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Aquifer Pollution Vulnerability Assessment in Kano, Nigeria Through Hybridization of DRASTIC Model

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Abstract: The groundwater pollution is an environmental concern, and generally the DRASTIC model is an appropriate central decision support tool. However, due to global hydrogeological variability, DRASTIC has been exposed to various modifications. This study employed various DRASTIC modification such as the single parameter sensitivity analysis (SPSA), analytic hierarchy process (AHP), frequency ratio (FR), and weight of evidence (WoE). In addition, various models were also developed through a hybrid of these methodologies. A total of fifteen approaches were realised. When the models were validated using nitrate, the correlation coefficient was found to be 0.84 for FR-AHP, 0.83 for FR-SPSA, 0.80 for AHP-SPSA, 0.79 for WoE-SPSA, 0.79 for FR-FRASTIC, 0.78 for DRASTIC-SPSA, 0.75 for FRASTIC-SPSA, 0.74 for WoE-AHP, 0.74 for DRASTIC-AHP, 0.73 for DRASTIC, 0.71 for WoE-FRASTIC, 0.68 for AHP-AHP, 0.65 for AHP- FRASTIC, 0.65 for FRASTIC, and 0.63 for FRASTIC-AHP. FR-AHP has proven the most effective approach; and when the model's vulnerability index was further classified into very low, low, medium, high and very high classes, it was found to cover 5, 16, 27, 22, and 30% of the study area, respectively. Moreover, when the average of the fifteen DRASTIC modification approaches employed was evaluated, it is found that 15% of its entire area is within very low vulnerability, 25% is low, 24% is medium, 21% is high, and 15% is very high..

Key words: DRASTIC model Sensitivity analysis Frequency ratio Analytic hierarchy process GIS

INTRODUCTION

DRASTIC model was originally introduced by the American water well association for implementation by the environmental protection agency (EPA) in assessing groundwater pollution. DRASTIC is an acronym for seven (7) geological and hydrogeological parameters adopted in the model, namely: D (depth of water), R (net recharge), A (aquifer media), S (soil media), T (topography), I (impact of the vadose zone), and C (hydraulic conductivity of the aquifer). The model was established based on Delphi technique; integrating the skills of over forty hydro-geologists, and later, developed by [4]. Protection of ground water from pollution is commonly a global political decision and the decisions are essentially aided by DRASTIC analysis [10;22;33]. Which is why the model is to date the most popular method of evaluating the intrinsic pollution vulnerability of groundwater [3;13;21;38;42;56;58;26;72]. It also gives reliable results in vast areas with a multifaceted geological structure [45].

The DRASTIC model has been exposed to various transformations of its parameters in a view to assess vulnerability of groundwater around the world [9;68;51;33;5;16;18;19;73; 2;52;59;24;75;60]. The parameters that made up the drastic may undergo modification by adding a new parameter or reducing from the prevailing ones to suit the geohydrology of a study area [32;67]. Based on area (close to 1 million km2) studied using GIS based DRASTIC, 50% is within medium to high vulnerability [27].

Sensitivity analysis (SA) was founded by [43] to help hydrologists in appraising the effect of an individual parameter vis-à-vis the weight's apportioned to it [23;48]. SA is central to achieving correct interpretation of the resulting vulnerability [48;54;58;64]. Although the weights were assigned based on the Delphi, certainly, there exists peculiarity between regions. As such the weight (theoretical) may be ineffective. The effect of weight assigned to a parameter is enormous towards achieving final vulnerability result [48;54]. Single parameter sensitivity analysis (SPSA) is most the recognized technique for SA [58; 25;46;20;31;12;48;37;63]

The analytic hierarchy process (AHP) was first recommended by [62]. It is a general system of measurement that is used to develop ratio scales from

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both discrete and continuous paired comparisons. The comparison to be paired may be sourced from actual measured data or a Delphi (consensus) process [61]. Hence, it is considered a technique for multi criteria decision making (MCDM). Successes of the AHP in solving critical decisions were reported as in [50;49;66;55;76]. A set of pair-wise comparison matrices (PCMs) was employed to study various criteria in the AHP. DRASTIC models ratings and weights can also be evaluated in the AHP process in accordance to their degree of significance in the model as reported in a study by [50;72;71;74;11].

Frequency ratio approach as a bivariate statistical analysis provides a new background in the assessment of groundwater vulnerability through calibration the ratings of the original DRASTIC parameters vis-a-vis the spatial distribution of nitrate samples and the hydrogeological parameters. The FR model is based on the observed associations between the DRASTIC parameters and nitrate distribution. Through FR model, the spatial relationships between the nitrate samples and parameters that contribute to the groundwater vulnerability map are ascertained. The FR was computed from the analysis of nitrate association and the parameters. Therefore, the FRs of each factor class or range was evaluated from their relationships with the nitrate samples [49].

Weight of Evidence (WoE) is a data driven Bayesian statistical method, in a long linear form that utilizes an identified or known occurrence of an event to generate a predictive probability from weighted evidences influencing the spatial distribution of the occurrence within a study area [78]. WoE technique is used to combine different spatial data sets in a GIS environment in a view to examining and relating their connections thereby generating predictive models [14]. It was initially employed for mineral potential mapping in places where specified mineral potentials are known [17;15] and land-slide susceptibility [47]. It has also been adopted for ecology and environmental health assessments [34;65;39]. It has been employed recently in groundwater vulnerability assessment [1; 69]

For a map to be utilized for land use management, 'it should be validated. Several methodologies exist for this purpose [77]. Nitrate is commonly for groundwater vulnerability maps validation because it is lacking in groundwater under natural condition. Hence, its presence suggests pollution susceptibility [67]. Assurance in vulnerability mapping is best achieved by comparing the outcome of different techniques and examining their reliability practically on a contaminated scenario [23]. This can be seen in a study by [33;9;36;40;57;50;49].

In this study, the generic DRASTIC as well as various modification of the models parameter, ratings and weights were employed. In addition, a hybrid of these approaches was also developed with a view to establishing the most effective groundwater vulnerability assessment methodology for the area under study.

STUDY AREA

Kano is one of the 36 states of Nigeria located in the Sudan Savannah between latitude 10o 23' 40'' and 12o 34' 24'' North, 7o 41' 15'' and 9o 21' 21'' East with a total area cover of 20,131 km2 shown in Figure 1. Its climate is seasonally arid. Rain falls between May and October with peak in August, and the mean annual rainfall is between 635 to 1000 mm.

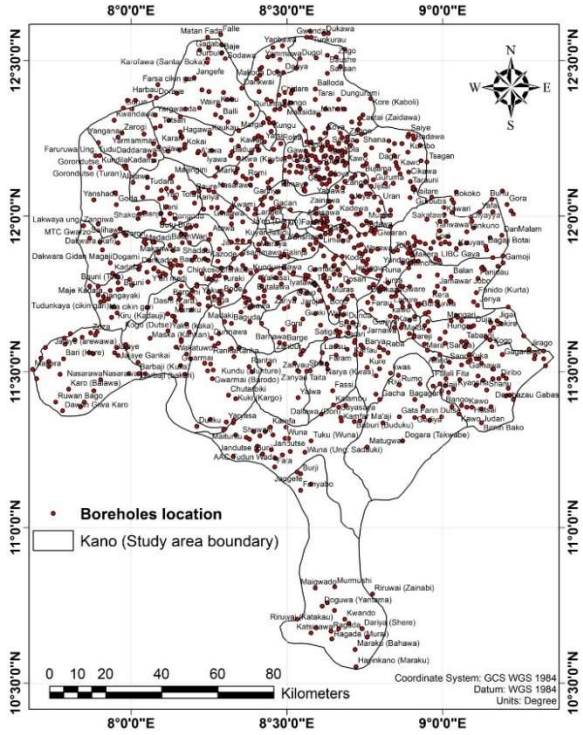


Fig. 1: Borehole locations in study area

Data sources for the model's parameters: The data used for the assessment of groundwater vulnerability are itemized below. The parameter maps for the DRASTIC and F were produced within the GIS environment using spatial analysis.

1. Well log Data (Hydro-Geological profile)} Kano Agricultural and Rural Development Authority (KNARDA (1990). Final Report: Rural Water Supply Project, Volume II - Summary of Hydro geological Data (Vol. II) WARDROP Engineering Inc.)
2. Meteorological Data: Kano state Water Board (KSWB. Technical Services Division)
3. Administrative Map of study area (Extent): Global Administrative Areas GADM (2009)
4. Chemical Parameters (Sample wells): Measured in the study area and location taken using geographical positioning system (GPS)
5. Topography: SRTM (30m) United States Geological Survey (USGS)

METHODOLOGY

Figure 2 indicates the general methodology adopted in the comparison of the groundwater vulnerability approaches and is itemized thus:

1. The standard DRASTIC methodology by (4) was employed: Since the hierarchy of the ratings and weights were established based on Delphi technique, the hierarchy was maintained in both models.
2. Modification of the DRASTIC weights using single parameter sensitivity analysis (SPSA): SPSA was conducted to ascertain contribution of each in attaining the degree of vulnerability index. New ratings were developed in accordance with the peculiar characteristics of the study area. The new ratings were made to replace the generic DRASTIC and a modified model were obtained.
3. Modification of the DRASTIC parameter: Fractures within the study area were delineated. A new parameter was developed to replace the depth to water which was characterized to be equal over the study area (i.e. parameter that contributes less to attaining the vulnerability level). Hence, FRASTIC model was obtained.
4. Development of new DRASTIC ratings and weights: Using AHP, new rates and weights were developed.
5. Modification of the DRASTIC ratings and weights: The standard DRASTIC weights/ratings were substituted with that of the new AHP ratings/weights.
6. Identification of an optimal model for Kano: This is accomplished by comparing the models with the nitrate map using Pearson's correlation coefficient.

