Jour. Geol. Soc. India (2024) 100 (6) : 852-862
https://doi.org/10.17491/jgsi/2024/173915

RESEARCH ARTICLE

DRASTIC-FS Model for Assessment of Groundwater Vulnerability in Alluvial Region between Mahi and Narmada Rivers, India

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Received: 16 April 2023 / Revised form Accepted: 23 August 2023

ABSTRACT

Vulnerability of groundwater to contamination in alluvial region between Mahi and Narmada rivers of Gujarat has been assessed in present study. There have been numerous studies that have analyzed DRASTIC models with weights suggested by the Delphi committee. These models have some limitations that have been overcome by optimizing the weights using artificial neural networks (ANNs). The "DRASTIC-FS" model has an additional layer that takes into account the impact of the physico-chemical properties of groundwater. The dominating factor scores (FS) at each well location were derived from the statistical analysis of the quality dataset. Factor score's rating and the weight have been assigned considering to its intervention and influence to vulnerability. The DRASTIC and DRASTIC-FS models were carried out in GIS environment to obtain vulnerability maps for 2018 pre and post monsoon seasons. The weights of variable parameters (i.e., D, R, I, C, and FS) have also been optimized using ANN (Artificial Neural Network) and the results were compared with the effective weights derived from SPSA method of sensitivity analysis. Using ANN optimized weights and groundwater nitrate concentrations, the vulnerability maps were validated. Vulnerability maps of DRASTIC-FS with ANN weights correlated well for the year 2018, 2019 and 2020 (Pearson's 'r'= 0.56, 0.65 and 0.50 respectively) with groundwater Nitrate concentrations proving its higher efficiency over the DRASTIC method (Pearson's 'r'= 0.36, 0.48 and 0.32).

Keywords: Groundwater, Contamination, Vulnerability, Factor Score, ANN

INTRODUCTION

Particularly in dry and semi-arid areas, the advancement of human life is greatly dependent upon utilization of drinkable groundwater. Over exploitation of such natural source for agronomic, house-hold as well as industrial purposes leads towards the decline of water table. The degree of change of climatic factors, geographic location and anthropogenic activities with their influence on groundwater has been the subject of conversation since a decade. In recent years, extensive research has been carried out regarding groundwater quality in India and all around the world. By the end of the 1960s, the idea of groundwater vulnerability was developed in France to raise awareness of groundwater pollution. (Insaf, 2005). The widely accepted definition of groundwater vulnerability is the characteristic of underlying aquifer system summed up from the influence of geogenic and human interventions explained by the US National Research Council in 1993 (Ewa Krogulec and Trzeciak, 2017). The index mapping models, statistics based methods and models based on process simulation are methodologies for assessment of vulnerability. The index based mapping has been the widely accepted approach among the groundwater researchers (Prashant Kumar, 2015). The DRASTIC approach is one of the traditional methods for assessing the susceptibility of groundwater to pollution (Aller Linda, 1985). Vulnerability assessment results in the form of a map showing sustainable to low, high and severe vulnerable areas from index based modeling. Based on the statistics of vulnerability map, critical zones can be identified that require repeated monitoring and also necessary steps can be taken towards groundwater remediation.

In central Gujarat, fluoride and nitrate as well as high salinity levels exist at certain locations above permissible limits (Krishnan, 2007; Patel, 2020). Dipesh Machiwal, (2018) reviewed present status of groundwater vulnerability assessment and associated future challenges highlighting the importance of accurate characterization of vadose zone parameters in the transmission of land-based pollutants into groundwater. Mamta Mehra (2016) developed an integrated assessment framework with the help of GIS for managing groundwater resources for agricultural purposes. Three different index based approaches namely, Groundwater Vulnerability Modeling, Groundwater Quality Modeling and Groundwater Potential Modeling were considered for the integrated assessment. Ravinder Kaur and Rosin (2009) explained the use of groundwater vulnerability assessment specifically for industrial and urban clusters as these areas have more probability of groundwater contamination. Weldon Lodwick (1990) developed map based suitability analysis from attribute errors and uncertainty associated with the outcome of index based geographical analysis. Their work proves to be a guideline in Map Removal Sensitivity Analysis.

An obstruction in accurate vulnerability assessment is the fixed weights of DRASTIC parameters based on expert's opinion of Delphi committee (Aller Linda, 1985) instead of scientific reasons demanding thorough research in optimizing the values of weights and ratings. Various statistical analysis such as Analytical Hierarchy Process (AHP), Fuzzy analysis even combined with neural network models may be suitable to optimize the weights assigned to DRASTIC parameters. The reduction and/or additive approach of a particular parameter in DRASTIC analysis may be adopted looking to the flat topography, enhanced with area specific anthropogenic activities influencing the geohydrology of study area. An important geo-environmental parameter has not been considered in vulnerability assessment is the key limitation of conventional DRASTIC method. In recent research works, modifications over conventional DRASTIC method have been made that explains the addition of anthropogenic factors in terms of Land Use changes as well as optimization of weights and ratings (Umar, 2010; Shirazi, 2013; Neshat, 2014; Fakhre Alam, 2014; Anjali Singh, 2015). Groundwater quality is influenced by regional land use land cover patterns, indicating the need of LULC as a newly added criterion (Fakhre Alam, 2014). Industrial and urban development are the significant anthropogenic sources from where the possibilities of groundwater contamination arise which can be interpreted in terms of a newly added parameter (Anjali Singh, 2015). The past research has found groundwater of urban zones to be more vulnerable to contamination. (NRC 1993; Fakhre Alam, 2014). In order to assess groundwater vulnerability in the Malaysian state of Melaka, Shirazi (2013) used the DRASTIC approach with GIS in mapping the level of risk also highlighting the improvement in DRASTIC method when combined with patterns of land use and nitrate concentration. For the Indo Gangetic Plains, Umar (2010) evaluated groundwater vulnerability and found that land use patterns significantly influenced the shallow aquifers qualitative and quantitative properties.

Aim of the present study is to upgrade the vulnerability assessment model by eliminating limitation of conventional DRASTIC model recommended by Aller Linda (1985). It has the limitations that weightage assigned to each parameter (D, R, A, S, T, I, C) based on expert judgement (Delphi Committee) doesn’t reflect the actual importance in the study area (Kumar, 2022). Therefore, to improve the accuracy of the findings, DRASTIC parameters weightage has been re-calibrated by using individual ANN, after considering hydro-geological base for upgraded DRASTIC-FS model. Application of machine learning algorithms which identify patterns and connections in the data that may not be apparent to human specialists, has been used to improve the DRASTIC method’s accuracy.

The site-specific parameters which were not taken into consideration by the original DRASTIC approach, have been added through introduction of novel parameter in the form of FS (Factor Score). The Factor score can be applied to any type of region in order to accommodate the external influences, which need to be incorporated into the model for higher accuracy. External influences can be the area specific such as excess use of fertilizer, industries effluent, dumping chemical effluent into the pit and faulty drainage (Kumar, 2022).

