (Fig. 5).

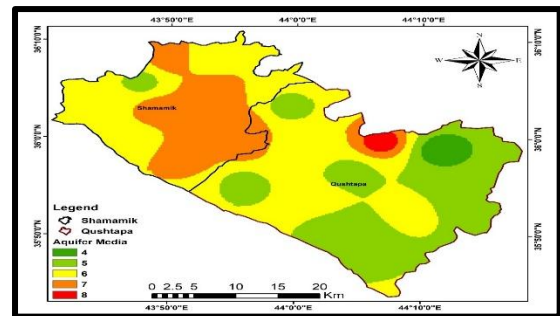


Fig. 5: Aquifer media rating map.

Soil Media (S)

This pertains to the most exposed stratum in the unsaturated zone. The soil layer can significantly influence the transport of potential contaminants (Ifediegwu and Chibuike, 2021). The soil media is detected by grain size analysis for 20 soil samples to a depth of 30 cm. Fine-textured soil is less sensitive than coarse-textured soil due to the accelerated movement of contaminants into the aquifer system. The soil media in the study area are divided into two types: areas with slightly coarse-textured soil, which is gravely silty sand, and the rest are silty sand soil. The classification of the soil is determined using GRADISTAT software based on the Folk and Ward (1957) classification. The soil is classified into two classes and rated as 7 and 8, representing gravely silty sand and silty sand soil, respectively (Fig. 6).

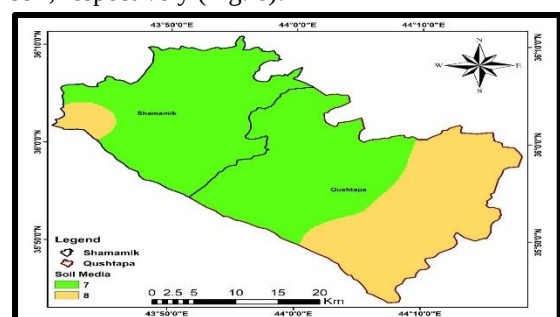


Fig. 6: Soil media rating map.

Topography (T)

This denotes the variety of land surface slope. Generally, low slope regions have increased susceptibility to groundwater contamination. The

topography is extracted from the DEM of the study area with 12.5m resolution. The slope% ranges between 0 and 43%; therefore, the topography is classified into 5 classes (Table 1). The low slope area is rated as 10, and the steep slope area is rated as 1 (Fig. 7).

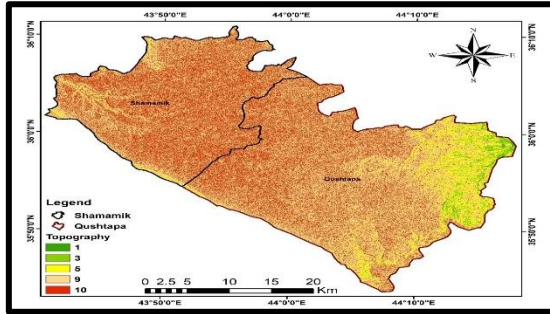


Fig. 7: Topography rating map.

Impact of Vadose Zone (I)

This refers to the distance between the soil media and the water table, representing the unsaturated zone. Similarly, as aquifer media, it is derived from the geological profile of the wells. Generally, larger grain size in materials correlates with increased susceptibility. From the geological profile of the wells, the component of this zone varies from gravel to clay; therefore, it is classified into 6 classes. The coarse-grain size materials, such as gravel, have a higher impact; that's why rated as 8, and the fine-textured material, such as clay, is rated as 3 (Fig. 8).

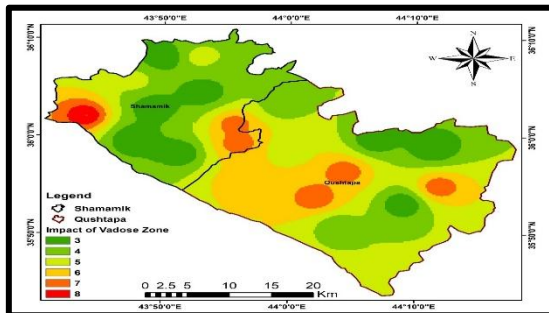


Fig. 8: Vadose Zone rating map.