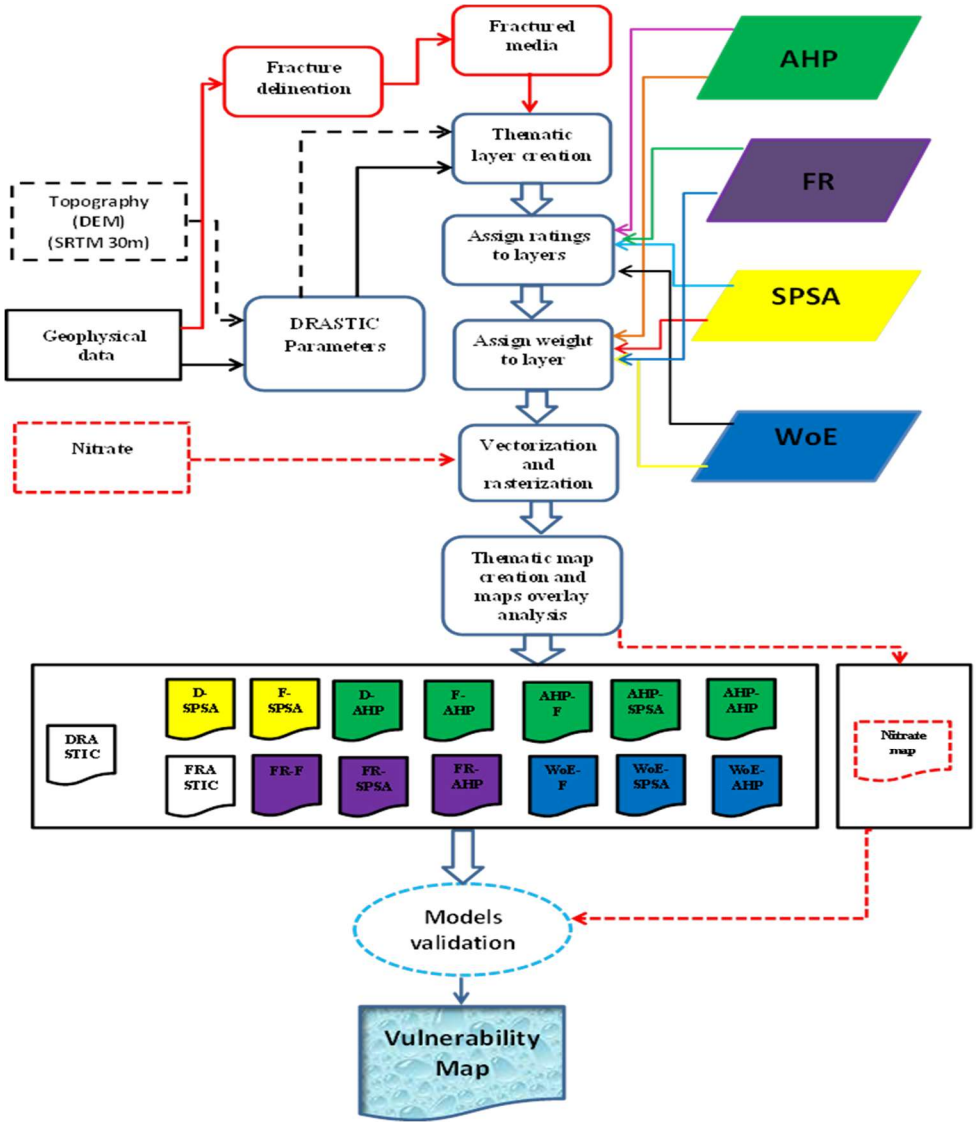


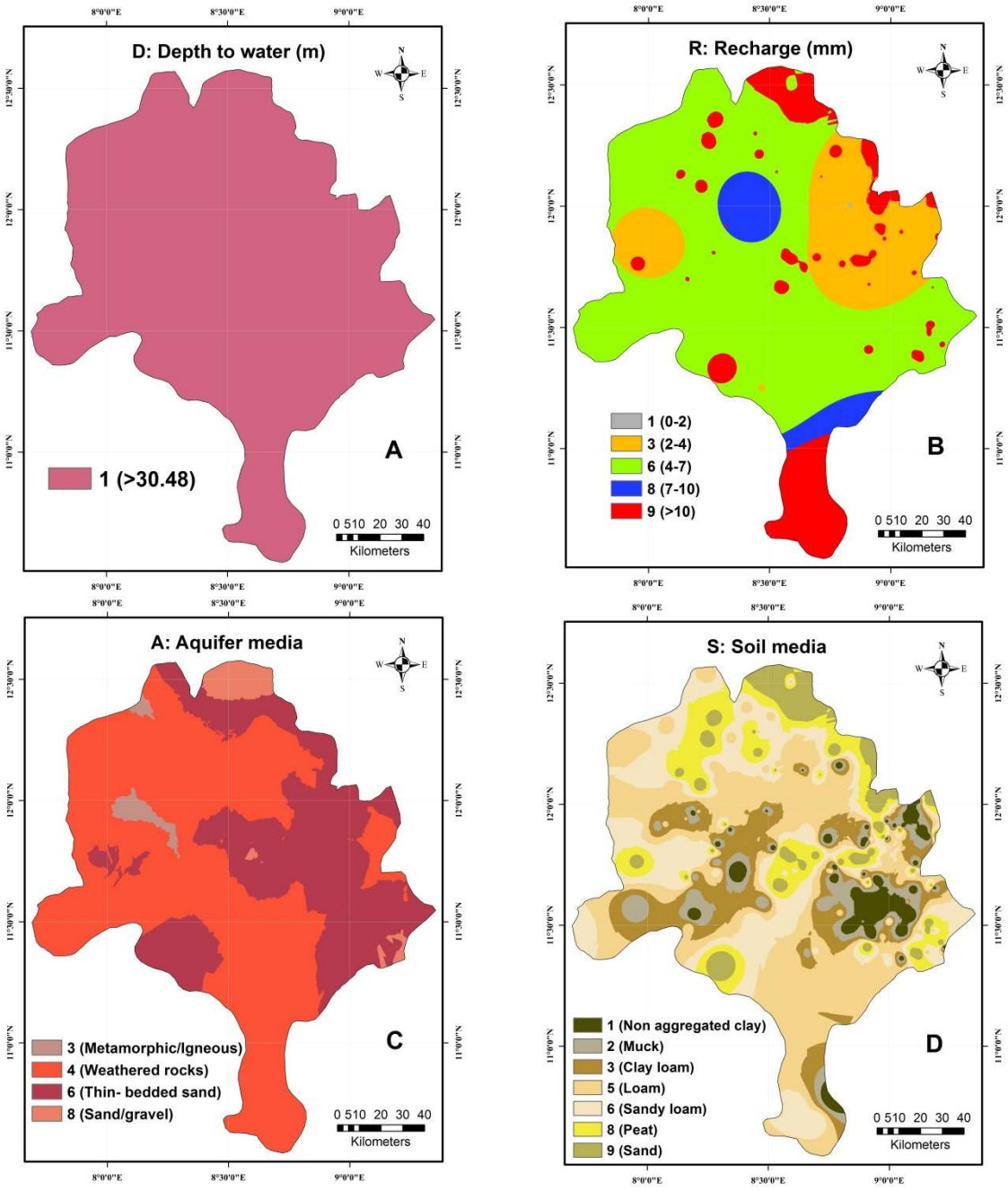
Fig 2:General methodology of the study.

DRASTIC model: Depth to water (D) is vertical distance from the ground surface to the water table. Recharge (R) is the quantity of water that penetrates over a unit area of land that consequently replenishes the groundwater. Aquifer media (A) signifies the potential attenuation characteristics of the aquifer material. Soil media (S) represents the topmost soil cover and weathered portion of the ground. Topography (T) refers to gradient or slope. Impact off vadose zone (I) is the texture of the soil medium between the water table and the unsaturated soil cover. Hydraulic conductivity (C) is the capability in which formation aquifer transmits water. Weight was assigned to each parameter in accordance with the area characteristics based on Aller et al. (1985). The Rating ranging from 1 to 10 was assigned to a parameter based on its pollution potentials, the higher the range; the greater the pollution potential.

These seven (7) parameters were interpolated in ArcGIS and the resulting thematic maps are shown in Figure 3(A, B, C, D E, F and G). Weight ranging from 1 to 5 was initially assigned to a parameter depending on its level of contribution to the pollution which was founded on the Delphi technique (Aller et al., 1985) as shown in Table 1.

Table 1: Ranges and ratings for DRASTIC parameters

DRASTIC Parameter	**Weight (W)**	**Range and Description**	**Rating (R)**	**Area Cover (%)**
Depth to water (m)	5 (21.7%)	>30.48	1	100
Recharge (inches)	4 (17.4%)	0-2	1	0.02
		2-4	3	18.95
		4-7	6	62.29
		7-10	8	5.90
		>10	9	12.84
Aquifer media	3 (13.0%)	Metamorphic/Igneous	3	1.60
		Weathered Metamorphic/Igneous	4	61.98
		Thin- bedded sand/ limestone shale	6	33.60
		Sand and Gravel	8	2.82
Soil media	2 (8.7%)	Non aggregated clay	1	4.08
		Muck	2	6.62
		Clay loam	3	14.24
		Loam	5	33.12
		Sandy Loam	6	23.25
		Peat	8	11.85
		Sand	9	6.84
Topography (Slope %)	1 (4.3%)	>18	1	0.18
		12-18	3	0.23
		6-12	5	0.71
		2-6	9	31.77
		0-2	10	67.11
Impact of vadose zone	5 (21.7%)	Silt/ Clay	1	28.88
		Shale	3	52.87
		Sandstone	4	16.28
		Metamorphic/Igneous	6	1.97
Hydraulic conductivity (m/day)	3 (13.0%)	0-4	1	91.08
		4-12	2	8.51
		12-29	4	0.39
		29-41	6	0.03
Fractured Media (m)	5	No fracture	1	65.89
		Fracture between 22.87-30.48	2	10.92
		Fracture between 15.4-22.86	4	7.66
		Fracture between 9.1-15.3	6	15.53


