ASSESSMENT OF GROUND WATER VULNERABILITY IN THE ALLUVIAL REGION BETWEEN MAHI AND NARMADA RIVERS OF GUJARAT

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Synopsis

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THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA

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CIVIL ENGINEERING

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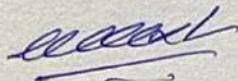
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SYNOPSIS

FOR THE PH.D.THESIS ENTITLED

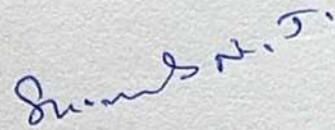# ASSESSMENT OF GROUND WATER VULNERABILITY IN THE ALLUVIAL REGION BETWEEN MAHI AND NARMADA RIVERS OF GUJARAT

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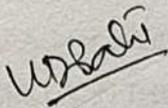
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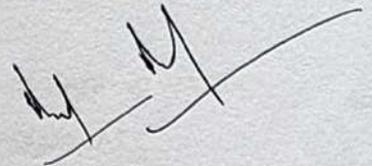
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2

Table of Contents

INTRODUCTION

In arid and semi-arid regions, where the population mostly relies on groundwater for their daily requirements, including drinking, domestic use and agricultural, groundwater is a key supply of freshwater (**Adimalla and Venkatayogi 2018**). The quality of groundwater water is an important aspect when it is being considered for human consumption as well as other purposes. The contamination of groundwater is a global concerns associated with public health as majority of the diseases in humans are caused by polluted water as a result of rapid growth in industries and urban areas (**Singh et al. 2004**). **Reddy A., (2014)** in their research explained hydro-geo-chemical evaluation of groundwater quality with the help of multivariate statistical analysis revealing higher nitrate accompanied by EC, Na^+, Cl^- and SO_4^{2-} exists in shallow zones caused from anthropogenic activities. **Krishnan S. et al. (2007)** in their work related to groundwater quality revealed that nitrate, fluoride and high salinity have been found to be above permissible limits in central Gujarat.

The impact of groundwater contamination is permanent while its remediation is costly which creates a need for regular monitoring of the groundwater quality. Various such research works in the field of groundwater hydrology in Indian and international context has been reviewed thoroughly which explained the fundamentals of groundwater contamination sources, groundwater quality and vulnerability modeling, public health risks and various management strategies associated with polluted groundwater.

Once the groundwater quality has been affected from undesired contaminant sources, it becomes a very difficult task to bring it back within its permissible standards. It is now essential to identify the sources of groundwater contaminants in order to understand the dominant contaminants brought on by anthropogenic and/or geogenic activities for the underlying aquifer (**Saidi et al., 2011**). The multivariate statistical analysis approach has been used in recent years to address groundwater source identification issues. Nevertheless, the research is currently limited to detecting anthropogenic and natural sources of contamination (**Kanchan and Ghosh 2014, Machiwal and Jha 2015,**). The type of source can be categorized based on data related to physico-chemical parameters of ground water samples obtained from various openwells and shallow tubewells. The principal component analysis (PCA), factor score analysis (FSA) and hierarchical cluster analysis (HCA) are some of these statistical methods used extensively with GIS environment to identify pockets of anthropogenic sources falling within one's area of study (**Kanchan and Ghosh 2014, Machiwal and Jha 2015**).

To raise awareness of groundwater contamination, the notion of groundwater vulnerability was first proposed in France at the end of the 1960s (**Babiker I. et al. 2005**). The potential of pollution

entering and spreading throughout the groundwater system is emphasized by this definition of groundwater vulnerability, which is the most frequently recognized approach. Two categories of vulnerability are identified in the current research data: intrinsic (natural) vulnerability and specific (integrated) vulnerability. In the selection of the most appropriate method to evaluate groundwater vulnerability, some considerations are taken in to account such as simple applications, data availability, result classification and their suitability for large areas. There are many different strategies for assessing vulnerability, including statistical methods, process-based simulation models, and index-based mapping models. Many scholars have been interested in the subject of index-based mapping **(Kumar P. et.al. 2015)**.

The highly vulnerable zones are usually difficult to monitor, as it requires the drilling of many observation wells which becomes expensive. High-vulnerability zones are usually difficult to monitor since they require drilling many observation wells, which become expensive. In addition to providing decision makers with a comprehensive picture of the areas that need close monitoring, the map also shows those areas that are less likely to become contaminated, which require less intensive monitoring. The DRASTIC method **(Linda A. et al. 1985)** is widely used as a method to assess groundwater vulnerability. The aquifer is evaluated using seven hydrological parameters, including Depth to water (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the vadose zone (I) and hydraulic Conductivity (C) of the aquifer.

In a recent comparison of DRASTIC, GOD and SINTACS to determine their performance for the vulnerability assessment in Ecuador, **Sharadqah (2017)** reported DRASTIC to be the most effective in terms of outcomes. The conventional DRASTIC model has been used with GIS environment to analyze groundwater vulnerability in India drawing attention towards vulnerability map showing low to high vulnerable areas along with sensitivity analysis and validation of results with groundwater nitrate **(Tomar T. et al. 2019)**.

Modifications over conventional DRASTIC methods are approached in many recent research works that explains the addition of anthropogenic factors in terms of Land Use changes, urbanization index as well as optimization of weights and ratings **(Alam F. et al. 2012, Neshat A. et al. 2014 and Singh A. et al. 2015)**. The limiting factor in accurate vulnerability assessment is the fixed weights and ratings of DRASTIC parameters which is based on expert's opinion recommended by **Linda A. et al. (1987)**. The reduction and/or additive approach of a particular parameter in DRASTIC analysis may be adopted looking to area specific anthropogenic activities influencing the hydrogeology of one's area of study.

The term "Groundwater Quality Index" refers to a rating that reflects the composite impact of many water quality criteria on the overall quality of water. It is widely regarded as an effective

technique for groundwater quality evaluation and management. The primary goal of the computation of the water quality index (WQI) is to transform the complex water quality information into data that is readily comprehensible and useful. It is a useful tool to assess how groundwater quality has changed over time and in different places. In recent years, WQI has been effectively used to evaluate the quality of groundwater as it helps in the interpretation of water quality issues by integrating complex data and producing an index that defines the status of water quality (**Mehra M. et al. 2016**).

The quality of groundwater physico-chemical parameters being above permissible limits mentioned in (**IS-10500-2012**) affects public health. Such effects tend to arise from direct consumption or dermal ingestion of contaminated groundwater which necessitated the estimation of hazard quotient and human health risk (**USEPA 1992, USEPA 1999**). The main causes of nitrate contamination in groundwater are farmed runoff, excessive fertilizer use, inadequate septic system construction, leaking urban sewers, dairy and poultry production as well as human and animal waste (**Stadler, 2008**). In urban areas with large concentrations of human and animal waste as well as agricultural districts with heavy fertilizer use, groundwater nitrate has been detected in higher concentrations.

Siddha and Sahu (2020) evaluated the groundwater quality of the Vishwamitri River Basin in Central Gujarat and evaluated its capacity to meet the agricultural and drinking requirements with a determination of the associated human-health risk. **Ahada and Suthar (2017)** evaluated Groundwater nitrate contamination in southern districts of Punjab, India and associated health risk for adults and children highlighting critical zones for each in GIS environment. Extensive research has been done considering the health risk due to groundwater nitrate as higher concentration in human body causes Methemoglobinemia (Cyanosis) also known as Blue Baby Syndrome (**Adimala and Li 2018, Bastani and Harter 2019, Li D. et al. 2021**).

The groundwater remediation is the process of reducing the contamination and restoring the groundwater quality near to its original state. This procedure is carried out either using an ex-situ method, in which groundwater must be removed by wells, treated on the surface and then returned below, or using an in-situ method, in which favorable environmental conditions must be created in order for toxins to degrade into less harmful byproducts (**Technical Report 5, 2018**). The nitrate removal technologies also known as denitrification methods involve some physical, biological and chemical processes.

Physical processes separate and dispose of the concentrated waste streams or used adsorbents produced by these removal techniques. The primary goal of biochemical processes is to convert nitrate ions to another form of nitrogen, such as ammonia or a less harmful form like nitrogen gas

(**Archana et al. 2012**). Depending on the type of treatment, intermediate compounds including nitrite, nitrous oxide and nitrogen dioxide may also be created (**Obiri-Nyarko et al. 2014**).

In the past few years, many of the researchers have worked upon groundwater sustainability and suitability of one remediation method over the others based on MCDA (multi criteria decision analysis) (**An D et al. 2015, An D et al 2016, Wang H et al. 2017, Li W et al. 2018, Li H et al. 2019**). **An D et al. (2015 & 2016)** used a combination of MCDA methods such as Fuzzy-AHP-ELECTRE and ranked the remediation alternatives PAT>AS>PRB>MNA, however this study was not pertaining to any particular contaminant but was more focused on criteria selection and their weightage. **Wang H et al. (2017)** used four different MCDA techniques which are WSM, WPM, CGT and TOPSIS on 18 different remediation alternatives with seven evaluating criteria considering contamination due to petroleum wells in Shengli oil fields.

Li W et al. (2018) screened various groundwater remediation alternatives using AHP-PROMETHEE methods of MCDA and enhanced the results with numerical simulation highlighting the efficiency of chemical reduction alternative over bioremediation method for Brownfield sites, China. **He L et al. (2019)** demonstrated the use of PROMETHEE-TOPSIS methods for selection of a suitable remedial measure considering groundwater naphthalene contamination over Anhui, China. The authors ranked 50 different remedial simulations based on four evaluating criteria emphasizing on pumping rates and total cost of remediation that enables the decision makers to choose appropriate groundwater management strategy.

The novelty of present research is the addition of a new parameter "Factor Score" (FS) in the conventional DRASTIC model creating a new DRASTIC-FS groundwater vulnerability model which is further enhanced with ANN (Artificial Neural Network) optimized weights. The groundwater vulnerability has been assessed for Pre-Monsoon as well as Post-Monsoon season to account for seasonal variations in depth to water table and groundwater recharge parameters. Groundwater nitrate concentrations collected from shallow tubewells and open wells, as well as Single Parameter Sensitivity Analysis (SPSA) and Map Removal Sensitivity Analysis (MRSA), were used to validate the final results.

The parameters of groundwater vulnerability and groundwater quality have been correlated using the Spearman's rho method, and the results showed a strong relationship between areas of high vulnerability and low water quality and vice versa. The health risk assessment has been enhanced with the addition of a few key parameters such as land use land cover, population density, water use scenario and average water demand which has helped in delineation of critical area that needs immediate attention.

Various remedial measures have been recommended for such critical area considering appropriate denitrification methods looking to location specific characteristics (LSC) and concentration of groundwater nitrate contamination. The analytical hierarchy process (AHP) method of multi criteria decision analysis (MCDA) has been applied to obtain the choice order of such remedial alternatives based on six fundamental criteria viz. initial cost (IC), operation and maintenance cost (OMC), remediation time (RT), pollution removal rate (PRR), ground water table (GWT) and pollution loading (PL).

OBJECTIVES OF THE RESEARCH: -

The objectives of the research are,

(1) To identify various sources of ground water contamination in study area.

(2) To develop suitable model for ground water vulnerability.

(3) To assess ground water vulnerability in study area.

(4) To develop the relationship between vulnerability parameter with ground water quality.

(5) To suggest the management strategy to minimize the risk on public health.

STUDY AREA

The study area of present research is an alluvial region between Mahi and Narmada rivers, which are following through the central part of Gujarat state, the area coverage is six blocks of Vadodara, three blocks of Panchmahal and three talukas of Bharuch district. Total area of the alluvial region is about 2750 km^2, residing between 72.51° to 73.64° Eastern longitude and 21.78° to 22.83° Northern latitude on a geographical basis.
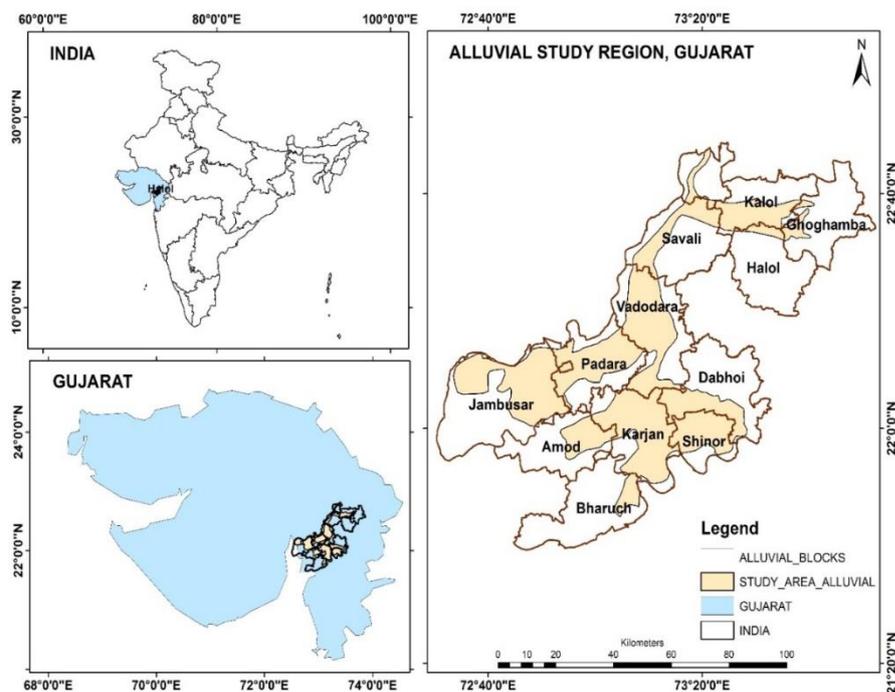

Fig.1: Alluvial study region, Gujarat, India

8

The alluvial region is situated in the transition zone between the arid North Gujarat plains and the South Gujarat districts with high rainfall. It has a subtropical climate with moderate humidity. Due to the region's hot, semi-arid environment and high potential evapotranspiration, it receives about 850 mm of rain yearly. March to July have hot weather with average maximum temperatures of 39 °C and lowest temperatures of 24 °C. From the middle of June to the middle of September, the southwest monsoon produces a humid climate. Average humidity is 55%. The average wind speed is 90.92 km/day. The average sunshine available in 24 hours are 8.45 hours, whereas the average evapotranspiration is 5 mm/day. The alluvial region has a varied agriculture crop production such as paddy, wheat, jowar, bajra, maize, pulses, cotton, oil groundnut, castor, tobacco, fodder, etc. (**DIPS Bharuch-2016, DIPS Vadodara-2016, DIPS Panchmahal-2017**)

One of the state's most industrially developed sectors is the alluvial region. Several enterprises, including petrochemical facilities, fertilizer factories, heavy water projects and oil refineries are situated close to Vadodara Taluka. Pharmaceuticals, engineering & equipment components, rubber-plastic, non-metallic mineral products, metal products, rubber-plastic and non-metallic mineral products are some of the other significant industries in the Vadodara Taluka. Several industrial notified areas have been formed and are managed by GIDC in various parts of the district (Gujarat Industrial Development Corporation Limited) (**DIPS Bharuch-2016, DIPS Vadodara-2016, DIPS Panchmahal-2017**).

Groundwater is found in both confined and unconfined conditions in the study area. Unconfined aquifers are created by saturated zones of unconsolidated shallow alluvium, weathered zones, shallow depth jointed and fractured rocks, whereas multi-layered aquifers beneath impervious clay layers in alluvium formation and interflow zones of basalts, inter-trapping beds, deep seated fracture zones and shear zones in Basalts, Granites and Gneisses create semi-confined to confined conditions (**GWB Bharuch-2014, GWB Vadodara-2012, GWB Panchmahal-2014**) As per recommendation of **GEC (2015)**, the water level fluctuation approach was used to calculate ground water recharge during the monsoon season, and the results were compared to recharge based on infiltration variables. In addition to rainfall, other factors such as seepage from canals, irrigation return flows, recharge from tanks, ponds and water-conservation structures, etc. were taken into account. It has been noted that the shallow aquifer's ground water quality differs depending on the type of underlying rock. In general, the quality of the Eastern hard rock sections is consistent and good in nature, whereas the quality of the western alluvium parts fluctuates greatly and has a large concentration of dissolved ions (TDS). The discharge in dug wells varies from 30 to 50 m³/day and in shallow tubewells it varies from 150 to 800 m³/day for a drawdown of 6 to 15m. The major part of the alluvial region observed depth to water level ranges 2 to 40 mbgl. (**GWB Bharuch-2014, GWB Vadodara-2012, GWB Panchmahal-2014**)

DATA COLLECTION

The data requirement and their collection for the purpose of this research is described in table-1. To achieve the objective of groundwater contaminant source identification, groundwater sample data of 50 openwells and shallow tubewells falling in the alluvial region were collected from MOJS-DDWAS (Ministry of Jal Shakti, Department of Drinking Water and Sanitation) portal for 2018-2020 time period of both pre and post monsoon seasons. The multivariate statistical analysis (Z-score, PCA, HCA and FSA) was applied on these data to obtain pockets of anthropogenic sources with the help of IDW (Inverse Distance Weighted) interpolation method in GIS environment.