Hydraulic conductivity (C)

This denotes the capacity of water-bearing formation materials to transmit groundwater. Therefore, the migration of contaminants is contingent upon this parameter (Aller et al., 1987). Decreased C indicates a lower risk of groundwater contamination, since contaminants may traverse the aquifers more slowly. In this study, the data for hydraulic conductivity are derived from the pumping test data obtained from the Erbil Surrounding Water Directorate. It varied from 0.0021 to 0.72 m/day. For all 20 wells, C is less

than 4 m/day; therefore, it is rated as 1 (Table 1 and Fig. 9).

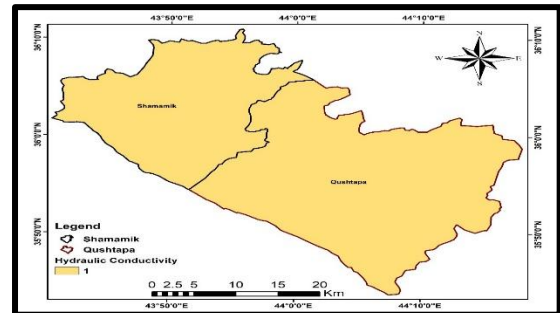


Fig. 9: Hydraulic conductivity rating map.

After generating a separate rating map for each parameter with ArcMap, by a numeric arrangement including weighting and rating, the DRASTIC Vulnerability Index (DI) value can be derived using equation (2).

$$DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \dots \dots \dots (2)$$

Where: D, R, A, S, T, I, and C stand for the seven parameters, and w and r represent the weight and rating of the parameters, respectively.

A larger DI value means greater aquifer vulnerability. The rating maps for both DRASTIC and Pesticide DRASTIC are the same since both use the same rating, and only the weights of the parameters will be different. Different DI values will be calculated for each model by inserting the theoretical weights of the parameters in Equation (2). The vulnerability values commonly vary between 23 and 230 for standard DRASTIC, as well as 26 and 256 in the Pesticide DRASTIC. Notably, based on Aller et al. (1987), there is no specific or formal categorization for vulnerability categories, and so the index is interpreted according to the relative distribution of values throughout the research area.

Sensitivity Analysis

Sensitivity analysis generally assesses the robustness and degree of uncertainty of output findings derived from multiple methodologies. The current study has used a single-parameter sensitivity test to evaluate the effect of each parameter on the last vulnerability index DI. It compares the given (theoretical) weight with the actual (effective) weight (Napolitano and Fabbri, 1996; Oke, 2020; Kirlas et al., 2022). It enables the researcher to assess the significance of subjective aspects in vulnerability methodologies (Gogu et al., 2003; Noori et al., 2019). The actual (effective)

weight for all seven parameters is derived by equation (3).

$$W = ((P_r P_w) / V) * 100 \dots\dots\dots (3)$$

Where: W denotes the actual weight of each parameter; P_r and P_w represent the rate and weight for each parameter, whereas V signifies the total vulnerability index (Ouedraogo et al., 2016).

When a parameter possesses an effective (actual) weight higher than the theoretical (given) weight, it exerts greater influence on the outcomes of the vulnerability model.

Validation Test

Validation test is a crucial process to ascertain the findings of the applied models and to choose the most suitable and reliable model for the study area (Saidi et al., 2011; Khan and Jhariya, 2019; Kirlas et al., 2022). The test employed to assess the reliability of the applicable model is the calculation of the coefficient of determination (R^2) between the DI value of DRASTIC and Pesticide DRASTIC and the Nitrate (NO_3) concentration in 20 groundwater samples in October 2024 (Table 3).

Table 3: Nitrate concentration in Qushtapa and Shamamik for validation.