D: Depth to water (m)
1 (>30.48)
A
R: Recharge (mm)
1 (0-2)
3 (2-4)
6 (4-7)
8 (7-10)
9 (>10)
B
A: Aquifer media
3 (Metamorphic/Igneous)
4 (Weathered rocks)
6 (Thin- bedded sand)
8 (Sand/gravel)
C
S: Soil media
1 (Non aggregated clay)
2 (Muck)
3 (Clay loam)
5 (Loam)
6 (Sandy loam)
8 (Peat)
9 (Sand)
D
0 5 10 20 30 40
Kilometers
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9°0'0"E

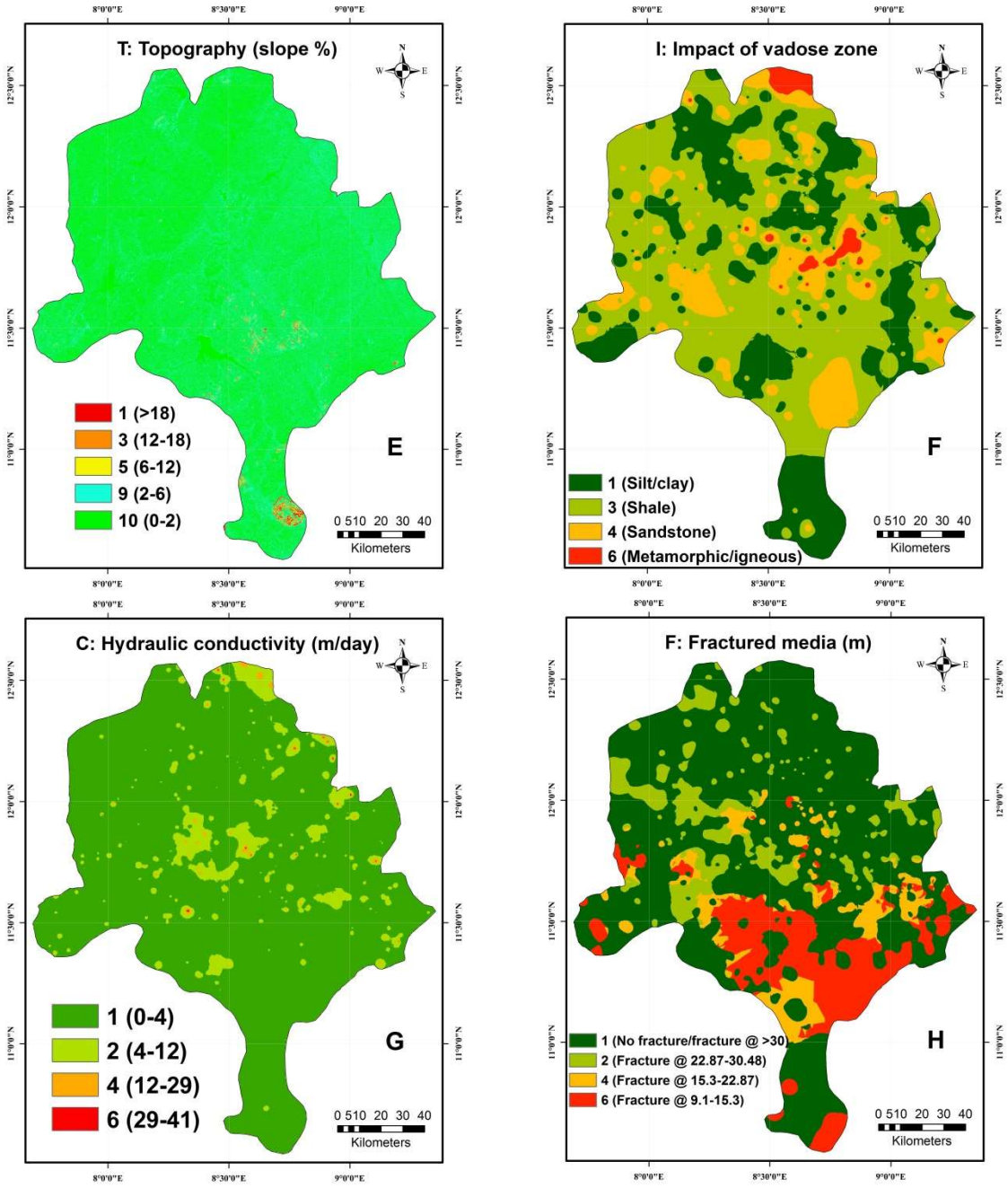


Fig. 3:Layer maps of the DRASTIC parameters

The product ratings and weights of the seven (or less) parameters made up the DRASTIC index given by Equation (1).

$$DI = \sum_{j=1}^{7}(W_j \times R_j) \quad (1)$$

where W is the weight, R is the rating while j represents the seven DRASTIC parameters.

When Equation1 was solved in the resulting DRASTIC index map is shown in Figure 4.

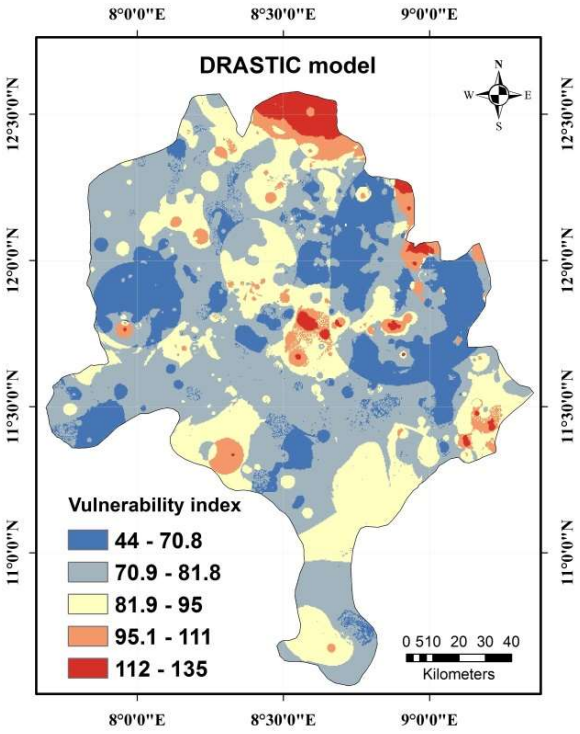


Fig. 4: General DRASTIC vulnerability index map

FRASTIC index: The 'FRASTIC Index' was obtained by replacing the Depth to water (D) [29] (Figure 3(A)) with the Fractured media (F) (Figure 3 (H) (the Fractured media was achieved by delineating the fractured zones within the study area [28] in the DRASTIC index evaluation method, while still maintaining the other 6 (R, A, S, T, I and C) parameter maps shown in Figure 3 (B, C, D, E, F and G) respectively. The choice of replacing D is based on the fact that the whole area is within the depth greater than 30.14m, hence characterized by common rating (i.e. 1)

The vulnerability index was evaluated based on Equation (1) and the resulting FRASTIC index map is shown in Figure 5.

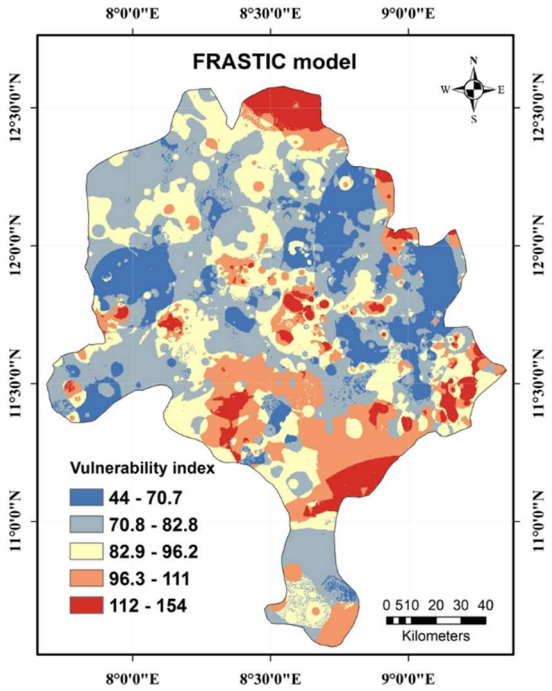


Fig. 5 FRASTIC vulnerability index pap [29]

This technique is adopted in this study to estimate, singly, the influence of the DRASTIC parameter in each pixel or grid by relating its pre-assigned or 'theoretical' weight with the computed 'real' or 'effective weight'.

Equation (2) is used for the evaluation of effective weight of a parameter within a grid or pixel in a GIS based vulnerability assessment.

$$W = (P_r P_w / V) \times 100 \quad (2)$$

where W is the "effective weight" of an individual parameter, *Pr* and *Pw* are correspondingly the rating and the weight value of each parameter and V is the general vulnerability index.

Table 2 shows the weighting of parameters based SPSA employing the generic DRASTIC method.

Similar technique was also employed in obtaining the effective weight of the parameters for the FRASTIC model. Table 3 shows the effective weight established for each parameter.

The new SPSA weights were made to replace the original DRASTIC and FRASTIC weights and further exposed to Equation (1). The vulnerability index maps obtained for the models are shown in Figure 6 (a and b), respectively.

