CHAPTER 6 ASSESSMENT OF GROUNDWATER VULNERABILITY

6.1 Groundwater Vulnerability Assessment

Groundwater vulnerability refers to how easily groundwater can become polluted or contaminated by human activities or natural processes. This is a critical concern because groundwater serves as a vital source of drinking water for many communities and supports various ecosystems. Understanding and assessing groundwater vulnerability help to ensure the protection and sustainable use of this essential resource.

In general, the term groundwater vulnerability is used to represent the fundamental characteristics of the aquifer which determine whether it is likely to be affected by an imposed contaminant load (National Research Council, 1993).

There are several methods for assessing groundwater vulnerability, each with its own advantages and limitations. These methods includes: GOD (Groundwater Occurrence, Overall Impact of vadose zone, and Depth to water), SINTACS (Single-Parameter Approach to Compute Subsoil Sensitivity to Contamination), PI (Pollution Index), SI (Susceptibility Index), COP (Cokriging and Pollution Potential), PEARL (Pesticide Evaluation at Regional Landscape), Susceptibility Mapping Using GIS and Remote Sensing, INDEX Method, Statistical and Machine Learning Approaches.

Among methods mention in above paragraph, The DRASTIC method is a widely used approach for evaluating groundwater vulnerability.

6.2 DRASTIC approach

The DRASTIC method for groundwater vulnerability assessment was developed by Aller, L. (Linda) C., Bennett, T., Lehr, J. H., Petty, R. J., and Hackett, G. (1987) in the United States. The name "DRASTIC" is represents the seven key parameters used in the method: Depth to water table, Net Recharge, Aquifer Media, Soil Media, Topography, Impact of vadose zone, and Conductivity of the aquifer. This method has become widely recognized and utilized in the field of groundwater protection and management. Each of these factors plays a role in determining how susceptible an area's groundwater is to contamination.

Depth to water table refers to how close the water table (the level where the ground is saturated with water) is to the surface. If the water table is shallow, pollutants can more easily reach the groundwater, making the area more vulnerable. Recharge is the process by which water infiltrates the ground and replenishes the aquifer. Higher recharge rates can enhance the movement of contaminants through the soil and into the groundwater.

Aquifer and soil media both relate to the type of materials present in the ground. Different geological and soil types have varying abilities to filter out and prevent contaminants from reaching the groundwater. Topography, or the shape of the land, influences how water flows over the surface and how contaminants might be transported. The vadose zone, the unsaturated zone above the water table can also, impact the movement of pollutants.

Conductivity of the aquifer material refers to how easily water can flow through it. This factor affects how quickly contaminants can travel through the ground and reach the groundwater. The DRASTIC method assigns weights and ratings to each of these factors, and by combining them, it creates a vulnerability index that categorizes areas having low, moderate, high or very high vulnerability.

Each thematic layer of DRASTIC index suggested by Aller Linda (1985) is associated with a weightage (W) and appropriate ratings (R). The product of rating and weights for each layer is summed up for a particular location which is denoted as vulnerability index. The governing equation for groundwater vulnerability assessment is given below.

$$\text{DRASTIC Index (Di)} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \qquad (2)$$

Where, Di = DRASTIC Index, DrDw = ‘r’ rating and ‘w’ weight of Depth to water level, RrRw = ‘r’ rating and ‘w’ weight of Net recharge (inches), ArAw = ‘r’ rating and ‘w’ weight of aquifer media, SrSw = ‘r’ rating and ‘w’ weight of Soil media, TrTw = ‘r’ rating and ‘w’ weight of Topography, IrIw = ‘r’ rating and ‘w’ weight of Impact of vadose zone and CrCw = ‘r’ rating and ‘w’ weight of Hydraulic conductivity.

6.2.1 Ratings of various Parameters

In the DRASTIC model, rating is essential components used to assess groundwater vulnerability to contamination which helps in quantifying the relative significance of different hydrogeological parameters and their potential impact on groundwater quality.

Rating of each hydrogeological parameter, such as Depth to Water (D), Recharge ®, Aquifer Media (A), Soil Media (S), Topography (T), Impact of Vadose Zone (I) and Conductivity (C) is assigned a rating based on its inherent characteristics. Ratings typically range from 1 to 10, with higher values indicating higher contribution in vulnerability index. These ratings reflect the susceptibility of each parameter to contaminant transport and influence the overall vulnerability assessment.

Depth to water Table

Water level depth is a significant layer in determining groundwater vulnerability of alluvial region to contamination. Water table being at deep levels allows contaminated water enough contact time with earth materials, where the attenuation processes become effective in reducing contaminant concentration. The depth data were obtained from the India WRIS online portal and processed in a GIS environment using the Inverse Distance Weighting (IDW) method to generate the maps.

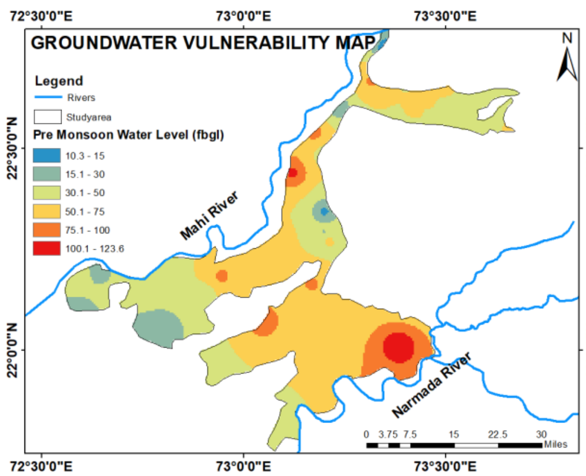


Fig 6.1 Groundwater Depth Pre-monsoon 2018

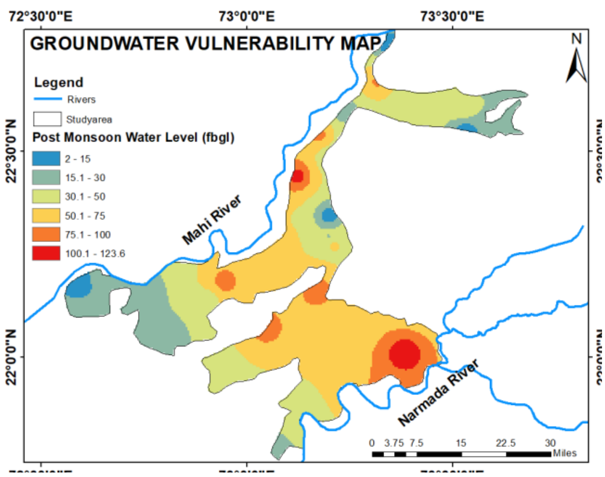
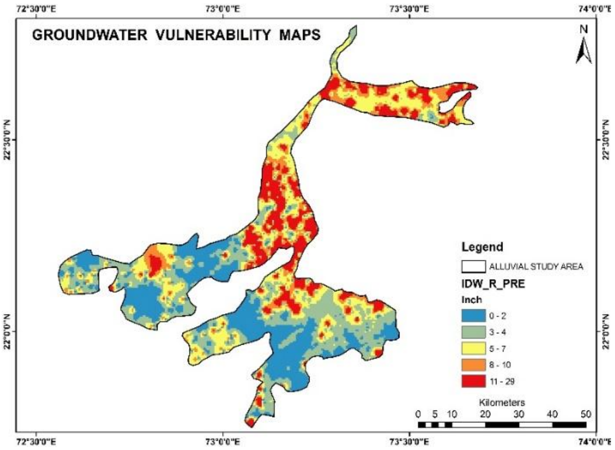


Fig 6.2 Groundwater Depth Post-monsoon 2018

Depth to groundwater is given the maximum weight (W=5) and ratings are discussed in table 6.10. The shallow groundwater levels are observed in a few pockets of northern, central and western regions (blue zone in figures 6.1 and 6.2) whereas deep levels are observed in western and central parts (red zone in figures 6.1 and 6.2) of the study area for both pre and post monsoon seasons.

Net Recharge

Groundwater Recharge is another significant parameter in vulnerability assessment as it transports contaminants from the surface to the shallow zones directly. It has been estimated as per GEC-2015 guidelines as shown in Annexure-I. An area with high groundwater recharge is at higher risk of contamination. This parameter is given the weight (W=4) and ratings are discussed in table 6.1. In the pre monsoon season (fig. 6.3) less groundwater recharge has been seen in Southern parts of study area (blue zone) but in the post monsoon (fig. 6.4) only a few pockets of Western parts (blue zone) showed less recharge, in other parts high recharge is demarcated by red zone.



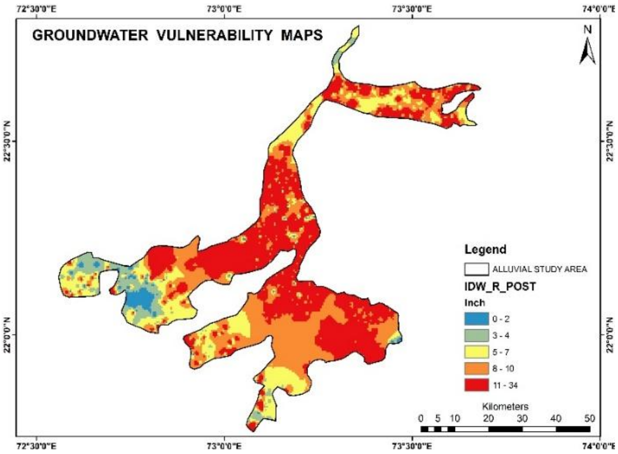


Fig 6.3 Net Recharge during non-monsoon (Pre-Monsoon)

Fig 6.4 Net Recharge during monsoon (Post-Monsoon)

Aquifer Media

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 litholog collected from the GWSSB department for the study area have been considered to develop the aquifer media which has a weight (W=3) and ratings as per (Aller et al. 1987) presented in table 6.2. The ratings of aquifer media for present study area are shown in fig. 6.5.

Soil Media

Soil media is also an important input model parameter as the net recharge infiltrates from various soil materials into the groundwater indicating the downwards movement of contaminants through the vadose zone. Moreover, where the soil zone is fairly thick, the attenuation processes of filtration, biodegradation, sorption and volatilization may be quite significant. Soil media ratings have been 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 weights (W=2) and their ratings are in table 6.2. The ratings of soil media for present study area are shown in fig. 6.6.

Topography

Topography controls the residence time of the water on the surface of the soil, thereby affecting the rate of infiltration. Topography in the form of percent slope has been determined in GIS with the help of spatial analyst tools considering USGS-SRTM Digital Elevation Model with 1 Arc-Second (30 meters) resolution (DEM). Topography ratings are in table 6.1. The spatial distribution of ratings of this parameter is shown in figure 6.7.

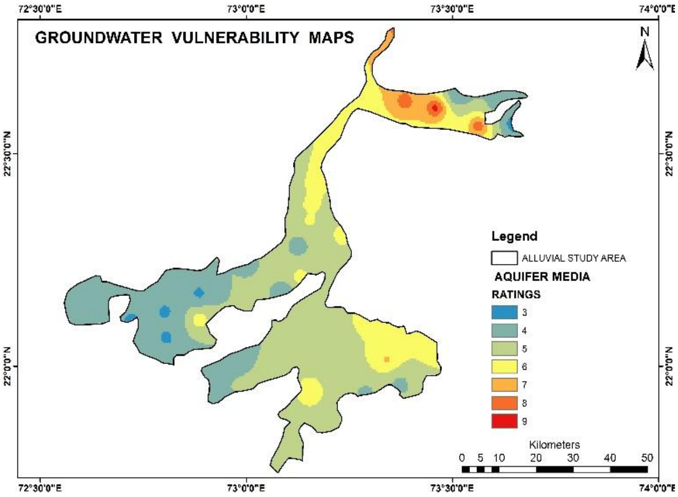


Fig 6.5 Aquifer media (Ratings)

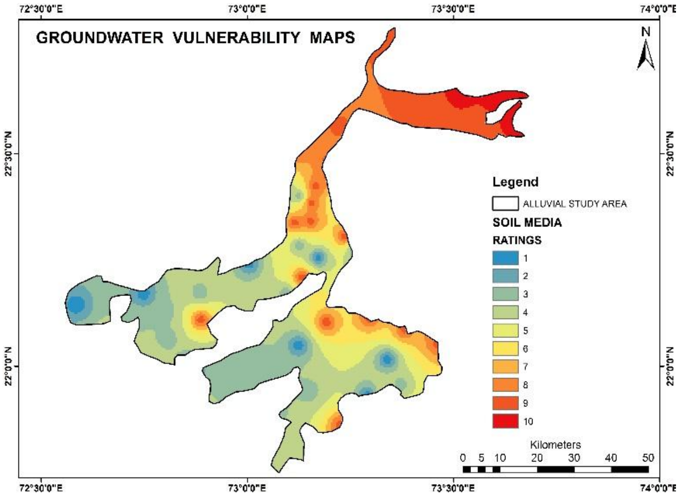


Fig 6.6 Soil media (Ratings)

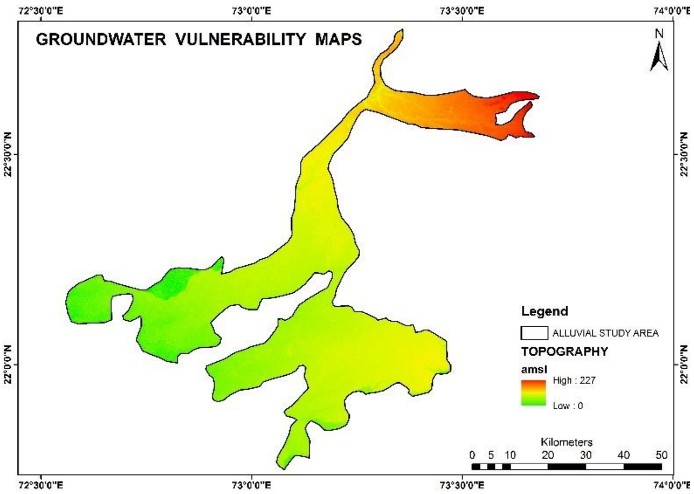


Fig 6.7 Topography (T)

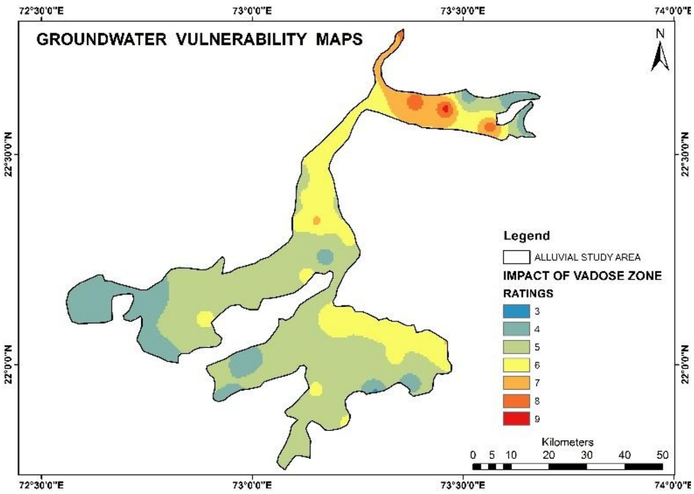


Fig 6.8 Impact of vadose zone (I)

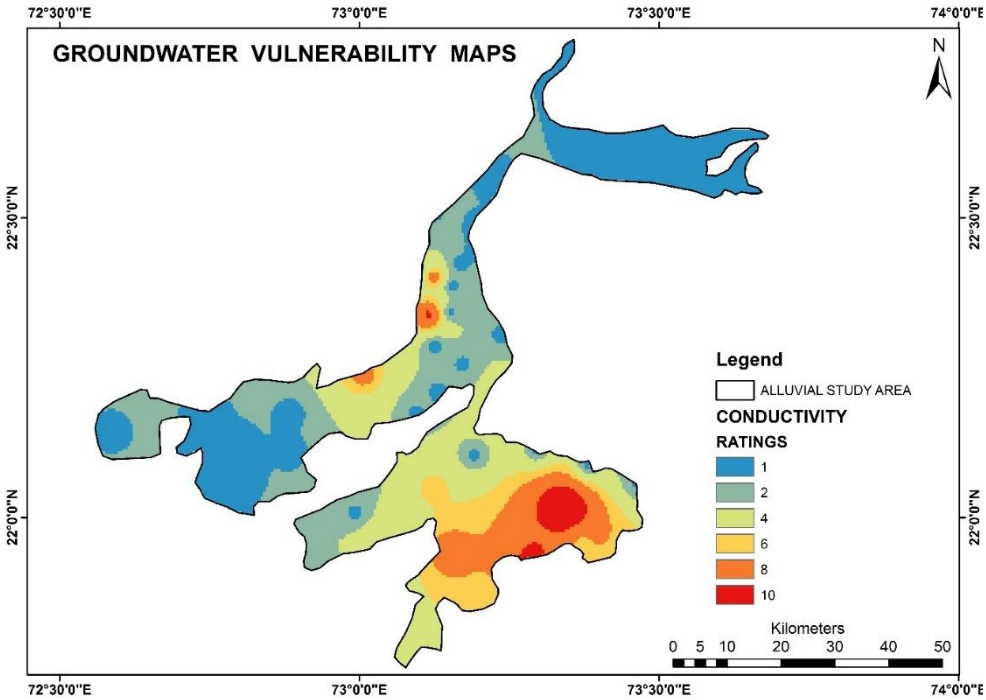


Fig 6.9 Conductivity (C)

Impact of Vadose zone

An integration of lithology and spatial distribution of depth of water table has been 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 6.2. The ratings of impact of vadose zone for present study area are shown in figure 6.8.

Hydraulic Conductivity

The representative values of hydraulic conductivity from USGS and CGWB reports have been assigned to each aquifer layer for all the available lithologs and its average value has been assigned with ratings which are in table 6.2. The spatial distribution of ratings of this parameter is shown in figure 6.9.

Table 6.1 Ratings of DRASTIC Parameters (Depth to water table, Net Recharge, Topography, Conductivity)

Depth to water table		**Net 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					-----	

Table 6.2 Ratings ® 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	Bedded limestone, sandstone, shale	6
Massive sandstone	6	Sandy loam	6	Sandstone	6
Massive limestone	6	Loam	5	Sand, gravel-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-aggregated clay	1	Karst limestone	10

6.2.2 Weights of various Parameters (Delphi Committee)

Weightage represents the relative importance or significance of each parameter in the vulnerability assessment. Parameters that have a greater influence on groundwater vulnerability are assigned higher weights, which reflect their relative contribution to the overall vulnerability index. Weightage values typically range from 1 – 5 or 1 – 10. These weights are important subjective and can be determined through expert judgment, statistical analysis or optimization techniques. Table 6.3 outline weights (W) utilized in the DRASTIC methodology according to Linda A. et al. in 1987.

Table 6.3 Weights of DRASTIC parameters by Delphi committee

DRASTIC Parameter	Weights by Delphi Committee
Depth	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of Vadose zone	5
Conductivity	3

6.2.3 Conventional DRASTIC Analysis

The conventional DRASTIC model has been attempted here to precisely verify whether it is efficient or deficient by adopting recommended weights and validation with Nitrate concentration.

Using the Model Builder dialog within the Arc-GIS environment, the above-mentioned model was constructed. The initial phase involves importing shape files such as Depth of Water, Net Recharge, Impact of Vadose Zone, Aquifer Media, Soil Media, and Topography. Subsequently, an interpolation process is executed for all parameters, except for Topography. In the case of the Topography raster file, the slope is calculated. It's important that during the slope calculation process, the output measurement part should be set to percentage rise.

The interpolation for all parameters is achieved using the Inverse Distance Weightage (IDW) method. In the subsequent step, the IDW-generated maps are transformed into rating raster files, accomplished through the application of the reclassify command within Arc-GIS. These specific ratings are mentioned in tables 6.1 and 6.2 which is suggested by Delphi Committee. The final phase involves the merge of these ratings, which are then multiplied by their respective weights are mentioned in table 6.3.

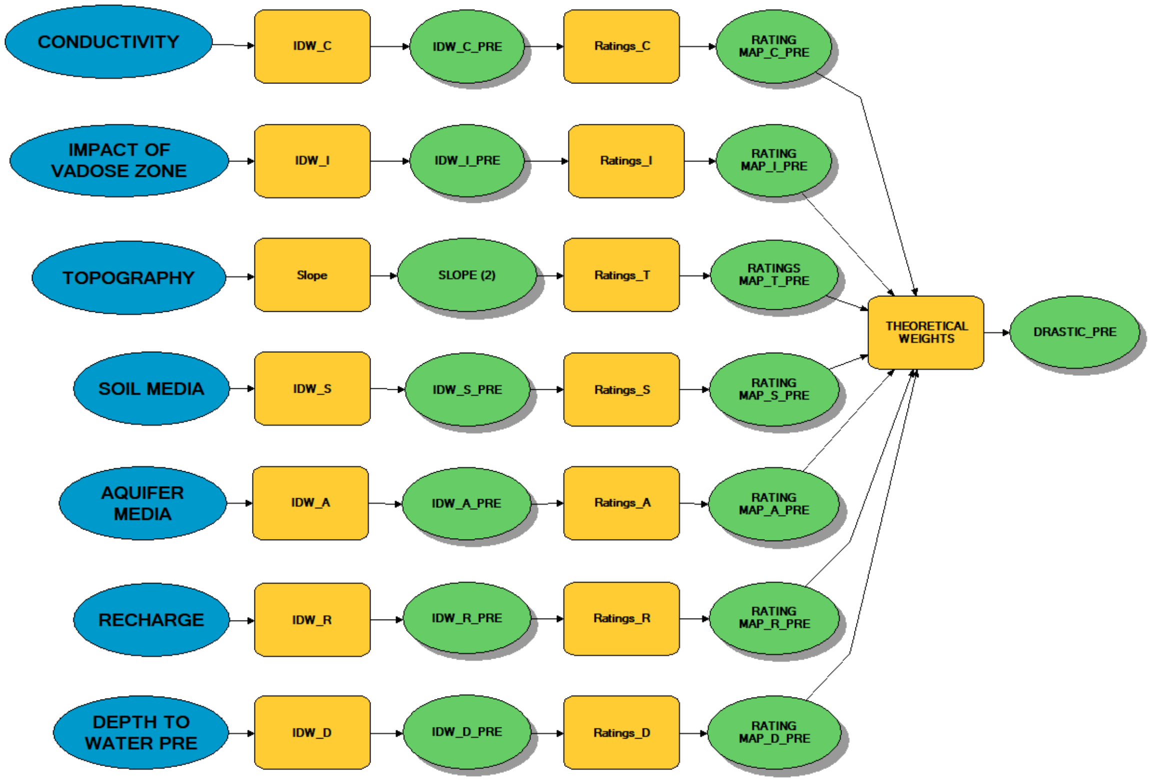


Fig 6.10 Conventional DRASTIC Model Diagram

6.2.4 DRASTIC Model Validation and Outcome

Following the integration of multiple model layers, including Depth of Water, Net Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone a DRASTIC-Index raster has been generated, as described in the figures 6.11 and 6.12.