The novelty of this research is the addition of a new parameter “Factor Score - (FS)” in groundwater vulnerability assessment. It represents the physico-chemical parameters of groundwater in such a form that explains the worsening of groundwater quality by anthropogenic activities. Thus, including it in the upgraded DRASTIC model will be significant in accurate identification of critical groundwater areas that require immediate attention. The DRASTIC-FS model was built to evaluate the groundwater vulnerability of the alluvial region between the Narmada and Mahi rivers in central Gujarat. The effective weights of vulnerability parameters of groundwater (D, R, A, S, T, I, C) were evaluated based on theoretical weights (Table 1) of each individual parameters from SPSA (Singh, 2015; Tomer, 2019). Another novel approach of present research is the use of artificial neural network (ANN) for optimization of weights of DRASTIC-FS parameters. D, R, I, C and FS were optimized as these individual parameters depend on other variables. The weights of parameters A, S and T are kept equal to the theoretical weights as per DRASTIC approach (Aller Linda, 1985) considering, they are independent parameters. The ANN optimized weights were compared with effective weights and considered to obtain final outcomes in terms of raster maps from DRASTIC-FS model. The validation of groundwater vulnerability for present study is done considering Pearson’s correlation (r) among groundwater nitrate, DRASTIC maps as well as DRASTIC-FS maps obtained with ANN optimized weights.

STUDY AREA

The alluvial region between Mahi and Narmada rivers of Gujarat (Fig. 1) is extended over 12 different talukas (blocks) among three districts namely, Panchmahal, Vadodara and Bharuch. Total area of

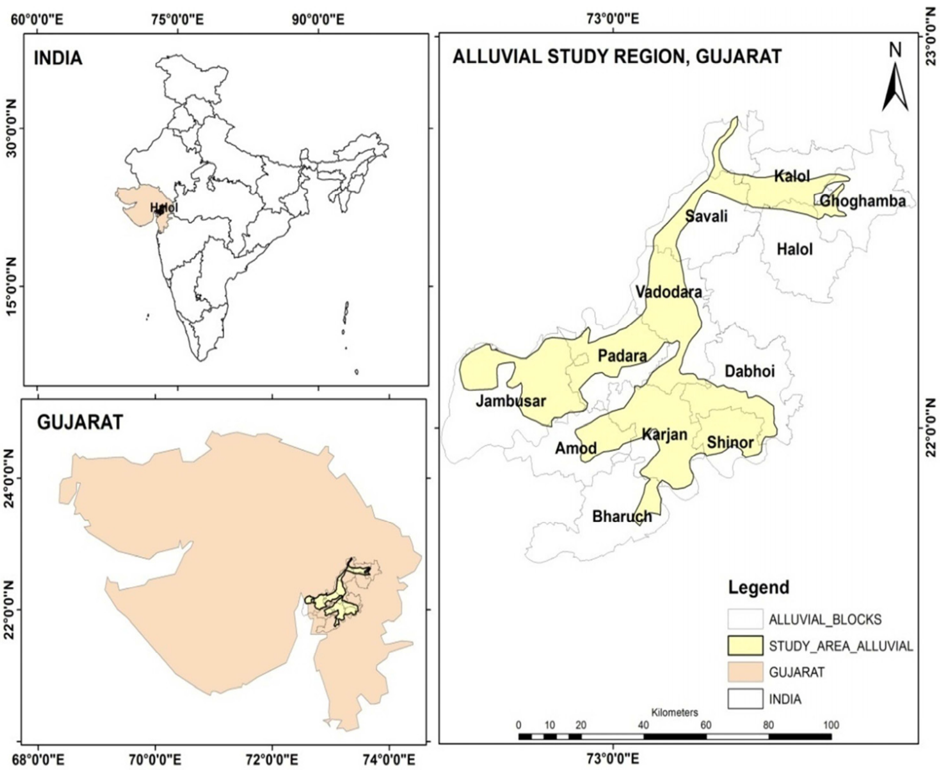

Fig. 1. Alluvial region between Mahi and Narmada River, Gujarat, India

the alluvial region is about 2775 km^2, residing between 21.78° to 22.83° N latitude and 72.51° to 73.64° En longitude. The general atmosphere of the study area is semi-arid with temperatures recording up to 45°C in summer, 8°C in winter and annual mean rainfall in the range of 900 mm occurs in present study area during monsoon season. In the research region, groundwater is the significant source for household, industrial and agricultural purposes. Prakash Gupte (2010) explained the occurrence of groundwater in the study region under both phreatic and confined conditions. A multilayered alluvial deposit and hard rock formations made of basalt and granite make up the study area's groundwater system. The general direction of groundwater flow is from NE to SW, with a gradually decreasing hydraulic gradient and the range of the water table is 4-35 mbgl.

From District Industrial Potentiality Survey (DIPS) reports of Panchmahal, Vadodara and Bharuch districts it is observed that the study area is engaged in (54%) agriculture activity and (46%) industrial activity stating its richness in agriculture as well as industry. Mining of lignite as fuel consumption of some of the mineral based industries such as Bricks manufacturing units, Silica Sand for their products like Birla Copper present in the study region (DIPS Bharuch District, 2016-2017). A cluster of small-scale industries such as 33 miscellaneous chemical-based industries, 41 process stone marbles industries, 64 chemical machinery parts producing units, 32 lather footwear producing units, etc. exist in study area (DIPS Vadodara District, 2016-2017). A total of 58 registered units of large-scale industries are present in Halol and Kalol talukas of Panchmahal district (DIPS Panchmahal District, 2016-2017).

ASSESSMENT OF GROUNDWATER VULNERABILITY

DRASTIC Index (Conventional model)

Each thematic layer of DRASTIC index suggested by Aller Linda (1985) is associated with a weightage (W) and appropriate ratings (R). For a certain area, the sum of the ratings and weights for each layer is referred to as the vulnerability index. The following equation serves as the basis for determining groundwater vulnerability where D (Depth to groundwater level), R (groundwater Recharge), A (Aquifer media), S (Soil media), T (Topography), I (Impact of vadose zone) and C (hyd. Conductivity) are the key parameters.

$$\text{DRASTIC Index } (D_i) = DrDw + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w, \quad (1)$$

Following data which represent each layer was collected and analyzed. The pre and post monsoon maps explaining the vulnerability index were developed for the year 2018 with assignment of R-ratings and W-weights to each parameter. DRASTIC-FS layers and the data sources are described below (Table 1).

Depth of Water Table (D): In assessing the alluvial region's groundwater vulnerability, depth parameter becomes a crucial layer. If the water table is deep, contaminated water has ample time to come in contact with the earth's components, allowing attenuation processes to reduce contaminant concentration. The D parameter is given the highest weight (W=5) and ratings are discussed in table 2 and figure 2. The data on groundwater levels of the year 2018 considering pre and post both the seasons were collected from India-WRIS portal.

Recharge (R): Net Recharge is another significant layer in vulnerability assessment as it transports contaminants from the surface to the shallow zones directly. The location having a high risk of contamination correlates with high groundwater recharge rate. All sources of groundwater recharge, including canals, irrigation from surface and groundwater sources, tanks-ponds and infrastructure of water conservation are considered for both the seasons (Fig.3) as per the GEC (Groundwater Estimation Committee-2015) report. This parameter is given the weight (W=4) and ratings are discussed in table 2.