Table 2: generic DRASTIC SPSA

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (W) (%)				
			Min	Max	Mean	SD	SPSA
D	5	21.70	3.70	11.36	6.42	0.95	**6.42**
R	4	17.4	5.33	57.14	29.62	7.20	**29.62**
A	3	13.0	9.38	37.50	18.14	4.0	**18.14**
S	2	8.70	2.22	28.57	12.94	4.44	**12.94**
T	1	4.30	1.10	20.83	12.34	2.07	**12.34**
I	5	21.70	4.39	42.25	16.34	6.46	**16.34**
C	3	13.0	2.38	24.32	4.19	1.24	**4.20**

Table 3: FRASTIC SPSA

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (W) (%)				
			Min	Max	Mean	SD	SPSA
F	5	21.70	3.70	60.00	11.67	8.47	**11.67**
R	4	17.4	5.33	56.25	27.56	7.26	**27.56**
A	3	13.0	9.30	36.73	17.16	4.26	**17.80**
S	2	8.70	1.90	27.69	12.27	4.51	**12.27**
T	1	4.30	0.88	20.83	11.33	2.30	**11.33**
I	5	21.70	3.90	42.25	15.41	6.31	**15.41**
C	3	13.0	1.90	22.28	3.96	1.24	**3.96**

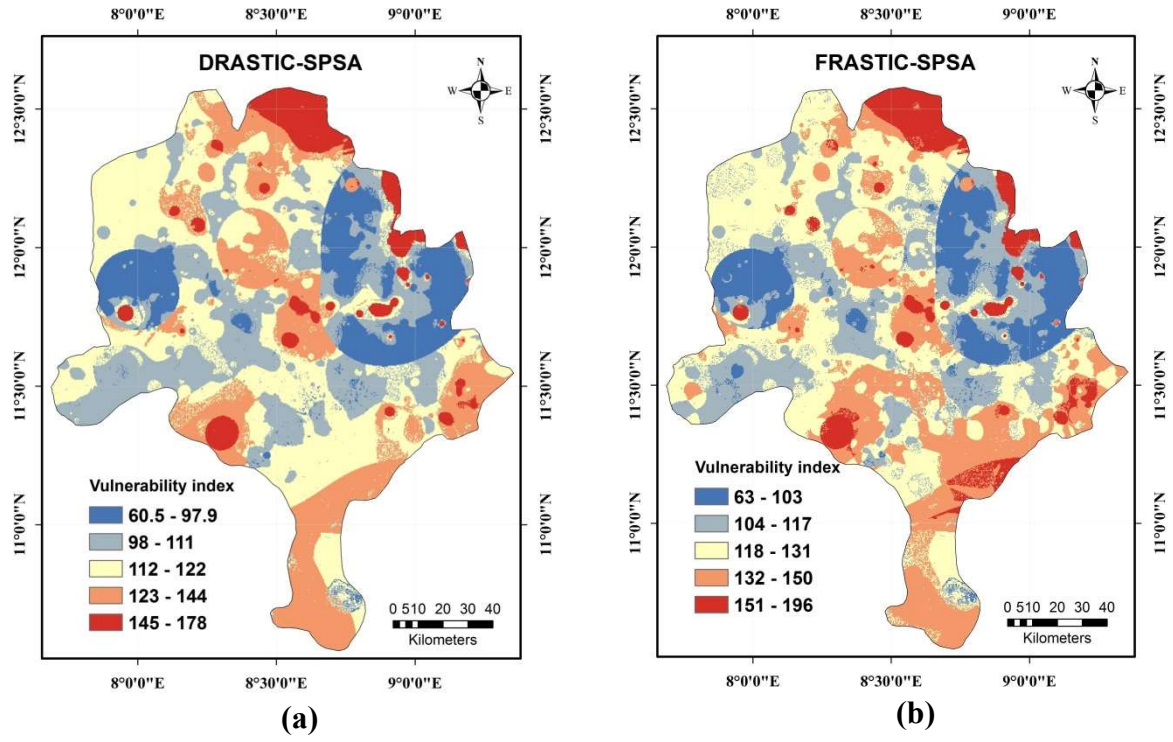


Fig. 6: (a) DRASTIC-SPSA and (b) FRASTIC-SPSA vulnerability index maps

Analytic Hierarchy Process (AHP): AHP generates weight for each parameter based on pairwise comparison of the DRASTIC parameters. The higher the obtained weight the more important the corresponding parameter. In AHP, scores are assigned to each option according to a pairwise comparison of the options based on that criterion. Higher score represents a better performance of the of the options vis-à-vis the criterion considered. The criteria weights and options scores are finally combined thereby ascertaining the global score (weighted sum of scores with respect to all criteria) for each option and resulting ranking. Results of the AHP method in Kano was carried out by [30] whereby the resulting vulnerability map is shown on Figure 7.

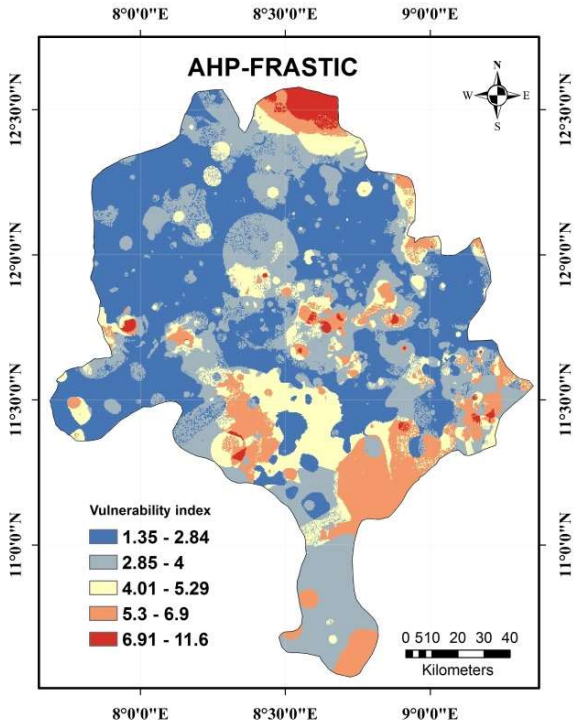


Fig. 7: AHP-FRASTIC vulnerability index map [29]

Frequency ratio (FR): Enhancing the rating scale rationality is vital for accurate groundwater vulnerability assessment results [8; 6]. In FR, the highest DRASTIC rate in an area under study was assigned a higher probability obtained using FR analysis; a relation was applied to obtain the other DRASTIC rates through adjusting the DRASTIC model rates vis-a-vis the FR approach comparison with the Wilcoxon modification, which is one of the most effective rating scale revisions [53;5].

Regions with no data have been assigned a value due to the nitrate interpolation of the collected samples as shown on Figure 14. Hence, nitrate is available in all DRASTIC layer ranges [49]. This method was adopted by [79[and the resulting map is shown on Figure 8.

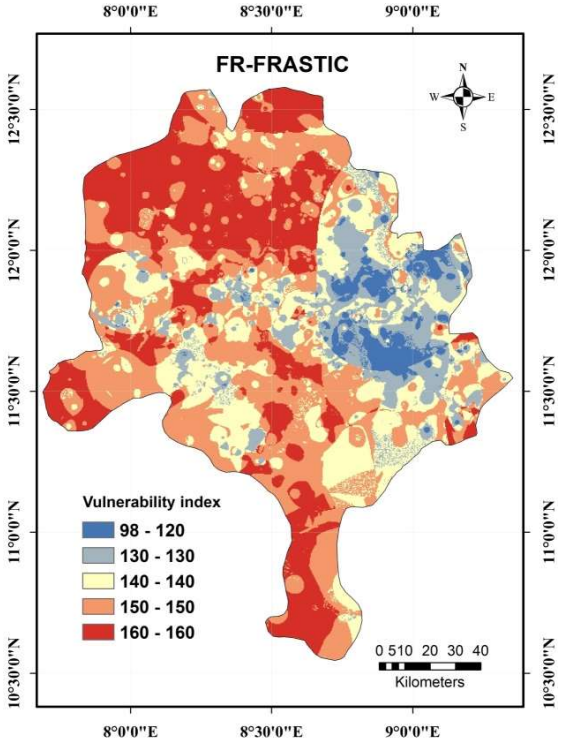


Fig. 8: FR-FRASTIC vulnerability index map [79]

Weight of evidence (WoE): WoE has been widely employed for land slide susceptibility and mineral resource assessment [70;41;15]. The application of WoE in hydrogeological studies is more recent when compared with other mentioned applications [44;7]. The WoE is employed to evaluate the relevance of each parameter range or class, thereby allowing range of values that influence the nitrate concentration to be determined. Two or more classes belonging to different factors having strong correlation with the nitrate can be combined [44].

The WoE is Bayesian statistical theorem. If a casual factor is denoted by B, the class or ranges in it are B_i and the supporting evidence is represented by s, Bayesian theorem can be employed to determine the conditional probability of having s given the class B_i based on Equation 3.

$$P(s|B_i) = \{P(B_i|s) \times P(s)\}/P(B_i) \quad (3)$$

where: $P(s|B_i)$ is the conditional probability to have B_i, given *s*; *P(s)* is the prior probability to find s within the study area (AS); $P(B_i)$ is the prior probability to find the class B_i within the study area AS.

The conditional probability to have s when the class B_i is not given is given by Equation 4.

$$P(s|\bar{B}_i) = \{P(\bar{B}_i|s) \times P(s)\}/P(\bar{B}_i) \quad (4)$$

where: $P(s|\bar{B}_i)$ is the conditional probability NOT to have B_i, given *s*; *P(s)* is the prior probability to find *s* within the study area (AS); $P(B_i)$ is the prior probability NOT to have the class B_i within the study area AS.

$$P(S) = area\ s/area\ AS \quad (5)$$

$$P(B_i) = area\ B_i / area\ AS \quad (6)$$
$$P(\bar{B}_i) = area\ \bar{B}_i / area\ AS \quad (7)$$
$$P(s|B_i) = (area\ s\ \cap B_i / area\ B_i)/P(B_i) \quad (8)$$
$$P(B_i|s) = (area\ s\ \cap B_i / area\ B_i)/P(s) \quad (9)$$
$$P(s|\bar{B}_i) = (area\ s\ \cap \bar{B}_i / area\ \bar{B}_i)/P(\bar{B}_i) \quad (10)$$
$$P(\bar{B}_i|s) = (area\ s\ \cap \bar{B}_i / area\ \bar{B}_i)/P(s) \quad (11)$$

In WoE analysis, the casual factor of each class weight is evaluated by combining positive (W^+) and negative (W^-) correlation values and by the difference or 'contrast' C between them thus:

$$W^+ = \ln\{P(B_i|s)/P(B_i)\} \quad (12)$$
$$W^- = \ln\{P(\bar{B}_i|s)/P(\bar{B}_i)\} \quad (13)$$
$$C = W^+ - W^- \quad (14)$$

$W^+ and\ W^-$ are zero (0) such that C=0 where a map pattern has a distribution that is spatially independent of the points; C is positive when there is positive spatial association (usually from 0-2) and C is negative for negative spatial association.