The conventional vulnerability index spans from 63 to 155 during the pre-monsoon season and from 74 to 165 during the post-monsoon season. In the DRASTIC model (as shown in fig 6.11 and 6.12), the following classes are defined: sustainable (< 90), less vulnerable (91-110), moderately vulnerable (111-120), highly vulnerable (121-140), and severely vulnerable (>140) which is shown are table 6.4.

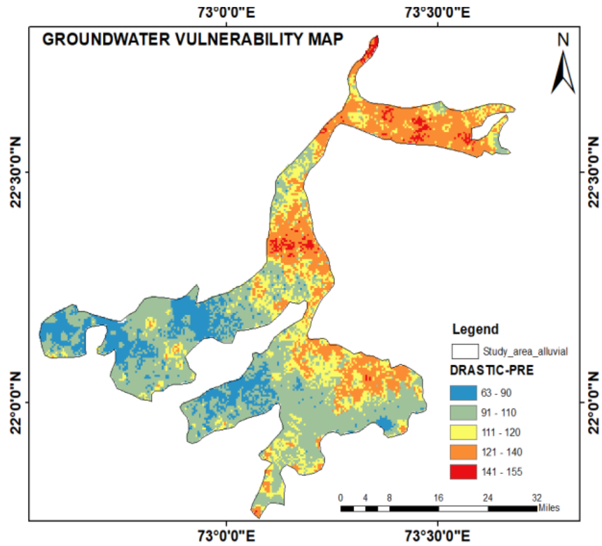


Fig 6.11 DRASTIC Vulnerability Map Pre-Monsoon

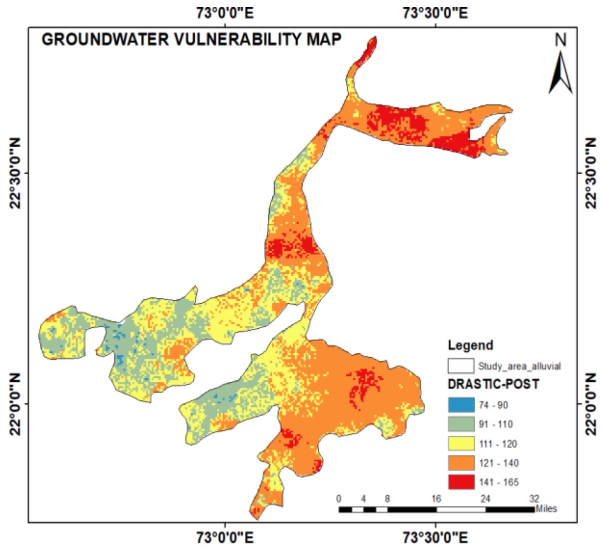


Fig 6.12 DRASTIC Vulnerability Map Post-Monsoon

Classification		**Pre-Monsoon**		**Post-Monsoon**	
		Area (Km^2)	**Area (%)**	**Area (Km^2)**	**Area (%)**
Sustainable	< **90**	382.62	14.2	15.20	0.6
Less vulnerable	**91 - 110**	1121.99	41.7	507.90	18.9
Moderately vulnerable	**110 - 120**	512.01	19.0	783.32	29.1
Highly vulnerable	**120 - 140**	619.63	23.1	1171.90	43.6
Severely vulnerable	> **140**	51.55	1.9	209.49	7.8

Table 6.4 Conventional Groundwater Vulnerability outcome in terms of % area

Model Validation

To validate the vulnerability index obtained from DRASTIC model, Nitrate concentration in groundwater of study area has been correlated with Pearson's method. 50 open and shallow wells samples obtained from MOJS-DDWAS to correlate Nitrate concentration. Usually, 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. In this study, it was assumed that the Nitrate concentration remained constant and the impact of denitrification on Nitrate concentrations was considered negligible within the range of the provided data.

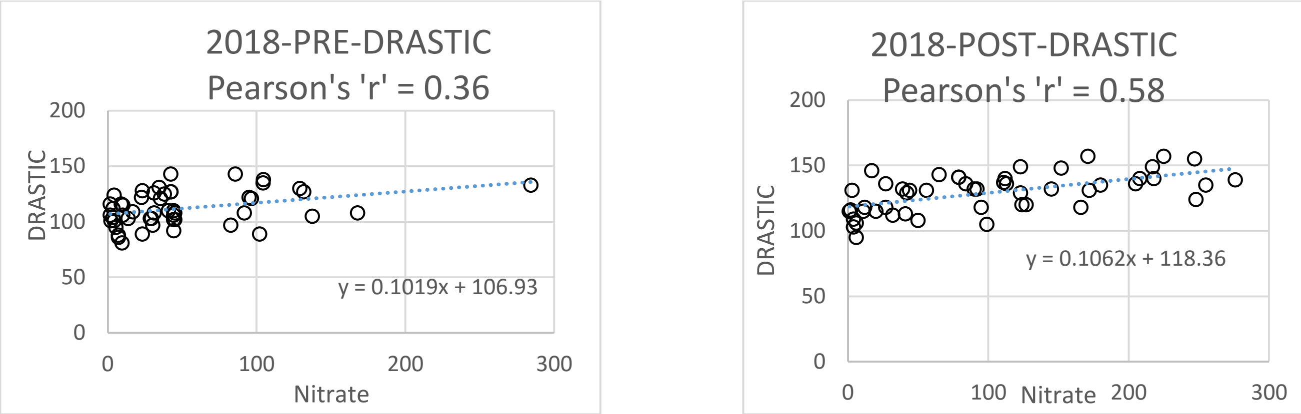


Fig 6.13 Correlation between DRASTIC and Nitrate – Pre-Post-Monsoon-2018

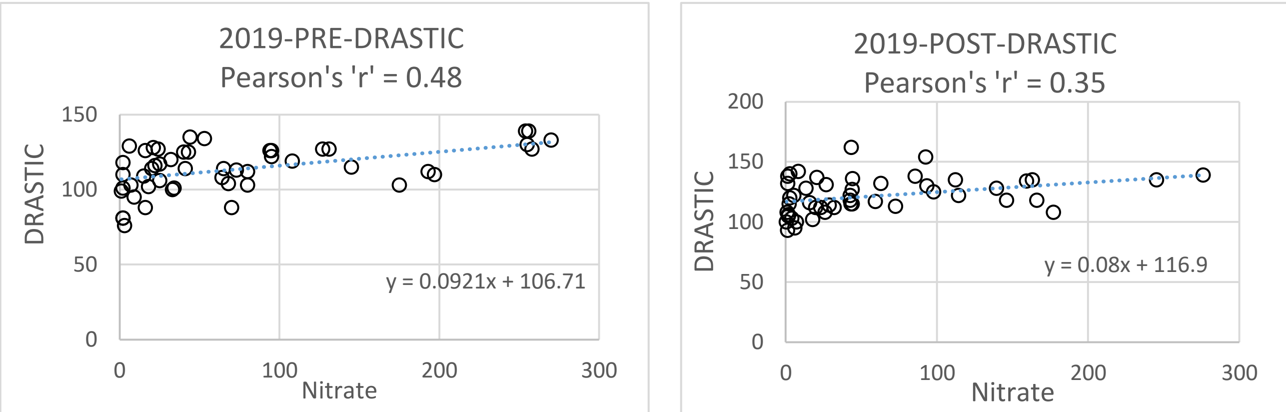


Fig 6.14 Correlation between DRASTIC and Nitrate – Pre-Post-Monsoon-2019

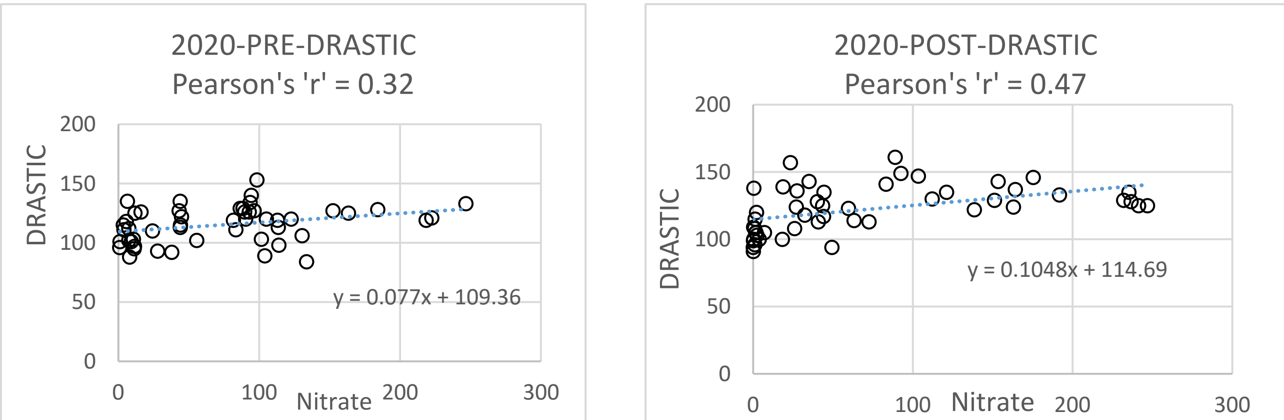


Fig 6.15 Correlation between DRASTIC and Nitrate – Pre-Post-Monsoon-2020

The results obtained from the conventional DRASTIC model indicate that, with the exception of the 2018-post monsoon season, there is no notable correlation between vulnerability parameters and Nitrate, as evidenced by the Pearson coefficient. The validation reveals the limitations of DRATIC model. Also, it has been observed that local anthropogenic activities with the study area have not been addressed by recommended 7 parameters from founder Aller Linda.

6.3 Limitations and Upgradation of Conventional DRASTIC Model

The conventional DRASTIC model, developed by Linda C. Aller and her team in 1987, has been a valuable tool for assessing groundwater vulnerability. Nevertheless, certain limitations must be acknowledged to optimize its application. Notably, the Delphi Committee-based weight assignment lacks a clear technical basis, possibly leading to inconsistent outcomes. Moreover, the model's hydrogeological focus might neglect the substantial impact of area-specific human activities on vulnerability. To enhance accuracy, introducing a parameter addressing local anthropogenic influences is essential.

6.3.1 Scope of Upgradation of Conventional DRASTIC Model

None of the geo-environmental parameter considered in vulnerability assessment is the key limitation of conventional DRASTIC method. In recent research works, modifications over conventional DRASTIC method are approached that explains the addition of anthropogenic factors in terms of Land Use changes as well as optimization of weights and ratings (Khan, et al., 2010; Shirazi, et al., 2013; Neshat et al., 2014; Alam et al., 2014; Singh et al., 2015). Groundwater quality is influenced by regional land use land cover patterns, indicating the need of LU/LC as a newly added criterion (Alam et al., 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 (Singh et al., 2015). The past research has found groundwater of urban zones to be more vulnerable to contamination. (NRC 1993; Alam et al., 2014). To overcome these issues two new parameters Factor score (FS) or External Influence (EI) are introduced in the conventional DRASTIC approach.

The outcomes of the conventional DRASTIC model have not been exhibited the significant correlation for three successive years. To fulfill this deficiency, the presence of additional parameters such as Factor Score (FS) or External Influence (EI) is deemed necessary. This will enhance the model's ability to capture the complexities in the relationship between the variables. Local objectionable anthropogenic activities' effect within the study area cannot be directly quantified but in the form of Factor Score (FS) it addresses the change in groundwater contamination. Factor Score (FS) is a composite representation of ten distinct physico-chemical parameters: pH, Total Dissolved Solids (TDS), Nitrate (NO_3), Fluoride (F), Chloride (Cl), Total Hardness (TH), Calcium (Ca), Alkalinity (ALK), Sulfate (SO_4), and Magnesium (Mg). This collective assessment of these parameters provides valuable insights into anthropogenic activities impacting the groundwater vulnerability.

Another novel parameter is External Influence (EI), summarizes the combined effects of industrial activities, Sewage Treatment Plant (STP) discharges and rural sanitation factors. By integrating these external factors into the model, a more comprehensive understanding of potential contamination sources and their influence on groundwater vulnerability is achieved.

To overcome the cited limitation of conventional DRASTIC model, there are two upgraded models are introduced in this research namely DRASTIC-FS and DRASTIC-EI.

6.3.2 ANN Optimized Weights of Parameters

Artificial Neural Networks (ANNs) are a class of machine learning models inspired by the structure and functioning of the human brain. They consist of interconnected nodes or artificial neurons organized into layers, typically an input layer, one or more hidden layers and an output layer. Each connection between neurons has a weight, and these weights are learned from data through a process called training (Yang, Z. et al., 2014).

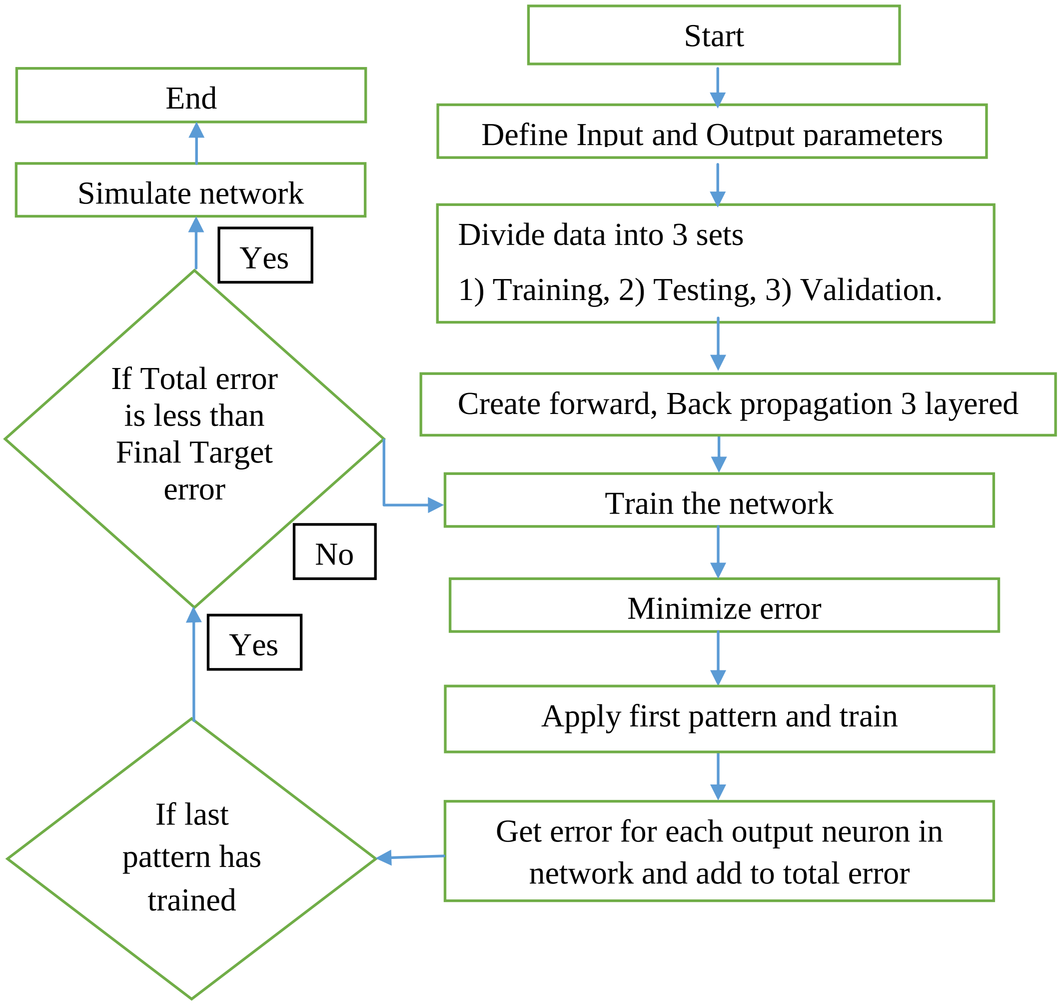


Fig 6.16 ANN Flow Chart

This Python code performs regression using a Multi-Layer Perceptron (MLP) Neural Network on a dataset. It starts by importing necessary libraries for data manipulation, machine learning and evaluation, such as Pandas, NumPy and scikit-learn. The data is then loaded from an Excel file and it is split into feature variables (X) and the target variable (y).

A train-test split is performed, with 67% of the data used for training and 33% for testing. The MLPRegressor neural network is configured with specific parameters, including the architecture of two hidden layers with 5 and 3 neurons, respectively, the maximum number of training iterations, the ReLU activation function, the Adam optimization algorithm and a convergence tolerance. The network is then trained on the training data.

After training, the neural network is used to make predictions on the test data, and these predictions are stored. The code prints the predicted values for the test data. Additionally, it calculates the average of the predicted values and rounds it to the nearest integer, printing both values. This code demonstrates a basic regression task by utilizing scikit-learn's MLPRegressor to build a neural network model, make predictions and evaluate the average prediction accuracy on a test dataset.

For such optimization, first the variable parameters have been assigned with factors on which they are depending. Then, the ratings of variable parameters and accompanying factors have been extracted for each cell of present study area which have been taken as input of the ANN model. This dataset has been divided into three parts namely, Training, Testing and Validation. Finally, ANN optimized weights mentioned in the following table 6.5 have been considered in the groundwater vulnerability assessment. The Python code has been utilized to generate the individual weights for an Artificial Neural Network (ANN), with a particular instance related to the depth to water (D) shown in Figure 6.17.

Table 6.5 ANN weight optimization

Parameters	**ANN weight optimization based on following factors**	**ANN Weights-Pre**	**ANN Weights-Post**
Depth (D)	Recharge, Aquifer media, Soil media, Topography, Vadose zone, Conductivity	3.8	4.3
Recharge (R)	Soil media, Topography, Vadose zone, LULC	5.2	7.9
Aquifer Media (A)	Constant parameters: ANN weights same as Theoretical weights of Delphi Committee (Linda Aller, 1985)	3.0	3.0
Soil Media (S)		2.0	2.0
Topography (T)		1.0	1.0
Impact of Vadose zone (I)	Depth, Recharge, Aquifer media, Soil media	5.2	5.2
Conductivity (C)	Depth, Recharge, Aquifer media, Vadose zone	3.3	3.1
Factor-Score (FS)	pH, TDS, NO_3, F, Cl, SO_4, Ca, Mg, TH, ALK	3.8	4.8
External Influence (EI)	Industry's location and distance to water body, Sewage Treatment Plant and Rural Sanitation	3.9	5.1

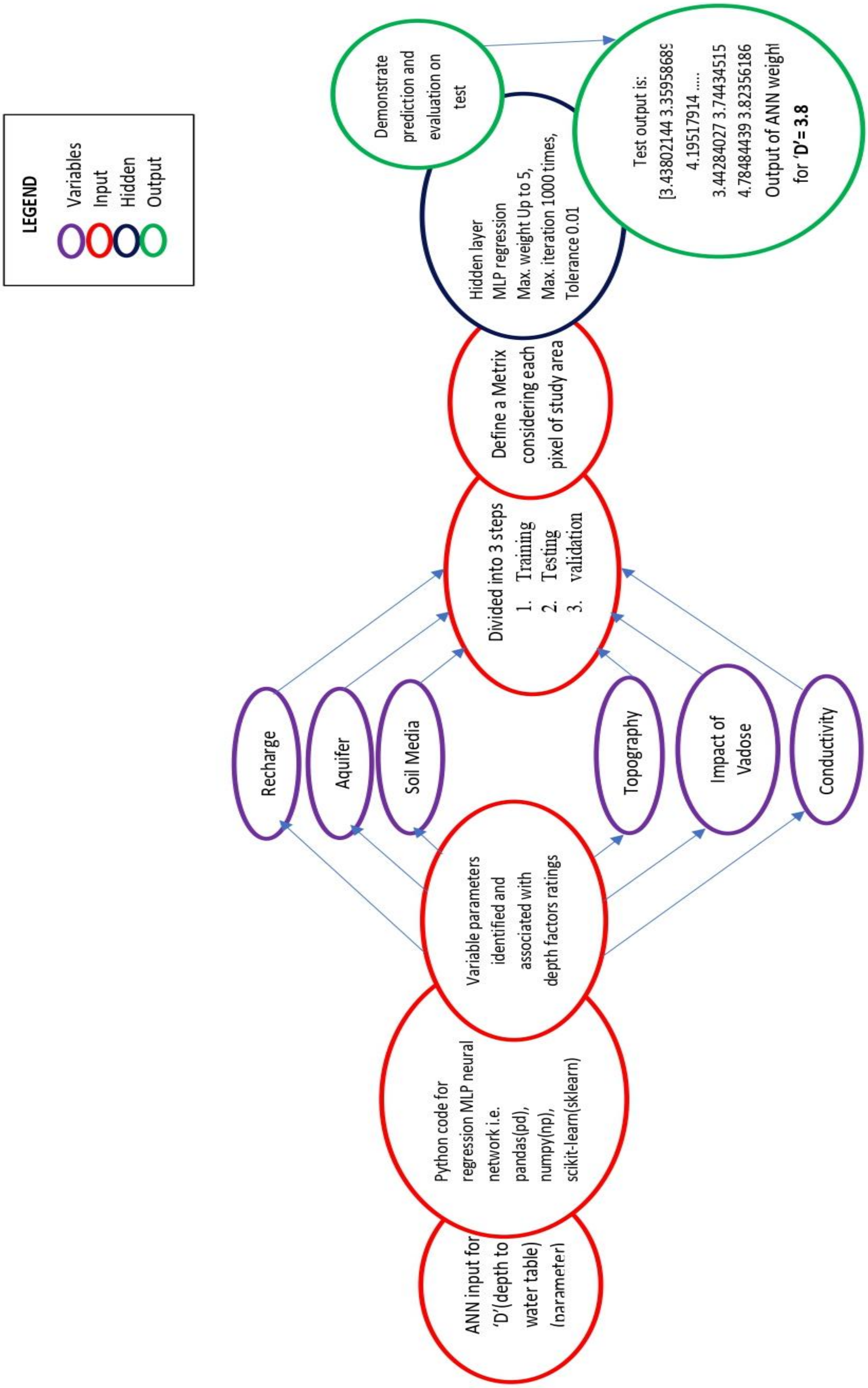


Fig 6.17 Graphical illustration of the ANN architecture

6.4 DRASTIC-FS Model (Modified Approach)

In this DRASTIC-FS Approach (Figure 6.18), in addition of DRASTIC model, a new parameter is introduced which is termed as Factor Score (FS). The direct quantification of the impact of local objectionable anthropogenic activities within the study area is responsible to make the groundwater vulnerable to contamination. This phenomenon has been addressed in the form of Factor Score (FS).