Table-1: Data requirement and collection

Sr.	Source	Description of collected data
Obj. 1: To identify various sources of ground water contamination in study area		
1	MOJS-DDWAS	Groundwater quality data (50 Wells) (2018Pre monsoon)
Obj. 2&3: To develop suitable model to assess the ground water vulnerability (DRASTIC Index)		
1	India WRIS	**For 'D':** Groundwater depth / Water level data (54 Wells) (2018 – Pre and Post monsoon)
2	SWDC, Ahmedabad	**For 'R':** Average Annual Rainfall (2000-2016) Canals, Tanks and Ponds, WCS polygons from google earth
3	CGWB-WCR, Ahmedabad	**For 'R':** Reference block wise Groundwater Recharge and Extraction (For recharge calculation), Hydraulic conductivity reference
4	GWRDC, Gandhinagar	**For 'A, S, I, C':** Lithology – Aquifer, Soil, Vadose zone, Hydraulic Conductivity
5	USGS Earth explorer	**For 'T':** SRTM Digital Elevation Map, Landsat 8 images, Land Use Land Cover
6	MOJS-DDWAS	**For 'FS':** Groundwater quality data (50 Wells) (2018 – Pre and Post monsoon) **For 'Model Validation':** (2018, 2019, 2020 – Pre monsoon)
Obj. 4: To develop the relationship between vulnerability parameter with ground water quality		
1	MOJS-DDWAS	**Groundwater quality data (50 Wells) (2018 – Pre and Post monsoon)
** Groundwater quality data has been shown in Annexure and all other data has been shown in Thesis.**		
Obj. 5: To suggest the management strategy to minimize the risk on public health		
1	USEPA guidelines	Groundwater nitrate daily consumption for adults and children
2	Primary data and GTS.	Groundwater quality samples (2018 Pre, 2021 Pre, 2022 Pre), Location specific characteristics.
3	MOJS-DDWAS	Groundwater quality data (OS-50) (2018, 2019, 2020 – Pre and Post monsoon) Water use scenario, Population distribution

The objective of groundwater vulnerability assessment was achieved using 50 observation wells of CGWB from India-WRIS portal for the time period 2018 (Pre and Post monsoon). Groundwater recharge was estimated as per (GEC-2015). Other sources of groundwater recharge such as canals, tanks, ponds and water conservation structures were digitized in google earth pro and imported in GIS environment. The estimated recharge was also checked against block-wise referenced values provided by CGWB-WCR, Ahmedabad. Aquifer media (A), Soil media (S), Impact of vadose zone (I) and hydraulic Conductivity (C) parameters of DRASTIC model were assigned the ratings based on 76 lithologs of the alluvial region for which the data was collected from GWRDC, Gandhinagar. Topography (T) parameter was obtained by collecting DEM (Digital Elevation Map) for the alluvial region from USGS Earth Explorer. The factor score (FS) parameter was estimated from above mentioned multivariate statistical analysis (PCA and FSA) applied on 50 openwells and shallow tubewells of MOJS-DDWAS portal for 2018 pre and post monsoon time periods.

The objective of public health risk assessment against groundwater Nitrate was achieved considering data from 50 openwells and shallow tubewells of 2018 pre and post monsoon time periods which also showed water use scenario, average water demand and population distribution at each sample location. The United States Environmental Protection Agency guidelines **(USEPA 1999)** were used to obtain hazard quotient (HQ) for children and adults. To minimize the health risk against groundwater nitrate, various groundwater management strategies were recommended.

METHODOLOGY

A comprehensive methodology to achieve objectives of present research
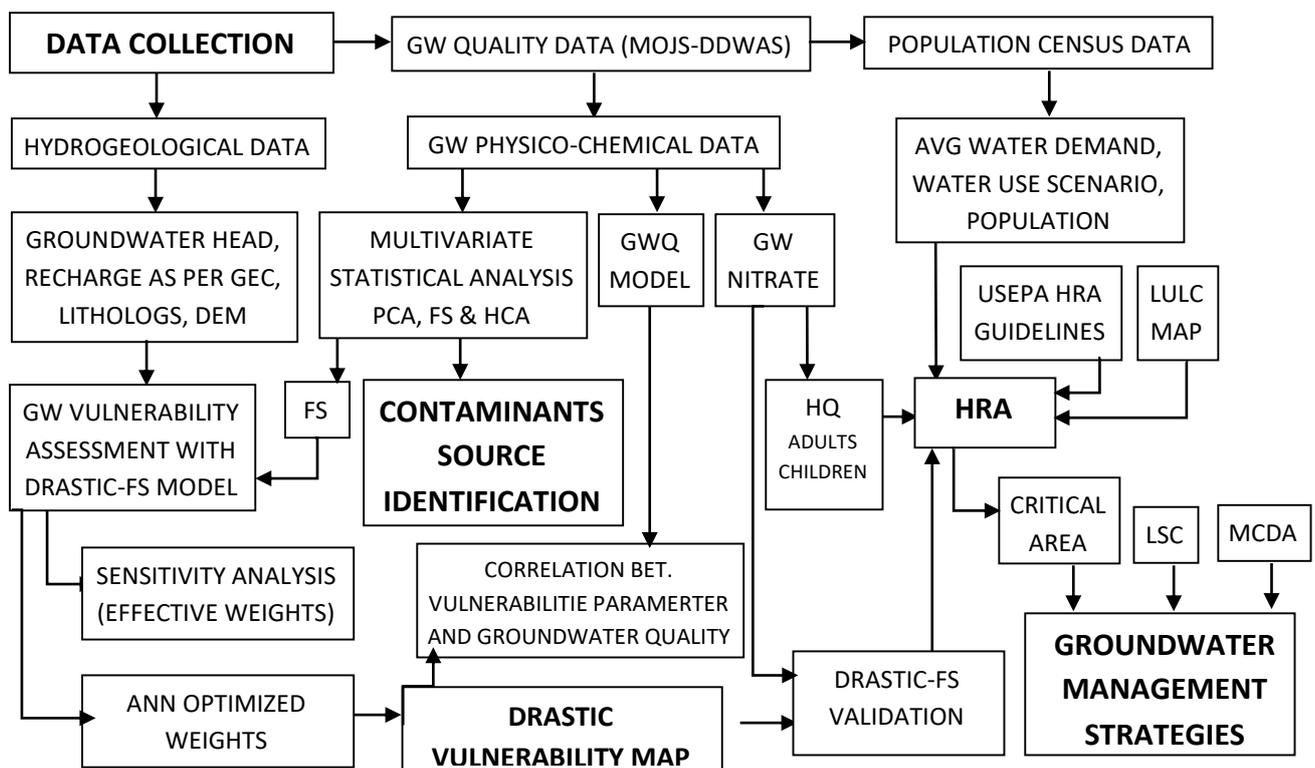

Fig. 2: A comprehensive flow chart of present research methodology

Objective1: To identify various sources of Groundwater contamination in study area.

Step 1: The first step is to perform multivariate statistical analysis on groundwater quality data collected from MOJS-DDWAS portal for 2018 both pre and post monsoon seasons.

Step 2: At each 50 well location 10 common groundwater quality parameters (pH, TDS, NO_3, F, Cl, SO_4, Ca, Mg, TH and ALK) were available which were imported in SPSS software and all the parameter values were transformed into Z-scores.

Step 3: The PCA was performed using these Z-scores and PCs (1-n) as well as FS were extracted at each well location.

Step 4: These FS values at each location was input in GIS environment to obtain their spatial distribution.

Step 5: The HCA was performed on all the well location which resulted into a Dendrogram that explained distribution of wells falling in the same clusters.

Step 6: From the Factor Score of each location will be used to reveal the type of sources of contaminations and corresponding reasons.

Objective 2 & 3: To develop suitable model to assess ground water vulnerability in study area.

Step 1: After the collection of required hydrogeological data, explore the data for development of DRASTIC model.

For 'D': Groundwater depth (from India WRIS)

For 'R': Average Annual Rainfall (2000-2016), Canals, Tanks and Ponds,

      Water Conservation Structures polygons from google earth

For 'R': Reference block wise Groundwater Recharge and Extraction

      (For net recharge calculation), Hydraulic conductivity reference

For 'A, S, I, C': Lithology – Aquifer, Soil, Vadose zone, Hydraulic Conductivity

For 'T' : SRTM Digital Elevation Map, Landsat 8 images, Land Use Land Cover

For 'FS': Groundwater quality data (50 Wells) (2018 – Pre and Post monsoon)

For 'Model Validation': (Groundwater quality data 2018, 2019, 2020.

Step 2: Study the limitations of DRASTIC analysis.

Limitation (1): Aller Linda has given Delphi Committee weights from 1 to 5 to vulnerability parameters D, R, A, S, T, I, C in the year1987. This weights are without any technical and logical base.

Limitation (2): Area specific anthropogenic activities are highly contributing element to groundwater vulnerability. It must be addressed by introduction of new parameter to assess GWV precisely.

Step 3: Using GIS tool, all required data input under the governing equation of DRASTIC. Topography file must be made as raster file from SRTM-DEM.

Few operation are frequently used such as Spatial Analyst Tool, Interpolation, Extraction, Weighted sum, Modal Builder in GIS.

Step 4: Create DRASTIC model using Molder builder tool in GIS and run inserting equations of the form of ratings and weights of each parameter as per recommendation by Aller Linda (1987).

Step 5: The DRASTIC-FS model has an additional layer that takes into account the impact of the anthropogenic activities in the form of FS (Factor Score). The 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 ranges.

Step 6: Using ANN program, the weights of each individual Vulnerability parameters (D, R, A, S, T, I, C, FS) are to scientifically and logically optimized and used for Calculation of revised DRASTIC-FS model. This optimized weights will overcome the limitation of conventional DRASTIC analysis.

Step 7: Create DRASTIC-FS model using Molder builder tool in GIS and run inserting modified equations of the form of ratings. The value of each parameter must be input as per ANN optimized weight.

Step 8: The output of the model have been obtained in the form of Raster map. This file have been used to extract pixel wise values of each vulnerability parameters.

Step 9: The sensitivity analysis (SPSA) have been performed and Theoretical Weight have been verified with Effective Weight and ANN optimized Weight.

Step 10: The Vulnerability output has been validated with single dominating water quality parameter NO_3. It has validated for 3 successive years 2018, 2019 and 2020.

DRASTIC Index

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.

DRASTIC Index (Di) = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw   (1)

Where, D = Depth to water level, R = Recharge (inches), A = aquifer media, S = Soil media, T = Topography, I = Impact of Vadose zone and C = Hydraulic conductivity.

Following tables (2, 3) represent ratings (R) and weights (W) adopted for DRASTIC approach based on **Linda A. et al. (1987)**.

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

Depth (W=5)		Recharge (W=4)		Topography (W=1)		Conductivity (W=3)	
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-3: Ratings (R) of DRASTIC Parameters (Aquifer media, Soil media, Impact of vadose zone)

Aquifer Media (W=3)		Soil Media (W=2)		Impact of Vadose zone (W=5)	
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

DRASTIC-FS index

In this DRASTIC-FS Approach, in addition to the 7 parameters of DRASTIC model, a new parameter as Factor Score (FS) which represents dominating contaminants of groundwater quality for each well location with the source of contamination in terms of Anthropogenic, Natural or Anthropogenic and Natural combined. The FS index has been obtained using Principle Component Analysis (PCA) and Factor Score Analysis (FSA) performed on secondary groundwater quality data (MOJS-DDWAS) of the time period 2018. The initially assigned weight significance of this layer is (W=5) and ratings R have been worked out in the following table-4.

Table-4: FS Index Weightage and Ratings

Sr. No.	Factor Score Range	Ratings (1-10)	Remarks
1	0 to 0.5	1	Non Polluted
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)

The formula for DRASTIC-FS index is as below:

$$DRASTIC - FS \ Index = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w + FS_r FS_w$$

Where, FS = Factor Score

DRASTIC-FS model has been built using model builder in GIS environment in which three processes take place. First process is to input model parameters which are DRASTICFS. 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. 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.

ANN Optimized Weights

The optimization of weights for D, R, I, C and FS parameters has been done with 3 layered artificial neural network (ANN) coded in python language. For such optimization, first the variable parameters have been assigned with factors on which they are depending. These factors are described for each individual parameters in the table below. 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-5 have been considered in the groundwater vulnerability assessment.

Table-5: Parameter depending on factors used for ANN weight optimization

Parameters	Parameter depending upon fallowing factors
Depth (D)	Recharge, Aquifer media, Soil media, Topography, Vadose zone, Conductivity
Recharge (R)	Soil media, Topography, Vadose zone, LULC
Aquifer Media (A)	Constant parameters: ANN weights same as Theoretical weights of Delphi Committee (Linda Aller, 1985)
Soil Media (S)	
Topography (T)	
Impact of Vadose zone (I)	Depth, Recharge, Aquifer media, Soil media
Conductivity (C)	Depth, Recharge, Aquifer media, Vadose zone
Factor-Score (FS)	pH, TDS, NO$_3$, F, Cl, SO$_4$, Ca, Mg, TH, ALK

Objective 4: To develop the relationship between Vulnerability parameters with Groundwater Quality

Step 1: Selection of type of well samples from unconfined aquifer.

Step 2: Assessment of groundwater quality Index

$$GWQI = \sum_{i=1}^{n} SIi$$

Step 3: Extract values of vulnerability parameters and groundwater quality index at each well location in the form of table.

Step 4: Correlation analysis between vulnerability parameters (D, R, A, S, T, I, C, FS) and water quality parameters (TDS, NO_3, F, and GWQI) in SPSS Spearman's RHO.

Step 5: Same input file of vulnerability parameters and water quality parameters must be used for correlation analysis using Python tool.

Step 6: Comment based on Outcome.

Objective 5: To suggest the management strategy to minimize the risk on public health.

Step 1: First step is to delineate dominating contaminant in groundwater and understand the extant of its concentrations in study area. In this study Nitrate has been observed up to 284mg/l.

Step 2: Hazard Quotient (HQ) for adults and children due to high Nitrate concentration have been determined with USEPA method.

HQ$_{nitrate}$ = CDI / RfD

CDI (Chronic daily intake) is the ingestion dose from drinking water (mg/kg/day).

RfD is reference dose (1.6 mg/kg/day) for non-carcinogenic health risk.

The Critical Area= Area having High Health Risk

Step 3: The critical area has been identified by HQ and with the addition of 3 logical components i. e. LULC, Water use scenario and Population distribution using GIS tool. All above 4 components have been used to generate HRA map which is built in GIS, by rating range of 1 to 5.

Step 4: Based on HRA model which is built in GIS, critical area has been decided and Ground Truth Study has been carried out. Primary data has been collected on May 2021 to verify the presence of high Nitrate concentration in groundwater.

Step 5: During GTS, groundwater samples and area specific characteristics have been obtained are necessary information to suggest appropriate remedial strategies at particular well location.

Step 6: There were 24 well location identified among 41 samples with high Nitrate in groundwater. Suggested Strategies were: PHYTO (Phytoremediation), PAF (Pump and Fertilize), PRB (Permeable Reactive Barrier), CHEM (Chemical injection), PAT (Pump and Treat)

Health risk assessment (HRA):

The human health risks due to high nitrates in groundwater have been assessed as per USEPA proposed HRA method. As the groundwater is the primary source of drinking water, oral ingestion is considered as the leading human exposure indicator (**Adimalla& Li 2018, Ahada & Suthar 2018**). The Health Risk Assessment is based on following governing equations. The ingestion of Nitrate ions with drinking water in human body is calculated by following equation,

$$\text{Chronic Daily Intake (CDI)} = \frac{C * IR * EF * ED}{BW * AT} \tag{3}$$

Chronic Daily Intake (CDI) is the ingestion dose from drinking water in (mg/kg/day). In the above equation, C is the concentration of nitrate ions evaluated in groundwater samples, in mg/l. IR is the average daily Ingestion Rate of drinking water, in L/day, the values of IR are 2 L/day for adults and 1 L/day for children. EF is the exposure frequency, in 365 days/year. ED is the exposure duration. BW is the body weight, 70 kg for adults and 15 kg for children. AT is the average exposure time, 10950 days and 5380 days for adults and children respectively (Ahada & Suthar 2018). By using the following equation, the Hazard quotient (HQ) is used to calculate the non-carcinogenic health risk,

$$\text{HQnitrate} = \frac{CDI}{RfD} \tag{4}$$

Where, RfD is the reference dose, in 1.6 mg/kg/day for non-carcinogenic health risk. $(HQ_{nitrate})<1$ is an acceptable level of non-carcinogenic risk and $(HQ_{nitrate})>1$ potentially known to cause health risks in individuals due to ingestion of nitrate contaminated groundwater.

Analytical Hierarchy Process (AHP)

One of the most popular MCDA approaches, the AHP was first introduced by Saaty (1980), and it combines qualitative and quantitative data to show the decision-makers' choice sequences (DMs). The starting step is to decompose the decision making problem in a hierarchical manner to develop the pairwise comparison matrix based on choice order of the alternatives (ranks) and criteria (weighs) considering from the inputs of DMs. A scale rating of nine orders in which 1 denotes equivalent and 9 indicates highest importance with 2 to 8 even numbers as intermediate ratings are assigned to each criteria and alternatives to compute weightage by following equation:

$$Pq = \lambda_{max} * q \tag{5}$$

Where, P is the comparison matrix of n dimension, λmax is the highest eigenvalue of P and q is eigenvector corresponding to λmax. The consistency of the comparison matrix has to be checked as the inputs from DMs might contradict their own preferences. The inclusion of consistency ratio (CR) in any MCDA method is a common practice to evaluate any inconsistencies in the comparison matrix.

$$CI = (\lambda_{max} - n)/ (n - 1) \tag{6}$$
$$CR = CI/RCI \tag{7}$$

Where CR is the consistency ratio, CI is the consistency index, RCI is the average random consistency index with the same dimension of the comparison matrix, n is the number of

criteria/alternatives. If the CR is greater than 10%, the matrix is said to be inconsistent and DMs are advised to revise the matrix until CR comes below 10%.

      Ground Truth Study (GTS): GTS is an important step which includes site exploration, primary data collection, sampling and laboratory testing of various physico-chemical groundwater parameters before opting for a suitable remediation method. After identification of the critical area based on health risk assessment using secondary data, it is at most necessary to verify present status of contaminants in groundwater by primary data collection. Also the local information should be collected that later on consider prescribing appropriate remedial strategy.

RESULTS AND DISCUSSIONS

(1) Identification of sources of contamination:

Principal Components and Factor Scores (PCA & FS): The variance values of groundwater quality parameters is shown in table-6 as the initial eigenvalues. The Extraction Sums of Squared Loadings of variables includes only Eigenvalue > 1 which means more total variation in the data than individual parameter, and factor with Eigenvalue < 1 explains less total variation. Now, only factors with Eigenvalue >1 are retained for further Rotation Sums of Squared Loadings which reduces the number of variables.

      In this research, three principal components with varimax rotation having eigenvalues greater than 1 which explained 78.69 % of cumulative variance were extracted in SPSS environment. The factor loadings for PC-1 showed that (TDS, NO3, Cl, SO4, Mg, TH) showed 51.44% of total variance from the dataset. The PC-2 highlighted 15.02% of variance with high positive loadings on (F, ALK) parameters. The PC-3 observed 12.23% variability containing (pH, Ca) parameters. The factor loadings for PCs are described in table-6. After the PC extraction, factor scores at each well location were used for spatial distribution of individual PCs as well as a composite PC in GIS environment considering IDW interpolation method **(Ghosh and Kanchan, 2014, Loganathan and Ahmed 2017)**. These maps highlighted the areas contaminated from anthropogenic sources having FS>2.