Sampling Location	NO_3 (mg/l)	Sampling Location	NO_3 (mg/l)
Qucha Blbas	24	Shekh Sherwan	38
Kardiz	29	Pirdawd	18
Dushiwan	25	Helawa	44
Dola Bakra	25	Jdida lak	21
Sebiran Ado	12	Awena	41
Dolaza	15	Sorbash Hawez	18
Grda Sor	21	Beryat	19
Grd Lanka	43	Bnberz	42
Grd Mala	24	Daldaghan	19
Sherawa	39	Dhemat	23

4. Results and Discussion

Standard DRASTIC Vulnerability Map

The final DRASTIC vulnerability map (Fig. 10) for the Qushtapa and Shamamik area is produced by integrating the rating maps of all factors inside the ArcGIS environment. It is classified according to the natural breaks of the Jenks (1967) approach. Numerous researchers employed this strategy, including regional researchers (Hamed et al., 2024) and foreign investigators such as Thapa et al. (2018), Wei et al. (2021), and Krlas et al. (2022). This signifies the

method's reliability and applicability across many geographical regions. Qushtapa and Shamamik are categorized into four classes according to the DI values, which range between 74 and 130. A high DRASTIC index value signifies an increased risk level in the region. Usually, a DI value higher than 200 is regarded as very highly vulnerable (Ncibi et al., 2020). The proportions for each DI class to the total area are presented in Table (4).

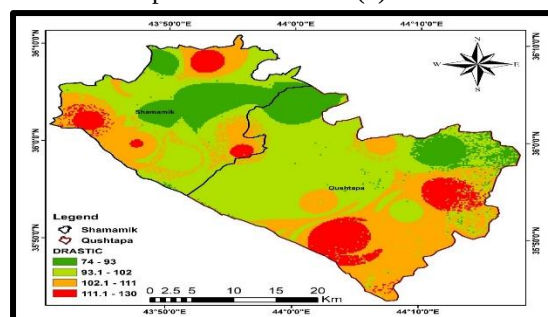


Fig. 10: DRASTIC Vulnerability map of Qushtapa and Shamamik.

The results show that the northwest and central regions of the Qushtapa and Shamamik area are characterized by elevated groundwater depth, exhibiting reduced vulnerability; similarly, locations with less permeable unsaturated zones are likewise less susceptible to contamination. Furthermore, the steep slope region, particularly the northeastern part of the research area with topography above 18%, exhibits reduced vulnerability. Regions with shallow groundwater depth and aquifer media consisting of porous materials like sand and gravel are more susceptible, particularly those with a mild slope of 2-12%.

Pesticide DRASTIC Vulnerability Map

The Pesticide DRASTIC map (Fig. 11) is also produced by integrating the rating maps of the same parameters using different weights. The region is categorized using the natural breaks of the Jenks (1967) approach, similar to a classic DRASTIC model. The area is categorized into four classes based on the DI value for the Pesticide DRASTIC map. The DI ranges between 96 and 168 and is classified into four classes. Aller et al. (1987) didn't propose an exact categorization for Pesticide DRASTIC. The proportions for each DI class to the total area are presented in Table (4). The vulnerability index (DI) value exceeding the classic or standard DRASTIC is consistent with the findings of Al-Abadi et al. (2017) and Kirlas et al. (2022).

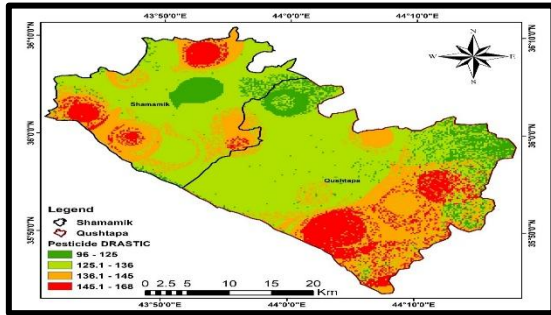


Fig. 11: Pesticide DRASTIC Vulnerability map of Qushtapa and Shamamik.

The distinction between the two produced maps lies in the fact that, for Pesticide DRASTIC, the region exhibiting low and high vulnerability classes has a broader expanse compared to the standard DRASTIC, while the categories of very low and moderate vulnerability classes occupy smaller areas. The discrepancies result from the differing weights assigned to the parameters. The sensitivity analysis is conducted to illustrate the degree of dependability. Current research has examined the influence of a single parameter.

Table 4: Classification of the study area according to Vulnerability classes.