The FS parameter has been obtained using multivariate statistical techniques, Principal Component Analysis (PCA) performed on secondary groundwater quality data (MOJS-DDWAS) of the time period 2018. The initially assigned weight significance of this layer is (W=5). The formula for DRASTIC-FS index is as below:

$$\text{DRASTIC-FS Index} = \text{DRASTIC Index (Di)} + FS_r FS_w \quad (3)$$

Where, FS = Factor Score

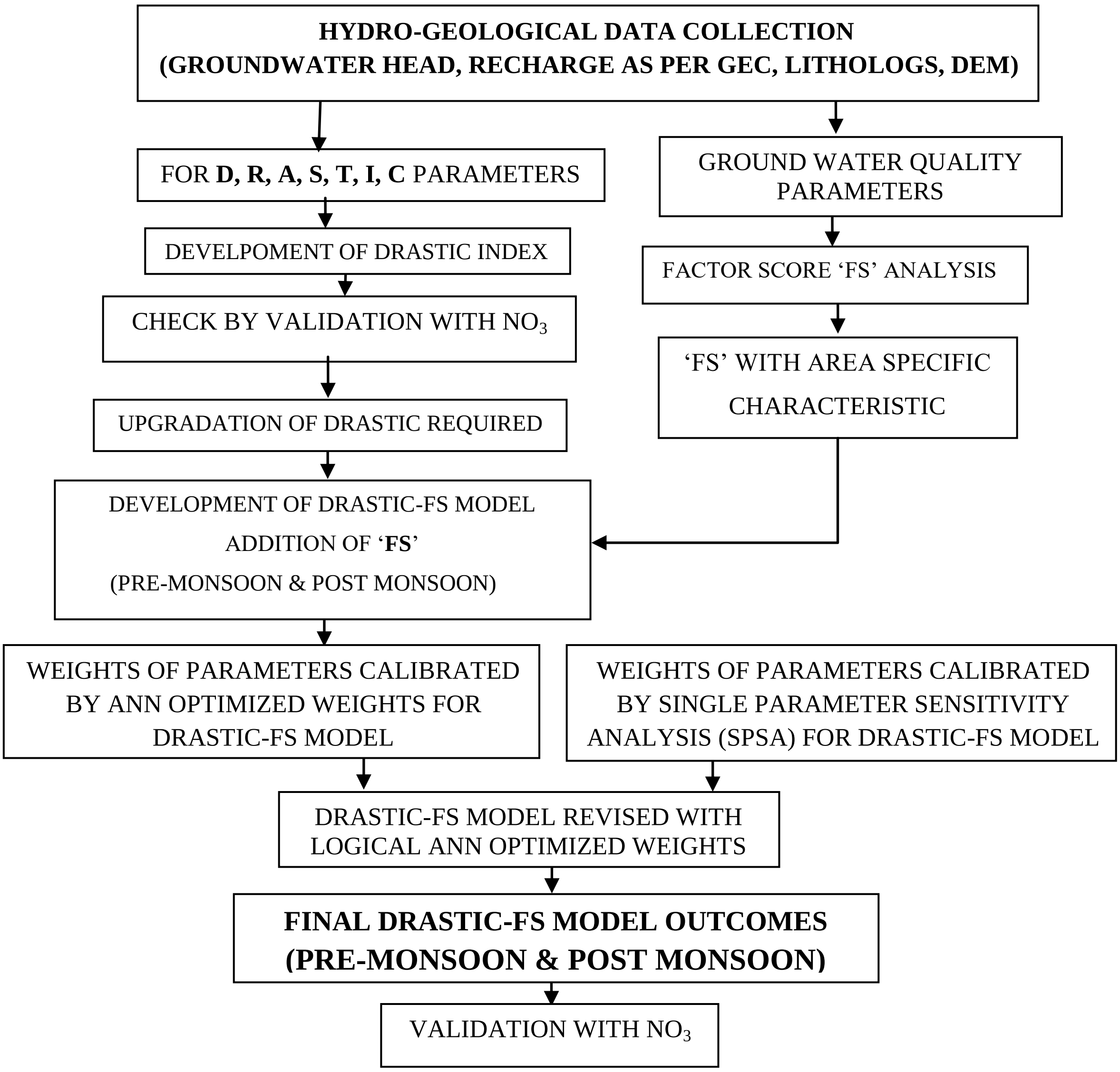


Fig 6.18 DRASTIC-FS Approach

DRASTIC-FS model has been developed using model builder in GIS environment in which three processes take place. First process is to input model parameters which are D, R, A, S, T, I, C, and 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 has been used.

6.4.1 Rating of New Parameter (FS)

The ratings for the factor scores (FS) are provided in Table 6.6, where it is clearly stated that higher factor scores correspond to higher ratings for the FS parameter in this study. This relationship between factor scores and ratings is visually represented in Figure 6.19 and Figure 6.20, which illustrate the FS parameter for both the pre-monsoon and post-monsoon seasons.

Table 6.6 'FS' Parameter Ratings

Sr. No.	Factor Score Range	Ratings (1-10)
1	0 to 0.5	1
2	0.5 to 0.75	5
3	0.75 to 2.0	
	[0.75-1.00]	6
	[1.00-1.25]	7
	[1.25-1.50]	8
	[1.50-2.00]	9
4	>2.0	10

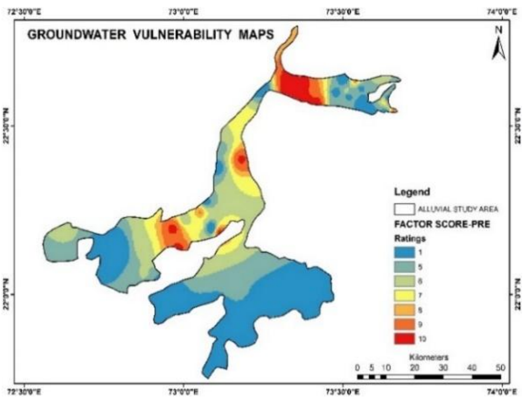


Fig 6.19 FS parameter Map Pre Monsoon

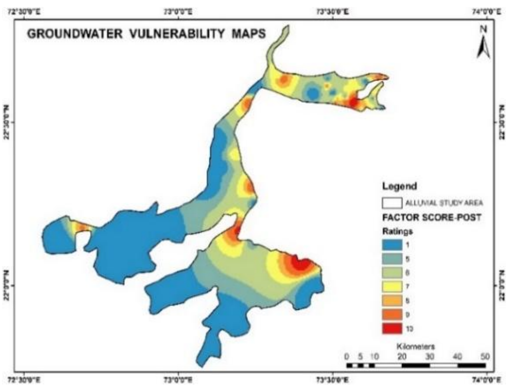


Fig 6.20 FS parameter Map Post Monsoon

Factor scores (FS) were calculated through Hierarchical Cluster Analysis (HCA) using the 2018 pre and post-monsoon water quality data (MOJS-DDWAS). The analysis revealed that the sources of contamination can be attributed to anthropogenic or Geogenic factors or combination of both anthropogenic and Geogenic.

6.4.2 DRASTIC-FS Analysis

In order to enhance the conventional model, specific enhancements are deemed necessary. As part of this improvement, the Factor Score (FS) parameter is introduced as the eighth component within the DRASTIC model framework (Figure 6.21). The concept of Factor Score has been briefly explained in Chapter 5, it is defined as a composite representation of the 10 groundwater quality parameters, achieved through the application of Principal Component Analysis (PCA).

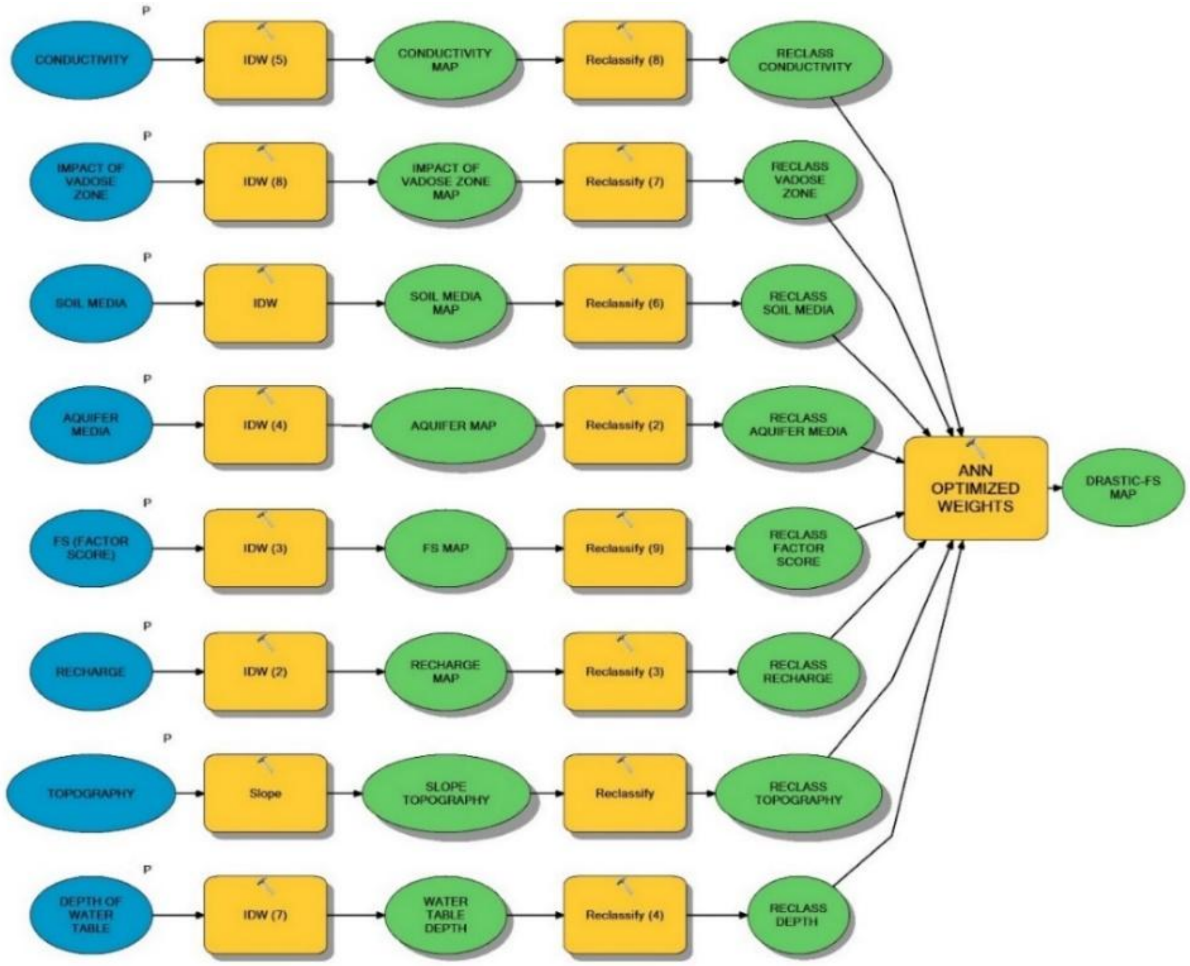


Fig 6.21 DRASTIC-FS Model Diagram

Single Parameter Sensitivity Analysis (SPSA)

Groundwater vulnerability maps generated from such models are said to be subjective as the weights and ratings assigned to parameters during 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 T. et al., 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 SPSA (Napolitano and Fabbri, 1996) as discussed below. This method finds the importance of single individual parameter on overall Vulnerability map while comparing 'theoretical' and 'effective' weights of each parameter. The measures of effective weight and Percent Deviation (PD) are formulated below.

$$We = [(\mathrm{Pr} * Pw)/Vi] * 100 \quad (4)$$

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

$$Mean\ Percentage\ Deviation\ (PD) = \left[\frac{We - Wt}{Wt}\right] * 100 \quad (5)$$

Where, We = Effective weight, Wt = Theoretical weight

DRASTIC-FS Single Parameter Sensitivity Analysis

From Single Parameter Sensitivity Analysis (tables 6.7 and 6.8), Recharge and Impact of Vadose zone 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 PD (%) of Impact of Vadose zone and Aquifer media are very less which highlighted their importance in producing accurate results. The combined consideration of effective weight and error in Conductivity and Recharge parameters highlighted obtaining accurate and detailed representative values.

Table 6.7 Single Parameter Sensitivity Analysis (FS) – Pre-Monsoon

Para.	Theoretical Weight	Theoretical Weight (%)	Effective Weight	ANN Optimized Weight	Effective Weight (%)				PD (%)	% Error bet. EW and ANN Weights
					Mean	Min	Max	St. Dev.		
D	5	17.9	4.16	3.8	14.84	3.62	32.89	5.28	16.88	-9.47
R	4	14.3	4.40	5.2	15.71	2.80	35.29	6.34	9.96	15.38
A	3	10.7	3.24	3.0	11.58	6.57	18.75	2.27	8.12	-8
S	2	7.14	2.18	2.0	7.77	1.32	20.62	2.88	8.84	-9
T	1	3.57	1.37	1.0	4.91	0.53	12.82	2.62	37.45	-37
I	5	17.9	5.62	5.2	20.08	11.70	33.33	3.40	12.42	-8.07
C	3	10.7	2.30	3.3	8.22	1.52	32.26	6.56	23.25	30.30
FS	5	17.9	4.73	3.8	16.88	3.33	40.65	10.71	5.47	-24.47
Total	28	100	28	--	100	-------				

Table 6.8 Single Parameter Sensitivity Analysis (FS) - Post-Monsoon

Para.	Theoretical Weight	Theoretical Weight (%)	Effective Weight	ANN Optimized Weight	Effective Weight (%)				PD (%)	% Error bet. EW and ANN Weights
					Mean	Min	Max	St. Dev.		
D	5	17.86	4.3	4.3	15.35	3.4	25.7	3.1	14.11	0.00
R	4	14.29	6.0	7.9	21.30	2.9	35.3	3.7	48.90	24.05
A	3	10.71	3.0	3.0	10.55	5.8	18.3	1.6	1.66	0.00
S	2	7.14	2.0	2.0	7.19	1.2	20.6	2.9	0.50	0.00
T	1	3.57	1.3	1.0	4.47	0.5	11.8	2.3	25.03	-30.00
I	5	17.86	5.1	5.2	18.34	11.2	35.7	2.6	2.58	1.92
C	3	10.71	2.0	3.1	7.04	1.5	23.6	5.0	34.35	34.37
FS	5	17.86	4.4	4.8	15.88	2.6	51.5	9.9	11.19	8.33
Total	28	100	28		100	-------				

Fig. 6.22 indicates that due to area specific variation, theoretical weights of all DRASTIC parameters vary against the effective weights. It reflects the limitation of DRASTIC method and required to modify the weight as well as addition of new parameter which represents the local anthropogenic activities.

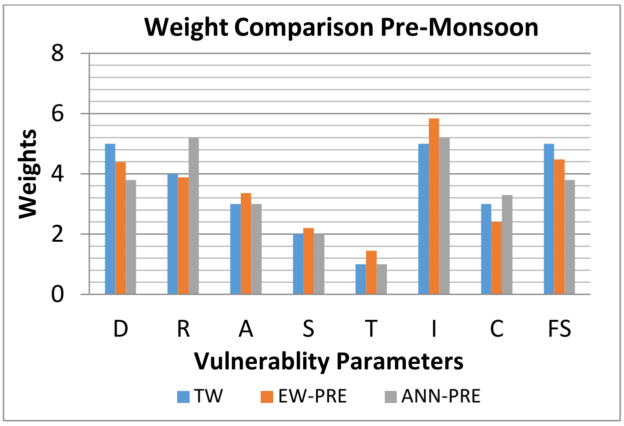


Fig 6.22 DRASTIC-FS Weights Comparison (Pre)

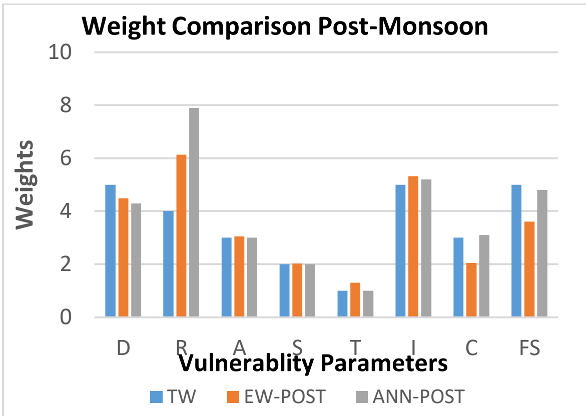


Fig 6.23 DRASTIC-FS Weights Comparison (Post)

The fig. 6.23 of Upgraded DRASTIC parameters weight assignment has not shown any variation between Theoretical weight and Effective weight of A (Aquifer media), S (Soil media), T (Topography) and I (Impact of Vadose zone). But there has been considerable variation noticed in Depth to water and Net Recharge due to hydrogeological characteristic of alluvial region of study area. 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 is increased in computation of vulnerability index. If any specific vulnerable anthropogenic/geogenic phenomena is observed than the impact must be incorporated with introduction of new parameters. In present study, Factor Score is introduced with initial theoretical weight 5 and nearly matched with effective weight 3.8 (Pre) and 4.8 (Post) based on single parameter sensitivity analysis.

6.4.3 DRASTIC-FS Model Validation and Outcome

Final outcome of the model comes in the form of a Vulnerability map classified in Sustainable, Less Vulnerable, Moderately Vulnerable, Highly Vulnerable and Severely Vulnerable classes. The DRASTIC-FS (ANN weights) model final vulnerability index (fig. 6.24 and 6.25) is mapped from 65 to 198 in that, sustainable (65-120), less vulnerable (120.1-140), moderately vulnerable (140.1-160), highly vulnerable (160.1-190) and severely vulnerable (190.1-198) are representative classes.

The distribution of study area (%) in each vulnerability class of the model (DRASTIC-FS) for both seasons (Pre and Post Monsoon) is shown below in table 6.9. The results from sustainable class show marginal decrease in percent (%) area for both the seasons. In pre monsoon season, less and moderately vulnerable classes show decrease and highly and severely vulnerable classes show increase in percent (%) area. In DRSTIC-FS post monsoon season, it has been observed that less and moderately vulnerable classes show increase in percent (%) area and highly vulnerable class show decrease in percent (%) area. This is because of higher infiltration rates and groundwater recharge in alluvial region resulting reduction of highly and severely vulnerable area significantly.

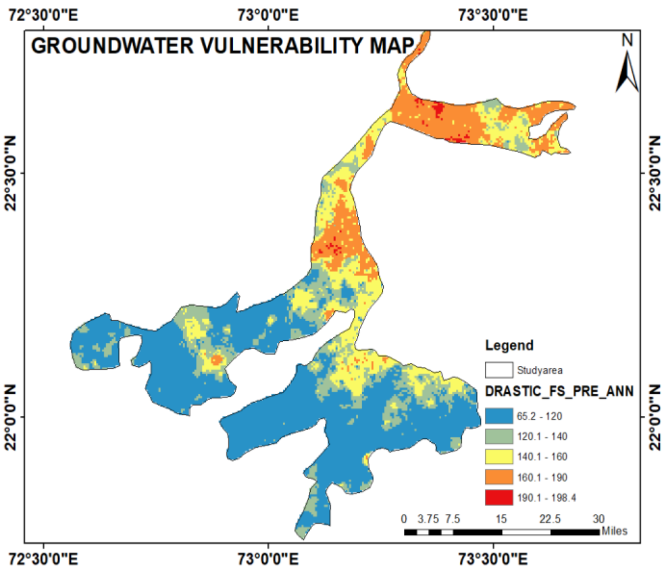


Fig 6.24 DRASTIC-FS Map Pre-Monsoon

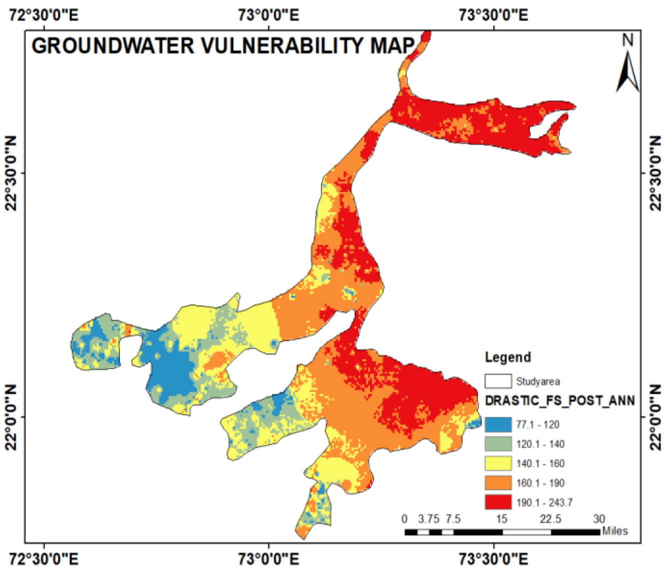


Fig 6.25 DRASTIC-FS Map Post-Monsoon

Table 6.9 Groundwater Vulnerability outcome in terms of % area

Classification		DRASTIC-FS (Pre)	DRASTIC-FS (Post)
Sustainable	**< 120**	49.55	7.19
Less Vulnerable	**120 – 140**	17.96	12.21
Moderately Vulnerable	**141 – 160**	17.57	20.56
Highly Vulnerable	**161 – 190**	14.26	32.82
Severely Vulnerable	**> 190**	0.66	27.22

The basic statistical summary of DRASTIC-FS model (pre-monsoon) is given below (table 6.10 and 6.11) 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 the variability of groundwater vulnerability for the study region. Final outcomes from aforementioned both the models are in terms of maps representing vulnerability index of groundwater prone to contamination.