The standard deviation of W is calculated using Equation 15:

$$S(C) = \sqrt{S^2W^+ + S^2W^-} \quad (15)$$

Where $S(W^+)$ is the variance of positive weights, and $S(W^-)$ is the variance of negative weights.

The variance of weights is evaluated using Equation 16:

$$S^2W^+ = (1/(area\ s\ \cap B_i + 1/(area\ B_i - area\ s\ \cap B_i)) \quad (16)$$

$$S^2W^- = (1/(area\ s\ \cap \bar{B}_i + 1/(area\ \bar{B}_i - area\ s\ \cap \bar{B}_i)) \quad (17)$$

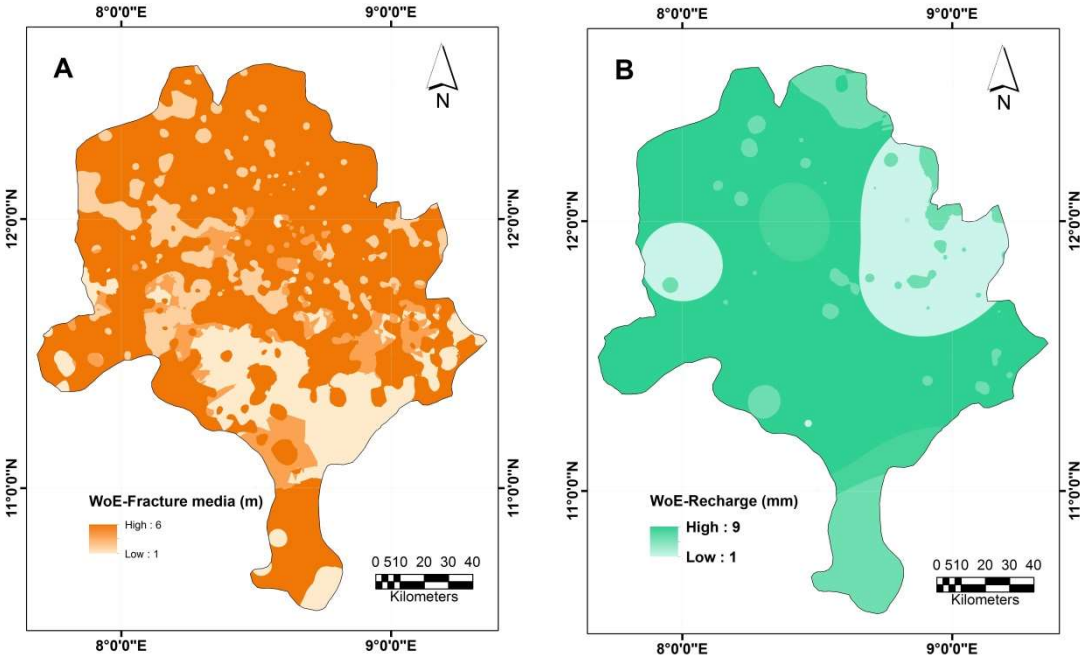
The normalized contrast or 'studentized contrast which is the measure of certainty with which a contrast value is known is obtained by using Equation 18

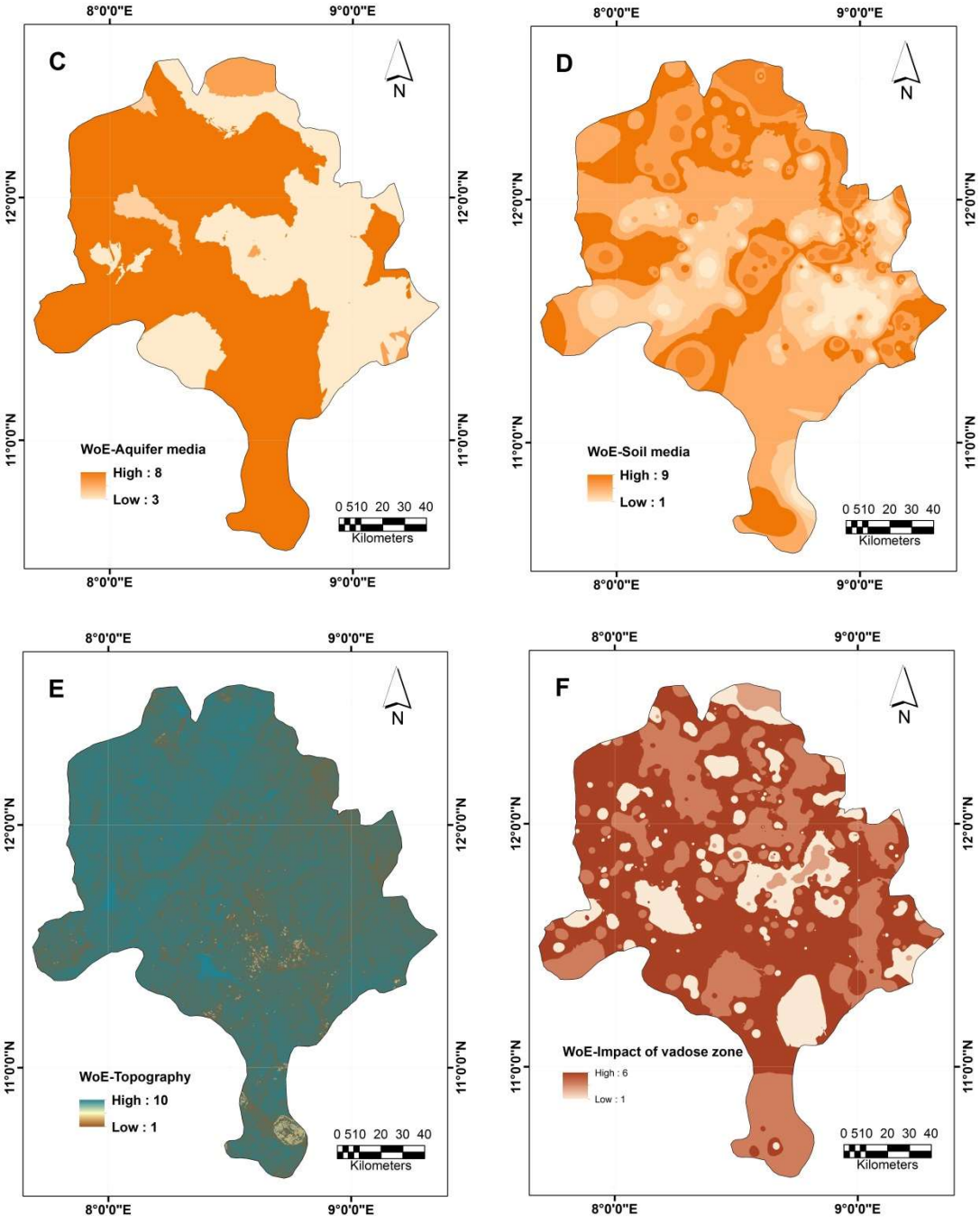
$$C/S(C) \quad (18)$$

The statistical significance of each class is designated by the magnitude of the studentized contrast.

In assigning the rank vis-à-vis the studentized contrast in this study, the DRASTIC ratings were maintained, however the ranking was in accordance with the evaluated contrast (studentized) (Table 4). The new WoE ratings obtained for the DRASTIC parameters are shown on Figure 9 (A-G).

Therefore, in a view to achieve the standardization based on the suggested classification (i.e. very low, low, medium, high and very high), the FRASTIC index map being the final outcome on which any decision is to be taken was further reclassified to comply with the suggested standard quantile classification using the 'Reclassify' spatial analyst tool. The vulnerability map obtained when the new WoE rating is shown on Figure 10.




C
N
WoE-Aquifer media
High : 8
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Kilometers
D
WoE-Soil media
High : 9
Low : 1
E
WoE-Topography
High : 10
Low : 1
F
WoE-Impact of vadose zone
High : 6
Low : 1
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11°0'0"N