Vulnerability Class	DRASTIC		Pesticide DRASTIC	
	DI value	Occupied Area	DI value	Occupied Area
Verv Low	74-93	15.65%	96-125	9.81%
Low	93.1-102	45.92%	125.1-136	53.47%
Moderate	102.1-111	29.16%	136.1-145	25.05%
High	111.1-130	9.27%	145.1-168	11.67%

Single parameter influence of weight-rating parameters on DRASTIC and Pesticide DRASTIC models

A sensitivity analysis using a single parameter is performed for all seven components of both models. The effective weight of the parameters in both models depends on the given theoretical weight. Babiker et al. (2005) revealed the weight and its reciprocal effect on the other parameters in each approach. The efficiency of the components in DRASTIC is presented in Table (5). The findings reveal inconsistencies between the theoretical weight and the actual effective weight identified in this study. In DRASTIC, the vadose zone (I) has the most effective weight of approximately 23.45% rather than 21.74%. This outcome is consistent with previous studies, including Şener and Şener (2015); Ouedraogo et al. (2016); Oke (2020); and Kirlas et al. (2022). The net recharge (R) and Aquifer media (A) exhibit a greater effective weight; however, they remain within the same efficiency rank. This observation

aligns with previous research, including Neshat and Pradhan (2017) and Kirlas et al. (2022). The two main parameters that dramatically indicate reduced effectiveness in weight are depth to water (D) and hydraulic conductivity (C), which demonstrate 13.07 % and 2.98 % rather than 21.73% and 13.043%, respectively. The DRASTIC result highlights the importance of the factors affecting groundwater vulnerability in the order of ($I > R > A > S > D > T > C$), as opposed to a theoretical order ($I \sim D > R > A \sim C > S > T$).

Table 5: Statistical evaluation of DRASTIC Single-Parameter sensitivity test.

Parameters	Theoretical weight	Theoretical Weight%	Mean Effective Weight	Mean Effective Weight%
D	5	21.74	3.00	13.07
R	4	17.39	4.51	19.60
A	3	13.04	4.01	17.44
S	2	8.69	3.35	14.56
T	1	4.35	2.04	8.88
I	5	21.74	5.40	23.46
C	3	13.04	0.68	2.98

On the other hand, in the Pesticide DRASTIC evaluation (Table 6), the soil media emerges as the most influential parameter, exhibiting a theoretical weight of approximately 27.7% rather than 19.23%. The second most significant parameter is topography (T), which demonstrates an effective weight of around 19.88% rather than 11.54%. The depth to groundwater (D) and hydraulic conductivity (C) parameters have a minimal impact exhibiting effective weights of around 9.75% and 1.48% respectively; in contrast to theoretical weights of 19.23% and 7.69%, instead of 19.23% and 7.69% respectively. This finding aligns with the findings of Kirlas et al. (2022). This study investigates the influence of parameters in Pesticide DRASTIC in the order of ($S > T > R > I > A > D > C$), in contrast to a theoretical order ($S > D > I > R > T > A > C$).

Table 6: Statistical evaluation of Pesticide DRASTIC Single-Parameter sensitivity test.

Parameters	Theoretical weight	Theoretical Weight%	Mean Effective Weight	Mean Effective Weight%
D	5	19.23	2.54	9.76
R	4	15.38	3.80	14.63
A	3	11.54	3.39	13.02
S	5	19.23	7.07	27.18
T	3	11.54	5.17	19.89
I	4	15.38	3.64	14.00
C	2	7.69	0.39	1.48

Validation Test

The Pearson correlation results indicate that the coefficient of determination R^2 for the standard

DRASTIC is 0.58, but for the Pesticide DRASTIC model it is 0.62 (Figs. 12 and 13). A stronger correlation with NO_3 concentration provides a more effective and accurate model of vulnerability (Kilrals et al., 2022). The results show that a Pesticide DRASTIC is superior and more precise than a standard DRASTIC model for evaluating groundwater vulnerability in the study area.

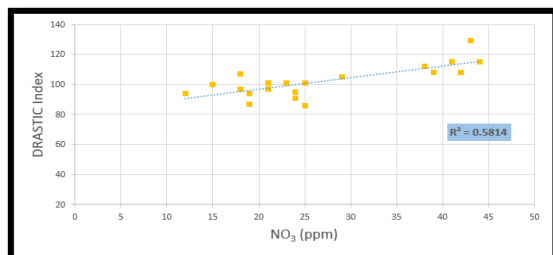


Fig. 12: Correlation of DRASTIC index with NO_3 values.