Table 6.10 Statistical summary of Ratings assigned in DRASTIC-FS model - Pre-Monsoon

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

Table 6.11 Statistical summary of Ratings assigned in DRASTIC-FS model - Post-Monsoon

Post-Monsoon	Depth	Recharge	Aquifer	Soil	Topography	Impact of Vadose Zone	Conductivity	Factor score
Average	4.39	7.99	5.02	5.20	6.34	5.23	3.38	4.59
Minimum	1.00	1.00	3.00	1.00	1.00	3.00	1.00	1.00
Maximum	7.00	9.00	9.00	10.00	10.00	9.00	10.00	10.00
St. Dev	0.963	1.468	0.879	2.26	3.22	0.82	2.46	2.91
CV (%)	21.95	18.38	17.52	43.4	50.7	15.6	72.93	63.27

DRASTIC-FS Model Validation

The correlation outcomes for the DRASTIC-FS Model using both Effective Weights (EW) and Artificial Neural Networks (ANN) Weights are shown in Figures 6.26 to 6.28. A Pearson's correlation coefficient 'r' was 0.56 between Nitrate and 2018-PRE-DRASTIC-FS Vulnerability Index, 0.65 between Nitrate and 2019-PRE-DRASTIC-FS Vulnerability Index, 0.50 between Nitrate and 2020-PRE-DRASTIC-FS Vulnerability Index, which validated the DRASTIC-FS model for Alluvial region between Mahi and Narmada rivers, India.

Similarly, a Pearson's correlation coefficient 'r' was 0.69 between Nitrate and 2018-POST-DRASTIC-FS Vulnerability Index, 0.50 between Nitrate and 2019- POST-DRASTIC-FS Vulnerability Index, 0.67 between Nitrate and 2020- POST-DRASTIC-FS Vulnerability Index, which validated the DRASTIC-FS model for Alluvial region between Mahi and Narmada rivers, India.

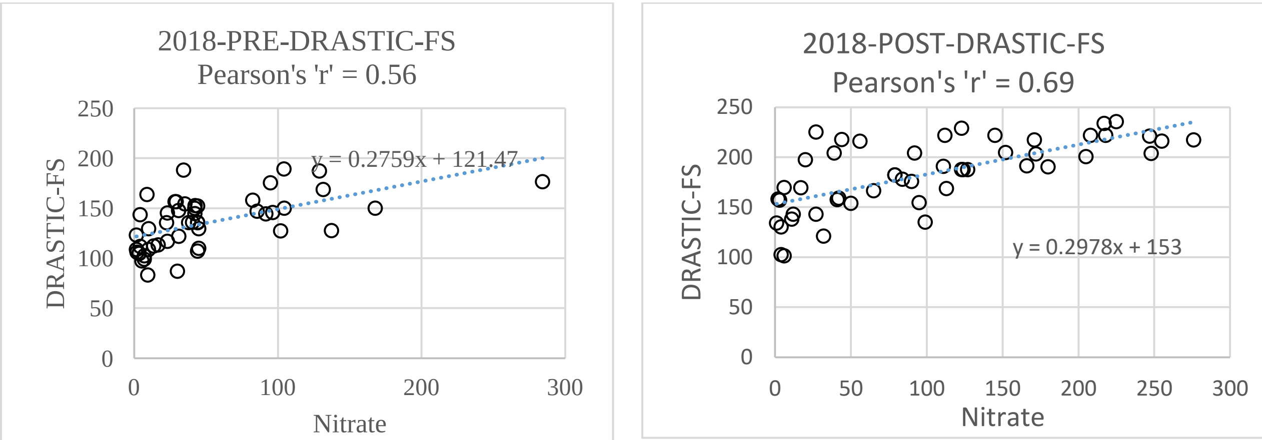


Fig 6.26 Correlation between DRASTIC-FS and Nitrate – Pre-Post-Monsoon-2018

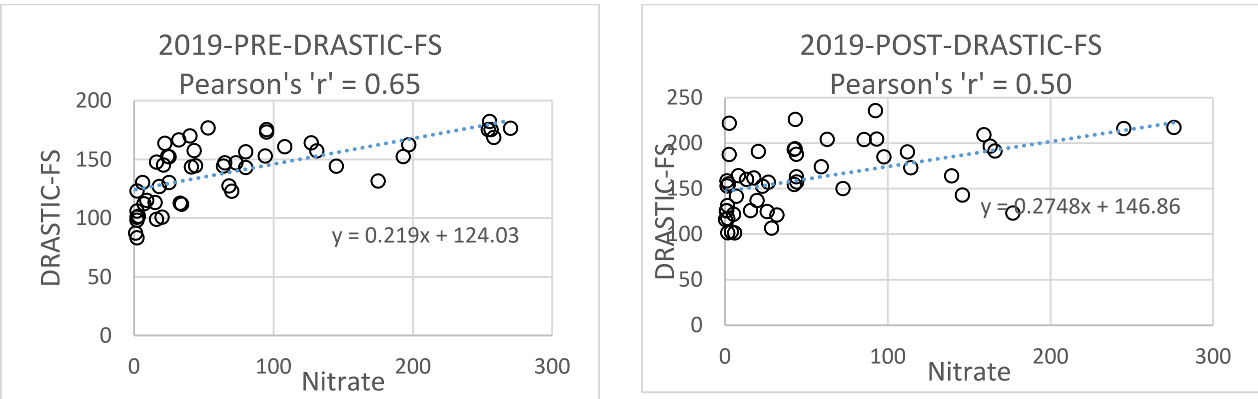


Fig 6.27 Correlation between DRASTIC-FS and Nitrate – Pre-Post-Monsoon-2019

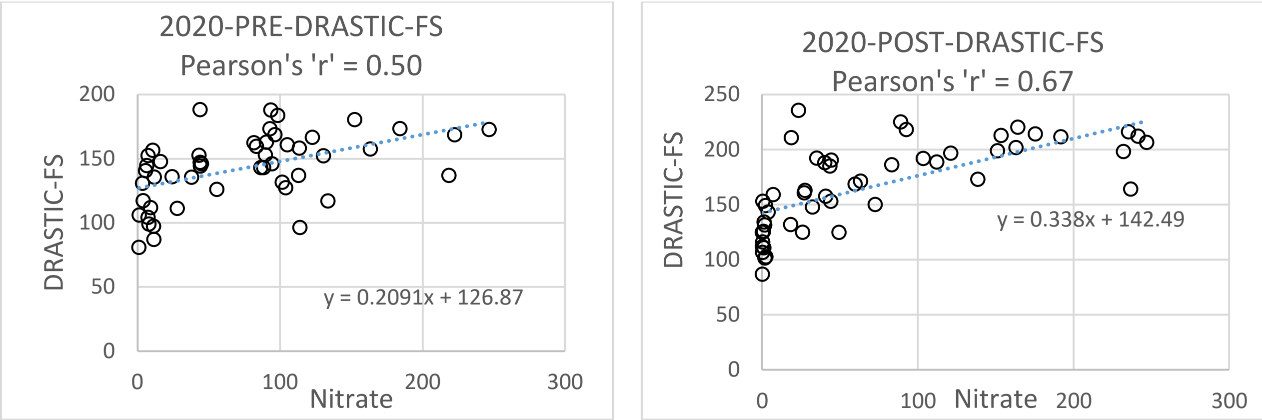


Fig 6.28 Correlation between DRASTIC-FS and Nitrate – Pre-Post-Monsoon-2020

6.5 DRASTIC-EI Model (Modified Approach)

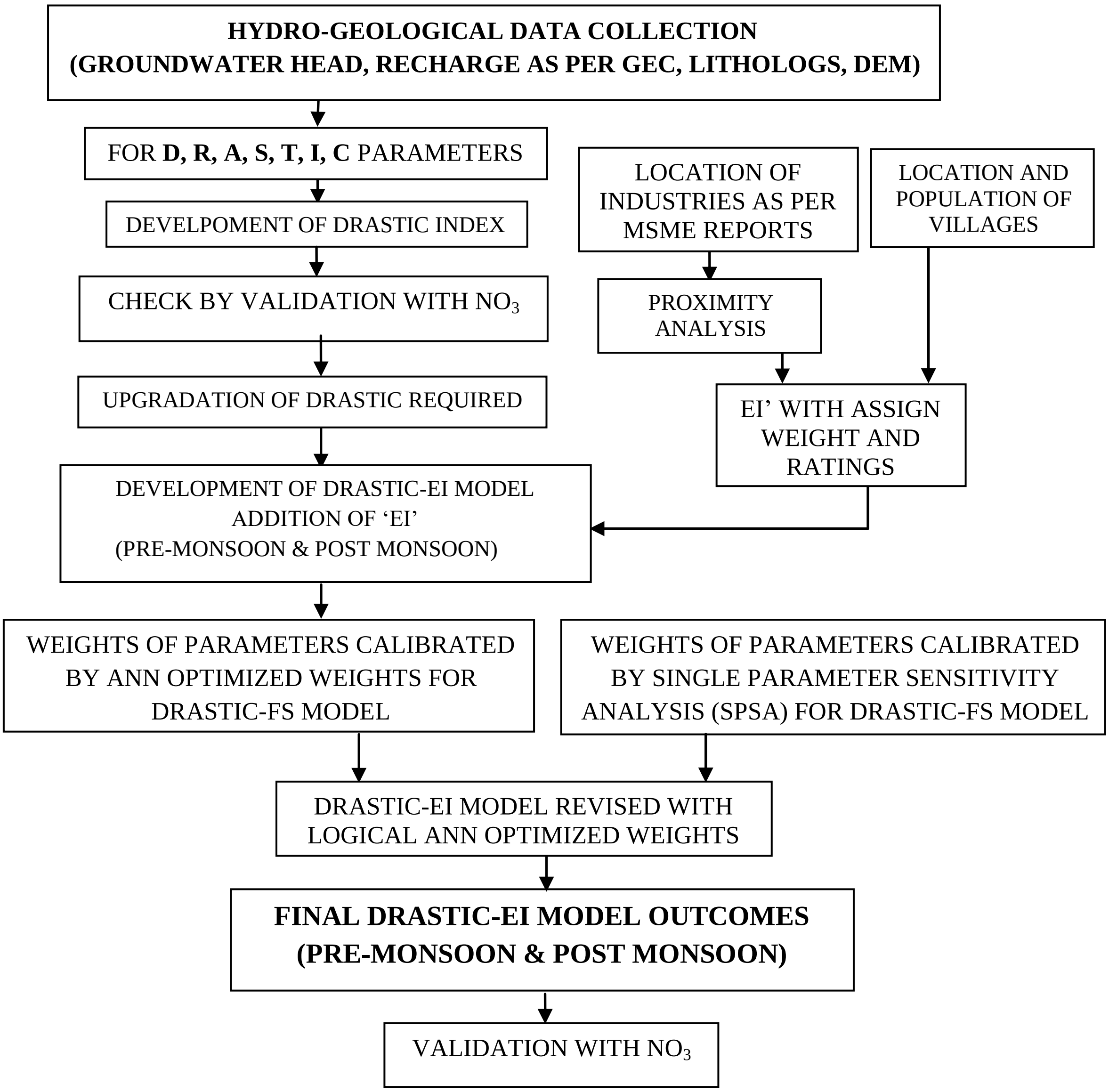


Fig 6.29 Methodology-Flow chart of DRASTIC-EI model

In this DRASTIC-EI Approach (Figure 6.29), in addition to DRASTIC model, a new parameter is introduced which is termed as External Influence (EI). Contaminants of groundwater quality for each well locations with the source represents of contamination in terms of Rural sanitation, Industrial bases and STPs (Sewage Treatment Plant). The initially assigned weight significance of this layer is (W=5). The formula for DRASTIC-EI index is as below:

$$\text{DRASTIC-EI Index} = \text{DRASTIC Index (Di)} + EIrEIw \qquad (6)$$

Where, EI = External Influence

6.5.1 Rating of New Parameter (EI)

The External Influence (EI) are combination of three factors which lead to increase contamination in the study area (Figure 6.30). The EI parameter depends on type and volume of industries, STPs (Sewage Treatment Plants) and rural sanitation. Industrial and STP raster analysis was carried out with the help of nearby industrial locations. Proximity analysis has been performed in the Arc-GIS environment to determine how close or far away industries are from any surface bodies (such as surface water bodies, water conservation structures and tanks and ponds), as shown in table 6.14. In proximity analysis, it is considered that industries higher rating is attained when industries are located less than 1.5 kilometers. Rating for Industrial and STPs raster wasn't changed during post-monsoon season.

Simultaneously raster of village population has been prepared which rating has only given to the rural part of the study area. In rural sanitation raster, urban zone lies in the study area provide with 0 rating. The probability of contaminants spread is considered to be higher in the post-monsoon season due to groundwater recharge, hence the rating is higher than in the post-monsoon season which mention in table 6.13.

Table 6.12 Rating of Location of Industries & STPs

Industrial Class and Ratings	**For both Pre and Post Monsoon**	
Type of Industry	Near To WB (0 to 1.5 Km)	Far From WB (> 1.5 Km)
Textile	3	1
Paper-Rubber-Plastic-Glass	5	2
Mech. Elec. Products	7	4
Agricultural Products-Pharmaceutical Industry	9	6
Petro-Chemicals-Minerals-Construction and STPs	10	8

Table 6.13 Ratings of Rural Sanitation

Rural Sanitation due to Population (Person)	**Rating (Pre-Monsoon)**	**Rating (Post-Monsoon)**
1 – 100	2	3
100 – 500	4	5
500 – 3000	6	7
3000 – 5000	8	9
5000+	9	10

Table 6.14 Proximity Analysis for Industries and STPs

(Far to the water bodies {> 1.5 km}, Near to the bodies {≤ 1.5 km})

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
1	20 Micron Ltd., Vadodara	Minerals & Specialty Chemicals Manufacturer	Petro-Chemicals-Minerals-Construction	2.30	2.28	2.00	2.00	Far	8
2	Abb Ltd, Vadodara	Electrical Equipment Manufacturing	Mech. Elec. Products	0.51	1.25	2.36	0.51	Nr	7
3	Alstom Projects India Ltd., Vadodara	Construction Company	Petro-Chemicals-Minerals-Construction	0.51	1.24	2.36	0.51	Nr	10
4	Amoli Organics P. Ltd., Vadodara	Pharmaceutical Industry	Agricultural Products-Pharmaceutical Industry	0.59	2.05	0.73	0.59	Nr	9
5	Apollo Tyres Ltd., Vadodara	Tyre	Paper-Rubber-Plastic-Glass	0.51	1.25	2.36	0.51	Nr	5
6	Asta India Ltd., Vadodara	Winding Wire	Mech. Elec. Products	3.66	8.37	5.43	3.66	Far	4
7	Ashwin Vanaspati Industries Ltd., Vadodara	Refined Oils (Maize Oil And Coconut Oil)	Agricultural Products-Pharmaceutical Industry	1.32	1.76	2.50	1.32	Nr	9
8	Benzo Petro International Ltd., Vadodara	Chemical Products (Aromatics, Intermediates, Solvents And Polymers)	Petro-Chemicals-Minerals-Construction	0.51	1.24	2.36	0.51	Nr	10
9	Baroda Vessels P. Ltd., Vadodara	Pharmaceutical Medicines	Mech. Elec. Products	2.50	3.32	1.60	1.60	Far	6
10	Biotor Industries Ltd., Vadodara	Pharmaceutical Products	Agricultural Products-Pharmaceutical Industry	0.49	1.24	2.34	0.49	Nr	9
11	Bombardier India Ltd., Vadodara	Textiles	Textile	2.17	8.34	2.80	2.17	Far	1
12	Cadila Health Care Ltd., Vadodara	Pharmaceutical Products	Agricultural Products-Pharmaceutical Industry	0.47	1.33	2.36	0.47	Nr	9
13	Cosmos Films Ltd., Vadodara	Packaging Films	Paper-Rubber-Plastic-Glass	2.47	4.37	0.60	0.60	Nr	5
14	Crompton Greaves Ltd., Vadodara	Power Transmission And Distribution, Industrial Automation	Mech. Elec. Products	0.44	1.28	2.32	0.44	Nr	7
15	Emco Ltd., Vadodara	Power Transformers, Distribution Transformers, Switchgear	Mech. Elec. Products	0.50	1.24	2.36	0.50	Nr	7

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
16	Gas Authority Of India, Vadodara	Liquefied Petroleum Gas (Lpg), Propane, Butane, Natural Gas Liquids	Petro-Chemicals-Minerals-Construction	0.51	1.25	2.36	0.51	Nr	10
17	Gsfc Ltd., Vadodara	Fertilizers, Chemicals, Petrochemicals, Plastics, And Textiles.	Petro-Chemicals-Minerals-Construction	0.50	1.24	2.36	0.50	Nr	10
18	Gujarat Adani Energy Ltd., Vadodara	Gas Distribution Network	Petro-Chemicals-Minerals-Construction	0.50	1.25	2.36	0.50	Nr	10
19	Kaps, Vadodara	Plastics	Paper-Rubber-Plastic-Glass	1.60	7.26	1.58	1.58	Far	2
20	Inox Air Products Lab., Vadodara	Industrial Gases, Oxygen, Nitrogen, Argon, Helium And Carbon Dioxide	Petro-Chemicals-Minerals-Construction	2.43	2.85	1.37	1.37	Nr	10
21	Jct Electronics Ltd., Vadodara	Televisions, Audio Systems	Mech. Elec. Products	1.68	1.64	2.27	1.64	Far	4
22	Indian Oil Corporation Ltd., Vadodara	Gasoline, Diesel, Kerosene, Lpg, Naphtha	Petro-Chemicals-Minerals-Construction	0.50	1.25	2.35	0.50	Nr	10
23	Jyoti Ltd., Vadodara	Pumps, Valves, Hydro Turbines	Mech. Elec. Products	0.50	1.24	2.36	0.50	Nr	7
24	Kemrock Industries & Export Ltd., Vadodara	Fiberglass Reinforced Plastic (Frp), Composites	Paper-Rubber-Plastic-Glass	2.15	2.17	2.17	2.15	Far	2
25	Larsen & Toubro Ltd., Vadodara	Reactors, Heat Exchangers, Pressure Vessels, Oil And Gas	Petro-Chemicals-Minerals-Construction	0.50	1.25	2.36	0.50	Nr	10
26	Kiri Dyes & Chemicals, Vadodara	Dyes, Pigments, Paper, Leather, Plastics	Textile	0.51	1.25	2.36	0.51	Nr	3
27	Gujarat Industries & Power Ltd., Vadodara	Papers	Paper-Rubber-Plastic-Glass	0.92	1.46	1.36	0.92	Nr	5
28	Panoli Intermediates (India), Vadodara	Pharmaceuticals, Agrochemicals	Agricultural Products-Pharmaceutical Industry	3.12	3.13	1.62	1.62	Far	6
29	Petro Net Lng Ltd., Vadodara	Lng (Liquified Natural Gas) Distribution	Petro-Chemicals-Minerals-Construction	0.50	1.24	2.36	0.50	Nr	10
30	Reliance Industries, Vadodara	Polyethylene, Polypropylene, PVC	Petro-Chemicals-Minerals-Construction	1.84	5.91	1.41	1.41	Nr	10
31	Sabic Innovative Plastics India Ltd., Vadodara	Plastic	Paper-Rubber-Plastic-Glass	1.20	2.91	4.52	1.20	Nr	5
32	Shankar Packaging Ltd., Vadodara	Packaging Bags	Paper-Rubber-Plastic-Glass	2.13	2.84	0.78	0.78	Nr	5

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
33	Dinesh Mills Ltd., Vadodara	Fabrics	Textile	0.66	0.95	2.46	0.66	Nr	3
34	Sterling Gilatine Ltd., Vadodara	Gelatin, Pharmaceutical-Grade Gelatin	Paper-Rubber-Plastic-Glass	2.07	3.91	0.57	0.57	Nr	5
35	Solaris Bio Chemicals, Vadodara	Biochemicals, Intermediates For The Pharmaceutical, Nutraceutical, Agrochemical Industries	Agricultural Products-Pharmaceutical Industry	0.50	1.24	2.35	0.50	Nr	9
36	Suzlon Energy, Vadodara	Wind Turbine Generators	Mech. Elec. Products	2.37	3.18	1.08	1.08	Nr	7
37	Transpek Industry Ltd., Vadodara	Sodium Hydro-sulphite, Potassium Permanganate, Hydrogen Peroxide, Zinc Dust	Agricultural Products-Pharmaceutical Industry	2.32	2.46	1.78	1.78	Far	6
38	Voltemp Transformer Ltd., Vadodara	Transformers	Mech. Elec. Products	0.50	1.24	2.36	0.50	Nr	7
39	Thermax Ltd., Vadodara	Textiles	Textile	2.26	6.08	1.75	1.75	Far	1
40	Benzo Petro International Ltd., Vadodara	Chemicals (Surfactants, Emulsifiers, Esters, Alkyl Phenols)	Petro-Chemicals-Minerals-Construction	0.50	1.25	2.36	0.50	Nr	10
41	Diamond Cables Ltd., Vadodara	Electrical Cables And Wires	Paper-Rubber-Plastic-Glass	1.65	4.38	0.00	0.00	Nr	5
42	E. I. Dupont India Ltd., Vadodara	Chemicals, Polymers, Engineering Plastics	Paper-Rubber-Plastic-Glass	2.53	2.82	0.90	0.90	Nr	5
43	Fag Bearing Ltd., Vadodara	Roller Bearings	Mech. Elec. Products	0.50	1.25	2.36	0.50	Nr	7
44	Gpt Pipe Industries P. Ltd., Vadodara	Pipes	Mech. Elec. Products	0.50	1.25	2.36	0.50	Nr	7
45	Deepak Nitrate Ltd., Vadodara	Chemicals And Intermediates	Petro-Chemicals-Minerals-Construction	1.37	1.31	2.53	1.31	Nr	10
46	Bharuch Textile Mills.	Cotton Yarn, Synthetic Yarn, Blended Yarn	Textile	2.15	10.98	2.80	2.15	Far	1
47	Faisal Fabrics Ltd., Estate, Bharuch.	Fabrics	Textile	3.88	3.88	2.75	2.75	Far	1