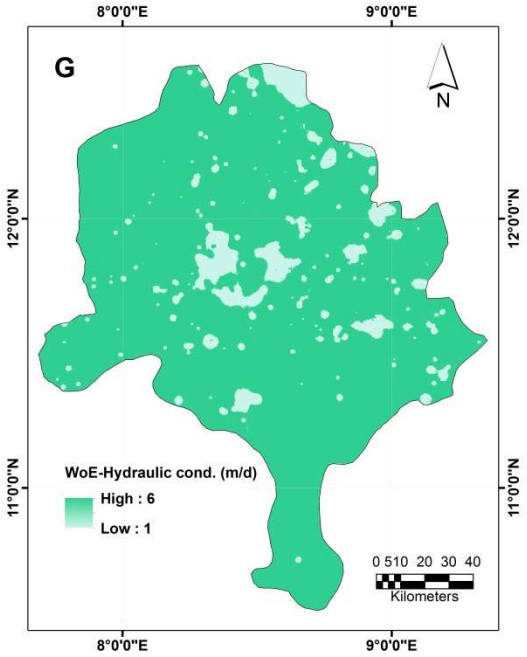


Fig. 9: Modified DRASTIC ratings using WoE approach

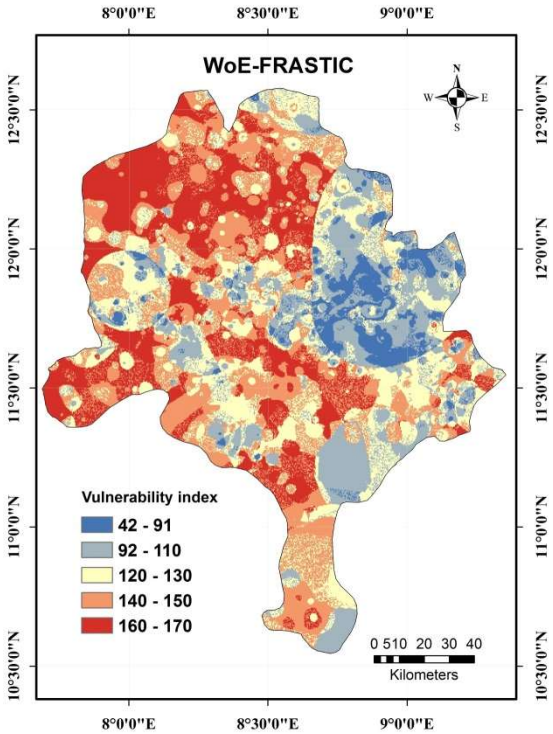


Fig. 10: WoE-FRASTIC vulnerability index map

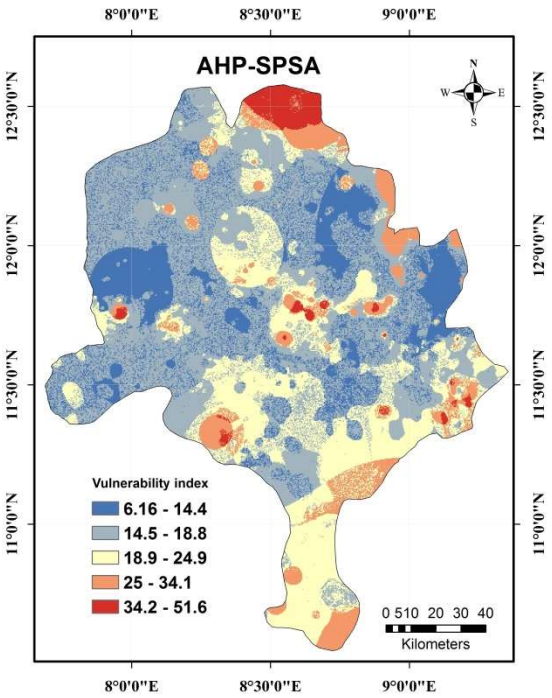
Table 4: Original and modified ratings using WoE method

Parameter	Rating	Concentration of nitrate (>=7mg/l) Occurrence					Concentration of nitrate (>=7mg/l) Non-occurrence					Weight of Evidence							WOE Rating
		$area\ B_i$	$P(B_i)$ (a)	$s \cap B_i$	$P(B_i\|s)$ (b)	D= b/a	$area\ \bar{B}_i$	$P(\bar{B}_i)$ (e)	$s \cap \bar{B}_i$	$P(\bar{B}_i\|s)$ (f)	G= e/f	W^+ = InD	W^- = InG	C	$S^2(W^+)$	$S^2(W^-)$	S(C)	C/S(C)	
Fracture media	1	12194070	65.89	7352852	70.89	1.08	6311821	34.11	3018970	29.11	0.85	0.07	-0.16	0.231647	0.00000034	0.00000063	0.000989	234.2993	6
	2	2021455	10.92	1011582	9.75	0.89	16484436	89.08	9360240	90.25	1.01	-0.11	0.01	-0.12636	0.00000198	0.00000025	0.001492	-84.6909	2
	4	1416710	7.66	781783	7.54	0.98	17089181	92.34	9590039	92.46	1.00	-0.02	0.00	-0.01679	0.00000285	0.00000024	0.001758	-9.55151	4
	6	2873656	15.53	1225605	11.82	0.76	15632235	84.47	9146217	88.18	1.04	-0.27	0.04	-0.31616	0.00000142	0.00000026	0.001299	-243.47	1
Recharge	1	3229	0.02	0	0.00	0.00	18502662	99.98	10371822	100.	1.00	0.00	0.00	-0.00017	0.00000000	0.00000022	0.000468	-0.37254	3
	3	3507456	18.95	1357783	13.09	0.69	14998435	81.05	9014039	86.91	1.07	-0.37	0.07	-0.43988	0.00000120	0.00000028	0.001216	-361.609	1
	6	11526740	62.29	6883931	66.37	1.07	6979151	37.71	3487891	33.63	0.89	0.06	-0.11	0.17815	0.00000036	0.00000057	0.000966	184.3582	9
	8	1092768	5.90	752031	7.25	1.23	17413123	94.10	9619791	92.75	0.99	0.21	-0.01	0.21971	0.00000426	0.00000023	0.002121	103.6089	8
	9	2375698	12.84	1378077	13.29	1.03	16130193	87.16	8993745	86.71	0.99	0.03	-0.01	0.039561	0.00000173	0.00000025	0.001407	28.11961	6
Aquifer media	3	295931	1.60	231113	2.23	1.39	18209960	98.40	10140709	97.77	0.99	0.33	-0.01	0.338191	0.00001975	0.00000022	0.00447	75.66492	4
	4	11470282	61.98	7529161	72.59	1.17	7035609	38.02	2842661	27.41	0.72	0.16	-0.33	0.485268	0.00000039	0.00000059	0.000988	490.9891	8
	6	6217214	33.60	2181837	21.04	0.63	12288677	66.40	8189985	78.96	1.19	-0.47	0.17	-0.64139	0.00000071	0.00000037	0.001035	-619.412	3
	8	522464	2.82	429711	4.14	1.47	17983427	97.18	9942111	95.86	0.99	0.38	-0.01	0.397228	0.00001311	0.00000022	0.003651	108.7851	6
Soil media	1	754558	4.08	77346	0.75	0.18	17751333	95.92	10294476	99.25	1.03	-1.70	0.03	-1.73299	0.00001441	0.00000023	0.003826	-452.974	1
	2	1224371	6.62	334168	3.22	0.49	17281520	93.38	10037654	96.78	1.04	-0.72	0.04	-0.75524	0.00000412	0.00000024	0.002087	-361.966	2
	3	2635034	14.24	1059455	10.21	0.72	15870857	85.76	9312367	89.79	1.05	-0.33	0.05	-0.378	0.00000158	0.00000026	0.001356	-278.785	3
	5	6129820	33.12	3462494	33.38	1.01	12376071	66.88	6909328	66.62	1.00	0.01	0.00	0.011716	0.00000066	0.00000033	0.000996	11.76709	5
	6	4302556	23.25	3222180	31.07	1.34	14203335	76.75	7149642	68.93	0.90	0.29	-0.11	0.397263	0.00000124	0.00000028	0.001232	322.479	9
	8	2192831	11.85	1375619	13.26	1.12	16313060	88.15	8996203	86.74	0.98	0.11	-0.02	0.128874	0.00000195	0.00000025	0.001483	86.9174	6
	9	1266721	6.84	840560	8.10	1.18	17239170	93.16	9531262	91.90	0.99	0.17	-0.01	0.182488	0.00000354	0.00000023	0.001942	93.97547	8
Topography	1	33003	0.18	7654	0.07	0.41	18472888	99.82	10364168	99.93	1.00	-0.88	0.00	-0.88342	0.00017010	0.00000022	0.013051	-67.6916	3
	3	43266	0.23	12660	0.12	0.52	18462625	99.77	10359162	99.88	1.00	-0.65	0.00	-0.65104	0.00011166	0.00000022	0.010577	-61.5501	5
	5	130791	0.71	58709	0.57	0.80	18375100	99.29	10313113	99.43	1.00	-0.22	0.00	-0.22343	0.00003091	0.00000022	0.005579	-40.0466	9
	9	5879108	31.77	3108828	29.97	0.94	12626783	68.23	7262994	70.03	1.03	-0.06	0.03	-0.08413	0.00000068	0.00000032	0.001003	-83.8483	1
	10	12419723	67.11	7183971	69.26	1.03	6086168	32.89	3187851	30.74	0.93	0.03	-0.07	0.099238	0.00000033	0.00000066	0.000994	99.79294	10
Impact of vadose zone	1	5345153	28.88	3140226	30.28	1.05	13160738	71.12	7231596	69.72	0.98	0.05	-0.02	0.066883	0.00000077	0.00000031	0.001039	64.39029	4
	3	9784009	52.87	5686133	54.82	1.04	8721882	47.13	4685689	45.18	0.96	0.04	-0.04	0.078603	0.00000042	0.00000046	0.000939	83.74038	6
	4	3011978	16.28	1347004	12.99	0.80	15493913	83.72	9024818	87.01	1.04	-0.23	0.04	-0.26425	0.00000134	0.00000027	0.001268	-208.359	1
	6	364751	1.97	198459	1.91	0.97	18141140	98.03	10173363	98.09	1.00	-0.03	0.00	-0.03022	0.00001105	0.00000022	0.003358	-9.00029	3
Hydraulic Conductivity	1	16833000	90.96	9640979	92.95	1.02	1672891	9.04	730843	7.05	0.78	0.02	-0.25	0.270791	0.00000024	0.00000243	0.001635	165.642	6
	2	1572070	8.49	682070	6.58	0.77	16933821	91.51	9689752	93.42	1.02	-0.26	0.02	-0.27677	0.00000259	0.00000024	0.001683	-164.496	1
	4	72210	0.39	39227	0.38	0.97	18433681	99.61	10332595	99.62	1.00	-0.03	0.00	-0.03134	0.00005581	0.00000022	0.007485	-4.18644	2
	6	5100	0.03	3200	0.03	1.12	18500791	99.97	10368622	99.97	1.00	0.11	0.00	0.11294	0.00083882	0.00000022	0.028966	3.899027	4

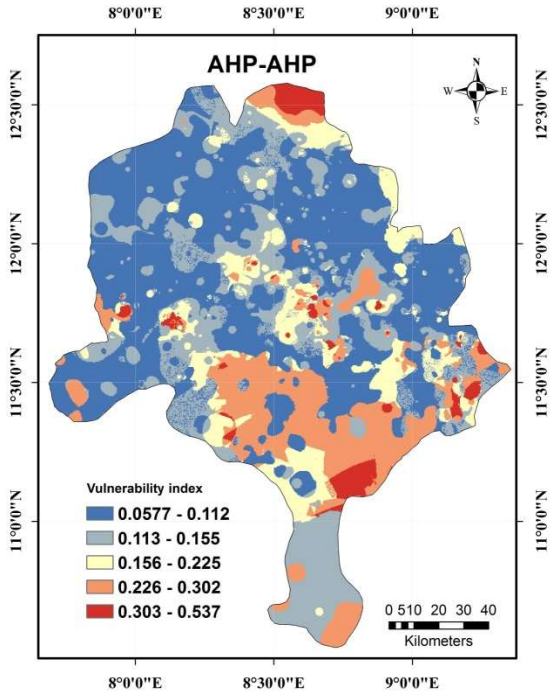
Note: D is not feasible with WoE approach due to the fact that the entire study area has a common rating (*i.e.* 1).