Table-6: Factor loadings for PCs after Varimax Rotation

Rotated Component Matrix			
GWQ Parameters	**Component**		
	PC-1	**PC-2**	**PC-3**
TDS	0.919		
NO$_3$	0.783		
Cl	0.705		
SO$_4$	0.943		
Mg	0.954		
TH	0.839		
ALK		0.818	
F		0.793	
pH			0.350
Ca			0.939

The majority of the contaminated pockets were identified in the northern (wells 6, 8, 15 and 24) and central parts (43 and 44) of the alluvial region showing factor score greater than 2 being considered as the anthropogenic contamination sources. The conventional agriculture practices, rapid growth of minerals and manufacturing industries as well as shallow depth of groundwater are the key anthropogenic sources responsible for contamination. The overlay analysis also highlighted a few pockets in the central alluvial region having factor scores greater than 1 which required continuous monitoring. With relatively deep groundwater and low factor scores for the perennial Mahi and Narmada rivers, the less contaminated wells were found in the Southern and Western regions of the alluvial zone.

Hierarchical Cluster Analysis (HCA):

In Hierarchical Cluster Analysis (**Machiwal and Jha, 2015**), the Z-scores obtained for the groundwater quality dataset 2018 pre-monsoon were used with the Ward's linkage approach and squared Euclidean distances as a measure of similarity (**Loganathan and Ahmed, 2017**).

The Hierarchical Cluster analysis distributed the dataset into 4 significant clusters. The Dendrogram obtained from HCA shown in fig. 4 helped in understanding the distribution of well location in each cluster (table-7) and range values of each quality parameter (table-8).

Table-7: Cluster Classification

Clusters	Well Locations
Cluster-1	1, 2, 4, 5, 7, 10, 11, 12, 13, 14, 16, 17, 18, 19, 20, 22, 23, 25, 27, 29, 30, 31, 33, 34, 35, 36, 40, 45, 46, 47, 48, 49
Cluster-2	3, 26, 32, 37, 38, 39, 41, 42, 43
Cluster-3	6, 8, 9, 15, 21, 28, 44, 50
Cluster-4	24

Table-8: Ranges of GWQ parameters for each cluster

Cluster	pH	TDS	NO$_3$	F	Cl	SO$_4$	Ca	Mg	TH	ALK
BIS	**6.5-8.5**	**500-2000**	**45**	**1.0-1.5**	**250-1000**	**200-400**	**75-2000**	**30-100**	**200-600**	**200-600**
1	7.49- 8.08	382 - 1558	2 -104	0.07 - 1.32	36 - 540	6 – 70	19 - 154	27 -112	168 - 768	228 - 550
2	6.89- 8.41	820 - 1618	4 - 45	0.72 - 2.15	84 - 568	11 - 64	14 - 61	15 - 60	104 – 404	446 - 825
3	7.3- 7.9	1144 - 2494	28 – 168	0.38 - 1.46	76 - 832	31 – 210	100 – 239	86 - 169	812 - 1196	404 - 828
4	7.00	4120	284	0.54	848	473	24	424	1810	602

The below fig. 3, is showing the cluster distribution of well locations obtained from HCA. The cluster 1 majorly located in southern parts showed 64% of the well samples with moderate mean values of pH (7.83), Ca (73 mg/L) and TH (418 mg/L) groundwater quality parameters. The figure 8 highlighted cluster 2 containing 18% of well samples in the central and western parts with high ALK (644 mg/L) and F (1.19 mg/L) parameters.

The Cluster 3, which included 12% of well locations with high mean values of NO3 (98 mg/L), Mg (122 mg/L) and TH (912 mg/L) explaining high anthropogenic sources in shallow aquifers of alluvial region. The well number 24 came under cluster-4 with the highest amount of NO_3 (284 mg/L), TDS (4120 mg/L), SO_4 (473 mg/L), Mg (424 mg/L) and TH (1810 mg/L) pointing towards severe contamination from anthropogenic sources.
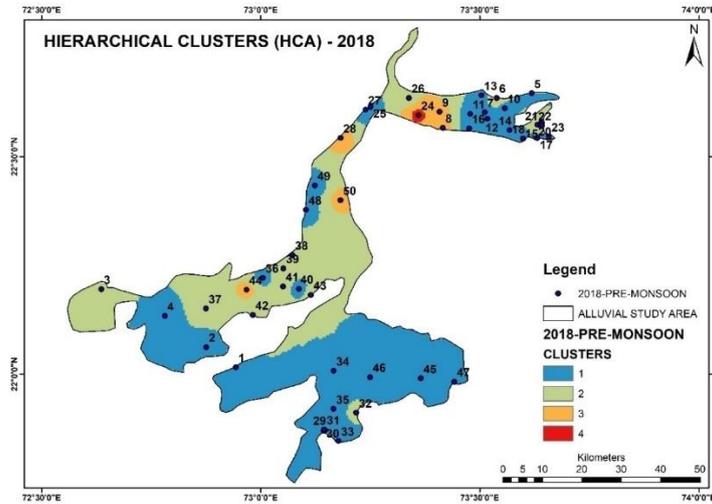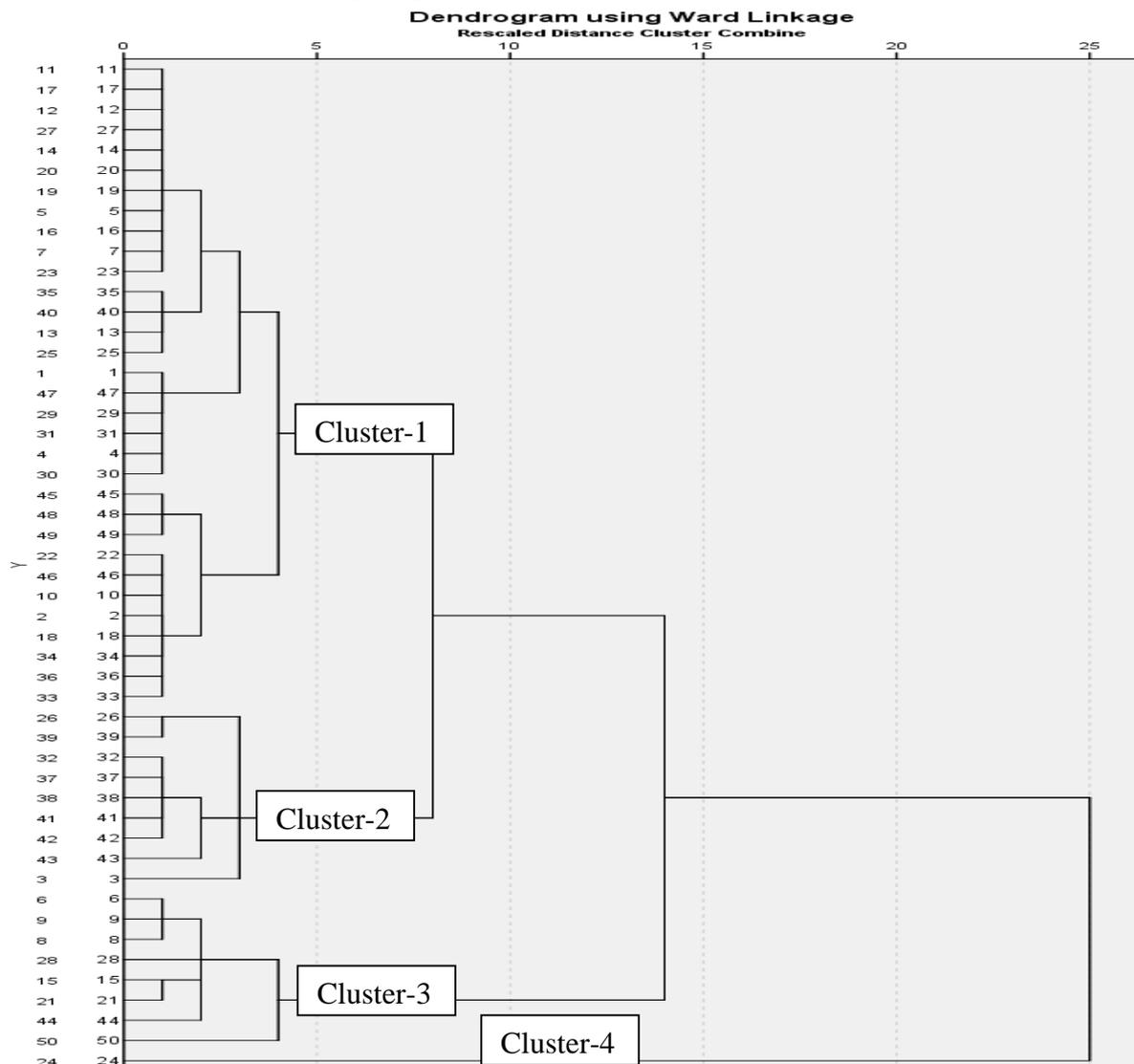

Fig. 3: Spatial distribution of Clusters from HCA

Fig. 4: Dendrogram for 2018-Pre-Monsoon data (MOJS-DDWAS)

20

DRASTIC-Model Outcomes:

Depth of Water table: When assessing an alluvial region's groundwater vulnerability to contamination, water level depth is a crucial layer to consider. The maximum weight (W=5) is assigned to the depth to groundwater, and ratings are described in table 2. The shallow groundwater levels are observed in a few pockets of Northern, Central and Western regions (blue zone in figures 5 & 6) whereas deep levels are observed in Western and Central parts (red zone in figures 5 & 6) of the study area for both pre and post monsoon seasons.
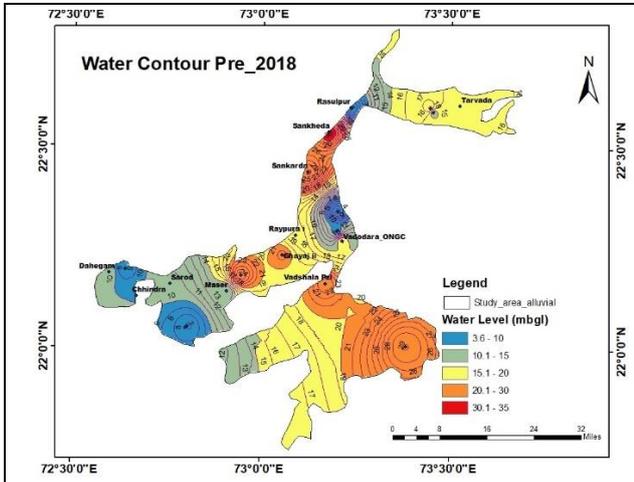
Fig. 5: Groundwater Depth Pre-monsoon 2018	Fig. 6: Groundwater Depth Post-monsoon 2018
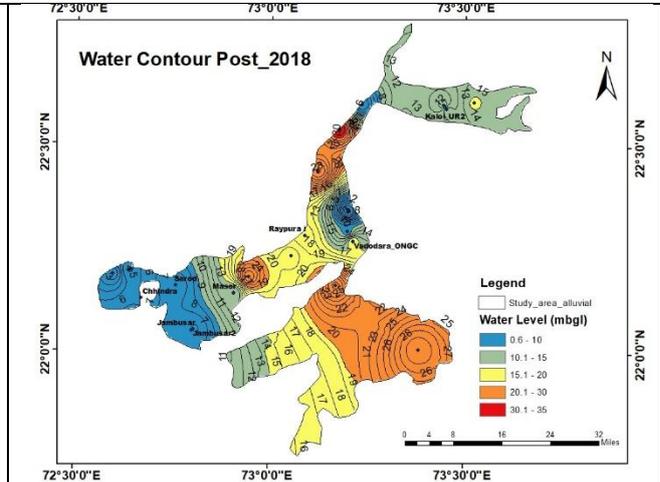
Recharge: Groundwater Recharge transports contaminants from the surface to the shallow zones directly. Contamination risks are greater in regions with high groundwater recharge. The ratings and weight (W=4) for this parameter are explained in table 2. In the pre monsoon season (fig. 7) less groundwater recharge has been seen in Southern parts of study area (blue zone) but in the post monsoon (fig. 8) only a few pockets of Western parts (blue zone) showed less recharge, in other parts high recharge is demarcated by red zone.
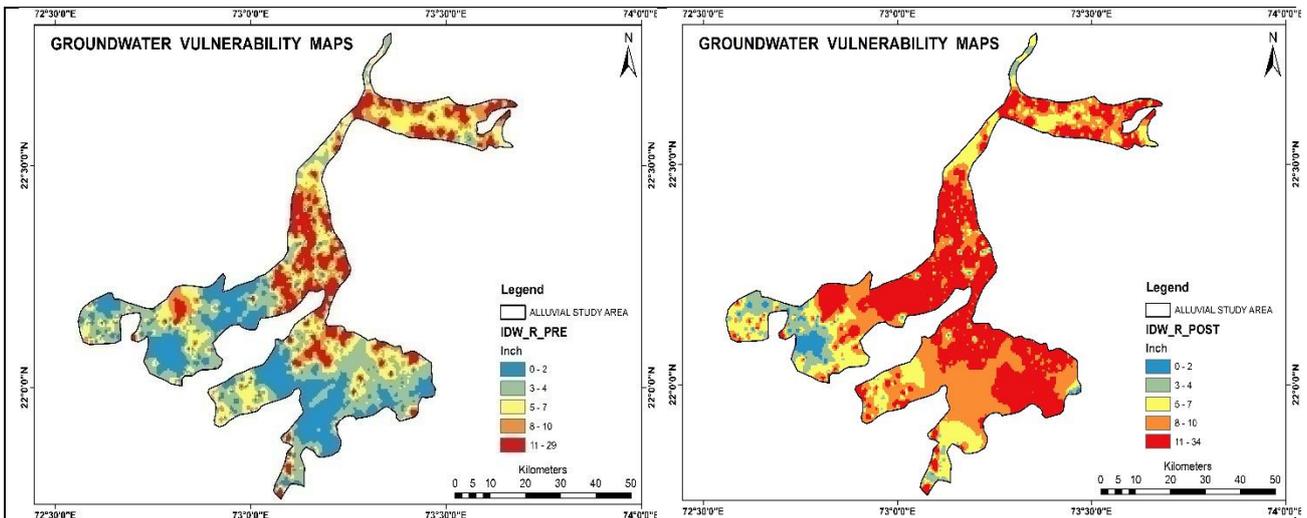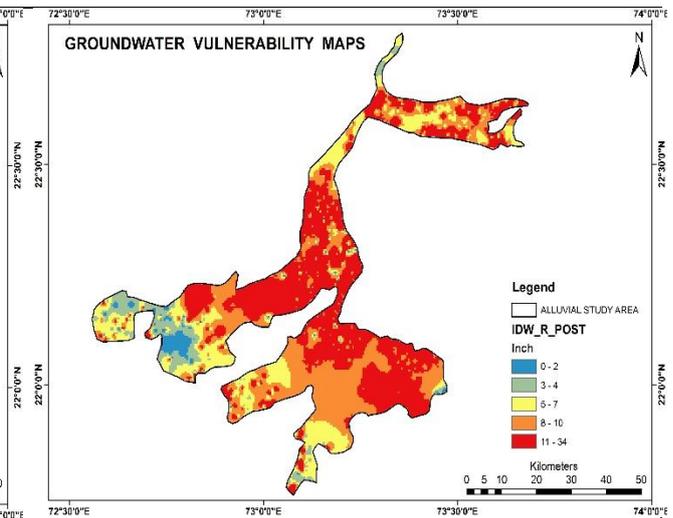

Fig. 7: Recharge Pre-Monsoon	Fig. 8: Recharge Post-Monsoon

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 (Aller et al. 1987). The litholog available 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) discussed in table-3. The ratings of aquifer media for present study area are shown in fig. 9.

Soil Media: Recharge from various soil materials into groundwater indicates the downward movement of contaminants through the vadose zone, which is an important input model parameter. Moreover, the attenuation processes of filtration, biodegradation, sorption, and volatilization may be highly considerable where the soil zone is fairly thick. 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 weight (W=2) and their ratings are discussed in table-3. The ratings of soil media for present study area are shown in fig. 10.

| Fig. 9: Aquifer media (Ratings) | Fig. 10: Soil media (Ratings) |
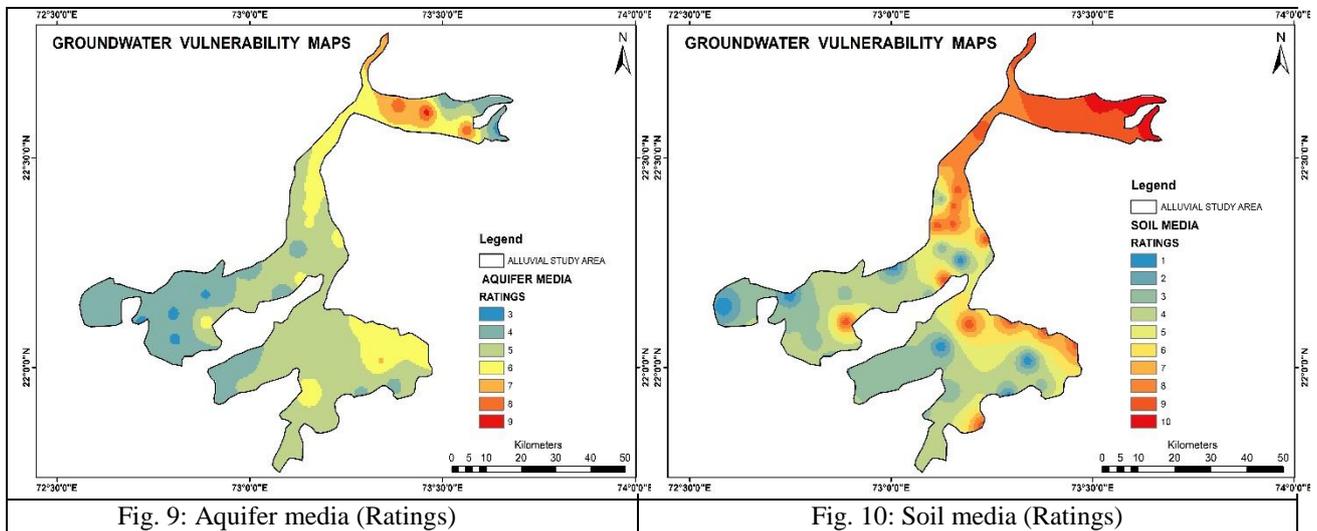
Topography: Topography controls the residence time of the water on the surface of the soil, thereby affecting the rate of infiltration. Topography in the form of percent slope has been determined in GIS with the help of spatial analyst tools considering USGS-SRTM digital elevation model (DEM). Topography ratings are discussed in table-2. The spatial distribution of ratings of this parameter is shown in figure-11.

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-3. The ratings of impact of vadose zone for present study area are shown in figure-12.