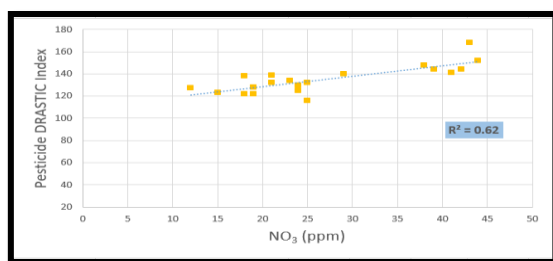


Fig. 13: Correlation of Pesticide DRASTIC index with NO_3 values.

5. Conclusion

The GIS-based DRASTIC and Pesticide DRASTIC models have been applied to assess the aquifer vulnerability in the Qushtapa and Shamamik areas. The results show that:

1. The aquifer in Qushtapa and Shamamik is situated within zones of varying vulnerability ranging from very low to high.
2. The Original DRASTIC index value ranges from 74-130, while the Pesticide DRASTIC index value ranges from 96-168.
3. The sensitivity analysis indicates that the essential vulnerability of Qushtapa and Shamamik areas for the DRASTIC model mostly arises from the vadose zone, whereas for the Pesticide DRASTIC model it mostly arises from the soil media.
4. The hydraulic conductivity parameter for both models show the least effective weight.
5. The vulnerability maps validation with nitrate concentration reveals that Pesticide

DRASTIC is a more accurate predictive method than the standard DRASTIC.

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7. Conflict of Interest

The authors declare that they have no conflict of interest.

8. Funding Statement

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9. Author Contributions

Seber M.M. Ameen: Collected the data for the study, analyzed and prepared the DRASTIC layers and maps, and prepared the first draft of the manuscript.

Rebwar N. Dara: Contributed to the research methodology, participated in fieldwork and data collection, supervised the study, and reviewed the first draft.

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التقييم الهيدروجيولوجي لقابلية تلوث المياه الجوفية باستخدام نموذج DRASTIC

ونموذج DRASTIC للمبيدات: دراسة حالة من منطقة قوشتبة وشمامك، ضمن حوض

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الملخص

المياه الجوفية مورد حيوي للمياه العذبة. وقد برز تقييم قابليتها للتلوث كأداة قوية للوقاية من تلوث المياه الجوفية وإدارته. وقد طبقت هذه الدراسة نموذجي DRASTIC ونموذج DRASTIC للمبيدات القياسيين القائمين على نظم المعلومات الجغرافية على منطقة قوشتبة وشمامك لتقييم وتحديد مناطق حساسية المياه الجوفية. يتراوح مؤشر قابلية DRASTIC للتعرض ما بين 74 و130، بينما يتراوح مؤشر قابلية DRASTIC للمبيدات ما بين 96 و168. ووفقاً لكلا الطريقتين، تم تصنيف منطقة الدراسة إلى أربع فئات: مناطق قابلية تعرض منخفضة للغاية ومنخفضة ومتوسطة وعالية. توضح النتيجة أن فئة القابلية المنخفضة للتعرض لكلا النموذجين احتلت أكبر مساحة والتي تبلغ حوالي 45.92٪ و53.47٪ من المساحة الإجمالية. بالإضافة إلى ذلك، أظهر تحليل الحساسية لمتغير واحد أن لـ DRASTIC منطقة غير مشبعة هي المتغير الأكثر فعالية لمؤشر القابلية للتعرض، بينما بالنسبة لـ DRASTIC للمبيدات الحشرية، فإن وسائط التربة هي المتغير الأكثر فعالية لمؤشر القابلية للتعرض. تم التحقق من صحة النماذج باستخدام تركيز NO_3 الذي يتراوح ما بين 12-43 مغم/لتر في منطقة قوشتبة، وبين 18-44 مغم/لتر في منطقة شمامك. أظهرت النتائج أن DRASTIC للمبيدات الآفات يظهر علاقة أعلى بنحو 0.62 من DRASTIC والتي تبلغ نحو 0.58، مما يشير إلى أن DRASTIC للمبيدات الآفات هو النموذج الأكثر دقة لتقييم ضعف طبقة المياه الجوفية في منطقة الدراسة.

الكلمات المفتاحية:

الموصلية الهيدروليكية، تحليل الحساسية، وسائط التربة، نترات.

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