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
48	Gujarat Narmada Velley Fertilize, Vadadla, Bharuch.	Fertilizer (Urea, Ammonium And Ammonium Sulphate)	Agricultural Products-Pharmaceutical Industry	7.63	20.40	7.06	7.06	Far	6
49	Mipco Seamless Ring Guj. Ltd., Bharuch.	Rubber	Paper-Rubber-Plastic-Glass	1.84	1.79	4.84	1.79	Far	2
50	Jhaveri Polymers Ltd., GIDC, Vadodara	Fabrics	Textile	1.80	9.23	2.70	1.80	Far	1
51	Gujarat Power Gen. Energy Corpn. Ltd., Bharuch.	Electricity	Mech. Elec. Products	2.18	7.10	1.30	1.30	Nr	7
52	Phillips Carbon Black Limited., Vadodara	Carbon Black	Paper-Rubber-Plastic-Glass	3.68	18.00	3.98	3.68	Far	2
53	Shree Marmada Alluminium Ltd Bharuch	Aluminium Product	Petro-Chemicals-Minerals-Construction	7.36	20.44	7.42	7.36	Far	8
54	Sonic Watches Ltd., Vadodara	Watches	Paper-Rubber-Plastic-Glass	4.64	4.81	10.77	4.64	Far	2
55	The Antizichan Bearings Corpn., GIDC, Bharuch.	Bearings	Mech. Elec. Products	7.84	20.88	7.76	7.76	Far	4
56	Videocon Narmada Ltd., Bharuch.	Electronic Appliances And Devices	Mech. Elec. Products	10.61	23.65	10.46	10.46	Far	4
57	Welspun Gujarat Sta. Rohrem Ltd., Vadodara	Steel Pipes And Tubes	Paper-Rubber-Plastic-Glass	0.50	1.25	2.36	0.50	Nr	5
58	Banco Products (India) Ltd., Ankhi, Bharuch	Clothing	Textile	2.23	3.43	2.22	2.22	Far	1
59	Jajodia Industries Limited, Baroda-Jambusar Road, Bharuch	Agricultural Products	Agricultural Products-Pharmaceutical Industry	2.60	2.17	1.90	1.90	Far	6
60	Scott Glass India Pvt.Ltd., Vill Ankhi, Bharuch	Fabrics And Glass	Paper-Rubber-Plastic-Glass	1.65	8.29	1.95	1.65	Far	2
61	Sevena Ceramics Ltd., Plot No. 1207, Vadodara	Ceramic Tiles	Petro-Chemicals-Minerals-Construction	3.20	13.51	1.50	1.50	Nr	10
62	Super Salts Ltd., Vadodara	Agricultural Products	Agricultural Products-Pharmaceutical Industry	1.11	11.72	3.88	1.11	Nr	9
63	Ajanta Paper & General Product, Bharuch	Paper	Paper-Rubber-Plastic-Glass	8.62	21.72	8.79	8.62	Far	2

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
64	Globbiz International Private Limited, Panchmahal	Minerals	Petro-Chemicals-Minerals-Construction	2.10	4.90	2.46	2.10	Far	8
65	Yunikon Industries Private Limited, Halol, Panch Mahals	Construction Company	Petro-Chemicals-Minerals-Construction	1.00	5.20	3.10	1.00	Nr	10
66	Parmar Stone Cruser Llp, Timba Road Taluko, Godhra, Panch Mahals	Crushed Stone, Gravel	Petro-Chemicals-Minerals-Construction	3.17	19.18	18.60	3.17	Far	8
67	Infinite Foam Private Limited, Gidc Halol Panch Mahals	Chemicals	Petro-Chemicals-Minerals-Construction	1.65	9.22	0.45	0.45	Nr	10
68	Acnova Pharmaceuticals Private Limited, Panchmahal	Pharmaceutical Products	Agricultural Products-Pharmaceutical Industry	1.72	1.49	3.85	1.49	Nr	9
69	Degna Bio Plantic Private Limited, Kalol, Panchmahal	Chemicals	Petro-Chemicals-Minerals-Construction	1.48	2.12	4.93	1.48	Nr	10
70	Krushipath Producer Company Limited, Kalol, Panchmahal	Chemicals	Petro-Chemicals-Minerals-Construction	1.85	2.50	2.26	1.85	Far	8
71	Rgabwala Steel Private Limited, Vadodara	Steel	Petro-Chemicals-Minerals-Construction	0.77	1.53	2.86	0.77	Nr	10
72	Stp_1_Tarsali, Vadodara	Water Treatment Plant	Petro-Chemicals-Minerals-Construction	0.16	5.39	1.47	0.16	Nr	10
73	Stp_2_Gajarwadi, Vadodara	Water Treatment Plant	Petro-Chemicals-Minerals-Construction	0.25	3.98	1.36	0.25	Nr	10
74	Monark Textile, Vadodara	Textiles	Textile	2.82	7.79	2.58	2.58	Far	1
75	Stp_3_Chhani, Vadodara	Water Treatment Plant	Petro-Chemicals-Minerals-Construction	0.28	6.65	1.63	0.28	Nr	10
76	Stp_4_Vuda, Vemali, Vadodara	Water Treatment Plant	Petro-Chemicals-Minerals-Construction	0.20	6.98	0.08	0.08	Nr	10
77	Safe enviro private limited magnad, Bharuch	Textiles	Textile	1.25	6.77	3.05	2.50	Far	1
78	Kangam works, Bharuch	Agricultural Products	Agricultural Products-Pharmaceutical Industry	0.66	6.69	0.05	0.05	Nr	9

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
79	VISHWA PVT. LTD, Bharuch	Textile	Textile	1.59	6.25	1.97	1.40	Nr	3
80	Mahadev textiles P. Ltd., Panchmahal	Textiles	Textile	3.41	4.99	2.38	2.38	Far	1
81	SHREYAS INDUSTRIES, Bharuch	Agricultural Products	Agricultural Products-Pharmaceutical Industry	0.67	6.71	0.07	0.07	Nr	9
82	LISEGA India Pvt. Ltd., Panchmahal	Electrical Equations	Mech. Elec. Products	2.11	2.23	3.01	2.11	Far	4
83	Gujarat Fluoro Chemicals Ltd., Panchmahal	Paper	Paper-Rubber-Plastic-Glass	1.94	2.87	1.40	1.40	Nr	5
84	Premdhara India LLP, Panchmahal	Agricultural Product	Agricultural Products-Pharmaceutical Industry	2.84	6.62	3.85	2.84	Far	6
85	Vaishnavi BMC, Bharuch	Agricultural Products	Agricultural Products-Pharmaceutical Industry	1.02	6.81	0.69	0.69	Nr	9
86	JSA Brick Works, Panchmahal	Bricks	Paper-Rubber-Plastic-Glass	2.77	1.54	1.86	1.54	Far	2
87	Cargo Papers P. Limited, Panchmahal	Paper	Paper-Rubber-Plastic-Glass	2.20	4.32	3.22	2.20	Far	2
88	Yeap Private Limited, Panchmahal	Rubber	Paper-Rubber-Plastic-Glass	1.90	4.83	2.73	1.90	Far	2
89	Krishna Kalol (Pms), Panchmahal	Automobile Parts	Mech. Elec. Products	1.90	3.82	2.30	1.90	Far	4
90	Kalol GIDC, Panchmahal	Paper And Plastics	Paper-Rubber-Plastic-Glass	3.06	4.96	1.42	1.42	Nr	5
91	Radici India Pvt. Ltd., Panchmahal	Textiles	Textile	1.88	1.56	1.69	1.56	Far	1
92	Rajpal Agriculture, Vadodara	Agricultural	Agricultural Products-Pharmaceutical Industry	1.50	2.36	4.64	1.50	Nr	9
93	Patels Textiles, Vadodara	Textiles	Textile	1.52	2.50	3.86	1.52	Far	1
94	KS Agrotech Pvt. Ltd, Vadodara	Agricultural	Agricultural Products-Pharmaceutical Industry	0.87	7.92	4.42	0.87	Nr	9
95	Maruti Tyres P. Ltd, Vadodara	Tyre	Paper-Rubber-Plastic-Glass	2.36	9.46	7.12	2.36	Far	2
96	Mamta automobile parts, Vadodara	Automobile Parts	Mech. Elec. Products	2.86	15.72	2.26	2.26	Far	4

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
97	PRAYUG AGRO PVT. LTD., Panchmahal	Agricultural	Agricultural Products-Pharmaceutical Industry	2.94	1.48	2.04	1.48	Nr	9
98	Shree Agro P. Ltd, Panchmahal	Agricultural	Agricultural Products-Pharmaceutical Industry	1.24	9.77	6.95	1.24	Nr	9
99	YOGI AGRO CENTER, Panchmahal	Agricultural	Agricultural Products-Pharmaceutical Industry	0.93	2.09	3.66	0.93	Nr	9
100	Krishna Plastics, Panchmahal	Plastics	Paper-Rubber-Plastic-Glass	1.62	5.60	1.72	1.62	Far	2
101	Siddhi Agro Chemicals, Panchmahal	Agricultural	Agricultural Products-Pharmaceutical Industry	0.11	2.91	0.77	0.11	Nr	9
102	Graphene Composites Ltd, Vadodara	Agricultural	Agricultural Products-Pharmaceutical Industry	4.59	7.40	1.49	1.49	Nr	9
103	Sibansee Agritech Pvt Ltd., Panchmahal	Agricultural	Agricultural Products-Pharmaceutical Industry	0.88	4.71	3.25	0.88	Nr	9
104	Shapire Synthetic P. Ltd, Panchmahal	Textiles	Textile	2.47	2.19	3.44	2.19	Far	1
105	Ami Pvt. Ltd, Vadodara	Plastics	Paper-Rubber-Plastic-Glass	5.03	9.22	3.12	3.12	Far	2
106	Narayanji E Cloth P. Ltd, Bharuch	Textiles	Textile	5.38	9.03	1.39	1.39	Nr	1
107	PILOT INDUSTRIES, Bharuch	Textiles	Textile	1.50	5.71	1.80	1.50	Nr	3
108	L&T MAHSR-C4, Vadodara	Construction Company	Petro-Chemicals-Minerals-Construction	1.89	6.71	2.36	1.89	Far	8
109	Walrus Seer Textile Mills, Vadodara	Textiles	Textile	2.56	9.59	2.25	2.25	Far	1
110	Hettich India Pvt Ltd, Vadodara	Automobile Parts	Mech. Elec. Products	2.65	2.95	1.55	1.55	Far	4
111	M R Agro, Bharuch	Agricultural	Agricultural Products-Pharmaceutical Industry	2.75	10.77	1.46	1.46	Nr	9
112	Saral Agro Pvt Ltd, Panchmahal	Agricultural	Agricultural Products-Pharmaceutical Industry	0.26	3.00	2.49	0.26	Nr	9
113	Sai Ash Polymers, Vadodara	Plastic	Paper-Rubber-Plastic-Glass	3.53	9.39	0.00	0.00	Nr	2
114	Daimond Textile P. Ltd, Bharuch	Textiles	Textile	7.82	4.69	2.63	2.63	Far	1
115	Sangita Rubber and Plastic, Bharuch	Plastic	Paper-Rubber-Plastic-Glass	1.88	5.13	1.94	1.88	Far	2

SR	Industry Name	Product Manufactured	Type of Industries	Distance to Nearest SWB (Km)	Distance to Nearest WCS (Km)	Distance to Nearest TP(Km)	Minimum Distance to WB (Km)	Near /Far WB	Rating
116	Jantran Head works, Bharuch	Automobile Parts	Mech. Elec. Products	6.15	3.17	3.34	3.17	Far	4
117	Premdhara Agro India LLP, Panchmahal	Agricultural Product	Agricultural Products-Pharmaceutical Industry	2.32	2.29	0.54	0.54	Nr	9
118	Earthmin Minerals, Panchmahal	Chemicals Products	Petro-Chemicals-Minerals-Construction	3.13	6.03	2.65	2.65	Far	8

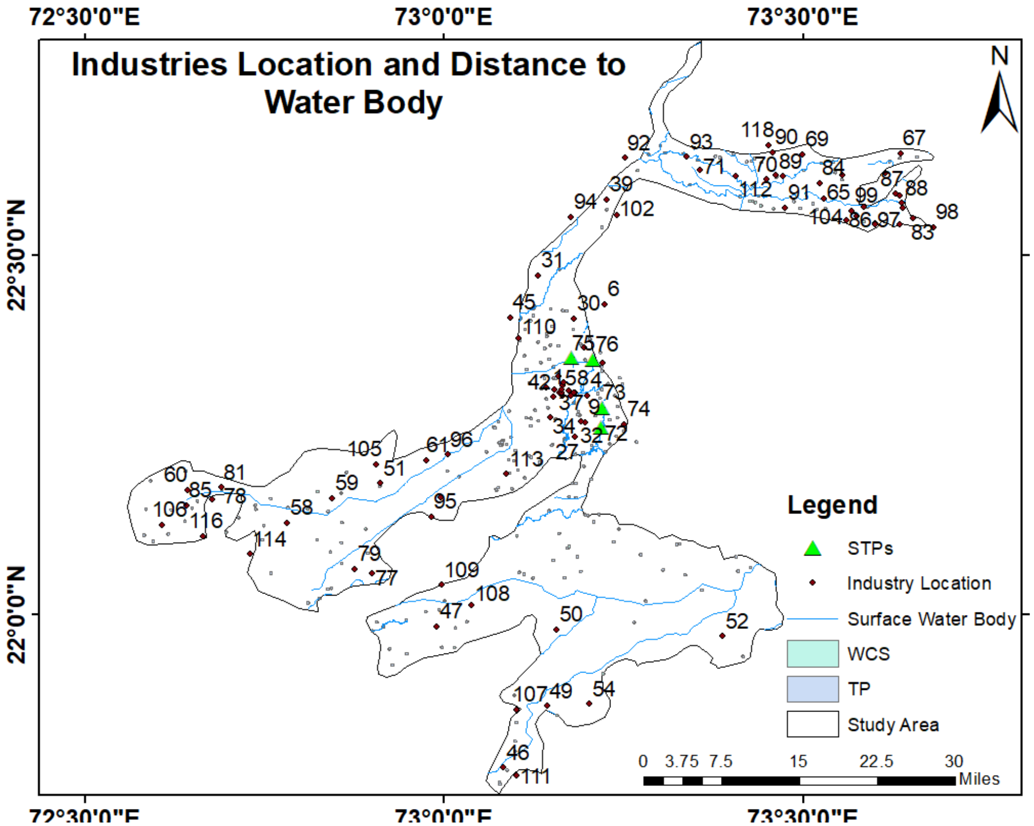
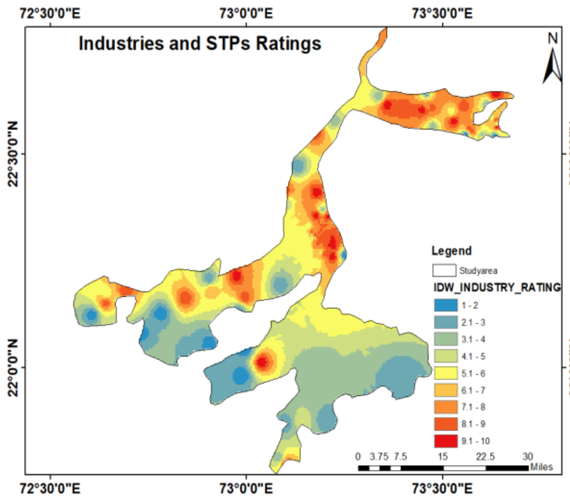


Fig 6.30 Industries Location and Distance to Water Body



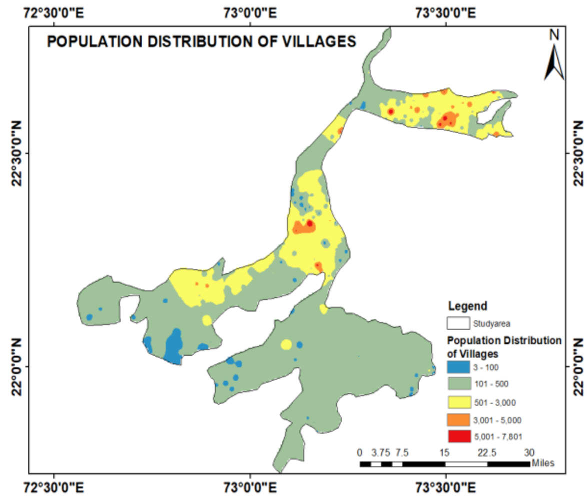
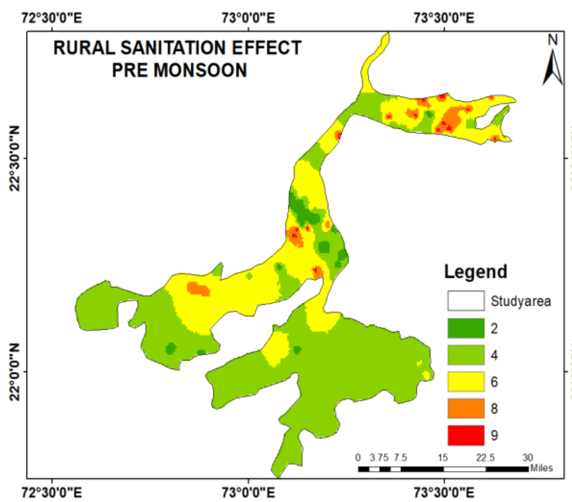


Fig 6.31 Industrial and STP Rating Map

Fig 6.32 Population Distribution of villages



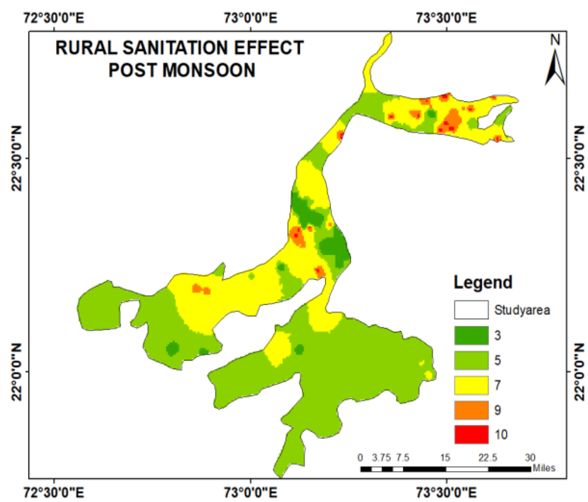
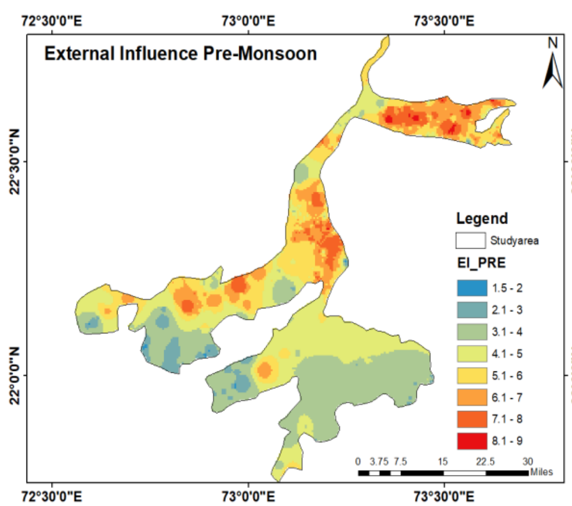


Fig 6.33 Rural sanitation Pre-Monsoon Rating

Fig 6.34 Rural sanitation Post-Monsoon Rating



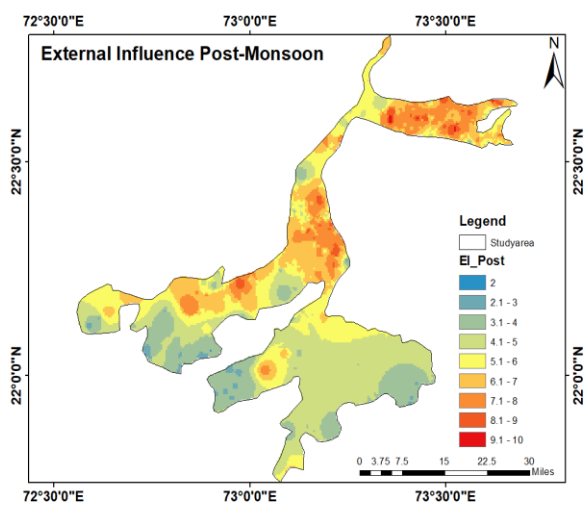


Fig 6.35 EI Pre-Monsoon

Fig 6.36 EI Post Monsoon

Individual ratings have been assigned to parameters D, R, A, S, T, I and C based on Aller Linda's recommendations. However, the rating for EI cannot be assigned individually, as it has been obtained from the integration of two raster outputs, (1) Location of Industries and STPs and (2) Rural Sanitation. Final step is to combine these raster maps (Figures 6.31 to 6.34) with the help of raster calculation tool in the Arc-GIS. EI map shown in figures 6.35 and 6.36 for pre monsoon and post monsoon respectively, the initial weight given to this parameter was W=5 and ratings of industries, STPs and rural sanitation maps are discussed in the table 6.12 and 6.13.