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 discussed in table-2. The spatial distribution of ratings of this parameter is shown in figure-13.
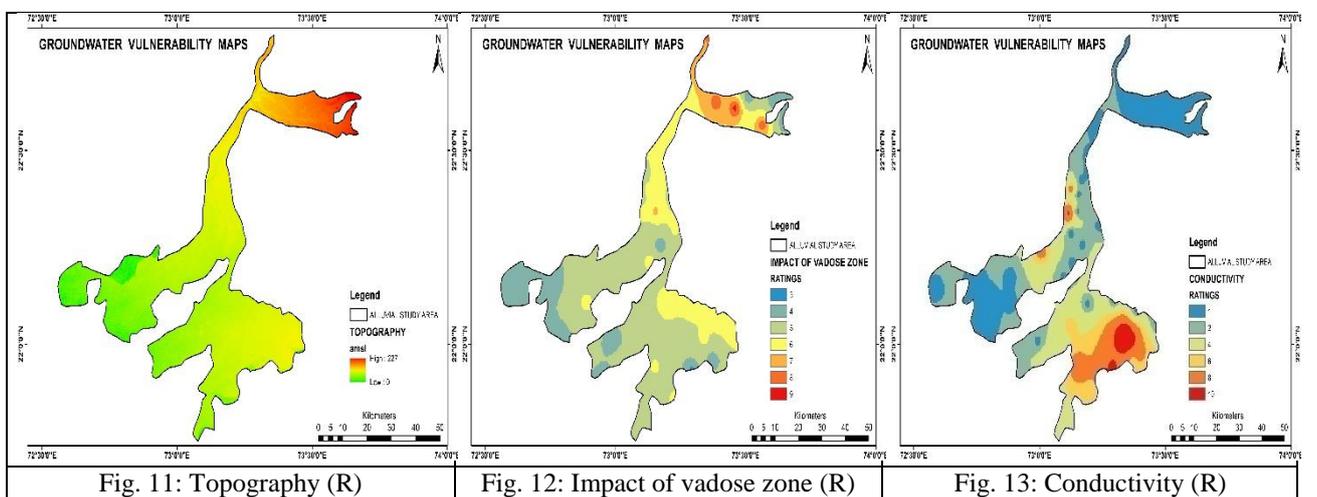

| Fig. 11: Topography (R) | Fig. 12: Impact of vadose zone (R) | Fig. 13: Conductivity (R) |

Table 9: Optimized weight of parameter by induvial ANN

Parameters	ANN Weights-Pre	ANN Weights-Post
Depth (D)	3.80	4.30
Recharge (R)	5.20	7.90
Aquifer Media (A)	3.00	3.00
Soil Media (S)	2.00	2.00
Topography (T)	1.00	1.00
Impact of Vadose zone (I)	5.20	5.20
Conductivity (C)	3.30	3.10
Factor-Score (FS)	3.80	4.80

DRASTIC and DRASTIC-FS Model Outcomes

After successful execution of final run, groundwater vulnerability maps of both the models DRASTIC pre-monsoon (fig. 14) and post-monsoon (fig. 15), DRASTIC-FS (ANN optimized weights) pre-monsoon (fig. 16) and post-monsoon (fig. 17) seasons are shown below.
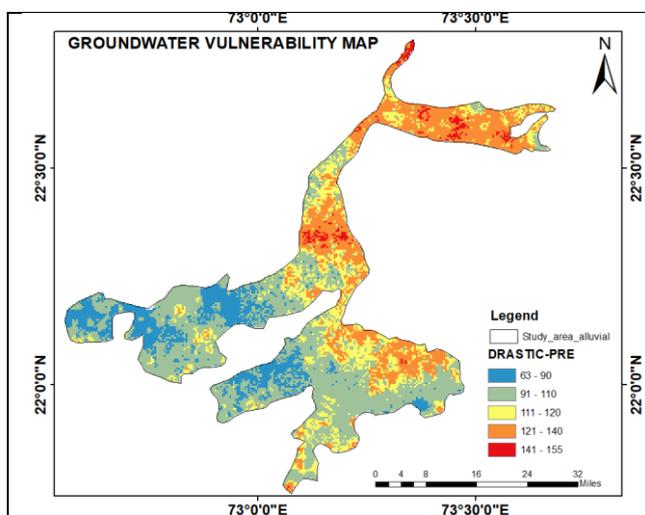

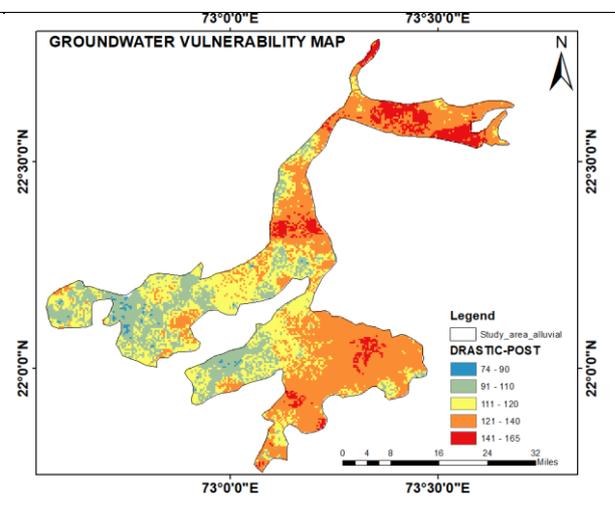Fig. 14: DRASTIC Vulnerability Map Pre-Monsoon

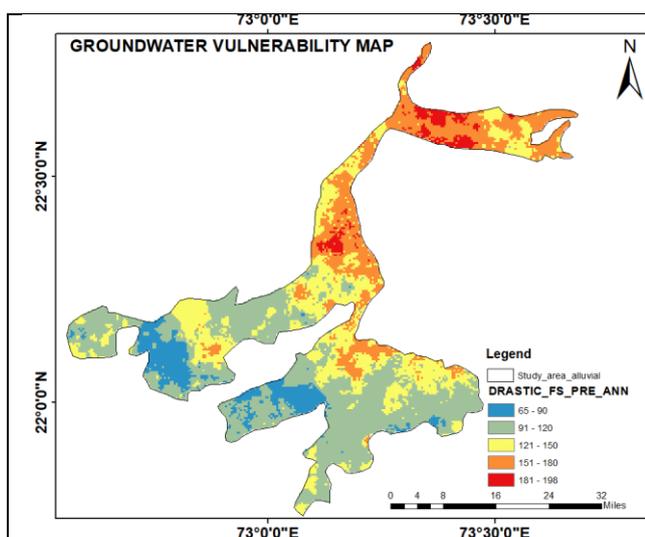Fig. 15: DRASTIC Vulnerability Map Post-Monsoon

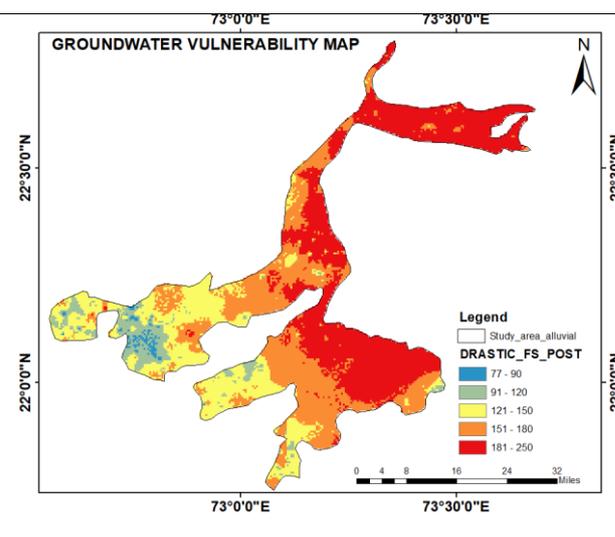Fig. 16: DRASTIC-FS-ANN Map Pre-Monsoon

Fig. 17: DRASTIC-FS-ANN Map Post-Monsoon

The basic statistical summary of DRASTIC-FS model (pre-monsoon) is given below (table-10,11) which highlights R, A, S, T, and I parameters to be highly contributing whereas D and C

23

parameters to be less contributing in overall groundwater vulnerability. 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-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-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

The groundwater vulnerability index ranges from 63 to 155 in pre-monsoon season from DRASTIC model (fig.-10) in that, sustainable (63-90), less vulnerable (91-110), moderately vulnerable (111-120), highly vulnerable (121-140) and severely vulnerable (141-155) are representative classes. The DRASTIC-FS (ANN weights) model final vulnerability index (fig.-12) is mapped from 65 to 198 in that, sustainable (65-90), less vulnerable (91-120), moderately vulnerable (121-150), highly vulnerable (151-180) and severely vulnerable (181-198) 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-12). 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.

Table-12: Groundwater Vulnerability outcome in terms of % area

Vulnerability Class	DRASTIC (Pre)	DRASTIC-FS (Pre)	DRASTIC (Post)	DRASTIC-FS (Post)
1-Sustainable	14.39	14.88	11.43	7.74
2-Less Vulnerable	25.51	31.02	28.98	20.99
3-Moderately Vulnerable	23.24	21.98	29.22	37.16
4- Highly Vulnerable	23.70	18.60	22.70	23.02
5-Severely Vulnerable	13.17	13.52	7.67	11.09

Validation of DRASTIC-FS Model

Validation from Single Parameter Sensitivity Analysis

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. (**TomerT. 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.

$$We = [(Pr * Pw)/Vi] * 100 \qquad \qquad …(8)$$

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

$$\text{Mean Percent Deviation (PD)} = [(We - Wt)/Wt] * 100 \qquad \qquad …(9)$$

Where, We = Effective weight   Wt = Theoretical weight

From Single Parameter Sensitivity Analysis (tables 13, 14), 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.

Table-13: Single Parameter Sensitivity Analysis – Pre-Monsoon

Parameter	Theoretical Weight	Theoretical Weight (%)	Effective Weight	Effective Weight (%)			
				Mean	Minimum	Maximum	St. Dev.
D	5	17.9	**4.16**	14.84	3.62	32.89	5.28
R	4	14.3	**4.40**	15.71	2.80	35.29	6.34
A	3	10.7	**3.24**	11.58	6.57	18.75	2.27
S	2	7.14	**2.18**	7.77	1.32	20.62	2.88
T	1	3.57	**1.37**	4.91	0.53	12.82	2.62
I	5	17.9	**5.62**	20.08	11.70	33.33	3.40
C	3	10.7	**2.30**	8.22	1.52	32.26	6.56
FS	5	17.9	**4.73**	16.88	3.33	40.65	10.71
Total	28	100	28	100			

Table-14: Single Parameter Sensitivity Analysis - Post-Monsoon

Parameter	Theoretical Weight	Theoretical Weight (%)	Effective Weight	Effective Weight (%)			
				Mean	Minimum	Maximum	St. Dev.
D	5	17.86	**4.3**	15.35	3.4	25.7	3.1
R	4	14.29	**6.0**	21.30	2.9	35.3	3.7
A	3	10.71	**3.0**	10.55	5.8	18.3	1.6
S	2	7.14	**2.0**	7.19	1.2	20.6	2.9
T	1	3.57	**1.3**	4.47	0.5	11.8	2.3
I	5	17.86	**5.1**	18.34	11.2	35.7	2.6
C	3	10.71	**2.0**	7.04	1.5	23.6	5.0
FS	5	17.86	**4.4**	15.88	2.6	51.5	9.9
Total	28	100	28	100			

From the figures (18 & 19), the variation in theoretical weights, effective weights and ANN optimized weights for DRASIC-FS approach have been shown. The fig. 18 indicated 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. The fig. 19 of DRASTIC-FS 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 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.
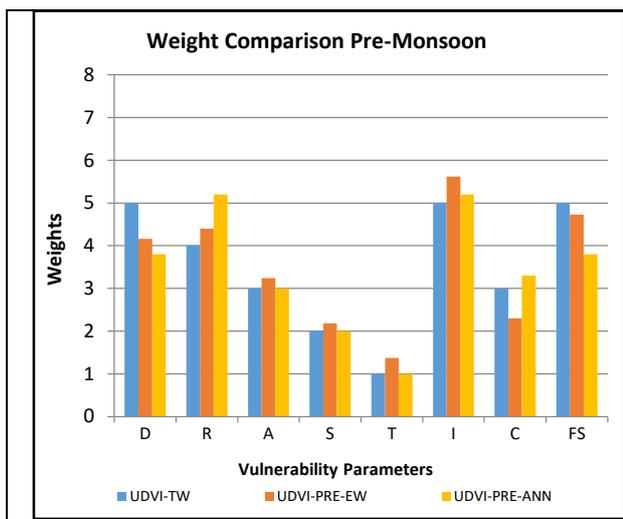
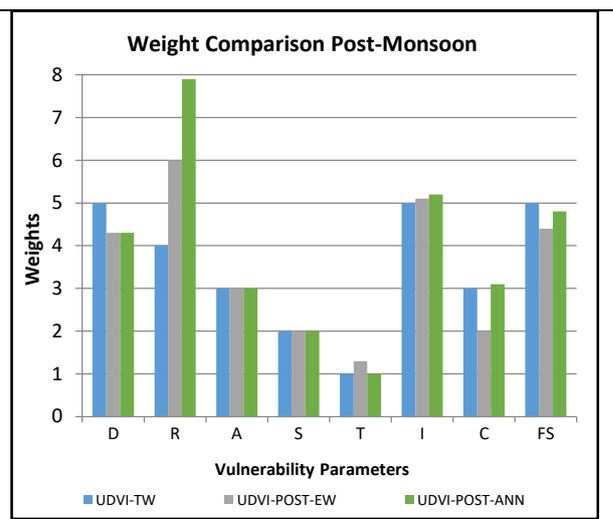|	
Fig. 18: DRASTIC-FS Weights Comparison (Pre)	Fig. 19: DRASTIC-FS Weights Comparison (Post)

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 well matched with effective weight 3 based on single parameter sensitivity analysis.

Validation of DRASTIC-FS Model with groundwater Nitrate

To validate the vulnerability index obtained from DRASTIC-FS models, Nitrate concentration in groundwater of study area has been correlated with Pearson's method. There were 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. A Pearson's correlation coefficient 'r' was 0.56 between nitrate and 2018-PRE-DRASTIC-FS Vulnerability Index, 0.36 between nitrate and 2018-PRE-DRASTIC Vulnerability Index, 0.65 between nitrate and 2019-PRE-DRASTIC-FS Vulnerability Index, 0.48 between nitrate and 2019-PRE-DRASTIC Vulnerability Index, 0.50 between nitrate and 2020-PRE-DRASTIC-FS Vulnerability Index, 0.32 between nitrate and 2020-PRE-DRASTIC Vulnerability Index which validated the DRASTIC-FS model for Alluvial region between Mahi and Narmada rivers, India. (Fig no: 20,21 & 22)
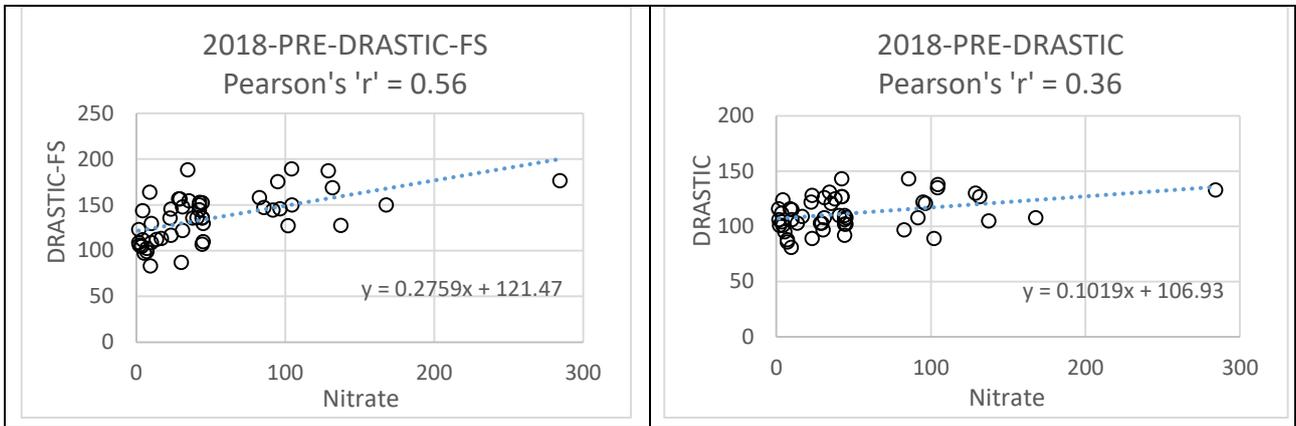
Fig. 20: Correlation between DRASTIC, DRASTIC-FS and Nitrate – Pre-Monsoon-2018
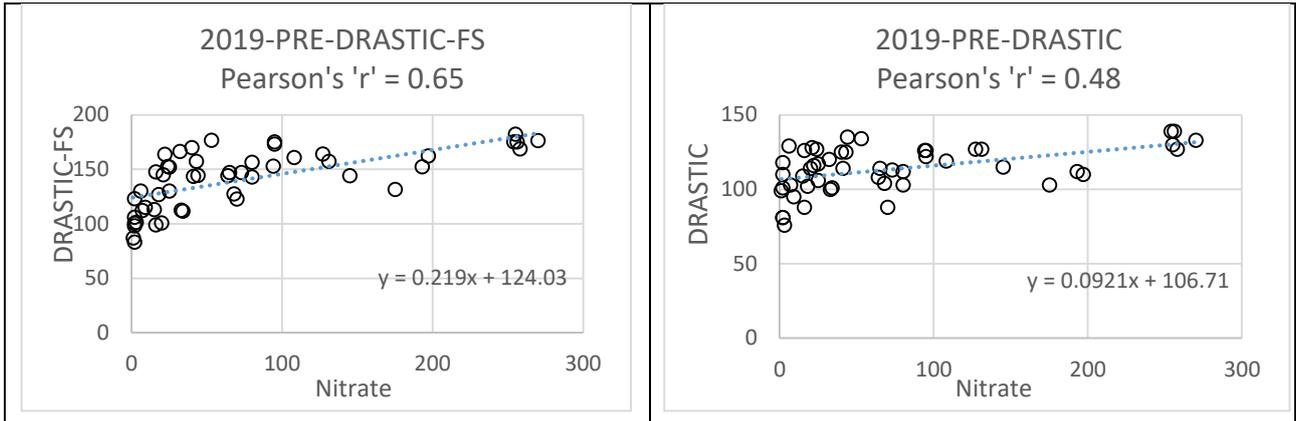