Hybridisation of models: The new ratings developed using the AHP, SPSA, FR, and WOE methods were made to replace the DRASTIC theoretical ratings. This is achieved using the 'Reclassify' Spatial Analyst Tool.

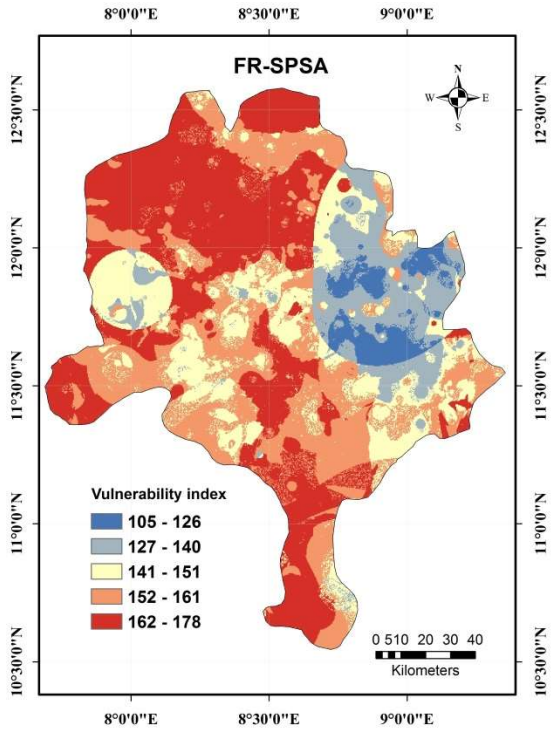
Figure 11 (A-G) shows the parameter rating maps of AHP-SPSA, AHP-AHP, FRASTIC-AHP, FR-SPSA, FR-AHP, WOE-SPSA, WOE-AHP models that were developed using various methods of rating.



(a)



(b)



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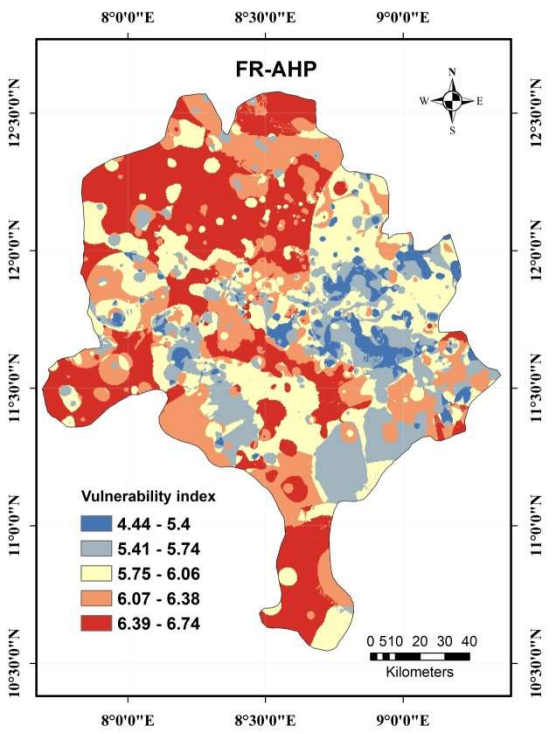
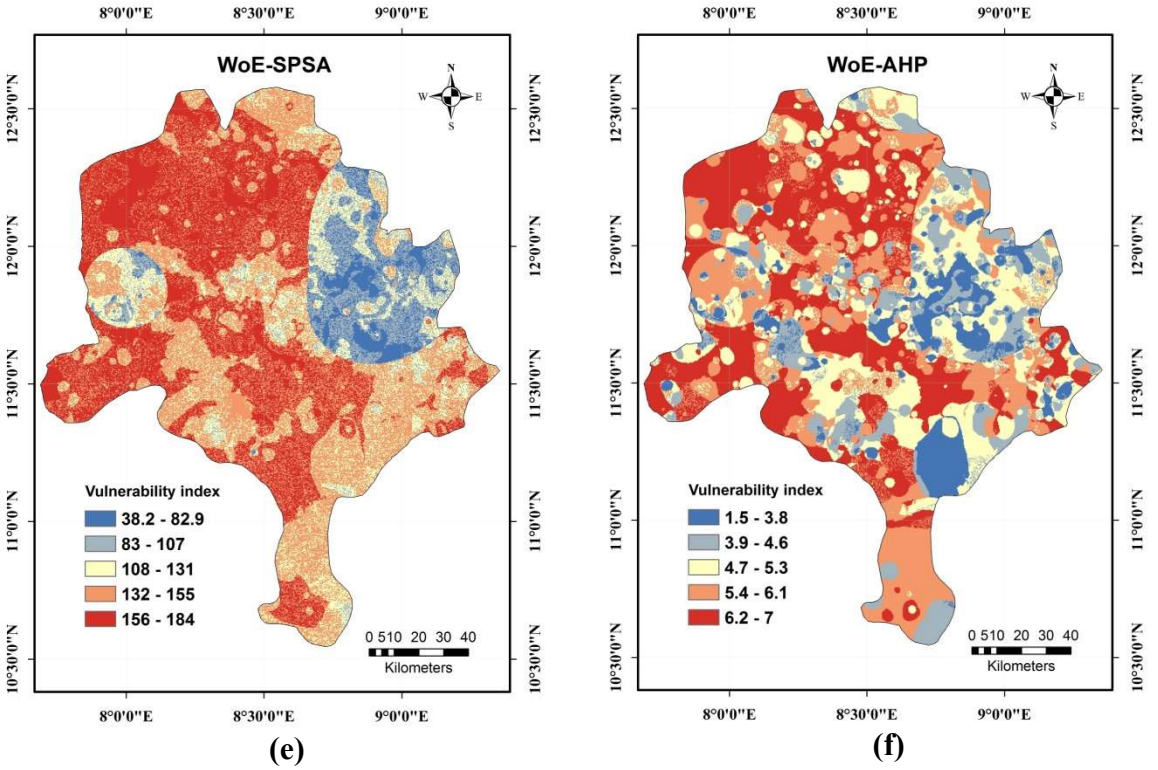


(d)



(e) (f)

Fig. 11: Hybrid vulnerability index map

Models' Comparative Analysis: Figure 12 shows the vulnerable area coverage when the vulnerability index for each model is divided into 5 equal classes (i.e. very low, low, medium, high, and very high). It has shown that AHP-AHP model recorded highest area coverage for 'very low' (44.29%) while D-AHP indicated the least area coverage of 6.17%. Generic DRASTIC recorded highest low class vulnerability area coverage of 45.86% as FRASTIC-SPSA recorded the least (23.22%). As for medium vulnerability area coverage the maximum is seen on DRASTIC-AHP (43.88%) and the minimum on AHP-AHP (11.76%).

For high vulnerability class area cover, FRASTIC-AHP has the highest (22.59%) while the least record is that by DRASTIC (5.24%).

The maximum area coverage according to very high vulnerability class is that attained in F-AHP model (13.77%) and the minimum is that of AHP-FRASTIC (1.76%).

When the average record for all the 5 classes of vulnerability in all the fifteen (15) models were taken, it was found that very low is 15%, low is 25%, medium is 24%, high is 21% and very high is 15% as shown in Figure 13.

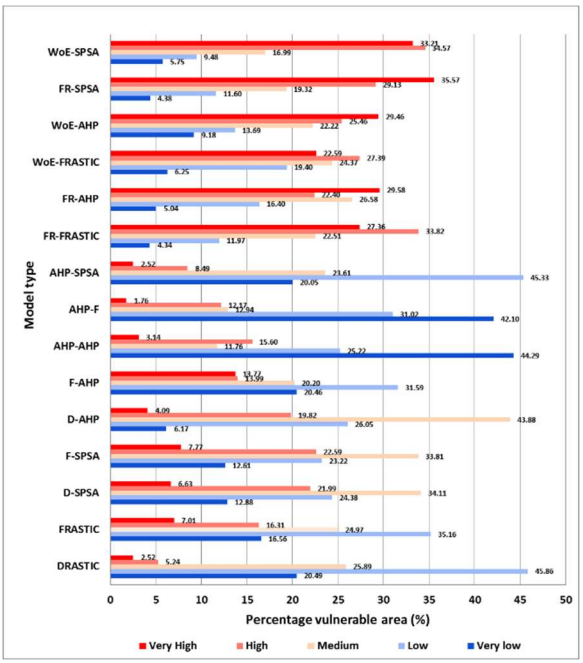


Fig. 12: Percent vulnerable area coverage for each model

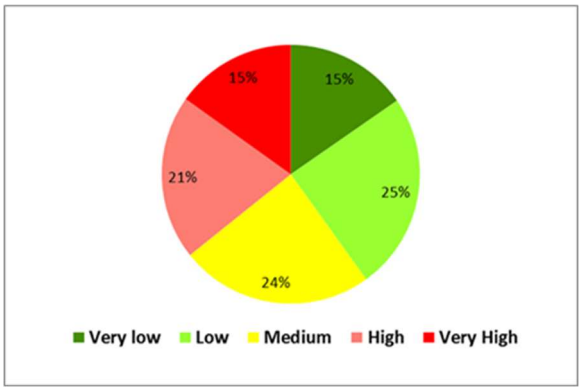


Fig. 13: Average vulnerable area coverage on 15 models

It has been established that when DRASTIC model is modified the validity of the model is usually enhanced. Furthermore, a hybrid of different approached often yields better and promising results.