6.5.2 DRASTIC-EI Analysis

Fig 6.37 DRASTIC-EI Model

The External Influence (EI) parameter is combination of three factors contributing to increased contamination in the study area. It is incorporated into the conventional DRASTIC approach to represent groundwater contamination, particularly from industries, Sewage

Treatment Plants (STPs) and rural sources. Industrial and STP raster analyses were conducted considering industries located nearly. Proximity analysis in Arc-GIS determined the distance between industries and surface bodies. Rural sanitation ratings were assigned to specific areas based on village population. Initial weight assigned was W=5; industry and rural sanitation ratings details are given in tables 6.12 and 6.13.

DRASTIC-EI Single Parameter Sensitivity Analysis

In the scope of the Single Parameter Sensitivity Analysis (tables 6.15 to 6.16), the Recharge and Impact of Vadose zone parameters show the most substantial effective weights. Meanwhile, the External Influence, Depth, Aquifer media and Conductivity parameters demonstrate moderately significant effective weights. Conversely, Soil media and Topography display lower effective weights, aligning with the theoretical suggestions.

The Impact of Vadose zone and Aquifer media parameters display negligible Percentage Deviation, underscoring their pivotal roles in generating precise outcomes. Notably, the combined consideration of effective weight and error assessment in Conductivity and Recharge parameters accentuates the importance of obtaining accurate and finely-tuned representative values.

Table 6.15 Single Parameter Sensitivity Analysis (EI) – Pre-Monsoon

Para	Theoretical Weight	Theoretical Weight (%)	Effective Weight	ANN Optimized Weights	Effective Weight (%)				PD	% Error bet. EW and ANN Weights
					Mean	Min	Max	St. Dev.	(%)	
D	5	17.86	4.0	3.8	14.4	3.2	35.7	5.9	16.56	-5.26
R	4	14.29	4.3	5.2	15.2	2.6	31.3	6.0	9.90	17.30
A	3	10.71	3.1	3.0	11.1	6.0	16.1	1.5	7.33	3.33
S	2	7.14	2.1	2.0	7.5	1.4	15.9	2.5	7.80	-5
T	1	3.57	2.1	1.0	7.4	0.6	11.8	1.3	112.80	-110
I	5	17.86	5.4	5.2	19.3	12.0	28.0	2.2	11.44	-3.70
C	3	10.71	2.2	3.3	7.7	1.6	27.3	5.8	26.27	33.33
EI	5	17.86	4.8	3.9	17.3	6.9	31.0	3.6	17.68	-23.07
Total	28	100	28		100	-------				

Table 6.16 Single Parameter Sensitivity Analysis (EI)- Post-Monsoon

Para	Theoretical Weight	Theoretical Weight (%)	Effective Weight	ANN Optimized Weights	Effective Weight (%)				PD (%)	% Error bet. EW and ANN Weights
					Mean	Min	Max	St. Dev.		
D	5	17.86	4.0	4.3	14.4	3.2	37.2	6.5	16.00	6.97
R	4	14.29	5.9	7.9	21.2	2.5	30.0	3.7	54.70	25.31
A	3	10.71	2.8	3.0	9.9	5.3	14.4	1.2	2.93	6.66
S	2	7.14	1.9	2.0	6.7	1.3	14.1	2.5	0.60	5
T	1	3.57	1.8	1.0	6.6	0.5	9.7	0.9	93.20	-80
I	5	17.86	4.8	5.2	17.3	10.7	25.0	1.8	1.36	7.69
C	3	10.71	1.9	3.1	6.7	1.5	22.2	4.8	34.67	38.70
EI	5	17.86	4.8	5.1	17.3	7.5	27.5	3.3	24.96	5.88
Total	28	100	28		100	-------				

Figures 6.38 and 6.39 represent the fluctuations observed in the External Influence (EI) parameter. The Artificial Neural Network (ANN) assigns External Influence weights of 3.9 and 5.1 for the pre-monsoon and post-monsoon seasons, respectively.

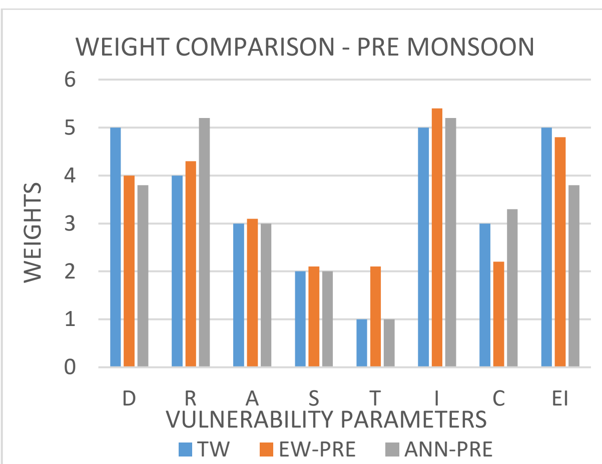


Fig 6.38 DRASTIC-EI Weights Comparison (Pre)

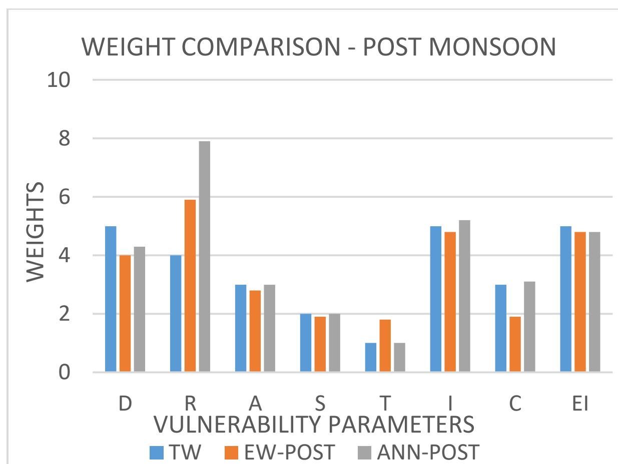


Fig 6.39 DRASTIC-EI Weights Comparison (Post)

6.5.3 DRASTIC-EI Model Validation and Outcome

After successful execution of final run, groundwater vulnerability maps of DRASTIC-EI (ANN optimized weights) pre-monsoon (fig. 6.40) and post-monsoon (fig. 6.41) seasons are shown below.

The basic statistical summary of DRASTIC-EI model (pre-monsoon) given below (table 6.17 and 6.18) 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 EI parameter and Conductivity parameter have very high coefficient of variation (CV) indicating their higher contribution in the variability of groundwater vulnerability for the study region. Final outcomes from aforementioned both the models are in terms of maps representing vulnerability index of groundwater prone to contamination.

Table 6.17 Statistical summary of Ratings assigned in DRASTIC-EI model - Pre-Monsoon

Pre-Monsoon	Depth	Recharge	Aquifer	Soil	Topography	Impact of Vadose Zone	Conductivity	EI
Average	3.86	5.33	5.02	5.20	9.88	5.22	3.38	4.72
Minimum	1.00	1.00	3.00	1.00	1.00	3.00	1.00	1.50
Maximum	9.00	9.00	9.00	10.00	10.00	9.00	10.00	8.90
St. Dev	1.42	2.49	0.88	2.26	0.94	0.82	2.46	1.28
CV (%)	36.79	46.81	17.54	43.50	9.47	15.64	72.93	27.07

Table 6.18 Statistical summary of Ratings assigned in DRASTIC-EI model - Post-Monsoon

Post-Monsoon	Depth	Recharge	Aquifer	Soil	Topography	Impact of Vadose Zone	Conductivity	EI
Average	4.29	7.99	5.02	5.20	9.88	5.22	3.38	5.22
Minimum	1.00	1.00	3.00	1.00	1.00	3.00	1.00	2.00
Maximum	10.00	9.00	9.00	10.00	10.00	9.00	10.00	9.40
St. Dev	1.82	1.47	0.88	2.26	0.94	0.82	2.46	1.28
CV (%)	42.32	18.43	17.54	43.50	9.47	15.64	72.93	24.47

Table 6.19 provides the distribution of the study area (%) across various vulnerability classes in the DRASTIC-EI model for both the Pre and Post Monsoon seasons. Notably, the sustainable class demonstrates a major decrease in area percentage during the post-monsoon period. In contrast, the pre-monsoon timeframe exhibits a decline in the percentage (%) area for the less and moderately vulnerable classes, while observing an increase in the highly and severely vulnerable classes.

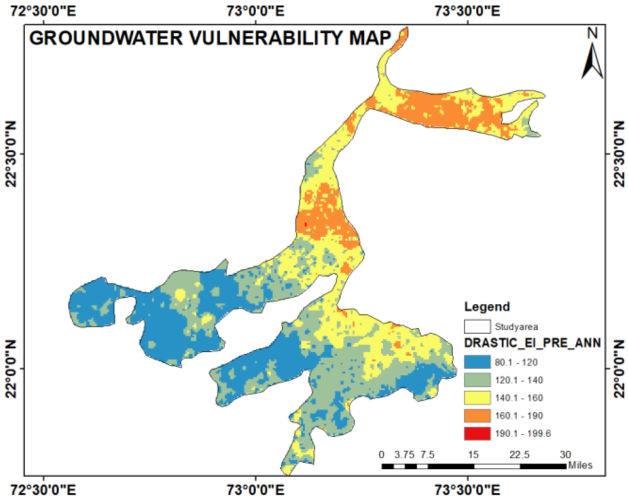


Fig 6.40 DRASTIC-EI Map Pre-Monsoon

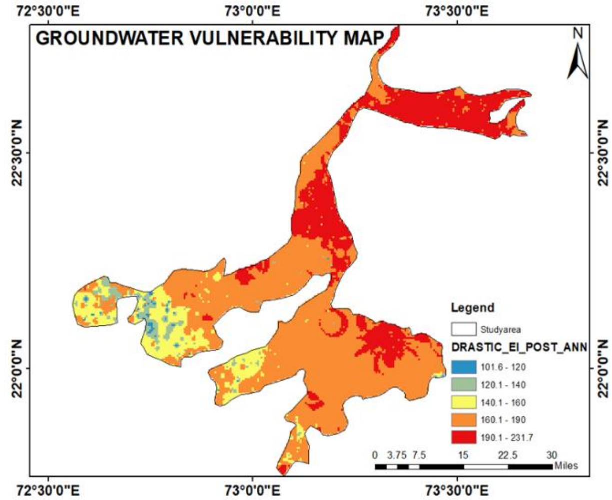


Fig 6.41 DRASTIC-EI Map Post-Monsoon

Table 6.19 Groundwater Vulnerability outcome in terms of % area

Vulnerability Class		**DRASTIC-EI (Pre)**	**DRASTIC-EI (Post)**
Sustainable	**< 120**	27.89	0.41
Less Vulnerable	**121 – 140**	31.49	2.91
Moderately Vulnerable	**141 – 160**	27.09	9.92
Highly Vulnerable	**161 – 190**	13.61	55.15
Severely Vulnerable	**> 190**	0.03	31.71

This shift can be attributed to heightened infiltration rates and improved groundwater recharge within the alluvial region. Consequently, this phenomenon contributes to a significant reduction in the extent of highly and severely vulnerable areas.

DRASTIC-EI Model Validation

In Figures 6.42 to 6.44, the presented correlation coefficients (r) reveal notable relationships. Specifically, a Pearson's correlation coefficient of 0.58 was observed between Nitrate and the 2018-PRE-DRASTIC-EI Vulnerability Index. Similarly, a correlation coefficient of 0.60 was established between Nitrate and the 2019-PRE-DRASTIC-EI Vulnerability Index. Notably, correlation of 0.52 identified between Nitrate and the 2020-PRE-DRASTIC-EI.

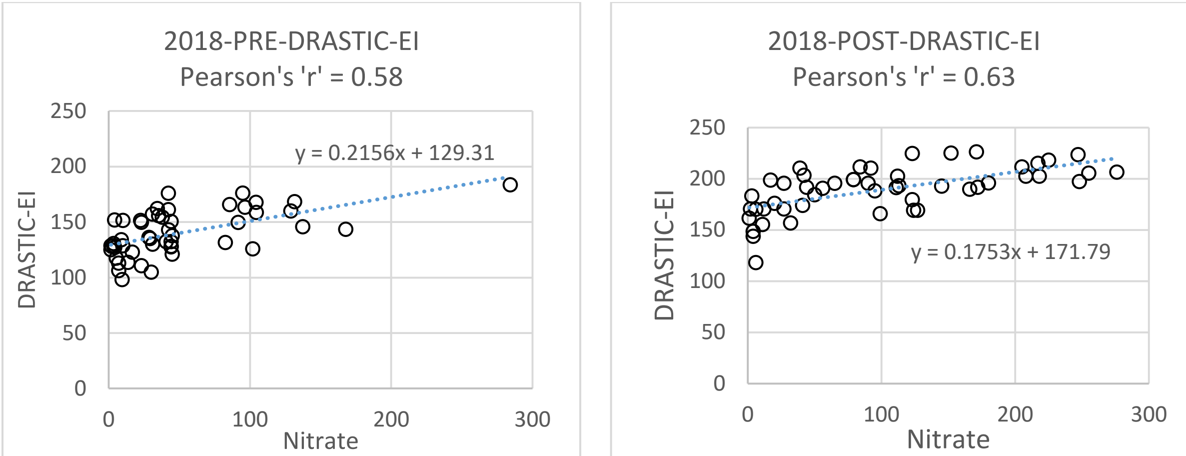


Fig 6.42 Correlation between DRASTIC-EI and Nitrate – Pre-Post-Monsoon-2018

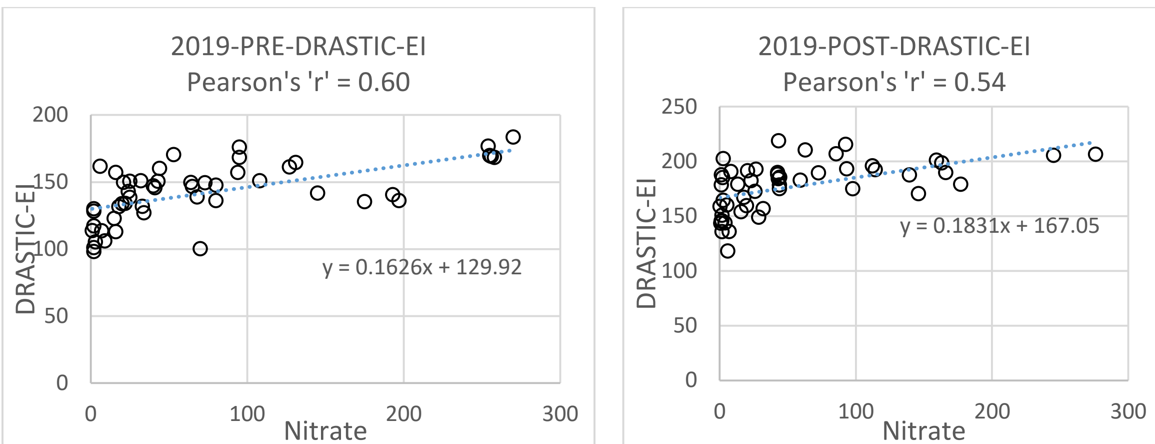


Fig 6.43 Correlation between DRASTIC-EI and Nitrate – Pre-Post-Monsoon-2019

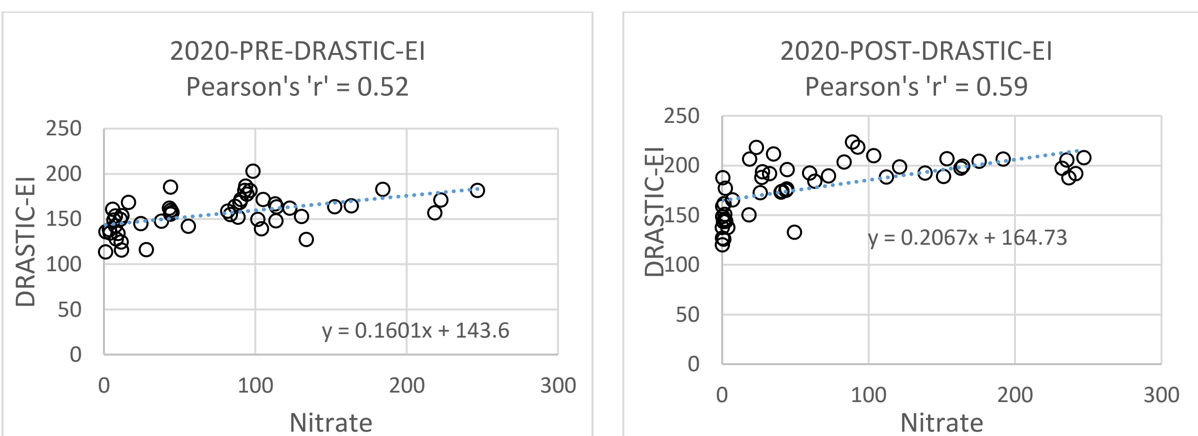


Fig 6.44 Correlation between DRASTIC-EI and Nitrate – Pre-Post-Monsoon-2020

For post monsoon, a Pearson's correlation coefficient of 0.63 was observed between Nitrate and the 2018-POST-DRASTIC-EI Vulnerability Index. Similarly, a correlation coefficient of 0.54 was established between Nitrate and the 2019-POST-DRASTIC-EI

Vulnerability Index. Notably, correlation of 0.59 identified between Nitrate and the 2020-POST-DRASTIC-EI-.

In study area, there is a significant problem with high Nitrate concentrations in the groundwater. This issue stems primarily from intense human activities, notably the excessive use of fertilizers in agricultural fields and high industrialization within the region. To assess the groundwater quality and vulnerability, a Factor Score (FS) and External Influence (EI) were employed, which likely takes into account various parameters, including Nitrate concentration. When the Factor Score and External Influence is high, it signifies poor groundwater quality, as high Nitrate levels often indicate contamination that renders the water unsafe for consumption. Moreover, areas with high Factor Scores and External Influence are also having more probability to further groundwater contamination, making them especially vulnerable.

To validate these findings and the correlation between high Factor Scores, External Influence and Nitrate concentrations, spanning a three-year period from 2018 to 2020, for both pre and post monsoon season, has been studied. This comprehensive validation ensures that the relationship between a high DRASTIC-FS Index, DRASTIC-EI Index and Nitrate concentrations remains consistent over time, underscoring the urgency of addressing this issue in the study area. High values of the DRASTIC-FS and DRASTIC-EI index matches with high Nitrate concentration within the study region and gives the good correlation.

These findings validate the efficacy of the DRASTIC-FS and DRASTIC-EI model for the Alluvial region situated between the Mahi and Narmada rivers in India.

6.6 Correlation Analysis

Correlation analysis holds significant importance in various fields of study and analysis. Its primary role lies in opening relationships between two or more variables, enabling researchers and analysts to grasp how changes in one variable might correspond to changes in another. This statistical method serves as a foundational step in data exploration and hypothesis testing, aiding researchers in identifying patterns and validating their assumptions. Moreover, correlation analysis plays a pivotal role in predictive modeling, where variables exhibiting strong correlations are often integrated into models to enhance their accuracy and effectiveness.

6.6.1 Groundwater Quality Index

The Groundwater Quality Index (GQI) plays a pivotal role in the assessment and visualization of groundwater quality across geographic regions. Using ArcGIS's powerful geospatial capabilities, hydrogeologists and environmental scientists can create detailed maps and spatial analyses that depict the distribution of GQI values throughout an area (Figure 6.45). By integrating groundwater quality data, into a GIS environment, professionals can develop GQI maps that offer valuable insights into the spatial variations of groundwater quality.

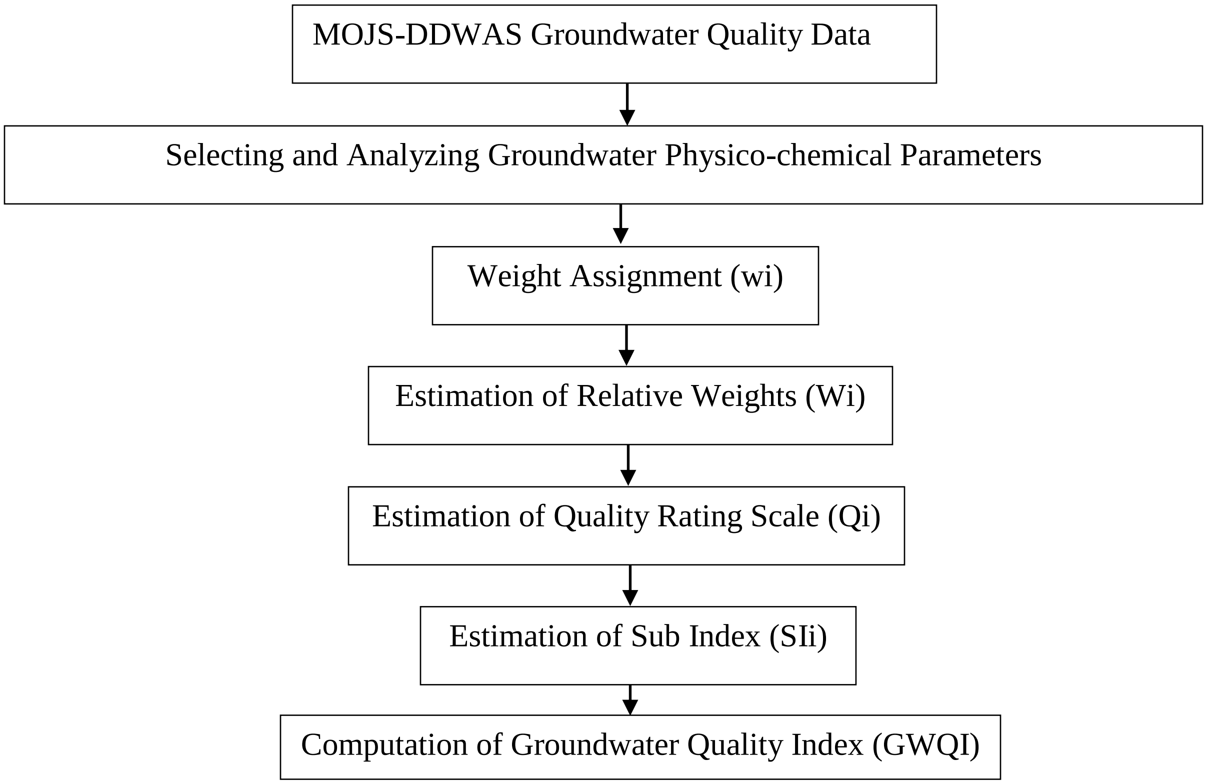


Fig 6.45 Methodology-Flow chart of GWQ Index

Table 6.20 Governing formulas of groundwater quality Index

(1)	**Relative Weight (Wi)**	$Wi = wi/\sum_{i=1}^{n} wi$	(7)
(2)	**Quality Rating Scale (Qi)**	$Qi = (Ci/Si) * 100$	(8)
(3)	**Sub Index (SIi)**	$SIi = Wi * Qi$	(9)
(4)	**Groundwater Quality Index (GWQI) per Well**	$GWQI = \sum_{i=1}^{n} SIi$	(10)

Where, wi = weight assigned to each parameter, Ci = parameter concentration, Si = parameter standard value as per IS:10500-2012

The Groundwater Quality Index was built in GIS environment considering MOJS-DDWAS 2018 data for pre and post monsoon season which consist of 10 different physico-chemical parameters with their standard limits as discussed in table 6.20. Based on the extensive literature review and the mean values of each parameter, appropriate weights were assigned. The outcomes are in terms of raster maps of groundwater quality index (figures 6.46 and 6.47) and individual parameters (figures 6.48 to 6.67). The index ranged value between (62-428) for pre monsoon and (48-382) for post monsoon highlighting higher groundwater contamination in the pre monsoon which is getting reduced in the post monsoon due to effect of rainfall recharge. The groundwater quality index was categorized into 5 classes Excellent Quality (<100), Good (101-150), Poor (151-200), Critical (201-250) and Unfit for drinking (>250).