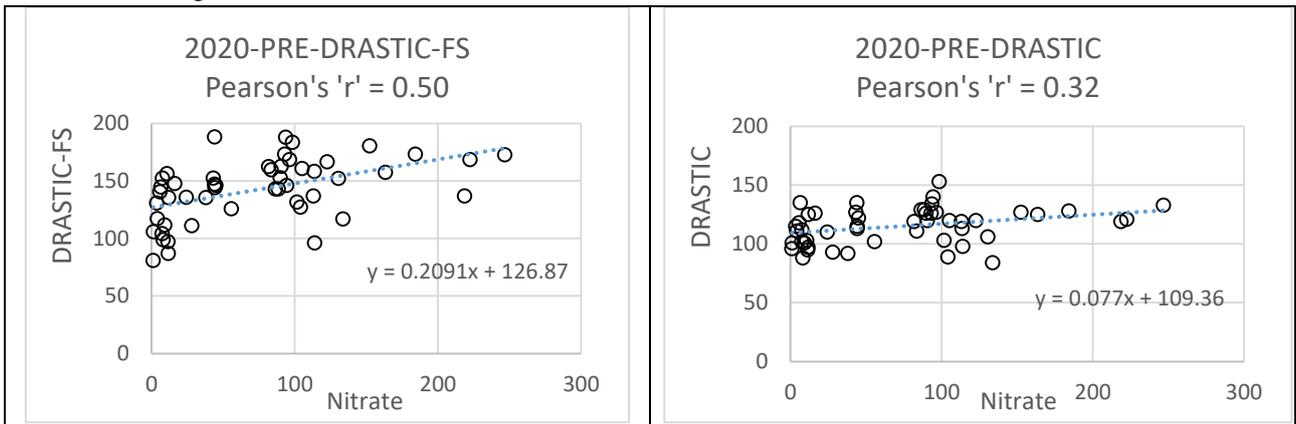Fig. 21: Correlation between DRASTIC, DRASTIC-FS and Nitrate – Pre-Monsoon-2019

Fig. 22: Correlation between DRASTIC, DRASTIC-FS and Nitrate – Pre-Monsoon-2020

Correlation between Vulnerability parameter and Water quality:

Table 15(a): Using Python Correlation Analysis (Pre-Monsoon)					Table 15 (b): Using SPSS Correlation Analysis (Pre-Monsoon)				
Vulnerability Parameters	**TDS**	**NO₃**	**F**	**GWQI**	**Vulnerability Parameters**	**TDS**	**NO₃**	**F**	**GWQI**
D	-0.269	-0.148	-0.037	-0.222	**D**	-0.26	-0.14	-0.03	-0.22
R	0.234	0.409	-0.060	0.355	**R**	0.23	0.4	0.06	0.35
A	0.298	0.428	-0.036	0.392	**A**	0.29	0.42	-0.03	0.39
S	0.342	0.577	0.027	0.528	**S**	0.34	0.57	0.02	0.52
T	0.000	0.000	0.000	0.000	**T**	-0.05	-0.07	-0.03	-0.07
I	0.368	0.512	-0.033	0.468	**I**	0.36	0.51	-0.03	0.46
C	0.003	-0.234	-0.077	-0.136	**C**	0	-0.23	-0.07	-0.13
FS	0.747	0.540	0.561	0.736	**FS**	0.74	0.54	0.56	0.73
DRASTIC_FS	0.542	0.657	0.225	0.684	**DRASTIC_FS**	0.51	0.64	0.2	0.66

The above tables 15 (a) and 15 (b) show relationship among leading groundwater quality and vulnerability parameters for 2018 pre and post monsoon seasons respectively derived from Spearman's rho correlation method using SPSS and Python Program.

The following correlation between individual groundwater quality parameters and vulnerability parameters values highlighted with blue color show near correlation (0.3-0.5) whereas values highlighted with red color show good correlation (0.5-0.8).

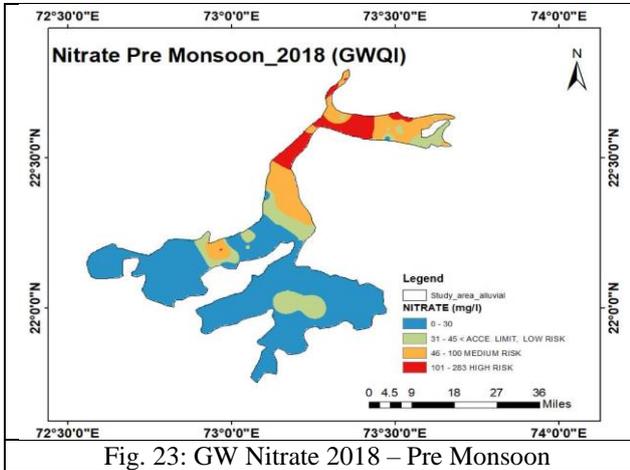## Vulnerability parameters with. Nitrate
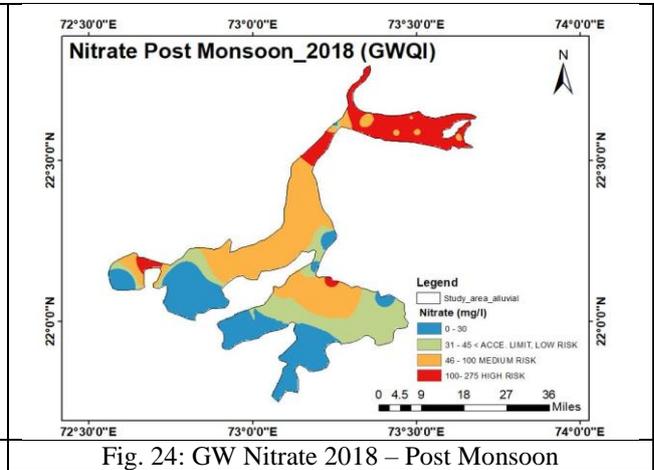

| Fig. 23: GW Nitrate 2018 – Pre Monsoon | Fig. 24: GW Nitrate 2018 – Post Monsoon |

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. This is in spite of decrease in Low Risk area, showing very High/shooting rise in Moderate & High Risk area. This suggest degrading of Groundwater Quality of the study area is greatly due to increased Nitrate concentration.

Table 16 Vul. Para. With NO$_3$

2018-Pre Monsoon	NO3
D	-0.14
R	0.40
A	0.42
S	0.57
T	-0.07
I	0.51
C	-0.23
FS	0.54
DRASTIC_FS	0.64

In the western parts of the alluvial region, low values of groundwater nitrate matches well with low ratings of Aquifer media, Soil media, Impact of vadose zone, FS parameter and DRASTIC-FS index whereas in the northern parts, high values of nitrate contamination matches 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 and industrial cluster is playing a key role for such contamination.
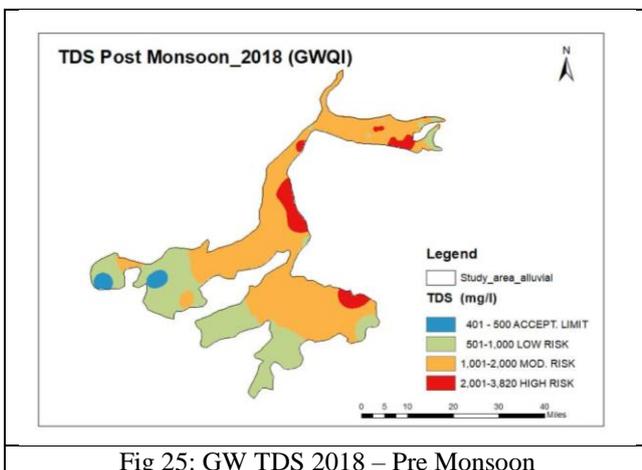
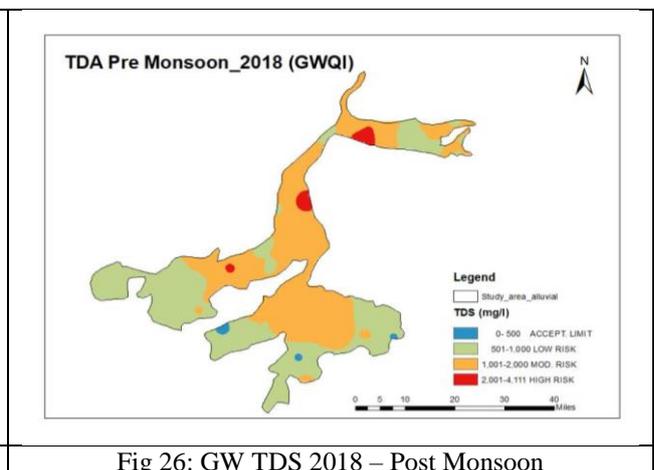## Vulnerability parameters with TDS

| Fig 25: GW TDS 2018 – Pre Monsoon | Fig 26: GW TDS 2018 – Post Monsoon |

More then 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 where as area under Moderate Risk increased to 121.5% and High Risk area is increased very significant by 28%.

Table 17 Vul. Para. With TDS

2018-Pre Monsoon	TDS
D	-0.26
R	0.23
A	0.29
S	0.34
T	-0.05
I	0.36
C	0.00
FS	0.74
DRASTIC_FS	0.51

The –ve correlation between Depth and TDS highlighted low ratings of 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 matches well with high ratings of the Soil media, Impact of vadose zone, FS parameter and DRASTIC-FS 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

Vulnerability parameters with Fluoride
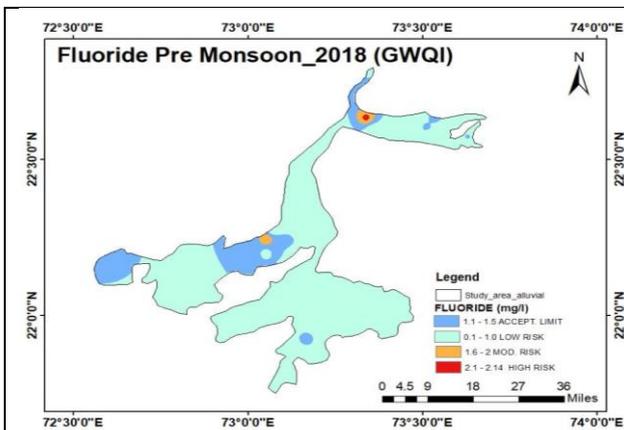
Fig 27: GW Fluoride 2018 – Pre Monsoon	Fig 28: GW Fluoride 2018 – Post Monsoon
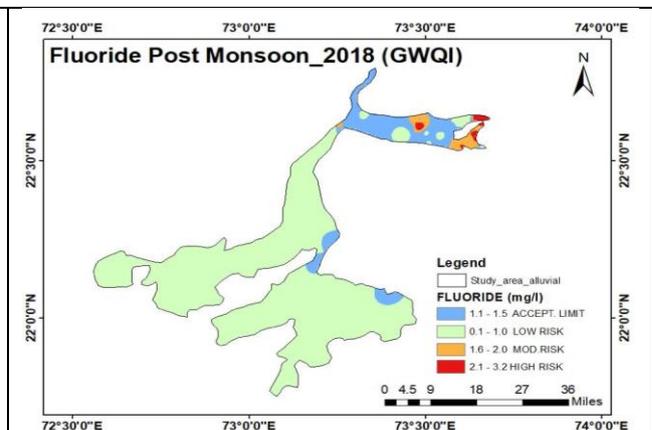
The 3rd Parameter Fluoride seems to have almost negligible variation except in some marginal area of Kalol, Ghogamba and a very small area near Padra. This is also confirmed from poor correlation ship in range of -0.07 to 0.06. This clearly indicates that groundwater vulnerability in the study area is mainly due to Nitrate and TDS.

Vulnerability parameters with GWQI

Fig 29: GWQI 2018 – Pre Monsoon	Fig 30: GWQI Nitrate 2018 – Post Monsoon

Above figures 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 18 Vul. Para. With GWQI

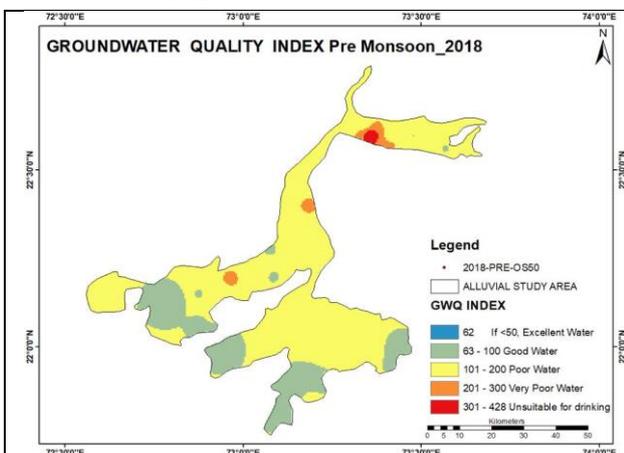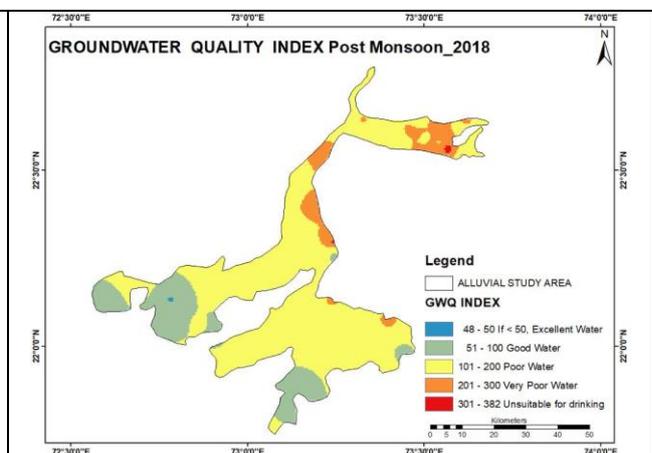| 2018- Pre Monsoon	GWQI
D	-0.22
R	0.35
A	0.39
S	0.52
T	-0.07
I	0.46
C	-0.13
FS	0.73
DRASTIC_FS	0.66

Recharge aquifer media and impact of vadose zone is having good correlation with GWQI while soil media has higher correlation with groundwater quality index which indicates top sandy soil play greater role for traveling contaminate from surface to sub surface at northern and central region.

Groundwater quality index has strong correlation with DRASTIC FS index which indicates aquifer system is vulnerable to contamination at Northern and Central region where groundwater quality is very poor.

Health Risk Assessment

The groundwater nitrate concentration above 45 mg/L proves to be harmful for human consumption (IS: 10500-2012). Groundwater Nitrate concentrations obtained from MOJS-DDWAS data (50 samples of 2018) was used to develop spatial distribution maps for both pre and post monsoon seasons in GIS environment (IDW-Interpolation) to visualize areas with high contamination. From these maps (Figures: 23, 24), only the blue zone indicates area where nitrate contamination is below Indian standards, everywhere else they are above the Indian standards. The highest nitrate contamination is found in certain pockets of northern, central and western regions. The lowest observed nitrate concentrations are in the range of 1 mg/L in Karjan block for both pre and post monsoon seasons whereas highest concentrations are in the range of 283 mg/L in Jambusar block and 275 mg/L in Padra block for pre and post monsoon seasons respectively. Both Padra and Jambusar blocks are highly dominated by industrial and agricultural activities.

These maps were further utilized in assessing the health risk for children and adults for both pre and post monsoon seasons. The figures 31 and 32 represents health risk to children and adults respectively for pre monsoon season. The figures 33 and 34 represents health risk to children and adults respectively for post monsoon season.
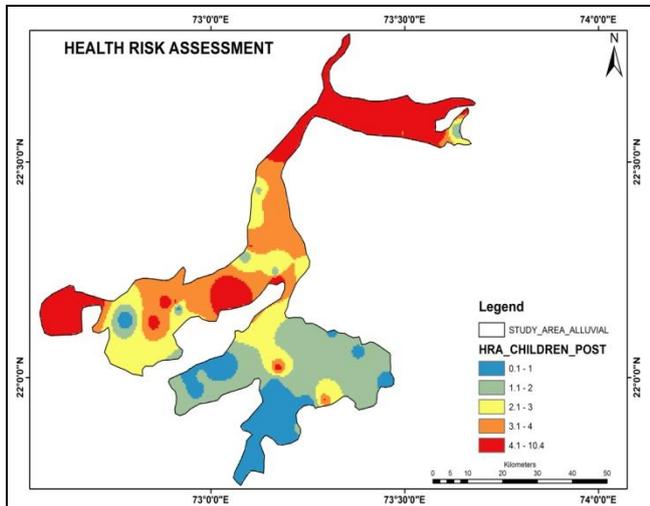
Fig. 31: Health Risk to Children – 2018-Pre Monsoon	Fig. 32: Health Risk to Adults – 2018-Pre Monsoon
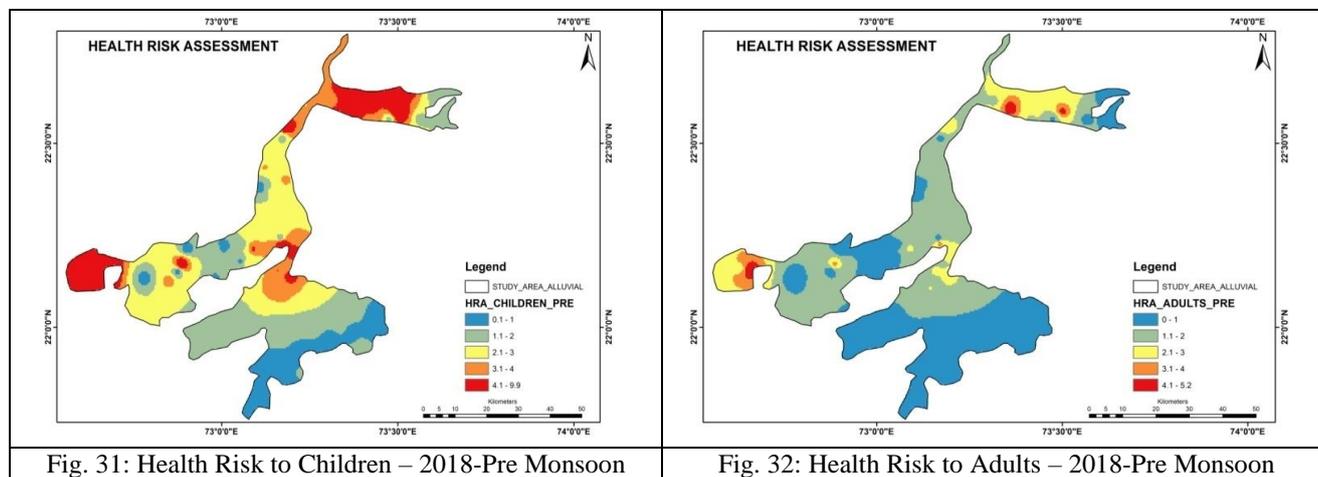
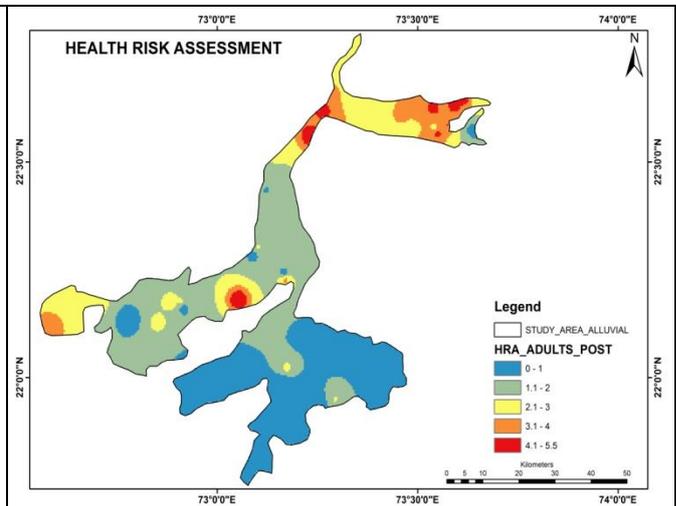| Fig. 33: Health Risk to Children – 2018-Post Monsoon | Fig. 34: Health Risk to Adults – 2018-Post Monsoon |

The health risk indices of children and adults both were reclassified into 5 classes in which class-1 represents index (0-1) as a no health risk and as we go to higher classes, the health risk becomes higher. The area distribution of assessed health risk is described in table-19 for children and adults respectively for both the seasons. From this table it is clear that more than 70% and almost 30% of the study area indicates health risks to children and adults respectively. Present study considers classes 2 and 3 to be moderately critical whereas 4 and 5 to be the most critical which is almost 20% and 30% for the children in pre and post monsoon season respectively as well as almost 2% and 5% for the adults in pre and post monsoon season respectively. Such critical area need to be prioritized with groundwater management strategies that minimize the health risk on public due to groundwater nitrate contamination.