This is evident in some studies carried out as shown in Table 5.

Table 5: Comparison of vulnerability index percentage area coverage for various studies

Percentage vulnerable class area cover of model adopted								
Model type	**VL**	**L**	**M**	**H**	**VH**	**NVC**	**City/ counrtry**	**Reference**
DRASTIC	5.75	13.34	30.81	44.29	5.8	0.37	Kerman plain, Iran	[50]
AHP-DRASTIC	8.49	22.99	13.87	20.59	34.06	0.45	Kerman plain, Iran	[50]
M/DRASTIC-AHP	17.65	11.5	37.28	27.52	6.05	0.65	Kerman plain, Iran	[50]
DRASTIC-AHP	11.88	24.24	32.58	24.3	7.09	0.81	Kerman plain, Iran	[50]
AHP-AHP	19.63	17.88	21.63	19.63	21.22	0.83	Kerman plain, Iran	[50]
FR-SPSA	15.25	20.57	34.75	27.69	1.78	0.77	Kerman plain, Iran	[49]
FR-AHP	7.77	23.88	33.14	29.52	5.69	0.80	Kerman plain, Iran	[49]
FR-DRASTIC	14.45	21.70	48.38	15.04	0.44	0.75	Kerman plain, Iran	[49]
DRASTIC	-	60	20	20	-	0.42	Nalgonda, India	[57]
DRASTIC-SPSA	4	26	59	4	7	0.58	Terengganu, Malaysia	[40]
DRASTIC	-	19	33	48	-	0.23	Northern Iran	[35]
M-DRASTIC	-	45	46	9	-	0.68	Northern Iran	[35]

Note: VL = Very Low, L = Low, M = Medium, H = High, V = Very High, NVC= Nitrate Validation Coefficient, AHP = Analytic Hierarchy Process, FR = Frequency Ratio, SPSA = Single Parameter Sensitivity Analysis.

Model validation and choice of appropriate approach. Since GIS-based maps are obtained through data interpolation; uncertainties are bound, however, in a quest to justifying the results obtained from the fifteen (15) approaches, the results are compared and examined comparatively with a nitrate concentration. In order to accomplish that, the fifteen (15) models were correlated with the conventional nitrate validation methodology. Figure 15 shows the correlation graph for the best method (i.e. FR-AHP) method

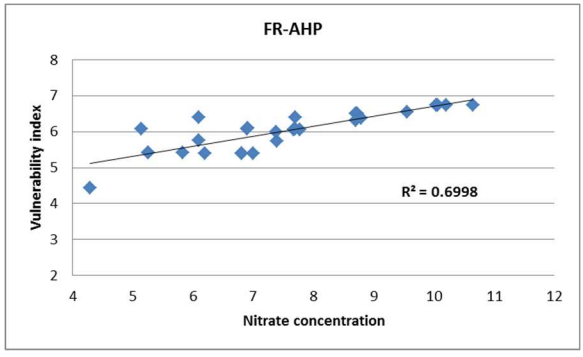


Fig 15: Pearson' correlation coefficient Graph for FR-AHP Model

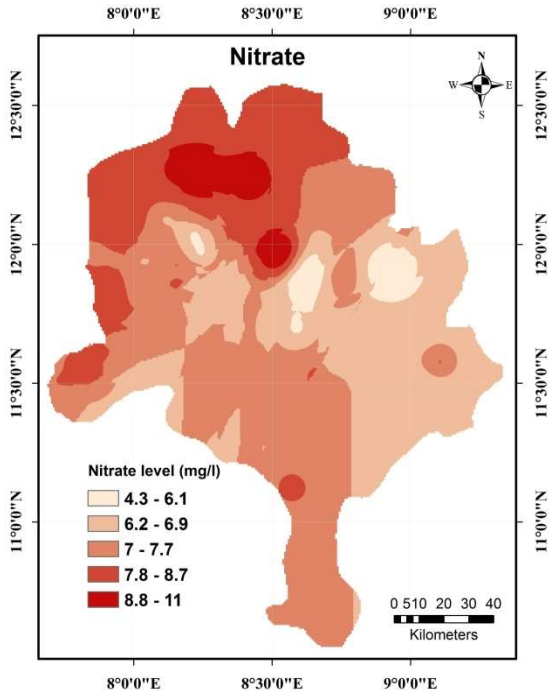


Figure 14: Nitrate concentration within the study area

Table 6: Pearson' correlation coefficient between nitrate and vulnerability index for various models

Pearson's correlation coefficient	Models	Rank
0.73	DRASTIC	10
0.65	FRASTIC	13
0.78	DRASTIC-SPSA	6
0.75	FRASTIC-SPSA	7
0.74	DRASTIC-AHP	8
0.63	FRASTIC-AHP	15
0.65	AHP- FRASTIC	13
0.68	AHP- AHP	12
0.80	AHP-SPSA	3
0.79	FR-FRASTIC	4
0.84	FR-AHP	1
0.71	WoE-FRASTIC	11
0.74	WoE-AHP	8
0.83	FR-SPSA	2
0.79	WoE-SPSA	4

This is achieved by comparing the vulnerability indices of each model and the nitrate contamination at a particular sample stations. The nitrate samples from 28 stations were used in this study. The nitrate data were interpolated using Kriging interpolation technique and the resulting nitrate concentration map is shown in Figure 14.

Values observed at each sample station from individual vulnerability maps were analysed using Pearson's correlation technique. Table 6 shows the resulting Pearson's correlation coefficients for each model.

From the coefficients obtained, it was found that the order of the degree of correlation is in the form FR-AHP> FR-SPSA> AHP-SPSA> WoE-SPSA = FR-FRASTIC> DRASTIC-SPSA> FRASTIC-SPSA> WoE-AHP = DRASTIC-AHP> DRASTIC> WoE-FRASTIC> AHP-AHP> AHP- FRASTIC> FRASTIC> FRASTIC-AHP.

According to the validated maps, the model that best suits the study area is the FR-AHP which correlated the best with the nitrate (i.e. 84%). Nitrate indicates the actual groundwater contamination trend of the study area.

The vulnerable areas were found to inhabit very low (4.44-5.4), low (5.41-5.74), medium (5.75-6.06), high (6.07-6.38) and very high (6.39-6.74) vulnerability ranges and the area coverage by each class is shown on Figure 16.

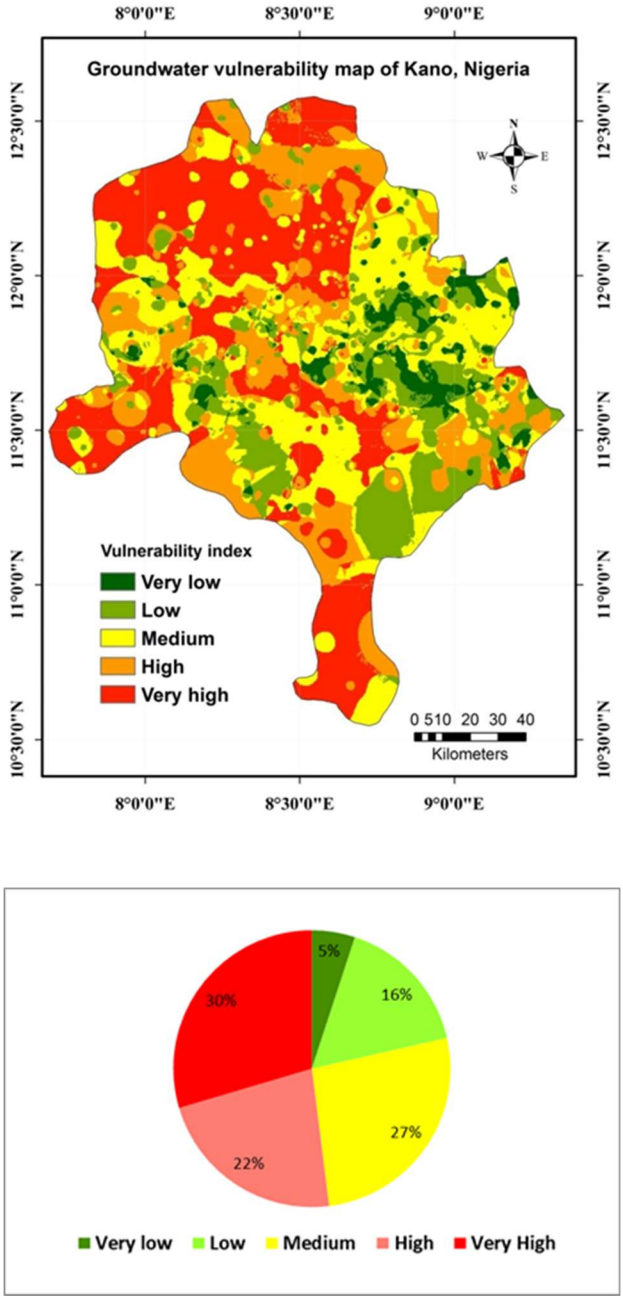


Fig. 16: Vulnerability map and class area coverage of Kano

CONCLUSIONS

When the GIS based DRASTIC model was modified to assess the groundwater pollution vulnerability in Kano, Nigeria, it was found that the depth to water (D)

parameter exerts least significant impact in DRASTIC index, and the modification of DRASTIC parameters, ratings, and/or weights based on a particular approach normally yields a good result. Moreover, the coupling/hybridization of these approaches revealed better results. The developed FRASTIC model which was realised by replacing depth to water (D) with the fractured media (F) has proven effective.

Consequently, the sixteen (15) modification approaches applied are based on the 'Fractured media' and an excellent correlation coefficient was obtained. 0.84 for FR-AHP. It is revealed that 14% of the entire area is within very low vulnerability, low is 24%, medium is 25%, high is 21%, and very high is 16% based on the fifteen (15) DRASTIC modification approaches employed in Kano.

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