Table 6.21 Groundwater quality parameters basic statistics and weight assignment

Sr.	Parameters	Avg.	Min	Max	St.Dev	CV	Std.L	Std.U	wi	Wi
1	**pH**	7.74	6.77	8.48	0.25	3.29	6.5	8.5	4	0.1212
2	**TDS**	1482.50	304	7390	987.16	66.59	500	2000	4	0.1212
3	**NO_3**	59.68	0	280	56.57	94.78	45	45	5	0.1515
4	**F**	0.79	0	8	0.80	100.78	1	1.5	4	0.1212
5	**Cl**	387.30	36	2545	341.78	88.25	250	1000	3	0.0909
6	**SO_4**	160.76	5	3222	330.90	205.84	200	400	4	0.1212
7	**Alkalinity**	479.01	176	1096	160.23	33.45	200	600	3	0.0909
8	**Ca**	50.79	3	570	65.67	129.30	75	200	2	0.0606
9	**Mg**	83.29	8	316	51.06	61.30	30	100	2	0.0606
10	**Hardness**	465.02	55	2622	332.99	71.61	200	600	2	0.0606
----------								Total	33	1

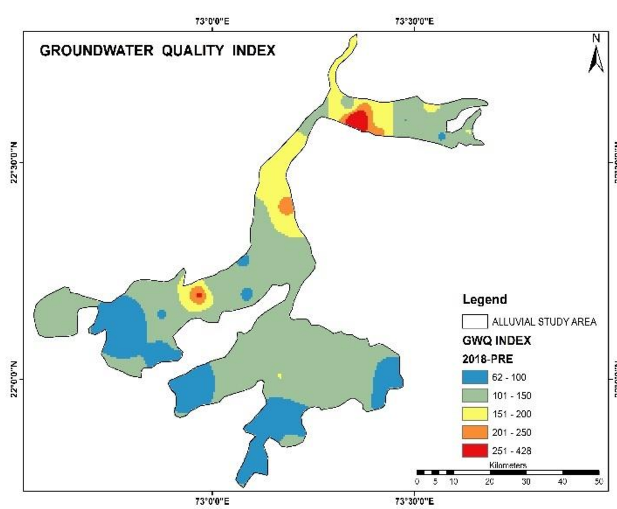


Fig 6.46 Groundwater Quality Index 2018-premonsoon

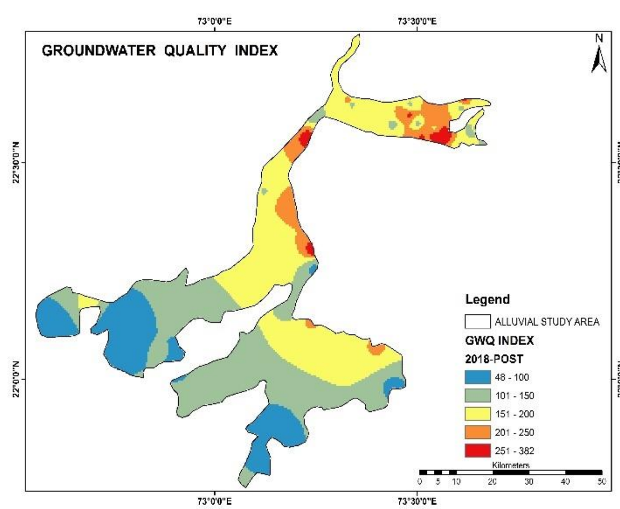


Fig 6.47 Groundwater Quality Index 2018-post-monsoon

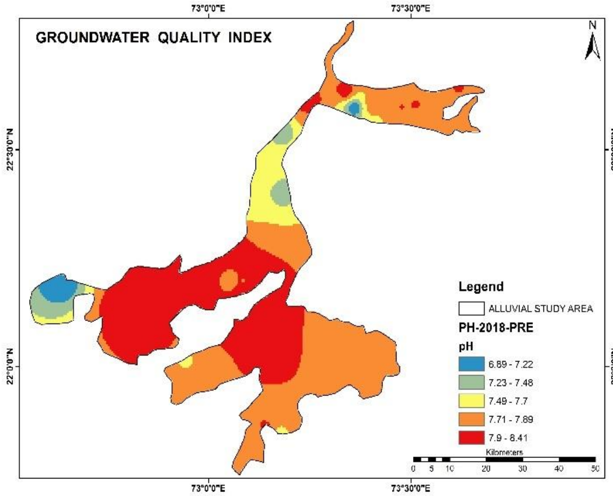


Fig 6.48 pH 2018-pre-monsoon

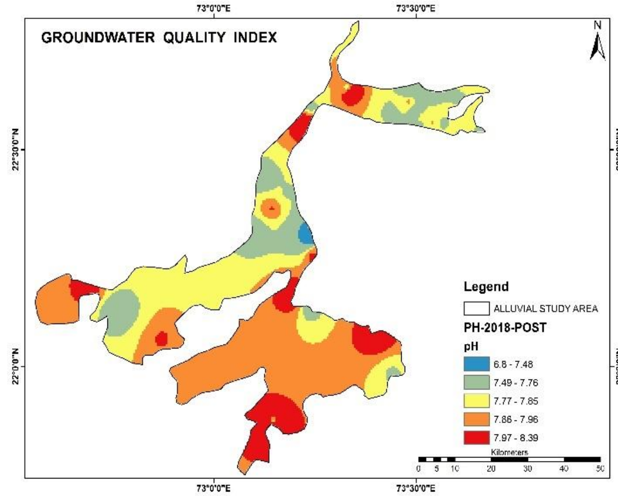


Fig 6.49 pH 2018-post-monsoon

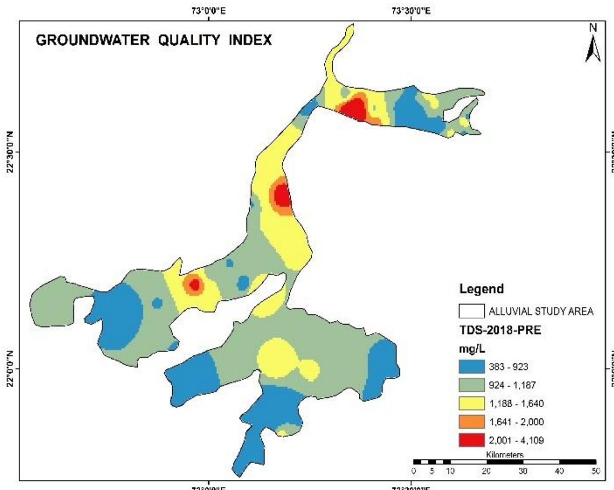


Fig 6.50 TDS 2018-pre-monsoon

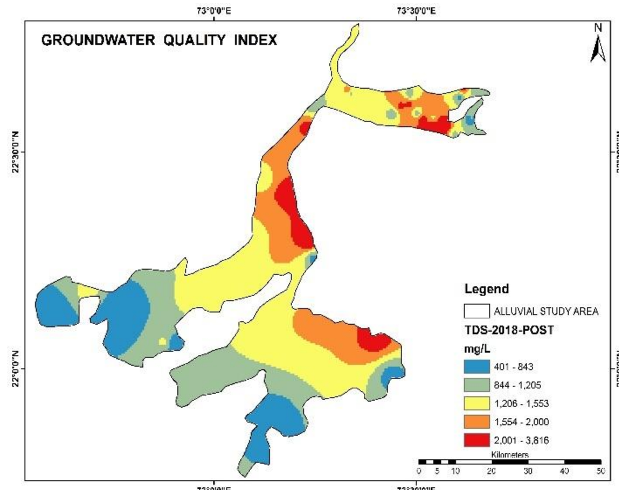


Fig 6.51 TDS 2018-post-monsoon

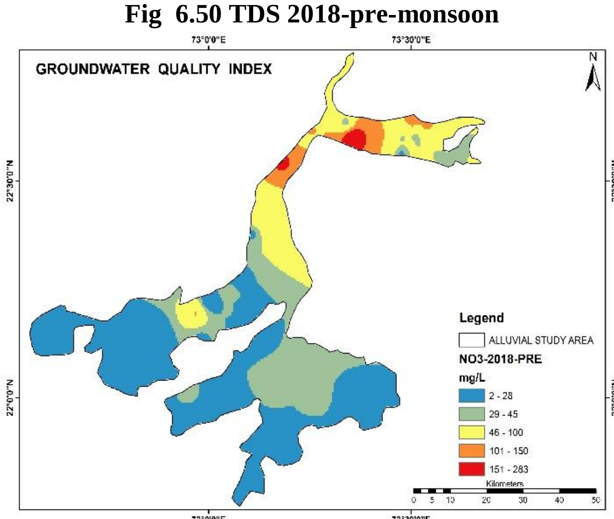


Fig 6.52 NO_3 2018-pre-monsoon

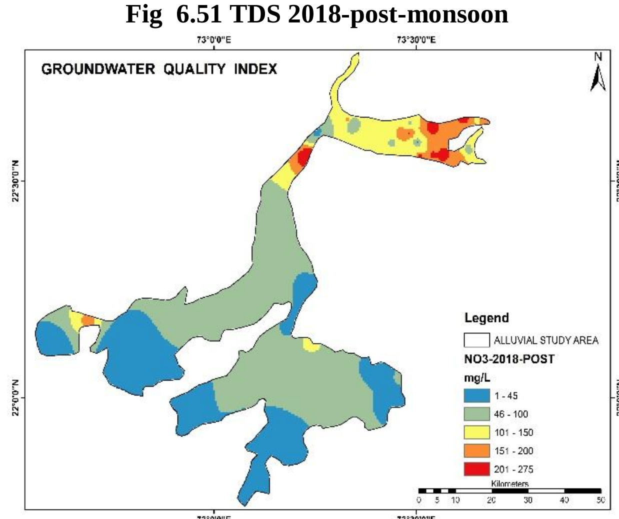


Fig 6.53 NO_3 2018-post-monsoon

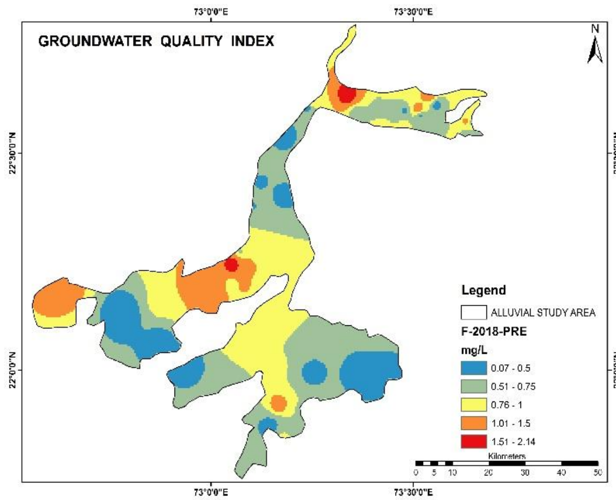


Fig 6.54 F 2018-pre-monsoon

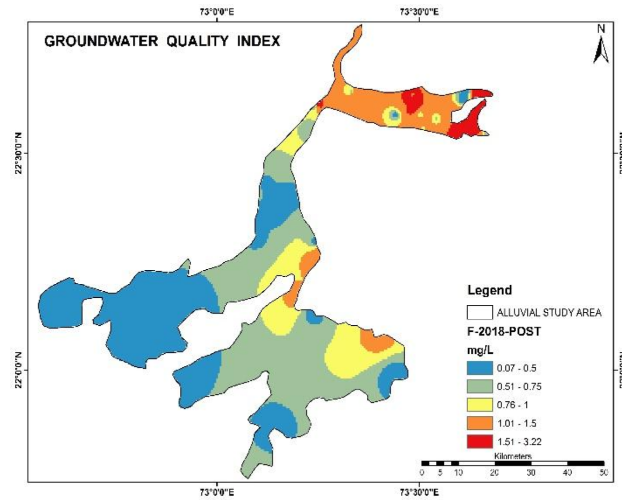


Fig 6.55 F 2018-post-monsoon

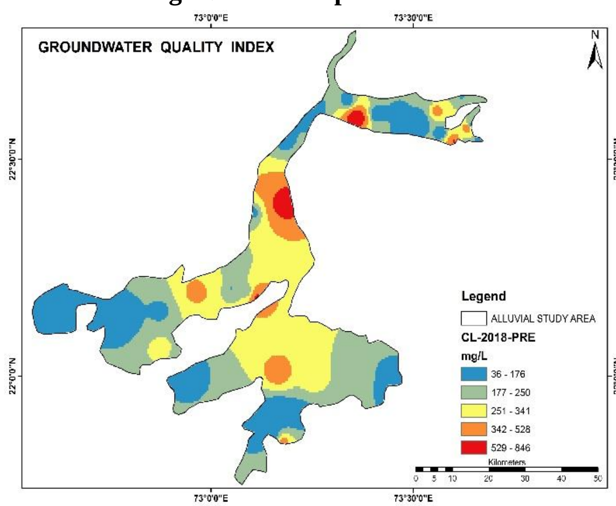


Fig 6.56 Cl 2018-pre-monsoon

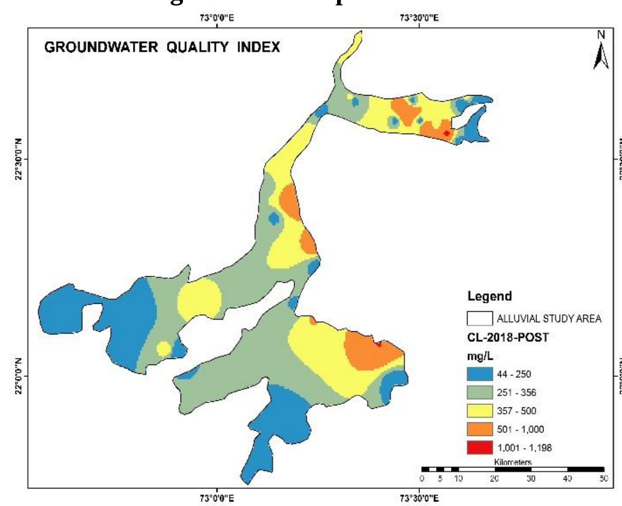
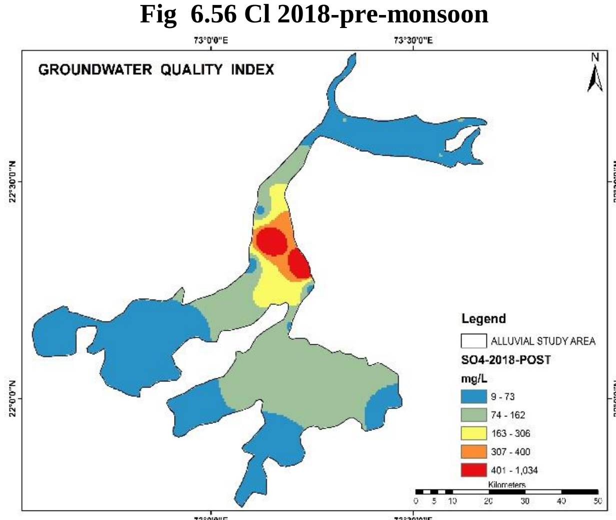