Aquifer Media (A): Aquifer media is often described as a compacted medium of different earthen materials at either consolidated or unconsolidated state (clay, sand, kankar, gravel, etc.). The aquifer media permits the conductance of flow along with contaminants in the subsurface zone. The lithologs available for the alluvial region were considered to develop the parameter map which has a weight (W=3) and ratings as per (Aller et al., 1985) shown in table 3. The ratings of various aquifer materials are shown in figure 4.

Soil Media (S): The S parameter is important as the net recharge infiltrates from various soil materials into the groundwater indicating the downwards movement of contaminants through the vadose zone. Additionally, the attenuation processes of filtration, biodegradation, sorption, and volatilization may be highly substantial if the soil zone is fairly thick. The S parameter ratings were assigned from lithology data considering top soil layer thickness. The alluvial region consists of clay with interbeds of sand and gravels. The soil media assigned with weight (W=2) and their ratings are discussed in table 3. The ratings of soil media for present study area are shown in figure 5.

Topography (T): The residence time of groundwater on the surface of the soil is dependent upon the topography which affects the infiltration rate. The T parameter in the form of percent slope was determined in GIS with the help of spatial analyst tools considering USGS-SRTM digital elevation model (DEM). Topography ratings are discussed in table 2. The spatially distributed map of T parameter is shown in figure 6.

Impact of Vadose Zone (I): An integration of lithology and spatial distribution of depth of water table was used to identify vadose zone for the alluvial region. The vadose zone is a significant model parameter with weight (W=5) and ratings are assigned from table 3. The ratings of I parameter for alluvial region is shown in figure 7.

Table 1. Drastic parameters with assigned weights and required data sources

Parameter	Theoretical Weight	Hydro-geological parameters	Data Sources
D = Depth to groundwater	5	Depth of water table/ Bore hole data	India-WRIS
R = groundwater Recharge	4	Daily Rainfall Data	SWDC
A = Aquifer media	3	Aquifer media/ in terms of Lithology	GWRDC
S = Soil media	2	Geology of Study Area	GWRDC
T = Topography	1	Digital Elevation Map of Alluvial region	SRTM/USGS Earth Explorer
I = Impact of vadose zone	5	Aquifer media/ in terms of Lithology	GWRDC
C = Hydraulic conductivity	3	Aquifer parameters range	CGWB, USGS reports
FS = Factor Score	5	Ground water quality parameters	MOJS-DDWAS

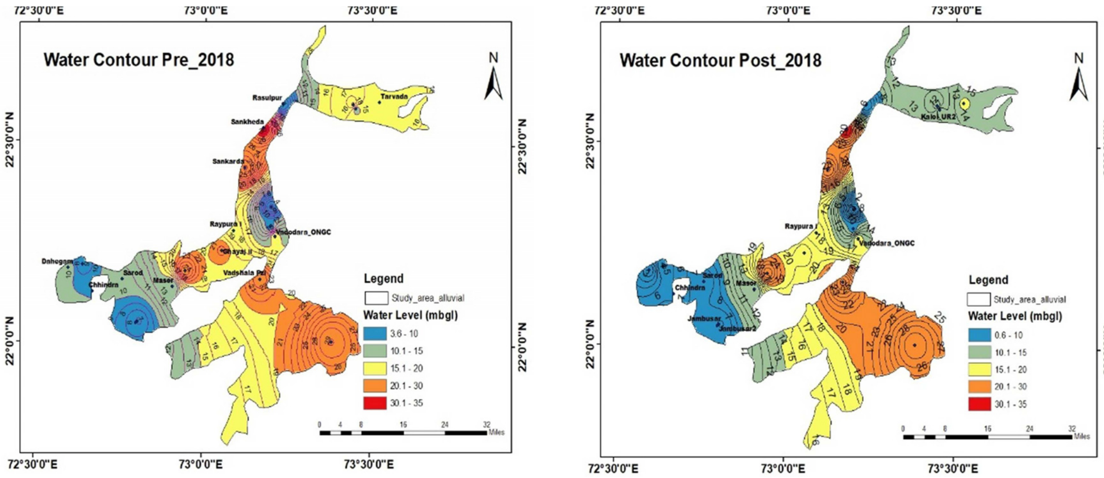

Fig 2. Groundwater Depth Pre- and Post-monsoon, 2018

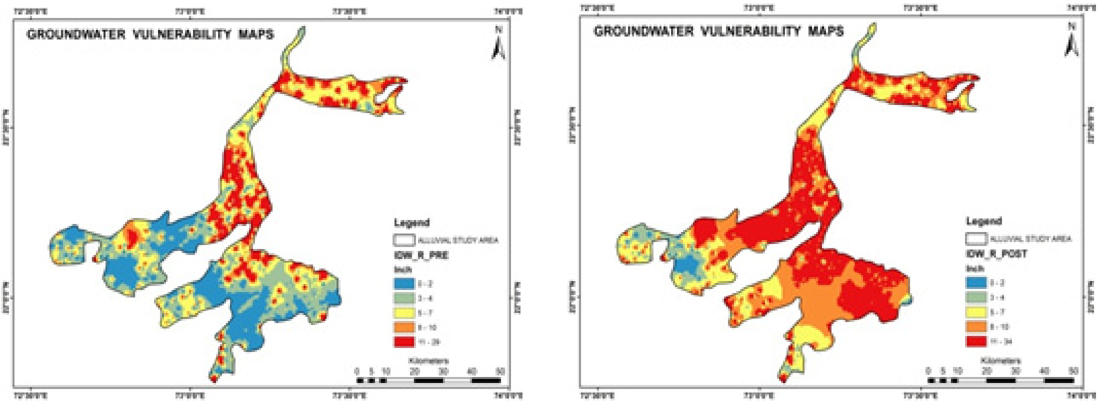

Fig 3. Net Recharge Pre- and Post-monsoon seasons

Table 2. Ratings (R) of DRASTIC Parameters (Depth, Recharge, Topography, Conductivity)

Depth		Recharge		Topography		Conductivity	
Range (ft)	R	Range (inches)	R	Range (% Slope)	R	Range (GPD/ft2)	R
0-5	10	0-2	1	0-2	10	1-100	1
5-15	9	2-4	3	2-6	9	100-300	2
15-30	7	4-7	6	6-12	2	300-700	4
30-50	5	7-10	8	12-18	3	700-1000	6
50-75	3	10+	9	18+	1	1000-2000	8
75-100	2	–		–		2000+	10
100+	1	–		–		–	

Hydraulic Conductivity (C): Representative values of hydraulic conductivity from USGS and CGWB reports were assigned to each aquifer layer for all the available lithologs and its average value was assigned with ratings which are discussed in table 2. The spatially distributed map of C parameter is shown in figure 8.

The parameters aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C) have the same ratings for both pre- and post-monsoon seasons as these are hydrological parameters that don't observe seasonal changes.