Table-19: Area Distribution of HRA for Children and Adults

| Class | HRA-Children | | | | HRA-Adults | | | |
| | Pre-Monsoon, 2018 | | Post-Monsoon, 2018 | | Pre-Monsoon, 2018 | | Post-Monsoon, 2018 | |
	Area (km^2)	% Area	Area (km^2)	% Area	Area(km^2)	% Area	Area(km^2)	% Area
1	698	25.16	791	28.50	1998	72.00	1475	53.13
2	1027	37.02	517	18.63	535	19.26	766	27.62
3	508	18.32	669	24.09	193	6.94	397	14.32
4	271	9.78	216	7.77	39	1.42	122	4.41
5	270	9.73	583	21.01	10	0.37	14	0.52
Total	2775	100	2775	100	2775	100	2775	100

As the main objective of this research is to suggest remedial measures to minimize public health risks, various other key parameters such as groundwater vulnerability (figures: 35, 36) and land use land cover (LULC) (fig. 37) were also developed which gave hydro-geological and physical characteristics of present study area. The groundwater vulnerability maps of both pre and post monsoon seasons developed from DRASTIC method revealed highly and severely vulnerable areas specifically in the north, central and western parts. The LULC map highlighted agriculture and non-agricultural land, major urban settlements and water bodies which was derived from supervised classification of Landsat-8 images obtained from USGS (United States Geological Survey) Earth Explorer.

Fig. 35: Groundwater Vulnerability Map – Pre Monsoon	Fig. 36: Groundwater Vulnerability Map – Post Monsoon
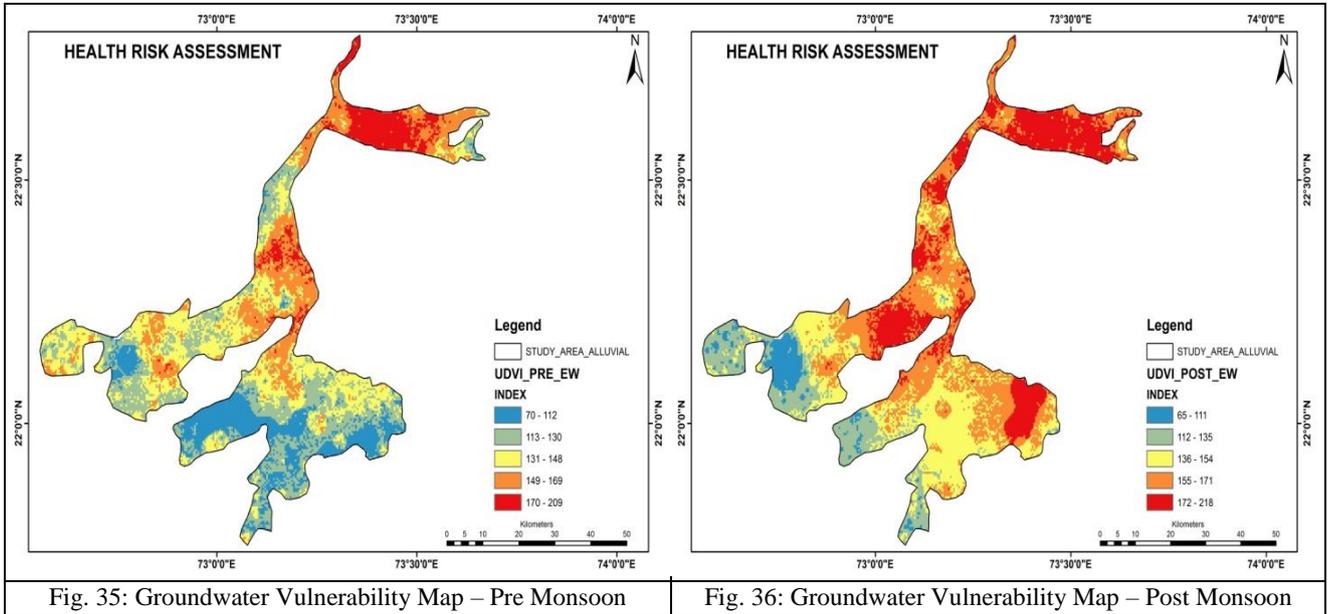
In addition to this, population distribution map and water use scenario map were also obtained from MOJS-DDWAS presented in figures 38 and 39 respectively. The water use scenario showed the distribution of the use of filter points, surface water sources, deep tube wells, shallow tube wells and open wells in the study area. These three groundwater sources are given ratings of 3, 4 and 5 respectively which indicate the probability of open wells getting contaminated is higher than shallow and deep tube wells respectively. This data gave significant knowledge about various water sources (groundwater, surface water or combined) currently being used by the population residing in the study region and their water dependency.

Fig. 37: Land Use Land Cover Map (LULC)
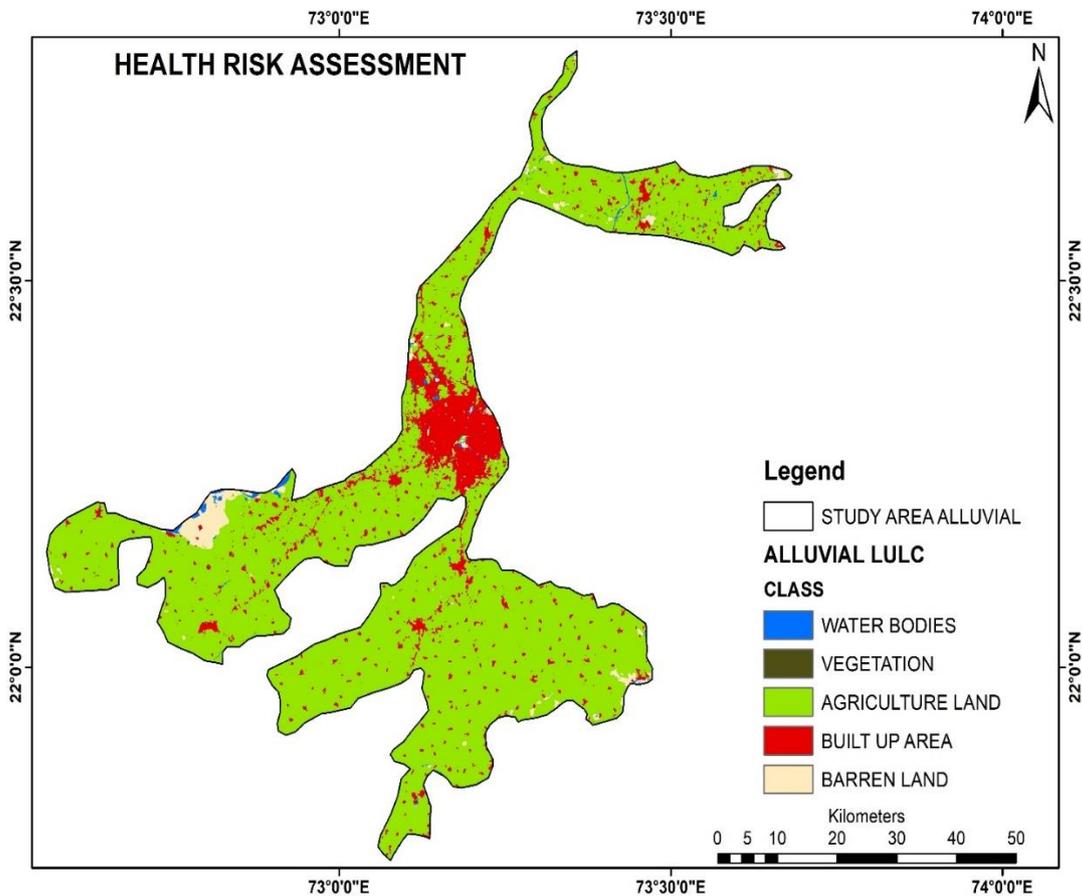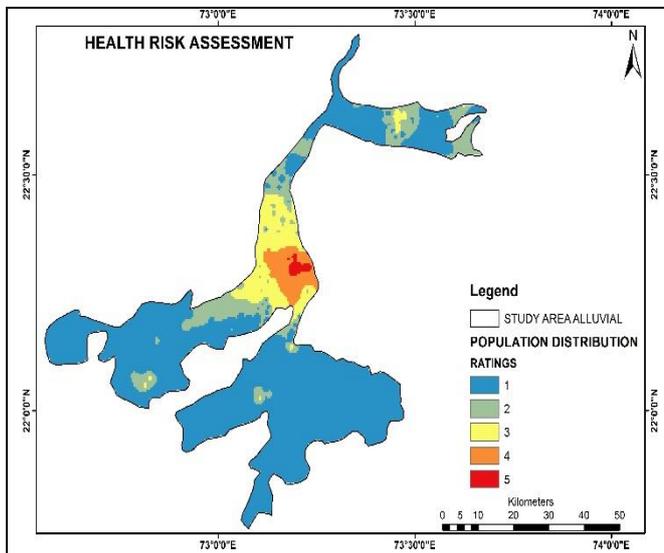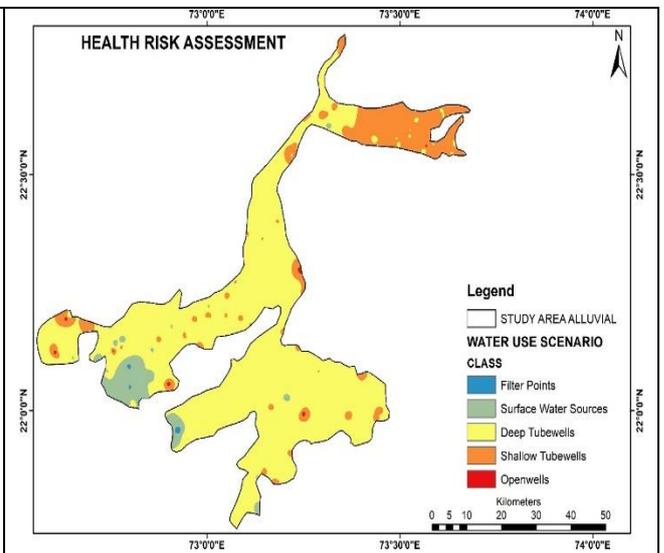
| Fig. 38: Population Distribution Map | Fig. 39: Water Use Scenario Map |

Apart from the conventional way of looking at Health risk assessment, present study adopted various other key parameters and prepared an inclusive outcome in the form of a map representing Health Risk Assessment with Population Census (figures 40, 41) with the help of overlay analysis in GIS environment. All the maps were reclassified into (1-5) classes, and overlaid on each other giving health risk with population census (HRA-Whole) for both pre and post monsoon seasons. Table-20 shows the area distribution of HRA-Whole in which it is observed that for the post monsoon season, the risk prone area (sum of class 4 and 5) almost doubles from 10.7% to 21.3% indicating the importance of seasonal analysis.
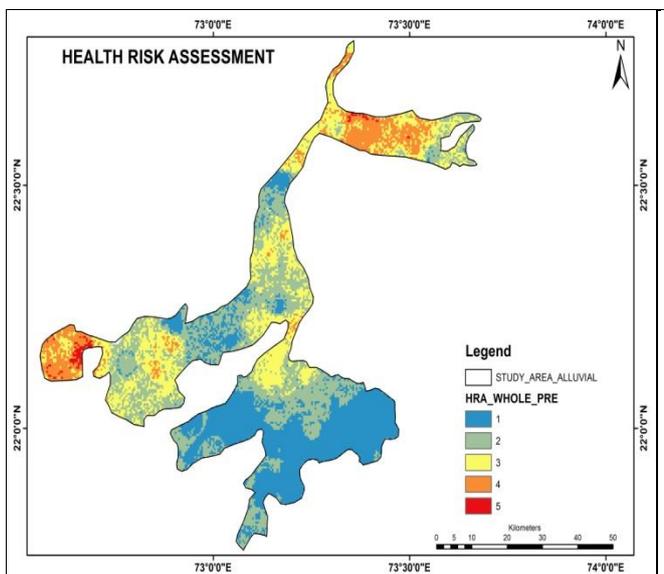
| Fig. 40: HRA-Whole – 2018-Pre Monsoon | Fig. 41: HRA-Whole – 2018-Post Monsoon |
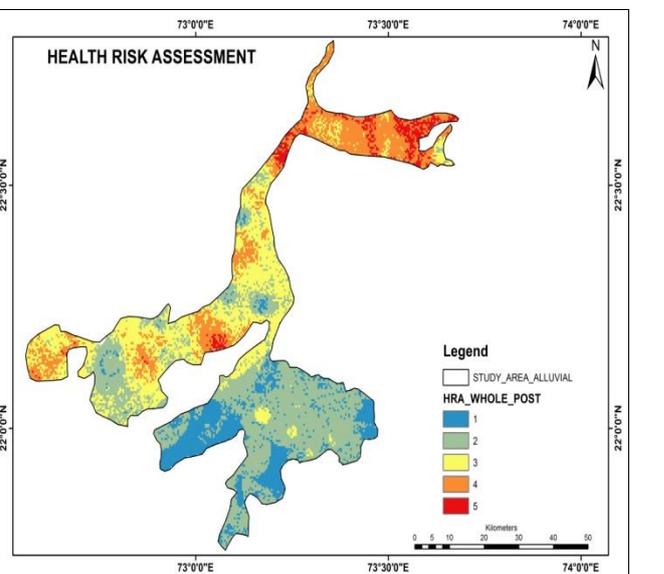
Table-20: Area Distribution of HRA-Whole

Class	Pre Monsoon 2018		Post Monsoon 2018	
	Area (km^2)	% Area	Area (km^2)	% Area
1	877	31.62	399	14.37
2	944	34.02	1034	37.25
3	657	23.66	753	27.13
4	274	9.89	488	17.57
5	23	0.81	102	3.69
Total	2775	100	2775	100

Groundwater Denitrification Strategy Optimization using AHP

Nitrate in groundwater can be controlled using conventional treatment methods, but they are expensive, both in terms of unit costs and environmental impacts. An alternate strategy to nitrate management based on in-situ bioremediation, using the natural denitrifying potential of aquifers, may have a variety of advantages, including financial gains and environmental sustainability **(Tompkins et al. 2001, Soloman et al. 2018)**. The Pump and treat method is adopted for denitrification at local level for highly concentrated nitrate plumes, before nitrate leeches deeper into the aquifer and disperses to impact a large area. This method is less efficient and proves costly if adopted for the large basin.

Other nitrate reduction methods are the Biological denitrification and the Chemical denitrification. The degradation and transformation of specific pollutants can only be achieved by specific microorganisms. Another limiting element is susceptibility to inhibition by toxic contaminants like heavy metals **(Hu et al. 2019)**. In-situ bioremediation is the process of degrading substances using either native or exogenous microorganisms by introducing microbial reagents and nutrients into groundwater **(Juwarkar et al. 2010)**. The basic idea behind bioremediation is to use microbial processes in technical and controlled treatment systems **(Langwaldt etal. 2000)**. Biological denitrification method is the most efficient method among all the denitrification methods, the efficiency of this method can reach nearly 100%, and comparatively less costly **(Burghate etal. 2013)**. Suitable environment enhances the efficiency, neutral pH is preferred and temperature below 5°C can inhibit denitrification. However, this method takes longer time, years and sometimes decades, and the second problem is Biofouling of aquifers **(Tompkins etal. 2001)**.

Chemical denitrification is also a good method for denitrification of groundwater, highly efficient, short remediation time and less expensive. Preferable pH and temperature are to be maintained to inhibit denitrification **(Bei Zet al. 2021)**. However, there is a possibility of secondary contamination and pH is a significant controlling factor for this treatment method. Most iron-based materials are used as ZVI (Zero valent iron). Permeable reactive barriers (PRB's) is a method of denitrification, expensive in nature, and proves economical for depth less than 50 feet and sometimes can be adopted up to 120 feet. The pump and fertilize is another method of denitrification, and can only be adopted in agricultural area at basin scale.

Ground Truth Study (GTS):

GTS is an important step which includes site exploration, primary data collection, sampling and laboratory testing of various physico-chemical groundwater parameters before opting for a suitable remediation method. After identification of the critical area based on health risk assessment using secondary data, it is at most necessary to verify present status of contaminants in groundwater by primary data collection. A total of 41 well samples were collected falling within the identified critical zones described in the following figures (42). The well location specific information was collected and considered for prescribing appropriate remedial strategy as mentioned in table-24.