Fig 6.57 Cl 2018-post-monsoon



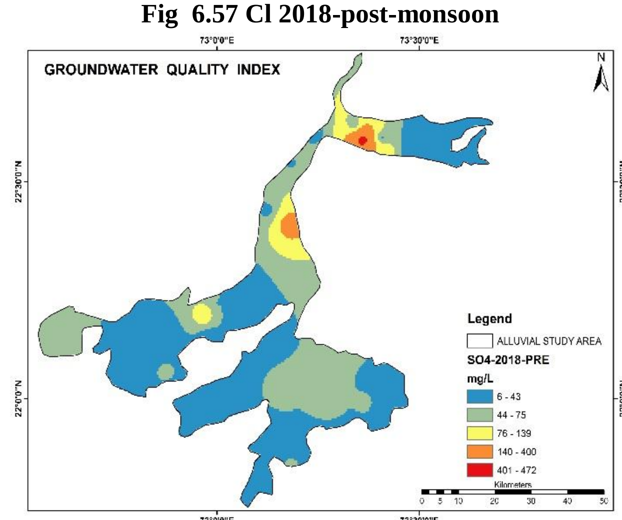


Fig 6.58 SO_4 2018-pre-monsoon

Fig 6.59 SO_4 2018-post-monsoon

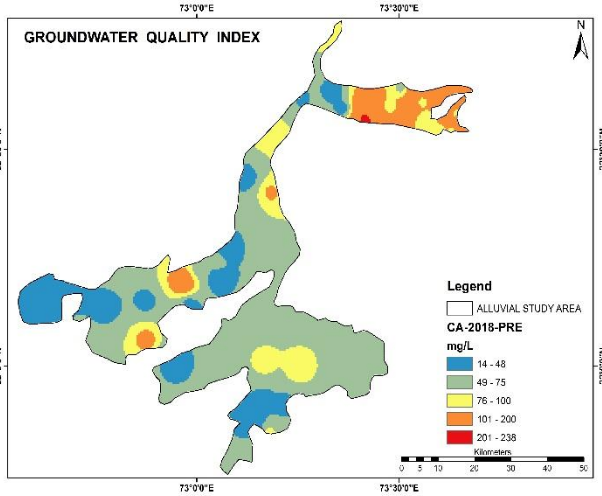


Fig 6.60 Ca 2018-pre-monsoon

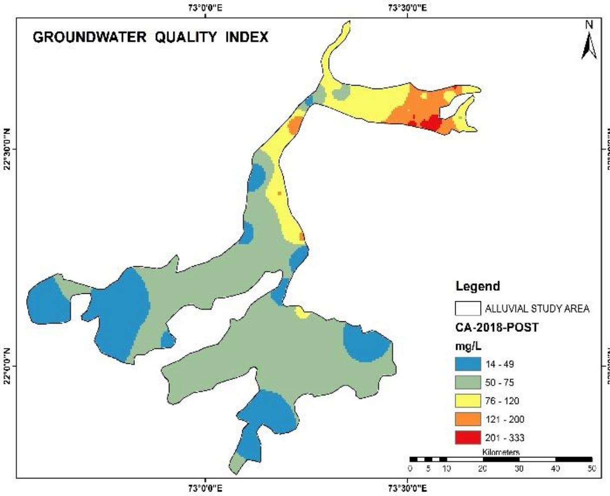


Fig 6.61 Ca 2018-post-monsoon

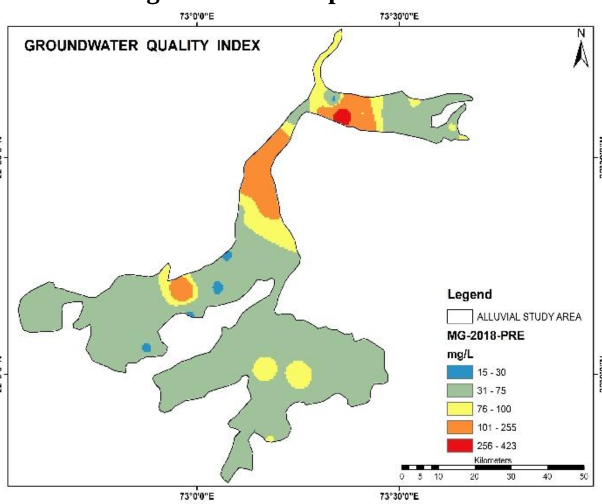


Fig 6.62 Mg 2018-pre-monsoon

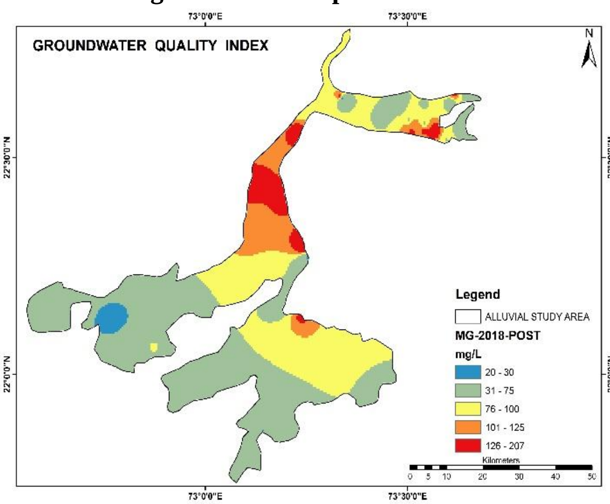


Fig 6.63 Mg 2018-post-monsoon

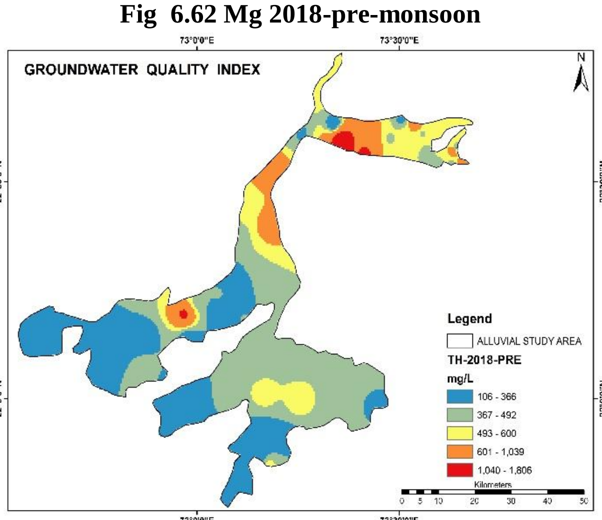


Fig 6.64 TH 2018-pre-monsoon

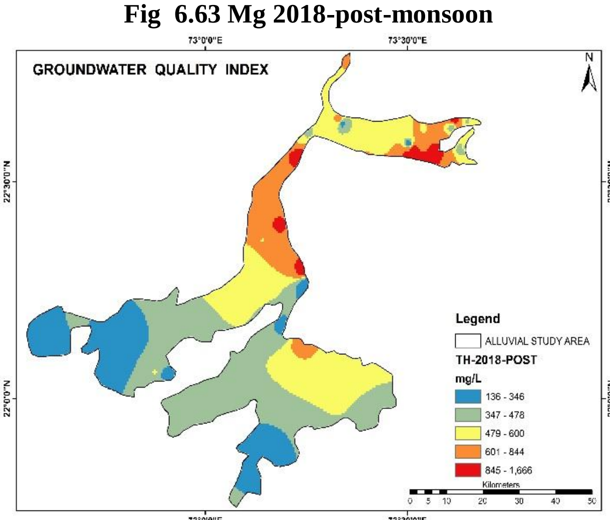


Fig 6.65 TH 2018-post-monsoon

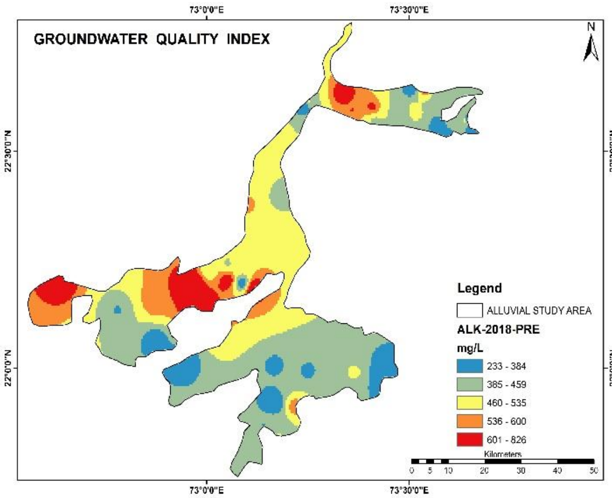


Fig 6.66 ALK 2018-pre-monsoon

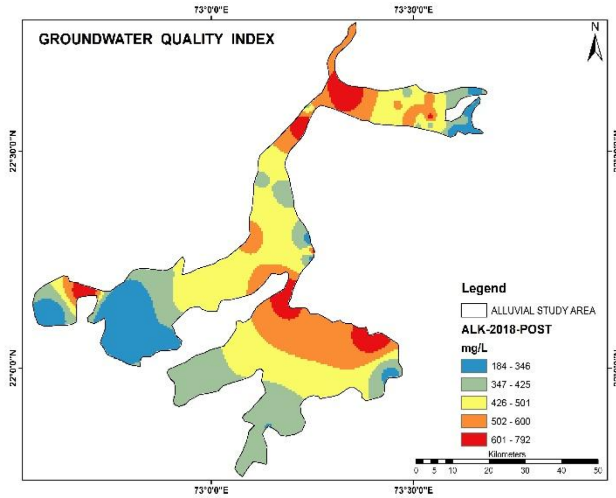


Fig 6.67 ALK 2018-post-monsoon

6.6.2 Correlation between Vulnerability Parameters and Groundwater Quality

The following tables 6.22 and 6.23 show relationship among groundwater quality and vulnerability parameters for 2018 pre and post monsoon seasons respectively derived from Spearman's rho correlation method. The values highlighted with blue color show near correlation (0.3-0.5) whereas values highlighted with yellow color show good correlation (0.5-0.8). Orange color represented as strong correlation between parameters (>0.8).

Table 6.22 Spearman correlation among Groundwater quality and vulnerability parameters 2018-Pre

2018-Pre-Spearman	GWQI	PH	TDS	NO_3	F	CL	SO_4	CA	ALK	MG	TH
D	-0.16	-0.01	-0.21	-0.07	-0.01	-0.25	-0.1	-0.12	0	-0.29	-0.23
R	0.45	-0.18	0.32	0.49	0.13	0.29	0.18	0.15	0.18	0.35	0.33
A	0.40	-0.3	0.3	0.43	-0.03	0.19	0.3	0.35	0.07	0.50	0.50
S	0.53	-0.24	0.34	0.58	0.03	0.24	0.17	0.48	0.01	0.49	0.58
T	-0.05	0.04	-0.03	-0.06	-0.03	0	-0.02	-0.02	-0.04	-0.04	-0.04
I	0.46	-0.21	0.36	0.51	-0.05	0.23	0.31	0.38	0.03	0.50	0.53
C	-0.14	0.03	0	-0.23	-0.08	0.19	0.05	-0.02	-0.21	-0.08	-0.01
FS	0.44	-0.15	0.41	0.36	0.15	0.18	0.34	0.12	0.28	0.35	0.32
EI	0.62	-0.11	0.48	0.56	0.43	0.30	0.30	0.22	0.51	0.45	0.42
DRASTIC-FS	0.64	-0.28	0.49	0.62	0.22	0.32	0.36	0.30	0.29	0.54	0.52
DRASTIC-EI	0.57	-0.28	0.4	0.61	0.11	0.32	0.29	0.36	0.11	0.56	0.55

Table 6.23 Spearman correlation among Groundwater quality and vulnerability parameters 2018-Post

2018-Post-Spearman	GWQI	PH	TDS	NO_3	F	CL	SO_4	CA	ALK	MG	TH
D	-0.21	-0.17	-0.33	-0.08	-0.27	-0.37	-0.55	-0.07	-0.47	-0.38	-0.24
R	0.51	-0.15	0.57	0.35	0.41	0.53	0.61	0.35	0.48	0.57	0.52
A	0.60	0.12	0.61	0.37	0.61	0.55	0.39	0.43	0.57	0.58	0.60
S	0.69	-0.22	0.57	0.57	0.54	0.49	0.20	0.57	0.39	0.55	0.67
T	-0.04	0.07	-0.01	-0.05	-0.03	0.01	0.01	-0.04	0.01	0	-0.04
I	0.64	-0.05	0.64	0.44	0.48	0.59	0.36	0.48	0.50	0.60	0.64
C	-0.09	0.39	0.04	-0.21	0.08	0.05	0.43	-0.17	0.12	0.11	-0.03
FS	0.52	0.09	0.42	0.43	0.52	0.36	-0.12	0.35	0.44	0.27	0.40
EI	0.57	-0.39	0.47	0.64	0.31	0.38	0.21	0.51	0.28	0.38	0.48
DRASTIC-FS	0.80	-0.04	0.76	0.56	0.78	0.66	0.46	0.61	0.65	0.68	0.75
DRASTIC-EI	0.73	-0.19	0.68	0.57	0.61	0.60	0.41	0.58	0.48	0.63	0.71

Vulnerability parameters with Nitrate

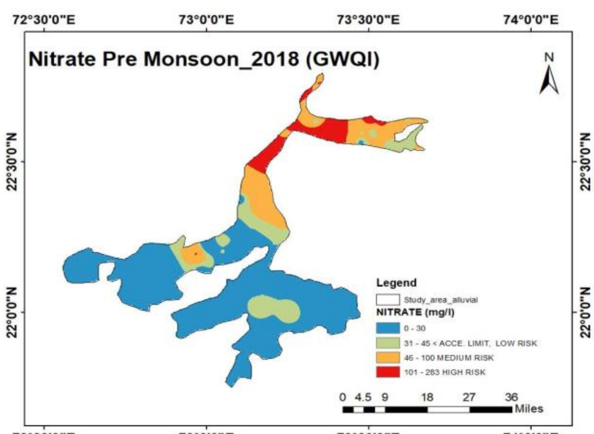


Fig 6.68 GW Nitrate 2018 – Pre Monsoon

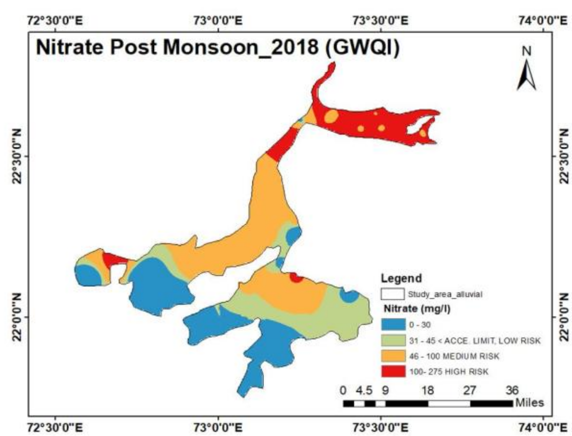


Fig 6.69 GW Nitrate 2018 – Post Monsoon

There is overall reduction in water quality of study area from 55.75% to 16.45% area under acceptable limit due to increased Nitrate concentration (Figures 6.68 and 6.69). This is in spite of decrease in Low Risk area, showing very High/shooting rise in Moderate & High Risk area. This suggests degrading of Groundwater Quality of the study area is greatly due to increased Nitrate concentration.

Table 6.24 Vul. Para. With NO_3

2018	NO_3 Pre	NO_3 Post
D	-0.07	-0.08
R	0.49	0.35
A	0.43	0.37
S	0.58	0.57
T	-0.06	-0.05
I	0.51	0.44
C	-0.23	-0.21
FS	0.54	0.43
EI	0.56	0.64
DRASTIC-FS	0.64	0.56
DRASTIC-EI	0.61	0.57

In the Western parts of the alluvial region, low values of groundwater Nitrate match well with low ratings of Aquifer media, Soil media, Impact of vadose zone, FS, DRASTIC-FS, EI parameter and DRASTIC-EI index whereas in the northern parts, high values of Nitrate contamination match well with high ratings of the same parameters.

In the Northern parts, the topsoil layer is very thin accompanied by sand-gravel bedded vadose zone and basaltic aquifer along with agricultural activities, industrial cluster and also high waste generated from rural area is playing a key role for such contamination. The relationship between the EI parameter and NO_3 is intensified during the post-monsoon season in the rural region of the study area due to a rise in recharge from the soak-pit tank. Observations indicate that during the post-monsoon season, Nitrate concentrations become more diluted due to recharge of water, leading to a decrease in their correlation with the DRASTIC-FS and DRASTIC-EI indices.

Vulnerability parameters with TDS

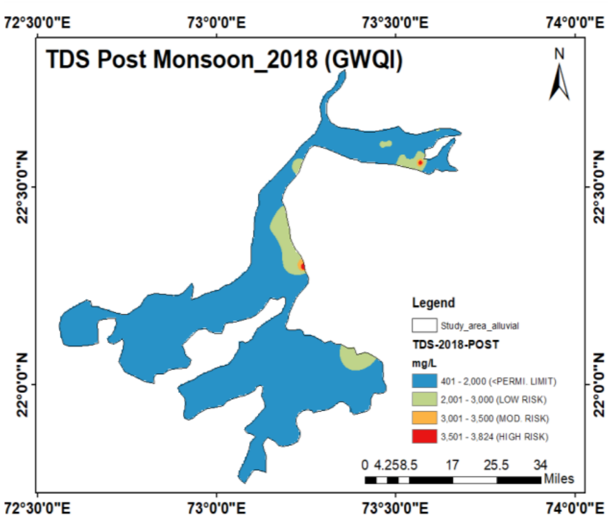


Fig 6.70 GW TDS 2018 – Pre Monsoon

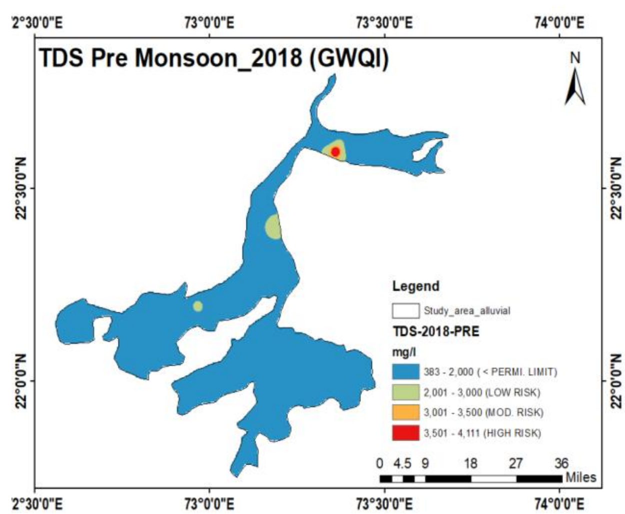


Fig 6.71 GW TDS 2018 – Post Monsoon

Figures 6.70 and 6.71 show TDS of pre and post monsoon seasons respectively. More than 99% of the area is found under low to High Risk in Pre-Monsoon which changed to at 48% in Post-Monsoon. Low Risk area is reached from Pre to Post Monsoon whereas area under Moderate Risk increased to 121.5% and High Risk area is increased very significant by 28%.

Table 6.25 Vul. Para. With TDS

2018	TDS Pre	TDS Post
D	-0.21	-0.33
R	0.32	0.57
A	0.3	0.61
S	0.34	0.57
T	-0.03	-0.01
I	0.36	0.64
C	0	0.04
FS	0.41	0.42
EI	0.48	0.47
DRASTIC-FS	0.49	0.76
DRASTIC-EI	0.4	0.68

The –ve correlation between Depth and TDS highlighted low ratings for Depth indicating deep groundwater table matching well with high ratings of TDS caused by over exploitation of groundwater resource.

In the Northern and central parts, high values of TDS match well with high ratings of the Soil media, Impact of vadose zone, EI, FS, DRASTIC-FS and DRASTIC-EI index. In the Northern and central parts, the topsoil layer is very thin accompanied by sand-gravel bedded vadose zone and aquifer along with agricultural activities and industrial cluster is playing a key role for such contamination.

It has been observed that relation between TDS, DRASTIC-FS and DRASTIC-EI parameter is significantly increased during post monsoon season because of increase in recharge of waste disposal from rural part of the villages, agricultural runoff and surrounding waste generate from industries.

Vulnerability parameters with Fluoride

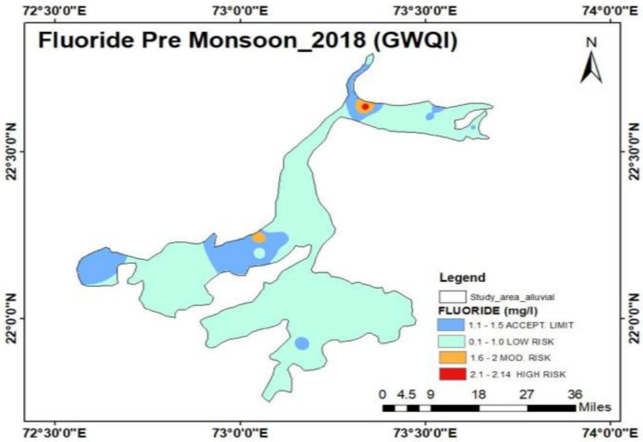


Fig 6.72 GW Fluoride 2018 – Pre Monsoon

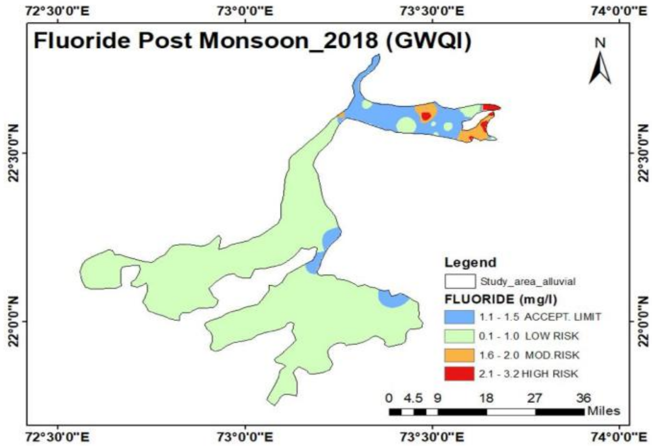


Fig 6.73 GW Fluoride 2018 – Post Monsoon

The 3rd Parameter Fluoride (Figures 6.72 and 6.73) seems to have almost negligible variation except in some marginal area of Kalol, Ghogamba and a very small area near Padra. This is also confirmed from poor correlation ship in range of -0.08 to 0.43 in pre-monsoon season. This clearly indicates that groundwater vulnerability in the study area is mainly due to Nitrate and TDS.

Table 6.26 Vul. Para. With F

2018	F Pre	F Post
D	-0.01	-0.27
R	0.13	0.41
A	-0.03	0.61
S	0.03	0.54
T	-0.03	-0.03
I	-0.05	0.48
C	-0.08	0.08
FS	0.15	0.52
EI	0.43	0.31
DRASTIC-FS	0.22	0.78
DRASTIC-EI	0.11	0.61

During the post-monsoon season, the recharge is closely linked to Fluoride levels, and also both impact of vadose zone and external influences is showing a near correlation. Additionally, the soil medium exhibits a significant association with Fluoride, highlighting the projecting role of sandy topsoil in increasing the movement of contaminants from the surface to the subsurface in the northern and central regions.

Fluoride shows a good correlation with various indices, including FS, DRASTIC-FS and DRASTIC EI, emphasizing the vulnerability of the aquifer system to contamination in the northern and central regions.

Vulnerability parameters with GWQI

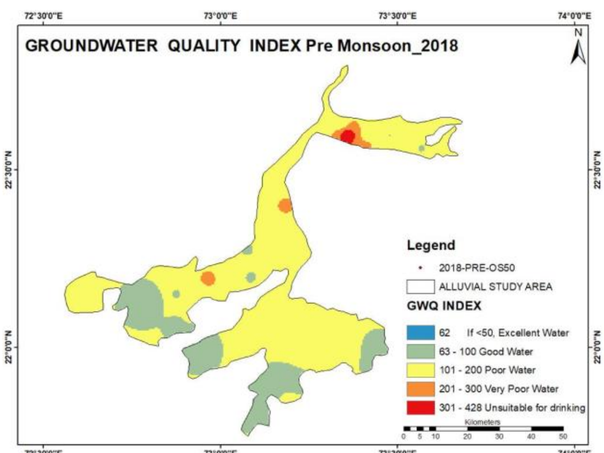


Fig 6.74 GWQI 2018 – Pre Monsoon

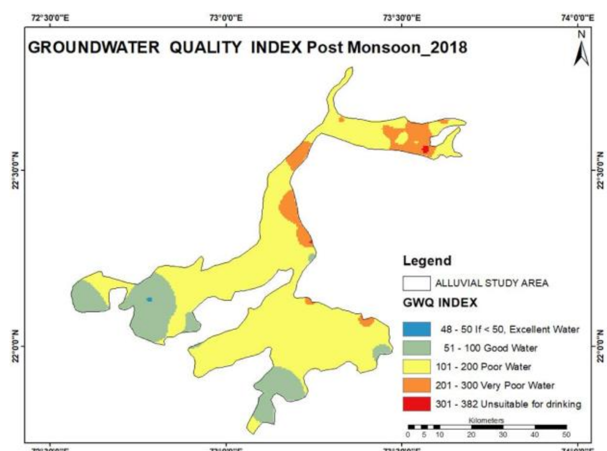


Fig 6.75 GWQI 2018 – Post Monsoon

Above figures (6.74 and 6.75) indicate there was no area having excellent quality of GW in pre monsoon and a very little area in post monsoon (2.1%). 77.86% of the study area is having poor to very poor quality of groundwater, In Pre-Monsoon which increased to 81.39% in Post Monsoon.

Table 6.27 Vul. Para. With GWQI

2018	GWQI Pre	GWQI Post
D	-0.16	-0.21
R	0.45	0.51
A	0.40	0.60
S	0.53	0.69
T	-0.05	-0.04
I	0.46	0.64
C	-0.14	-0.09
FS	0.44	0.52
EI	0.62	0.57
DRASTIC-FS	0.64	0.80
DRASTIC-EI	0.57	0.73

Recharge (R), aquifer media (A), impact of vadose zone (I) and FS parameters showed near correlation (0.3 to 0.5) with GWQI while soil media (S) and EI indicated good correlation (0.5 to 0.8) with GWQI which indicated top sandy soil play greater role in traveling contaminants from surface to sub surface in Northern and Central region.

Groundwater quality index has good correlation with EI, DRASTIC-FS and DRASTIC EI index in pre monsoon season whereas with DRASTIC-FS index it showed strong correlation (0.80) in the post monsoon. Such relationships drew attention towards poor to very poor GWQI in Northern and Central regions which validated high to extreme vulnerability of underlying aquifer system to contamination for the same regions.

According to the findings presented in table 6.27, it states that there is a significant increase in the correlation between the Groundwater Quality Index (GWQI) and the DRASTIC-FS and DRASTIC-EI parameters in the post monsoon season. This increasing correlation suggested that recharge during the monsoon season plays a crucial role in the study area.