DRASTIC-FS Index (Upgraded model)

DRASTIC-FS is introduced to assess the groundwater vulnerability

Table 3: Ratings (R) of DRASTIC Parameters (Aquifer media, Soil media, Impact of vadose zone)

Aquifer Media		Soil Media		Impact of Vadose zone	
Range	R	Range	R	Range	R
Massive shale	2	Thin or absent/gravel	10	Silt/clay	1
Metamorphic/igneous	3	Sand	9	Shale	3
Weathered metamorphic/igneous	4	Peat	8	Limestone	6
Thin bedded sand stones, limestone shale sequence	6	Shrinking and/or aggregated clay	7	Sandstone	6
Massive sandstone	6	Sandy loam	6	Bedded limestone, sandstone, shale	6
Massive limestone	6	Loam	5	Sand, gravel with silt & clay	6
Sand and gravel	8	Silty loam	4	Metamorphic/igneous	4
Basalt	9	Clay loam	3	Sand and gravel	8
Karst limestone	10	Muck	2	Basalt	9
——-		Non-shrinking, non-aggregated clay	1	Karst limestone	10

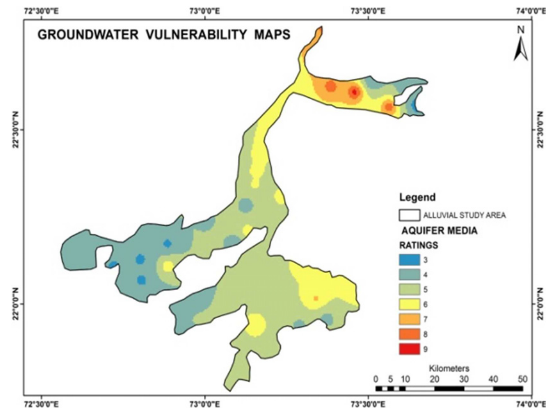

Fig 4. Aquifer media (Rating)

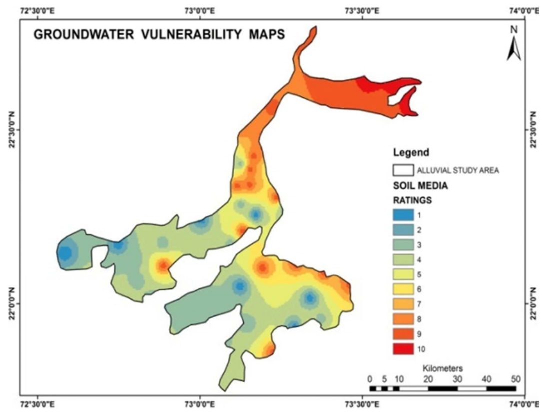

Fig 5. Soil media (Rating)

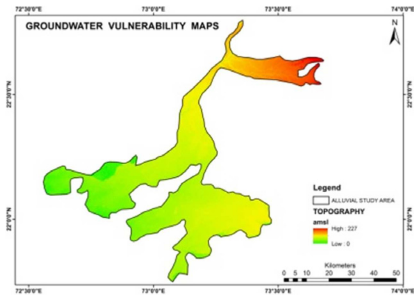

Fig 6. Topography (Rating)

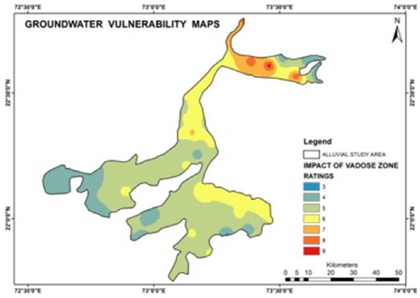

Fig 7. Impact of vadose zone (Rating)

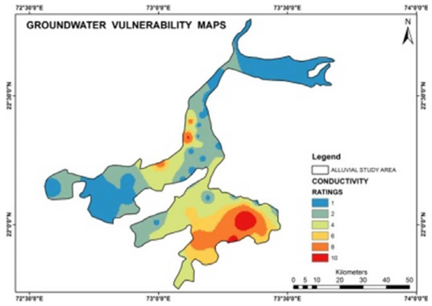

Fig 8. Conductivity (Rating)

with addition of a new parameter termed as Factor Score (FS). The Factor Score parameter will represent the various anthropogenic activities which cannot be quantified and highly responsible to make groundwater vulnerable such as disposal of industrial effluent directly to pit, chemical waste disposal unlawfully to river, sewage disposal from STPs and municipal waste including land fill site in urban and rural sanitation, etc. The FS parameter was obtained from factor scores derived from Principal Component Analysis (PCA) which was performed on the groundwater quality data (MOJS-DDWAS-2018). It represents various sources of contamination in terms of Natural or Anthropogenic. The initially assigned weight significance of this layer was (W=5) and ratings R have been shown in table 4. The formula for DRASTIC-FS Vulnerability index is as follows:

$$\text{DRASTIC-FS Vulnerability} = \text{DRASTIC Index } (D_i) + FS_r FS_w \quad (2)$$

Where, FS = Factor Score.

Figure 9 explains the stepwise procedure on how the groundwater vulnerability was assessed with both DRASTIC and DRASTIC-FS model with final outcome.

Table 4. FS Index Weightage and Ratings

Sr No.	Factor Score, Range	Ratings (1-10)	Remarks
1	0 to 0.5	1	Within permissible limit
2	0.5 to 0.75	5	Natural + Anthropogenic Source
3	0.75 to 2.0 [0.75-1.00] [1.00-1.25] [1.25-1.50] [1.50-2.00]	 6 7 8 9	Anthropogenic Source (Highly Contaminated)
4	>2.0	10	Anthropogenic Source (Vulnerable)

ANN Optimized Weights

The conventional DRASTIC index has been practiced by assigning fixed weight of D, R, A, S, T, I and C parameters as per Delphi approach recommended by founder of this method Aller Linda (1985). A novel and logical approach of optimization of weight of each parameter was performed in present research with the use of individual artificial neural network (ANN) considering dependent variables using Python language. The optimization of weights for D, R, I, C and FS parameters was done with 3 layered artificial neural networks (ANN) coded in Python program. For such optimization, first the variable parameters have been assigned with factors/elements on which they are depending. These factors/elements are described for each individual parameters in the table 8. Then, the ratings of variable parameters and accompanying factors/elements were extracted for each cell of present study area which were taken as input of the ANN model. This dataset is divided into three parts namely, Training, Testing and Validation. Finally, ANN optimized weights were taken into account to assess DRASTIC-FS index for the alluvial region.