Delineation of Nitrate in Groundwater:

The UV spectro-photometric screening method has been used to determine nitrate from the screening samples. The sample preparation is the key phenomenon in any kind of experiment. Here 10 ml screened sample is taken and by adding distilled water a 50 ml solution is made, than 1 ml HCL is added before taking the absorption of samples. Then, nitrate calibration curve (fig. 43) is prepared as per APHA (1998). The absorption values of each sample which have been taken with

reference to stock nitrate solution in photo-spectrometer, for the range of 220 nm and 275 nm from which the respective values of nitrate concentration have been obtained.
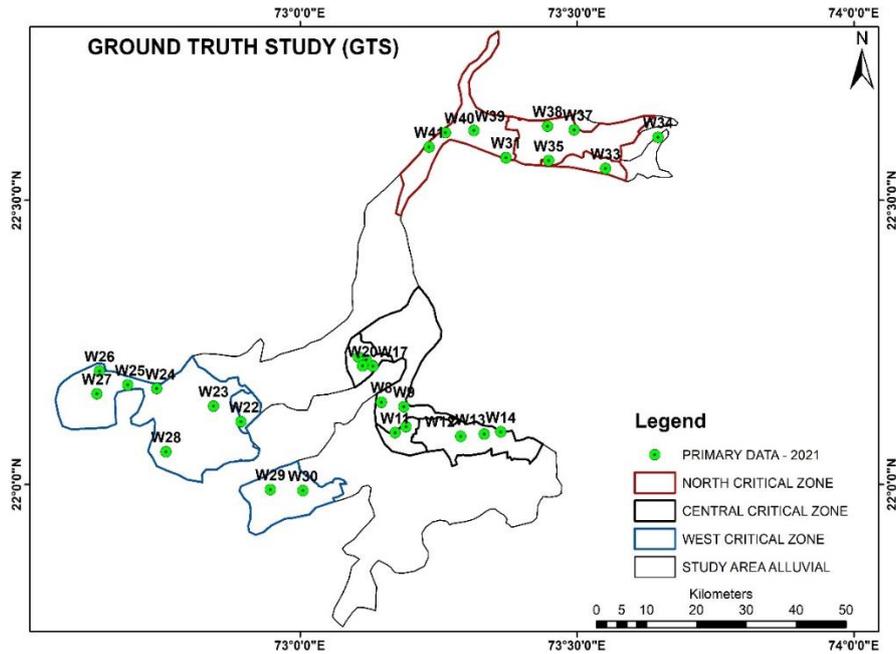
Fig. 42: Primary data collection in critical zones
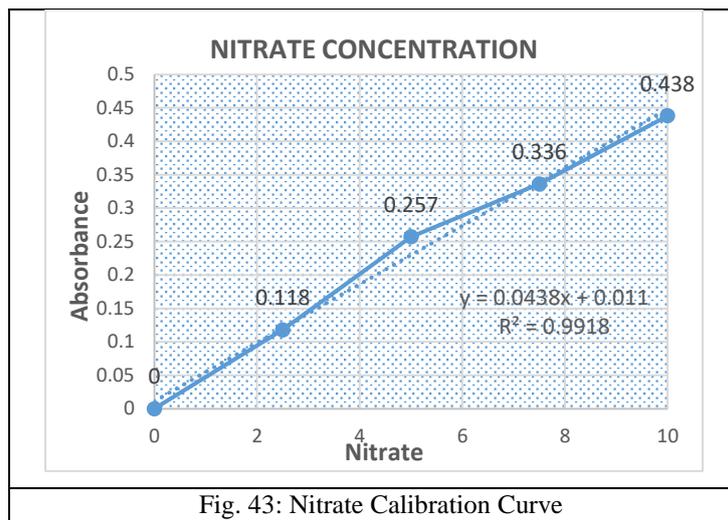
Fig. 43: Nitrate Calibration Curve

The AHP method was applied to evaluate alternatives for each criteria mentioned in table-23 to 28 representing remediation alternatives comparison matrix for initial cost (IC), operation and maintenance cost (OMC), remediation time (RT), pollution removal rate (PRR), ground water table (GWT) and pollution loading (PL) respectively. The weights obtained for each criteria and each remedial alternative per criteria have been termed as local weights mentioned in table-29.

Table 21: Criteria comparison matrix

1	IC	OMC	RT	PRR	GWT	PL	WT.	λmax	6.52
IC	0.05	0.12	0.03	0.03	0.07	0.06	0.06	CI	0.10
OMC	0.03	0.06	0.03	0.05	0.09	0.08	0.05	RCI	1.24
RT	0.21	0.24	0.12	0.07	0.18	0.08	0.15	CR	8.33
PRR	0.26	0.18	0.24	0.14	0.12	0.11	0.17		
GWT	0.26	0.24	0.24	0.43	0.36	0.45	0.33		
PL	0.21	0.18	0.35	0.28	0.18	0.23	0.24		
SUM	1.00	1.00	1.00	1.00	1.00	1.00	0.43		

Table-22: Average random consistency index RCI

N	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table-23: Remedial alternatives comparison matrix for initial cost (IC)

IC	PHYTO	PAT	PAF	PRB	CHEM	WT.	λmax	5.17
PHYTO	0.26	0.31	0.22	0.35	0.38	0.31	CI	0.04
PAT	0.05	0.06	0.09	0.04	0.04	0.06	RCI	1.12
PAF	0.53	0.31	0.44	0.35	0.38	0.40	CR	3.77
PRB	0.07	0.13	0.11	0.09	0.06	0.09		
CHEM	0.09	0.19	0.15	0.17	0.13	0.14		
SUM	1.00	1.00	1.00	1.00	1.00	1.00		

Table-24: Remedial alternatives comparison matrix for operation and maintenance cost (OMC)

OMC	PHYTO	PAT	PAF	PRB	CHEM	WT.	λmax	5.09
PHYTO	0.10	0.13	0.11	0.07	0.08	0.10	CI	0.02
PAT	0.05	0.07	0.09	0.05	0.06	0.06	RCI	1.12
PAF	0.38	0.33	0.44	0.44	0.49	0.42	CR	2.02
PRB	0.19	0.20	0.15	0.15	0.12	0.16		
CHEM	0.29	0.27	0.22	0.29	0.24	0.26		
SUM	1.00	1.00	1.00	1.00	1.00	1.00		

Table-25: Remedial alternatives comparison matrix for remediation time (RT)

RT	PHYTO	PAT	PAF	PRB	CHEM	WT.	λmax	5.09
PHYTO	0.07	0.09	0.05	0.05	0.06	0.06	CI	0.02
PAT	0.33	0.44	0.38	0.44	0.49	0.42	RCI	1.12
PAF	0.13	0.11	0.10	0.07	0.08	0.10	CR	2.02
PRB	0.20	0.15	0.19	0.15	0.12	0.16		
CHEM	0.27	0.22	0.29	0.29	0.24	0.26		
SUM	1.00	1.00	1.00	1.00	1.00	1.00		

Table-26: Remedial alternatives comparison matrix for pollution removal rate (PRR)

PRR	PHYTO	PAT	PAF	PRB	CHEM	WT.	λmax	5.09
PHYTO	0.10	0.11	0.13	0.07	0.08	0.10	CI	0.02
PAT	0.38	0.44	0.33	0.44	0.49	0.42	RCI	1.12
PAF	0.05	0.09	0.07	0.05	0.06	0.06	CR	2.02
PRB	0.19	0.15	0.20	0.15	0.12	0.16		
CHEM	0.29	0.22	0.27	0.29	0.24	0.26		
SUM	1.00	1.00	1.00	1.00	1.00	1.00		

Table-27: Remedial alternatives comparison matrix for groundwater table (GWT)

GWT	PHYTO	PAT	PAF	PRB	CHEM	WT.	λmax	5.43
PHYTO	0.38	0.25	0.49	0.29	0.30	0.34	CI	0.11
PAT	0.13	0.08	0.12	0.05	0.04	0.08	RCI	1.12
PAF	0.19	0.17	0.24	0.38	0.44	0.28	CR	9.65
PRB	0.13	0.17	0.06	0.10	0.07	0.10		
CHEM	0.19	0.33	0.08	0.19	0.15	0.19		
SUM	1.00	1.00	1.00	1.00	1.00	1.00		

Table-28: Remedial alternatives comparison matrix for pollution loading (PL)

PL	PHYTO	PAT	PAF	PRB	CHEM	WT.	λmax	5.09
PHYTO	0.07	0.09	0.05	0.05	0.06	0.06	CI	0.02
PAT	0.33	0.44	0.38	0.44	0.49	0.42	RCI	1.12
PAF	0.13	0.11	0.10	0.07	0.08	0.10	CR	2.02
PRB	0.20	0.15	0.19	0.15	0.12	0.16		
CHEM	0.27	0.22	0.29	0.29	0.24	0.26		
SUM	1.00	1.00	1.00	1.00	1.00	1.00		

Table-29: Weights of criteria and alternatives from AHP

CRITERIA	WT.	PHYTO	PAT	PAF	PRB	CHEM	PHYTO	PAT	PAF	PRB	CHEM
IC	0.06	0.31	0.06	0.40	0.09	0.14	0.018	0.003	0.024	0.005	0.009
OMC	0.05	0.10	0.06	0.42	0.16	0.26	0.005	0.003	0.023	0.009	0.014
RT	0.15	0.06	0.42	0.10	0.16	0.26	0.009	0.061	0.015	0.024	0.039
RE	0.17	0.10	0.42	0.06	0.16	0.26	0.017	0.072	0.011	0.028	0.046
GWT	0.33	0.11	0.19	0.20	0.11	0.19	0.037	0.062	0.064	0.038	0.061
PL	0.24	0.14	0.23	0.23	0.14	0.22	0.032	0.054	0.056	0.033	0.053
TOTAL	1.00	0.56	0.95	0.98	0.57	0.93	**0.119**	**0.257**	**0.192**	**0.136**	**0.221**

From the results of AHP, highest eigenvalue (λmax) of the criteria comparison matrix (table-21) is 6.52, the consistency index (CI) is 0.10, the average random consistency index (RCI) of six criteria is 1.24 given in table-22 and submitting above values in equation (6) and (7), the consistency ratio (CR) of criteria comparison matrix is found to be 8.33% which is less than 10% making the comparison matrix to be consistence.

The product of local weights of respective criteria and alternatives have been termed as global weights which helped in determining the choice order of remedial measures based on sorting values from high to low highlighting the preferential sequence as PAT.,CHEM.,PAF.,PRB.,PHYTO. Such choice order was then applied at each primary well location falling in the critical area with nitrate concentration above permissible limit and respective location specific characteristics (LSC) as described in table-30.

The location specific characteristics (LSC) such as rural area, agricultural activities, lack of drainage of sewers, animal husbandry, etc. has further helped in assigning the remedial measures to each well location that showed nitrate contamination above permissible limit. In the northern region, majority of population is involved in agricultural activities, and there are some industries nearby Kalol city area thus the use of Pump and Fertilize (PAF) and Phytoremediation methods for denitrification are the most suitable methods.

In the western region, the population is involved in agricultural activities and there are other sources of nitrate injection in groundwater i.e. rural sanitation consisting of soak pits thus Phytoremediation, Pump and Fertilize (PAF) and Permeable Reactive Barrier (PRB) are the recommended methods for denitrification. The central region consists Makarpura industrial area, and sub-urban area of Vadodara city Danteshwar, Tarsali having high density population thus Pump and Treat (PAT), Phytoremediation and Pump and Fertilize (PAF) methods are suggested for denitrification of groundwater. To increase the efficiency of Pump and Treat (PAT) method for denitrification purpose the cost-benefit analysis is required.

Table-30: Groundwater Nitrate from primary data collection and sample location specific characteristics

Sr.	Zone	Block	Village	Location	NO₃	LSC (Location Specific Characteristics)	Suitable Remedial Strategy
W1	Central	Vadodara	Panigate	Bauchawad, Yakutpura,Panigate	73.76	Urban highly population area, improper sewerage	Chemical Reduction, Phytoremediation
W3	Central	Vadodara	Kevdabaug	BatukMandir, Kevdabaug	140.83	Urban highly population area, improper sewerage	Pump And Treat
W7	Central	Vadodara	Tarsali-2	BhathijiMandir, Tarsali	93.01	Sub-urban area, polluted Vishwamitri river stretch	Chemical Reduction, Phytoremediation
W9	Central	Vadodara	Por	Icici Bank Building, Por Village	124.13	Rural area, agricultural activities, improper sewerage	Pump And Fertilize, Phytoremediation
W10	Central	Karjan	Bamangam	BhathijiMaharaj Temple	108.35	Rural area, agricultural activities, improper sewerage	Pump And Fertilize, Phytoremediation
W11	Central	Karjan	Manglage	Varahi Mata Temple	112.11	Rural area, agricultural activities	Pump And Fertilize, Phytoremediation
W12	Central	Dabhoi	Parikha	RamdevMandir, Opp. Gram Panchayat	55.23	Rural area, agricultural activities, improper sewerage	Phytoremediation
W13	Central	Dabhoi	Mandala	Near RangaiKaansh, Mandala	68.53	Rural area, agricultural activities	Phytoremediation
W16	Central	Padra	Chansad-1	Opp. Baps Shree Swaminarayan Mandir	155.96	Rural area, agricultural activities, soak pits leachate	Chemical Reduction, Phytoremediation
W17	Central	Padra	Chansad-2	Opp. Panchayat Karyalay, Chansad	140.83	Rural area, agricultural activities, soak pits leachate	Chemical Reduction, Phytoremediation
W19	Central	Padra	Darapura	Farm near entrance of Darapura Village	122.66	Rural area, polluted Darapura lake, agricultural	Pump And Fertilize, Phytoremediation
W22	Central	Padra	Kanzat	Near Amba Mata Temple and Pond	62.94	Rural area, agricultural activities	Phytoremediation
W25	West	Jambusar	Nahar	Near Bhathiji Temple and Pond	95.5	Rural area, agricultural, sea water intrusion	PRB, Phytoremediation
W27	West	Jambusar	Hamdpor	Village Vasahat, near large Pond	69.36	Rural area, agricultural, sea water intrusion	PRB, Phytoremediation
W30	West	Amod	Suthodara	Village Vasahat near Pond	46.97	Rural area, agricultural activities	Phytoremediation
W31	North	Savli	Tulsipura	Near Pond and VillaeVasahat	167.61	Rural area, agricultural activities	Chemical Reduction, Phytoremediation
W31a	North	Savli	Tulsipura	Near Pond and VillaeVasahat	204.22	Rural area, agricultural activities	Chemical Reduction, Phytoremediation
W32	North	Halol	Dharampuri	Masonry Well in Farm, Village Vasahat	129.91	Industrial effluents, agricultural activities	Pump And Treat, Phytoremediation
W33	North	Halol	Muladhari	Rameswar Temple, Panigate	78.72	Rural area, agricultural activities,	Pump And Fertilize, Phytoremediation
W34	North	Ghoghamba	Raveri	Near Karad Canal, Ghoghamba Village	48.62	Agricultural activities, soakpits leachate	Phytoremediation
W35	North	Kalol	Madhvas	Muvla area Opp. Mahvir Park	67.61	Industrial effluents, agricultural activities	Phytoremediation
W36	North	Kalol	Kalol City	Private Farm of Virendra Patel in Kalol	102.94	Industrial effluents, agricultural activities	Pump And Fertilize, Phytoremediation
W37	North	Kalol	Delol	Near Panchvati Lemon farm, Delol	116.7	Agricultural activities, soakpits leachate	Pump And Fertilize, Phytoremediation
W39	North	Savli	Mevli	Farm near Mevli Village Vasahat	133.49	Agricultural activities, soakpits leachate	Pump And Fertilize, Phytoremediation

CONCLUSIONS

1. The multivariate statistical analysis methods PCA, FSA and HCA and 10 parameters is used on a large study area to obtain 3 PCs viz; PC-1 (TDS, NO_3, Cl, SO_4, Mg, TH), PC-2 (F, ALK) and PC-3 (pH, Ca) based on the inter correlation of water quality parameters. A composite PC map is prepared in GIS using overlay analysis which suggests that majority of the well having factor scores higher than 2 are located in cluster 3 and 4 indicating these clusters, mainly part of Kalol and Savli Taluka are affected by anthropogenic sources.

2. Another key anthropogenic source is the rapid growth of Petroleum and Mineral based industrial manufacturing units and improper disposal of industrial wastes into small drains including Mini river, especially in the Northern parts of the alluvial region.

3. From the study it is concluded that the weights of variable parameters (D, R, I, C, FS) should be determined using any AI technique, instead of accepting its values recommended by Delphi committee of Aller Linda et. al. in 1985. An individual ANN for each parameter is first time introduced in this type of study and separate ANN for each of above variable parameter is developed for Pre and Post Monsoon period to obtain optimized weights for each variable and compared with theoretical weights obtained by conventional approach. This comparison reveal the limitation of conventional DRASTIC model. The noticeable difference in weight between Theortatical weitht and ANN optimized weight for Racharge were 4 and 5.2 and for depth 5 and 3.8 in Pre-monsoon as shown in table on 9 page no: 23.

4. Conventional DRASTIC is found here to be inefficient in determining its relative significance and impact on vulnerability of the study area. Physico-chemical parameters of groundwater in the form of factor score (FS) represents objectionable contribution of pollutants by local industries causes groundwater being vulnerable. This parameter is duly considered in analysis.

5. This research validated modified DRASTIC model with Groundwater Nitrate concentration for 3 successive years (2018, 2019, and 2020) by performing Pearson correlation. Higher 'r'= 0.56, 0.65 and 0.50 respectively of correlation coefficient for the modified DRASTIC model over Conventional DRASTIC model (Pearson's 'r'= 0.36, 0.48 and 0.32) proves superiority of the former over the later.

6. A good correlation between Vulnerability parameters 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. These are the leading contributors which is making the groundwater vulnerable. These is also verified in Ground Truth Study.

7. The Nitrate concentration in the groundwater extends up to 283 mg/l in pre monsoon. There are total three critical areas identified in the Northern, Western and Central parts of the study area that showed high health risk.

8. The AHP method of MCDA based on six fundamental evaluation criteria initial cost (IC), operation and maintenance cost (OMC), remediation time (RT), pollution removal rate (PRR), groundwater table (GWT) and pollution loading (PL) is used to prioritize the remedial method. For well of urban region the values of Global weight obtained on which the preference of remedial method is recommend as PAT.= 0.257, CHEM.= 0.221, PAF. = 0.192, PRB. = 0.136 and PHYTO. = 0.119

9. Majority of population in the Northern region, is involved in agricultural activities. Also some industries are located nearby Kalol city area hence use of Pump and Fertilize (PAF) and Phytoremediation methods in combination is the most suitable method for denitrification in this part of the study area.