DRASTIC-FS model has been built using model builder in GIS environment in which three processes take place (Fig.10). First process is to input model parameters which are DRASTIC-FS. All the model parameters pass through IDW (Inverse Distance Weightage Method) interpolation tool giving spatial distributions. The IDW methods considers higher influence of near known values over far known values to predict values at unknown locations. Second process is to assign ratings (1-10) for each model parameter within the model using reclassify tool. Third process is the calculation of all raster maps integrating their respective weightage for which the Weighted Sum tool is used. Final outcome of the model is the raster maps of DRASTIC-FS index classified in Sustainable, Less Vulnerable,

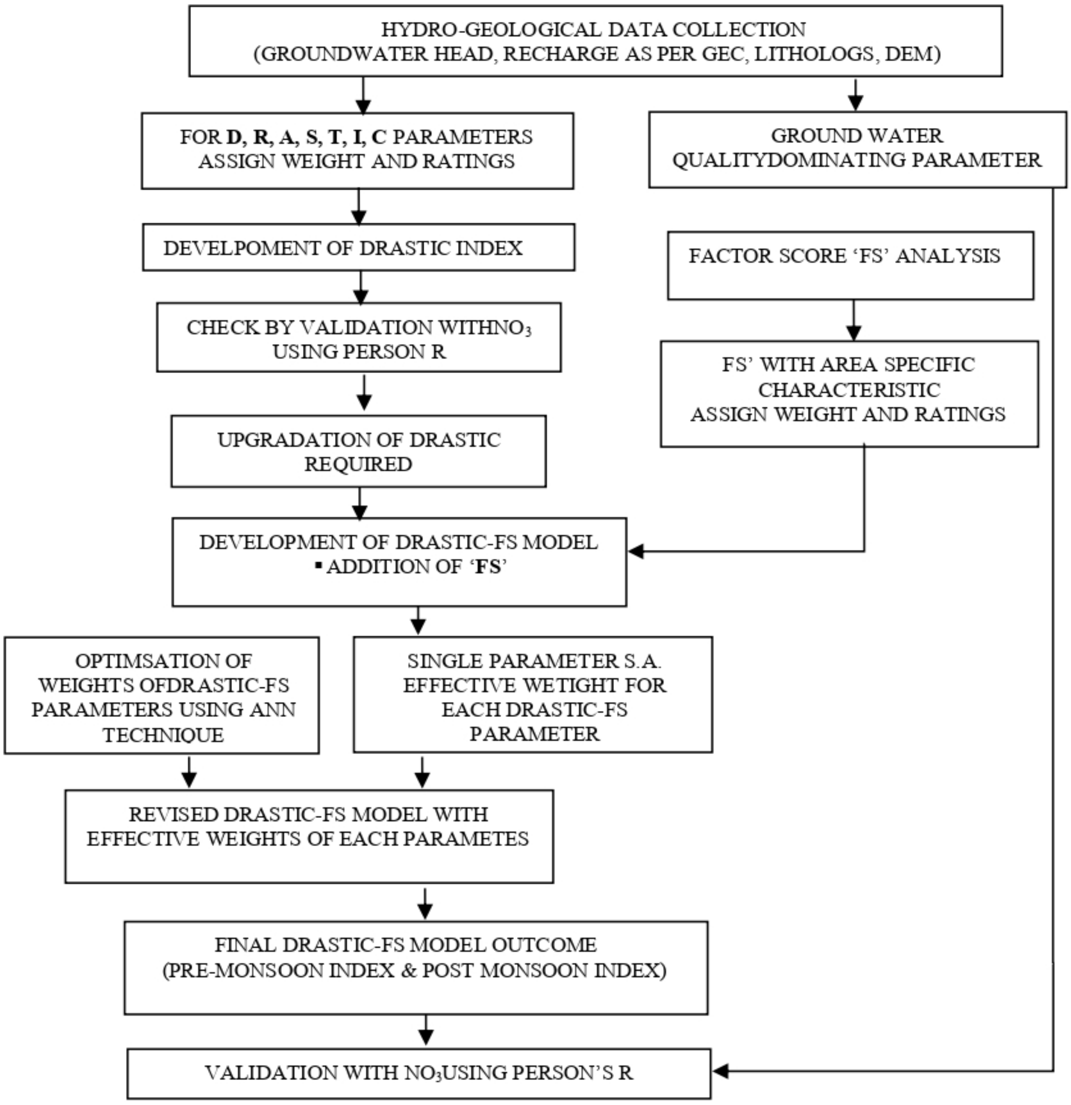

Fig 9. Methodology flowchart

Moderately Vulnerable, Highly Vulnerable and Severely Vulnerable classes.

DISCUSSION

After successful execution of final run, groundwater vulnerability maps of both the models DRASTIC pre-monsoon and post-monsoon (Fig.11) and DRASTIC-FS (ANN optimized weights) pre-monsoon and post-monsoon (Fig.12) seasons are shown in terms of maps representing vulnerability index below.

The basic statistical summary of DRASTIC-FS model (pre-monsoon) is given in table 5 which highlights R, A, S, T, and I parameters to be highly contributing whereas D and C parameters to be less contributing in overall groundwater vulnerability from examining the average values. The newly added FS parameter and Conductivity parameter have very high coefficient of variation (CV) indicating their higher contribution in groundwater vulnerability for the alluvial region.

The groundwater vulnerability index ranges from 63 to 155 in pre-monsoon season from DRASTIC model (Fig. 11) in Sustainable (63-90), Less Vulnerable (91-110), Moderately Vulnerable (111-120), Highly Vulnerable (120-140) and Severely Vulnerable (140-155) are representative classes. From DRASTIC-FS (ANN weights) model final vulnerability index (Fig.12) is mapped from 64 to 244 in Sustainable (64-100), Less Vulnerable (101-120), Moderately Vulnerable (121-140), Highly Vulnerable (141-160) and Severely Vulnerable (161-244) are representative classes.

The distribution of study area (%) in each vulnerability class of both the models (DRASTIC and DRASTIC-FS) for both seasons (Pre and Post Monsoon) is mentioned below (Table 6). The results from sustainable class show marginal decrease in percent area in post-

Table 5. Statistical summary of Ratings assigned in DRASTIC-FS model

Pre-Monsoon	Depth	Recharge	Aquifer	Soil	Topography	Impact of Vadose Zone	Conductivity	Factor score
Average	3.87	5.33	5.02	5.20	6.34	5.23	3.38	4.54
Minimum	1.00	1.00	3.00	1.00	1.00	3.00	1.00	1.00
Maximum	9.00	9.00	9.00	10.00	10.00	9.00	10.00	10.00
St. Dev	1.37	2.49	0.88	2.26	3.22	0.82	2.46	2.31
CV (%)	35.25	46.81	17.52	43.45	50.70	15.61	72.93	50.80

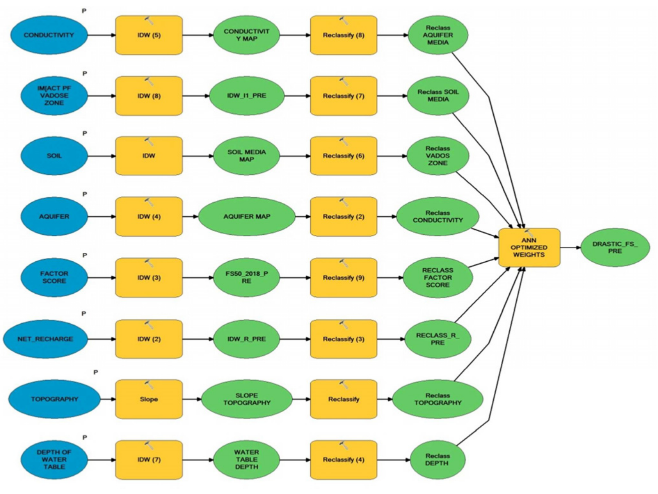

Fig 10. DRASTIC-FS Model in GIS Environment

Table 6. Groundwater Vulnerability outcome in terms of % area

Vulnerability Class	DRASTIC		DRASTIC-FS-ANN	
	Pre-Mon	Post-Mon	Pre-Mon	Post-Mon
1-Sustainable	14.39	0.58	16.07	2.25
2-Less Vulnerable	41.87	18.90	30.72	4.86
3-Moderately Vulnerable	18.87	29.20	20.63	12.20
4-Highly Vulnerable	22.94	43.65	17.49	20.52
5-Severely Vulnerable	1.92	7.67	15.08	60.17

Table 7. Single Parameter Sensitivity Analysis (Pre& Post-Monsoon)

Parameter	Theoretical Weight	Theoretical Weight (%)	Effective Weight	
			Pre-Mon	Post-Mon
Depth (D)	5	17.9	4.16	4.3
Recharge (R)	4	14.3	4.40	6.0
Aquifer Media (A)	3	10.7	3.24	3.0
Soil Media (S)	2	7.14	2.18	2.0
Topography (T)	1	3.57	1.37	1.3
Impact of Vadose zone (I)	5	17.9	5.62	5.1
Conductivity (C)	3	10.7	2.30	2.0
Factor-Score (FS)	5	17.9	4.73	4.4

monsoon seasons of DRASTIC-FS model as compared to DRASTIC. In pre monsoon season, less vulnerable class decrease in DRASTIC whereas it increases in DRASTIC-FS. Similarly in post monsoon season, highly vulnerable class decreases in DRASTIC whereas it increases in DRASTIC-FS model in percent area. The observed variation between DRASTIC and DRASTIC-FS outcome indicates the limitation of conventional DRASTIC and justify the necessity of upgradation as DRASTIC-FS model.

DRASTIC-FS Model Validation

Groundwater vulnerability maps generated from such models are said to be subjective as parameter assigned ratings and weights during the analysis is based on expert opinions and previous works. This unavoidable subjectivity is often characterized by sensitivity with major emphases on individual input parameters. (Tomer, 2019). The sensitivity analysis is known to be a handy tool to validate and to evaluate reliability and consistency of vulnerability maps before implementation in socio-economical as well as hydrological policy making. Present work has taken consideration of both the methods of analyzing sensitivity SPSA (Napolitano and Fabbri, 1996) which are discussed below.

Single Parameter Sensitivity Analysis: The SPSA approach compares theoretical (TW) and effective (EW) weights of each parameter to determine the significance of a single individual parameter on the overall vulnerability map. The measures of EW and Percent Deviation (PD) are formulated below.

$$We = [(Pr * Pw)/Vi] * 100 \quad (3)$$

Where, We = Effective weight; Pr = Parameter Rating; Pw = Parameter Weight; Vi = Vulnerability Index

$$\text{Mean Percent Deviation (PD)} = [(We - Wt)/Wt] * 100 \quad (4)$$

Where, We = Effective weight; Wt = Theoretical weight

From the SPSA (Table 7), the R and I parameters indicate highest effective weights whereas Factor-score, Depth, Aquifer media and Conductivity parameters show moderate effective weights. Soil media and Topography indicate lower effective weights which matched with theoretical weights. The consideration of effective weight in Conductivity and Recharge parameters highlighted obtaining accurate and detailed representative values. One of the available index methods such as DRASTIC is having wide usage but it has area specific limitations and required up-gradation with respect to environmental and geological characterization of the study area. Weights recommended in Conventional DRASTIC Analysis are required to be computed looking to the hydro-geological characteristics of study area.

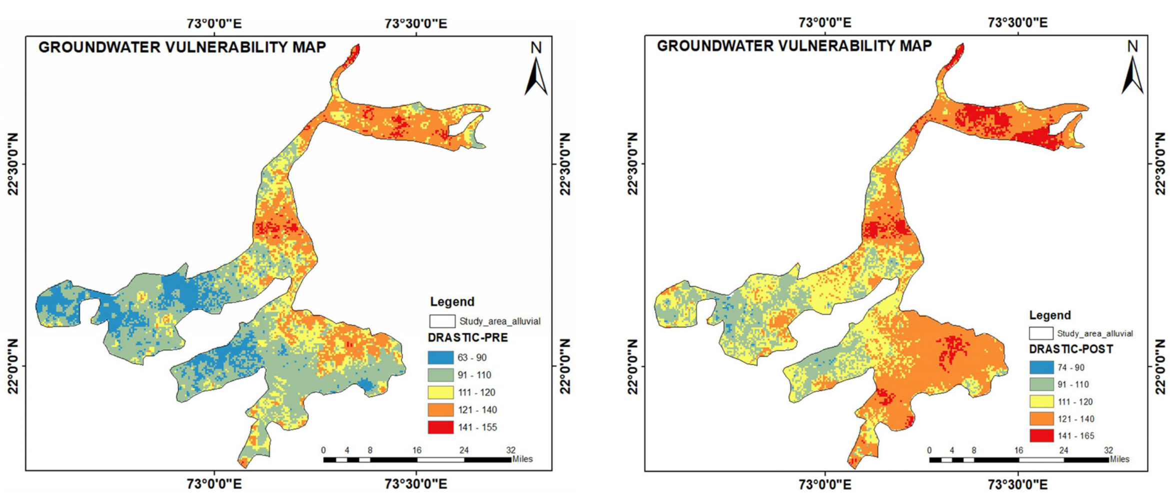

Fig 11. DRASTIC Vulnerability Maps of Pre- and Post-Monsoon

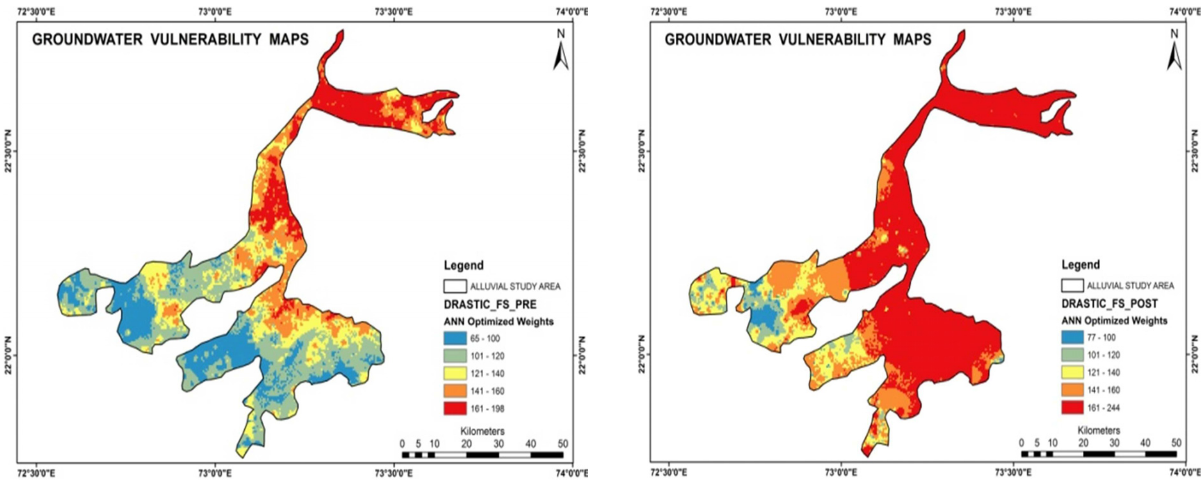

Fig 12. DRASTIC-FS Vulnerability Maps of Pre- and Post-Monsoon with ANN Optimized Weights