10. In the Western region also, the population is involved mainly in agricultural activities however in addition to it there are other sources of Nitrate injection in groundwater like rural sanitation consisting of soak pits hence Phytoremediation, Pump and Fertilize (PAF) and Permeable Reactive Barrier (PRB) are the recommended methods for denitrification for this part of the study area.

11. The central region consists Makarpura industrial area, and sub-urban area of Vadodara city Danteshwar, Tarsali having high density population hence Pump and Treat (PAT), Phytoremediation and Pump and Fertilize (PAF) methods are suggested for denitrification of groundwater. To increase the efficiency of Pump and Treat (PAT) method the cost-benefit analysis is required.

PUBLICATIONS

PAPER PRESENTED AT INTERNATIONAL CONFERNCE AND PUBLISHED.

At International Conference, Thailand Presented):

1. "Review of significant works in assessment of ground water vulnerability in India". International Journal of Advance Engineering & Research Development (IJAERD) [Volume 04, Issue 02, February 2017 ISSN: 2348-6406, UGC Approved Journal]

2. "Analytical study of physico-chemical parameters of ground water for industrial area in western region of Vadodara District, Gujarat". IJSRD - International Journal for Scientific Research & Development [Volume 05, Issue 03, June 2017, ISSN: 2321-0613, UGC Approved Journal]

At International Conference, ITM Universe, Vadodara Presented):

3. "A study of various approaches for identification of sources of ground water contamination: An Indian Context." International Journal of Advance Engineering and Research Development (IJAERD) [Volume 5, Special Issue 03, February 2018. ISSN 0973-4562, UGC Approved Journal]

PAPER SENT FOR PUBLICATION TO SCOPUS INDEXEDINTERNATIONAL JOURNAL

1. "Contaminant source identification in groundwater of the alluvial tract between Mahi and Narmada rivers of Gujarat, India" re sent on Feb 2023 under review to publication to Scopus indexed International Journal of Environmental Earth Science, ISSN 2509-9434.

2. "DRASTIC-FS model for assessment of groundwater vulnerability in alluvial region between Mahi and Narmada rivers, India" re sent on Feb 2023 under review to publication to Scopus indexed International Journal of Population and Environment, ISSN 1573-7810.

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ANNEXURES I

MOJS-DDWAS Groundwater quality data (2018-Pre monsoon)

SR	District	Block	Village	Source	Latitude	Longitude	pH	TDS	NO₃	F	Cl	SO₄	Ca	Mg	TH	ALK
1	Bharuch	Amod	Vedcha	Shallow Tubewell	22.015626	72.943070	7.66	382	30	0.21	36	6	22	37	216	256
2	Bharuch	Jambusar	Jafarpara	Open well	22.061978	72.875670	7.96	1008	14	0.19	292	46	120	28	420	296
3	Bharuch	Jambusar	Kavi	Open well	22.195323	72.636001	6.89	996	7	1.38	104	64	16	43	220	668
4	Bharuch	Jambusar	Nondhana	Open well	22.133854	72.781111	8.08	588	9	0.07	80	23	37	35	240	380
5	Panch Mahals	Kalol	Adadara	Shallow Tubewell	22.646063	73.618754	7.92	942	44	0.80	168	24	119	72	596	432
6	Panch Mahals	Kalol	Alali	Shallow Tubewell	22.635123	73.538779	7.80	1354	129	1.46	224	35	166	99	828	568
7	Panch Mahals	Kalol	Alva	Shallow Tubewell	22.602179	73.511642	7.96	856	35	1.30	132	25	114	69	572	480
8	Panch Mahals	Kalol	Bakrol	Shallow Tubewell	22.566359	73.415924	7.66	1809	104	0.78	232	112	239	144	1196	428
9	Panch Mahals	Kalol	Bedhiya	Shallow Tubewell	22.603151	73.408605	7.88	1144	132	0.62	76	41	166	99	832	628
10	Panch Mahals	Kalol	Devpura	Shallow Tubewell	22.611365	73.557365	7.87	1287	96	0.30	450	23	93	56	468	412
11	Panch Mahals	Kalol	Jetpur	Shallow Tubewell	22.598398	73.478261	7.90	616	42	0.42	64	21	86	52	432	491
12	Panch Mahals	Kalol	Medapur	Open well	22.587207	73.517653	7.74	736	42	0.45	60	27	110	66	552	490
13	Panch Mahals	Kalol	Shaktipura	Shallow Tubewell	22.641422	73.504198	7.70	786	137	0.92	212	10	57	35	284	296
14	Panch Mahals	Halol	Arad	Open well	22.561229	73.568108	7.70	584	38	0.60	84	18	75	45	376	320
15	Panch Mahals	Halol	Govindpuri	Shallow Tubewell	22.573575	73.631665	7.90	1478	28	1.30	448	31	144	86	720	444
16	Panch Mahals	Halol	Navaria	Open well	22.564894	73.476012	7.78	740	23	0.80	84	22	109	66	544	412
17	Panch Mahals	Ghoghamba	Dhaneshwar	Shallow Tubewell	22.543069	73.631231	7.89	798	42	0.54	192	16	86	52	428	408
18	Panch Mahals	Ghoghamba	Jitpura	Shallow Tubewell	22.541712	73.598965	7.89	1312	31	0.80	540	17	86	52	428	372
19	Panch Mahals	Ghoghamba	Kanbipalli	Shallow Tubewell	22.577437	73.640175	7.80	662	44	0.94	80	14	70	42	352	456
20	Panch Mahals	Ghoghamba	Kumbhar Palli	Shallow Tubewell	22.577848	73.642155	7.80	518	41	0.80	92	10	61	36	304	276
21	Panch Mahals	Ghoghamba	Ranipura (dam)	Shallow Tubewell	22.571486	73.638536	7.78	1778	29	0.72	508	41	184	110	920	556
22	Panch Mahals	Ghoghamba	Rayan Muvada	Shallow Tubewell	22.571230	73.642055	7.72	1052	44	0.68	296	20	103	62	516	328
23	Panch Mahals	Ghoghamba	Savapura	Shallow Tubewell	22.545865	73.657977	7.82	1102	83	0.70	128	32	154	92	768	228
24	Vadodara	Savli	Dhantej	Shallow Tubewell	22.595273	73.360274	7.00	4120	284	0.54	848	473	24	424	1810	602
25	Vadodara	Savli	Kalupura	Shallow Tubewell	22.614267	73.250771	7.99	822	104	0.88	108	37	19	46	236	464

SR	District	Block	Village	Source	Latitude	Longitude	pH	TDS	NO$_3$	F	Cl	SO$_4$	Ca	Mg	TH	ALK
26	Vadodara	Savli	Dipapura	Shallow Tubewell	22.635083	73.338365	8.01	1020	34	2.15	112	45	14	24	136	704
27	Vadodara	Savli	Rasawadi	Shallow Tubewell	22.608294	73.239200	7.94	734	86	0.35	104	33	72	56	412	276
28	Vadodara	Savli	Wankaner	Shallow Tubewell	22.543114	73.182610	7.30	1310	168	0.34	135	40	100	140	828	487
29	Vadodara	Karjan	Vadava	Shallow Tubewell	21.871356	73.146472	7.90	772	2	0.29	156	30	48	41	292	436
30	Vadodara	Karjan	Delvada	Shallow Tubewell	21.870076	73.143891	8.04	582	3	0.52	104	14	22	27	168	360
31	Vadodara	Karjan	Somaj	Shallow Tubewell	21.872436	73.144918	7.74	578	10	0.42	72	26	41	43	284	384
32	Vadodara	Karjan	Fatepur	Shallow Tubewell	21.911216	73.217983	7.84	820	4	0.74	84	22	35	38	248	596
33	Vadodara	Karjan	Pura	Shallow Tubewell	21.846364	73.177747	7.58	1418	2	0.82	428	57	91	88	596	464
34	Vadodara	Karjan	Sandarna	Shallow Tubewell	22.007471	73.166414	8.04	1556	45	0.79	476	60	91	88	596	360
35	Vadodara	Karjan	Saniyad	Shallow Tubewell	21.919963	73.166132	7.86	410	3	1.32	48	21	34	36	236	280
36	Vadodara	Padra	Bhoj	Shallow Tubewell	22.221413	73.005110	8.04	1056	2	1.12	308	42	67	65	440	460
37	Vadodara	Padra	Brahmanvasi	Shallow Tubewell	22.150838	72.875035	8.11	898	7	0.86	148	22	35	41	260	596
38	Vadodara	Padra	Chokari	Shallow Tubewell	22.273760	73.072250	7.95	940	10	0.72	232	11	17	21	132	488
39	Vadodara	Padra	Dabhasa	Shallow Tubewell	22.243011	73.051750	7.98	886	45	1.98	176	38	61	60	404	446
40	Vadodara	Padra	Goriyad	Shallow Tubewell	22.195859	73.087332	7.88	674	4	1.04	192	26	41	42	280	296
41	Vadodara	Padra	Pipli	Shallow Tubewell	22.201581	73.051033	7.74	1102	31	0.88	172	12	16	15	104	700
42	Vadodara	Padra	Sadra	Shallow Tubewell	22.136073	72.981860	8.02	1403	23	1.18	272	13	20	24	152	825
43	Vadodara	Padra	Shihor	Shallow Tubewell	22.182023	73.114620	8.41	1618	9	0.82	568	36	57	57	380	772
44	Vadodara	Padra	Vishrampura	Shallow Tubewell	22.194093	72.967710	7.98	2236	102	1.36	440	114	182	169	1160	828
45	Vadodara	Shinor	Simli	Shallow Tubewell	21.990325	73.365538	7.72	1018	17	0.33	236	44	73	72	484	468
46	Vadodara	Shinor	Tinglod	Openwell	21.993000	73.249902	7.88	1270	44	0.34	296	58	94	88	600	368
47	Vadodara	Dabhoi	Bhimpura	Shallow Tubewell	21.982612	73.441960	7.76	480	5	0.36	76	21	60	36	304	240
48	Vadodara	Vadodara	Karchiya	Openwell	22.377866	73.103213	7.49	900	23	0.49	147	70	49	71	415	550
49	Vadodara	Vadodara	Sankarda	Shallow Tubewell	22.433878	73.123409	7.59	1260	92	0.47	360	31	25	112	523	525
50	Vadodara	Vadodara	Sisva	Openwell	22.400058	73.182021	7.31	2494	95	0.38	832	210	109	131	812	404

ANNEXURES II

MOJS-DDWAS Groundwater quality data (2018-Post monsoon)

SR	District	Block	Village	Source	Latitude	Longitude	pH	TDS	NO₃	F	Cl	SO₄	Ca	Mg	TH	ALK
1	Bharuch	Jambusar	Amanpor Mota	Openwell	22.12588	72.75626	7.58	428	4	0.38	116	9	21	20	136	204
2	Bharuch	Jambusar	Bojadra	Openwell	22.05637	72.90022	7.9	512	1	0.13	84	16	40	46	292	328
3	Bharuch	Jambusar	Jafarpara	Openwell	22.06198	72.87567	8	1280	11	0.19	448	9	62	80	488	332
4	Bharuch	Jambusar	Nahar	Openwell	22.17589	72.68945	8.09	1370	166	0.37	236	14	58	56	380	740
5	Bharuch	Jambusar	Nondhana	Openwell	22.13385	72.78111	7.73	400	4	0.26	112	10	22	21	144	184
6	Bharuch	Jambusar	Salehpor Sang	Openwell	22.12304	72.60688	7.9	406	6	0.22	44	13	34	31	216	284
7	Panch Mahals	Ghoghamba	Damanpura	Shallow Tubewell	22.63941	73.64751	7.78	838	145	3.2	128	18	91	55	456	308
8	Panch Mahals	Ghoghamba	Gorada	Shallow Tubewell	22.54306	73.60124	7.9	1514	218	2.72	380	28	134	81	672	300
9	Panch Mahals	Ghoghamba	Goya Sundal	Shallow Tubewell	22.54171	73.59897	7.74	852	112	2.29	148	18	94	57	472	252
10	Panch Mahals	Ghoghamba	Kanbipalli	Shallow Tubewell	22.57785	73.64216	7.79	702	127	1.1	84	15	82	49	408	220
11	Panch Mahals	Ghoghamba	Kharkhadi	Shallow Tubewell	22.54182	73.59953	7.72	1068	208	0.95	52	28	146	87	728	372
12	Panch Mahals	Ghoghamba	Poyali	Shallow Tubewell	22.54327	73.66751	7.69	866	113	0.54	152	19	96	58	480	264
13	Panch Mahals	Ghoghamba	Tadkundla	Shallow Tubewell	22.57744	73.64017	7.8	968	124	3.85	156	22	112	67	560	364
14	Panch Mahals	Halol	Arad	Shallow Tubewell	22.56123	73.56811	7.72	3882	247	1.48	1224	78	339	203	1696	500
15	Panch Mahals	Halol	Govindpuri	Shallow Tubewell	22.57358	73.63166	7.76	566	41	1.46	76	14	67	40	336	372
16	Panch Mahals	Halol	Maruva	Shallow Tubewell	22.57424	73.51546	7.82	2348	123	1.36	752	48	205	123	1024	432
17	Panch Mahals	Halol	Maswad	Shallow Tubewell	22.55885	73.50957	7.74	2412	217	0.91	636	54	232	139	1160	376
18	Panch Mahals	Halol	Varasada (govi	Shallow Tubewell	22.56323	73.54115	7.86	2452	225	1.01	676	52	227	136	1136	372
19	Panch Mahals	Kalol	Adadara	Shallow Tubewell	22.64516	73.61621	7.79	2154	255	0.07	424	102	227	136	1136	420
20	Panch Mahals	Kalol	Alva	Shallow Tubewell	22.57915	73.54104	7.78	1398	152	0.67	348	24	118	71	588	676
21	Panch Mahals	Kalol	Barola	Shallow Tubewell	22.58831	73.44071	7.7	866	84	0.36	172	19	96	58	480	432
22	Panch Mahals	Kalol	Bhukhi	Shallow Tubewell	22.62606	73.60734	7.72	716	180	0.05	76	12	77	46	384	372
23	Panch Mahals	Kalol	Ghoda	Shallow Tubewell	22.61099	73.48147	7.88	2242	205	3.23	968	21	107	64	536	460
24	Panch Mahals	Kalol	Khadki	Shallow Tubewell	22.60709	73.46171	7.8	2168	171	1.22	932	24	110	66	548	536
25	Panch Mahals	Kalol	Khandeval	Shallow Tubewell	22.63356	73.48387	7.58	854	90	1.48	160	18	96	58	480	376

SR	District	Block	Village	Source	Latitude	Longitude	pH	TDS	NO3	F	Cl	SO4	Ca	Mg	TH	ALK
26	Panch Mahals	Kalol	Medapur	Shallow Tubewell	22.58836	73.50263	7.64	892	42	0.81	136	23	119	72	119	596
27	Panch Mahals	Kalol	Nevariya	Shallow Tubewell	22.56609	73.4957	7.72	1708	111	1.08	440	38	174	105	872	596
28	Panch Mahals	Kalol	Utarediya	Shallow Tubewell	22.62276	73.53953	7.72	1604	248	1.46	496	22	114	67	564	532
29	Vadodara	Dabhoi	Bhimpura	Shallow Tubewell	21.98261	73.44196	7.74	618	32	0.21	104	27	50	57	360	320
30	Vadodara	Dabhoi	Kajapur	Shallow Tubewell	22.07573	73.39972	8.18	2542	27	1.22	1012	114	18	100	576	740
31	Vadodara	Dabhoi	Vayadpur	Shallow Tubewell	22.36463	73.14272	7.98	1410	79	0.87	348	64	42	137	668	500
32	Vadodara	Karjan	Delvada	Shallow Tubewell	21.87008	73.14389	8.48	512	2	0.47	96	18	22	25	160	308
33	Vadodara	Karjan	Somaj	Shallow Tubewell	21.87244	73.14492	7.6	564	12	0.4	48	34	53	52	352	396
34	Vadodara	Padra	Gavasad	Openwell	22.16039	72.94403	7.82	1362	99	0.36	440	39	62	61	408	464
35	Vadodara	Savli	Dhantej	Shallow Tubewell	22.55811	73.23216	8.36	2262	276	0.52	495	102	152	158	1030	737
36	Vadodara	Savli	Dipapura	Shallow Tubewell	22.63508	73.33836	8.34	1144	44	1.47	172	51	56	24	238	717
37	Vadodara	Savli	Gutardi	Shallow Tubewell	22.64148	73.33159	7.73	1702	172	0.7	414	77	80	132	742	747
38	Vadodara	Savli	Khokhar	Shallow Tubewell	22.61427	73.25077	7.82	910	17	1.87	152	41	24	89	426	566
39	Vadodara	Savli	Parthampura (	Shallow Tubewell	22.60829	73.2392	7.51	1062	65	0.53	263	47	68	76	485	384
40	Vadodara	Savli	Vemer	Shallow Tubewell	21.87244	73.14492	7.6	1242	27	1.81	333	56	16	41	208	586
41	Vadodara	Vadodara	Ankhol	Openwell	22.2975	73.2436	6.8	3822	56	0.39	850	1036	141	207	1205	287
42	Vadodara	Vadodara	Bajva	Openwell	22.36463	73.14272	7.97	1750	79	0.32	200	691	55	112	598	470
43	Vadodara	Vadodara	Dhanora	Shallow Tubewell	22.25409	73.2486	8.07	458	3	1.3	69	13	16	31	167	303
44	Vadodara	Vadodara	Hansapura	Shallow Tubewell	22.40006	73.18202	8.04	1596	39	1.56	424	72	16	28	157	768
45	Vadodara	Vadodara	Kajapur	Shallow Tubewell	22.16616	73.19726	8.27	1254	20	1.23	202	64	35	36	235	792
46	Vadodara	Vadodara	Ratanpur	Shallow Tubewell	22.43388	73.12341	7.65	1288	50	0.47	290	51	19	154	680	414
47	Vadodara	Vadodara	Salad	Shallow Tubewell	22.13364	73.23847	7.66	1912	123	0.28	525	159	82	134	755	586
48	Vadodara	Vadodara	Sankarda	Shallow Tubewell	22.30983	73.09747	7.62	1236	95	0.38	340	19	39	105	529	540
49	Vadodara	Vadodara	Sisva	Openwell	22.40006	73.18202	7.75	2798	92	0.29	820	395	122	150	921	376
50	Vadodara	Vadodara	Tatarpura	Shallow Tubewell	22.26891	73.2535	7.92	1168	6	1.38	260	76	13	24	130	624