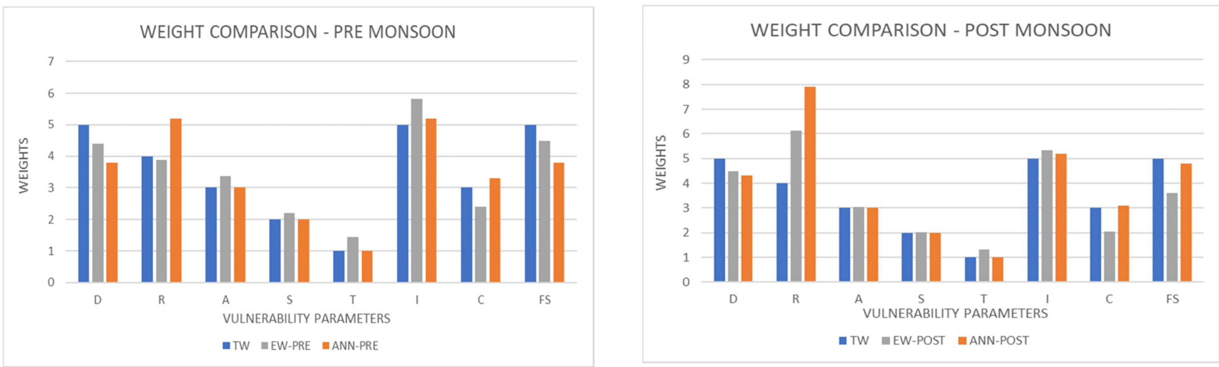

Fig 13. Comparison in Weights of DRASTIC-FS parameters (Pre-Monsoon and Post-Monsoon)

In figure 13, the variation in theoretical weights, effective weights and ANN weights from DRASTIC-FS approach are shown. The bar graph of Pre-monsoon indicates that due to area specific variation, theoretical weight of all DRASTIC parameters varies with calculated effective weight. The bar graph of Post-monsoon DRASTIC parameters weight assignment has not shown any variation between TW and EW of A (Aquifer media) and S (Soil media). But there is considerable variation noticed in Net Recharge due to shallow water table, alluvial soil and heavy rainfall in the alluvial region. Here the Depth to water below ground and Recharge are basic governing elements and having higher impact on Vulnerability index. Though the Hydraulic Conductivity is a constant parameter with respect to time, it varies in space domain in study region, hence its effective weight varies in computation of vulnerability index.

If any specific vulnerable anthropogenic/geogenic phenomena is observed then the impact must be incorporated with introduction of new parameters. In the present study, Factor score is introduced with initial theoretical weight 5 and well matched with effective weight 4.73 based on single parameter sensitivity analysis and 3.8 with ANN optimization of weight. Where as in post-monsoon the weight of Factor score 4.8 was very close to theoretical weight 5.0.

Validation of Model with Groundwater Quality Parameter of Nitrate

To validate the vulnerability index obtained from DRASTIC-FS models, Nitrate concentration in groundwater of study area was correlated with Pearson's method. In the study region, there is no evidence of denitrification strategies being implemented or any reports

Table 8. ANN optimized weight (Pre- and Post-Monsoon)

Parameters	Following variable elements on which the DRASTIC parameters are depending	ANN Opt. Weights	
		Pre-Monsoon	Post-Monsoon
Depth (D)	Recharge, Aquifer media, Soil media, Topography, Vadose zone, Conductivity	3.80	4.30
Recharge (R)	Soil media, Topography, Vadose zone, LULC	5.20	7.90
Aquifer Media (A)	Constant parameters: ANN weights same as Theoretical weights of Delphi Committee (Linda Aller, 1985)	3.00	3.00
Soil Media (S)		2.00	2.00
Topography (T)		1.00	1.00
Impact of Vadose zone (I)	Depth, Recharge, Aquifer media, Soil media	5.20	5.20
Conductivity (C)	Depth, Recharge, Aquifer media, Vadose zone	3.30	3.10
Factor-Score (FS)	pH, TDS, NO_3, F, Cl, SO_4, Ca, Mg, TH, ALK	3.80	4.80

of local government taking action to address high nitrate concentrations. As a result, the nitrate levels in groundwater have been consistently considered constant and the impact of denitrification on nitrate concentrations has been negligible within the range of available data. There were 50 open and shallow wells samples of groundwater quality parameters obtained from the database of MOJS-DDWAS (Ministry of Jal Shakti, Department of Drinking Water And Sanitation, Govt. of India) to correlate Nitrate concentration.

Nitrate concentration in groundwater found above 45 mg/l due to anthropogenic activity such as use of nitrogen containing phosphate fertilizers, agricultural waste, animal manure, septic and sewage discharge. A Pearson's correlation coefficient 'r' was 0.36 between Nitrate and 2018-DRASTIC Vulnerability Index whereas 0.56 between Nitrate and 2018-DRASTIC-FS-ANN Vulnerability Index. Similarly, it was 0.48 between Nitrate and 2019-DRASTIC Vulnerability Index whereas 0.65 between Nitrate and 2019-DRASTIC-FS-ANN Vulnerability Index. Successively even in the year 2020, it was 0.32 between nitrate and 2020-PRE-DRASTIC Vulnerability Index whereas 0.50 between Nitrate and 2020-DRASTIC-FS-ANN Vulnerability Index. The following figures 14 to 19 show the validation of DRASTIC and nitrate as well as DRASTIC-FS-ANN and nitrate for the pre-monsoon season in 2018, 2019 and 2020.

In the current study, the nitrate concentrations were found to correlate with the DRASTIC-FS index, indicating an increasing trend with Pearson's coefficient 'r' of 0.56 and 0.65 in the years 2018 and 2019, respectively. This strong correlation highlights the influence of anthropogenic activities on the rising nitrate, as nitrate does not have a natural source in the groundwater system. Furthermore, in the year 2020, the Pearson's coefficient was observed to be 0.5, which is close to the value of 0.56 observed in 2018.

These correlations validated the DRASTIC-FS-ANN model and prove to be superior model than conventional DRASTIC model for the alluvial region between Mahi and Narmada rivers, India.

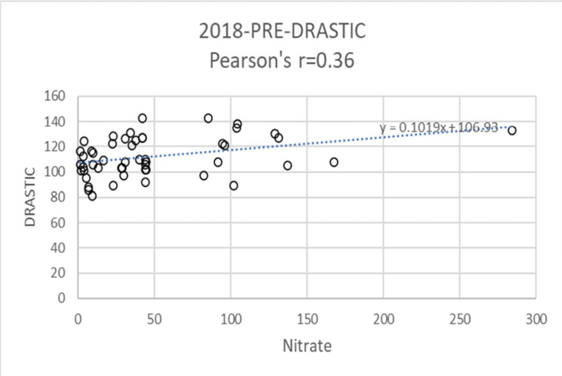

Fig 14. DRASTIC and Nitrate (2018)

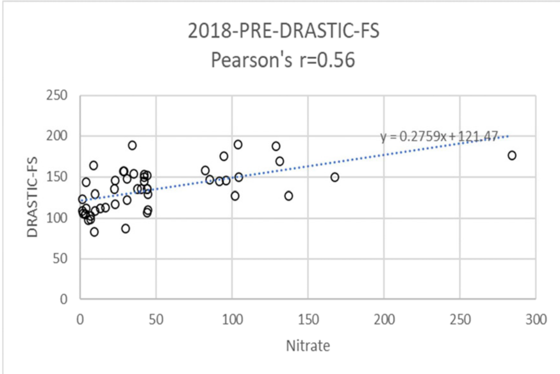

Fig 15. DRASTIC-FS-ANN and Nitrate (2018)

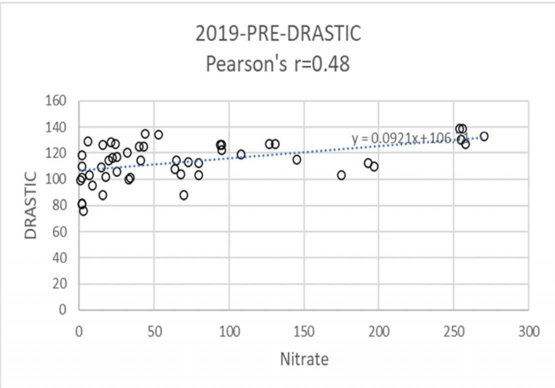

Fig 16. DRASTIC and Nitrate (2019)

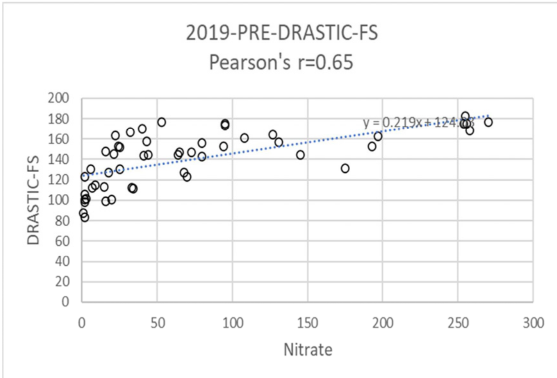

Fig 17. DRASTIC-FS-ANN and Nitrate (2019)

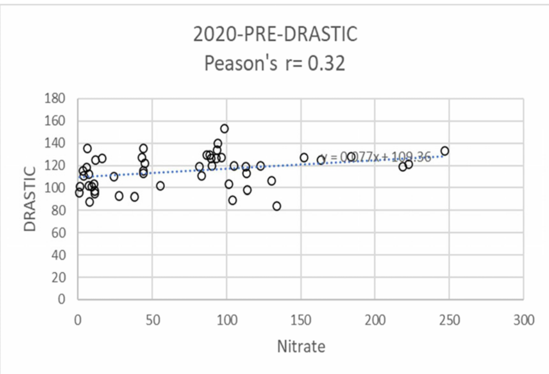

Fig 18. DRASTIC and Nitrate (2020)

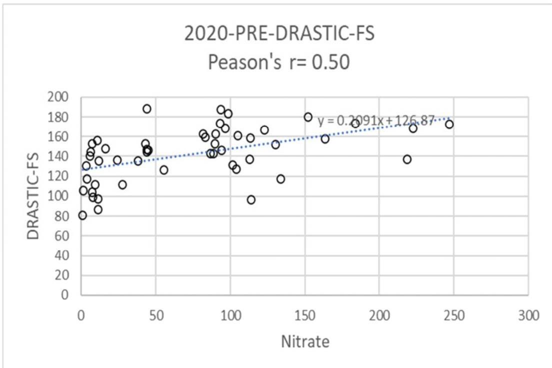

Fig 19. DRASTIC-FS-ANN and Nitrate (2020)

CONCLUSIONS

Present study area includes industrial hub of central Gujarat, where due considerations of hazardous activities of disposal of harmful effluents in certain industrial pockets near Vadodara district are drawn. Such phenomenon needs to be evaluated using effective vulnerability tool which overcomes the available index methods of conventional analysis. DRASTIC is having wide usage but it has area specific limitations and required to be upgraded with respect to environmental and geological characterization of the study area for each individual analysis.

1. Physico-chemical parameters of groundwater in the form of factor score (FS) represents objectionable interventions and anthropogenic contribution towards groundwater being vulnerable which cannot be omitted in such analysis.
2. The weights of variable parameters such as D, R, I, C and FS must be logically determined using ANN, instead of recommended by Delphi committee of Aller Linda (1985). Such optimized weights for each parameter of DRASTIC analysis must be considered for final outcomes in terms of vulnerability maps.
3. DRASTIC-FS model is developed in GIS environment based on logical weights of each parameter such as D, R, I, C and FS with the help of Artificial Neural Network (ANN) model.
4. An individual ANN for each parameter is first time introduced using Python programming language and 10 separate ANN developed for 5 variable parameters (Pre- and Post-Monsson) for DRASTIC-FS model and compared with theoretical weights which reveal the limitation of DRASTIC model.
5. The influence/effects of parameters D, R, I and C from DRASTIC index as well as newly developed FS (Factor Score) parameter varies in pre- and post-monsoon seasons which indicated that vulnerability assessment must be considered for both the seasons.
6. The sensitivity analysis of DRASTIC-FS model highlighted the importance of the groundwater recharge (R), vadose zone (I), hydraulic Conductivity (C), groundwater depth (D) and FS parameters as the effective weights from SPSA are higher for present study area.
7. This study validated DRASTIC-FS model with Groundwater Nitrate concentration for 3 successive years (2018, 2019, 2020) by performing Pearson correlation. The correlation coefficient 'r' is higher in the DRASTIC-FS Vulnerability model over Conventional method drawing attention to the superiority of the former over the later.
8. In evaluating the groundwater vulnerability, DRASTIC-FS approach is seen more rational and conclusive when compared to the groundwater's nitrate concentration. The DRASTIC-FS model can be applied on other regions with adjustments in weights and ratings for location specific hydrogeological conditions.
9. A good correlation between DRASTIC-FS model outcomes and groundwater nitrate concentrations suggests the influence of anthropogenic activities such as excess use of fertilizers, seepage of effluent systems of STP and Industrial units are the leading causes for making the groundwater, vulnerable.

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