Executive Summary of PhD Thesis

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

THESIS

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BREIF THESIS SUMMARY

Assessment of groundwater vulnerability is crucial for sustainable water resource management in alluvial regions. This abstract provides an executive summary of a comprehensive study conducted to assess groundwater vulnerability in the alluvial region situated within the inter-basin of the Mahi-Narmada rivers (termed as Mahi-Narmada inter basin now onwards) flowing through Gujarat, India. Objectives are to identify different groundwater contamination sources, considering them appropriate groundwater vulnerability models are developed. Validated vulnerability model's parameters have been correlated with groundwater quality parameters to identify dominating contaminant. Subsequently, suitable methods are suggested to mitigate its concentration in groundwater, thereby minimizing risks to public health. To identify potential sources of groundwater contamination, an extensive investigation of the study area was conducted, considering various anthropogenic factors such as industrial effluent disposals, agricultural practices and urbanization. Multivariate statistical analysis was employed to identify and map sources of contaminants. This approach provided a comprehensive understanding of how anthropogenic activities affect groundwater quality, utilizing techniques such as Principal Component Analysis (PCA), Factorial Spatial Analysis (FSA) and Hierarchical Cluster Analysis (HCA).

A DRASTIC model (Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and Conductivity) was developed by Aller Linda in the year 1987 to evaluate groundwater vulnerability. Additional parameters, including layers of industries, sewage treatment plants, and rural sanitation, were incorporated to enhance the model's accuracy. Weights were assigned to the model's parameters using ANN, and a vulnerability index was calculated to identify areas at higher risk of groundwater contamination in an Arc-GIS environment. The assessment integrated datasets, including hydrogeological and geospatial information. Hydrogeological data provided insights into aquifer characteristics, while geospatial information helped understand soil characteristics in the study area. The new parameters, FS and EI, introduced in the DRASTIC model, were validated using Pearson Co-efficient with nitrate concentrations in groundwater for three successive years (2018, 2019, and 2020) during pre- and post-monsoon seasons. Groundwater quality correlations were analysed to establish the relationship between vulnerability and groundwater quality parameters using Single Parameter Sensitivity Analysis (SPSA). The Pearson Co-efficient results between vulnerability parameters and groundwater quality parameters showed significant correlations with Groundwater Quality Index (GWQI), NO_3, TDS, TH and Ca. Areas with higher vulnerability index values are primarily associated with

intensive agricultural activities, industrial zones, and densely populated urban areas, indicating that higher vulnerability corresponded to poorer water quality. This underscores the need for effective management strategies to safeguard public health.

Findings from the groundwater vulnerability assessment in the alluvial region between the Mahi-Narmada Rivers provide valuable insights for sustainable water resource management. Integrating contaminant source identification, an upgraded DRASTIC model and hydrogeological investigations allows for a comprehensive understanding of groundwater vulnerability and its relationship with water quality. Due to anthropogenic activities, nitrate concentration in groundwater is continuously increasing, causing serious health concerns for infants and elders. Identifying "critical areas" for urgent remediation is imperative, particularly given the expansive area of 2750.15 sqkm, such as the current study area. According to the USEPA's proposed Health Risk Assessment, children face a greater health risk as the HQ increases to 10, compared to adults (HQ increases to 5). The novelty of this study is the inclusion of hydrogeological parameters such as land use maps, water use scenarios, and population distribution in addition to the conventional method of health risk assessment.

The study also suggests a suitable denitrification method based on the Analytical Hierarchy Process (AHP) of Multi-Criteria Decision Analysis (MCDA). The AHP method is used to recommend nitrate reduction methods for each well identified through sampling and testing as high-risk based on nitrate concentrations above 45 mg/l. The study considered five leading nitrate reduction methods: phytoremediation, pump and treat, pump and fertilizer, permeable reactive barrier and chemical reduction. These methods were evaluated using six criteria: initial cost (IC), operation and maintenance cost (OMC), reduction time (RT), removal rate (RR), groundwater table (GWT), aquifer material (AM), location-specific characteristics (LSC), and contaminant loading (CL). The most suitable method for the northern critical area is chemical reduction since the region is mostly covered in sandy soil and has a groundwater table between 30 to 50 feet. PAF is recommended for the western critical area, which is close to the Mahi Estuary and contains clay loam soil. Suburban settlements in the central critical zone, with groundwater levels between 15 to 70 feet, require remediation using a permeable reactive barrier and a pump and treat method.

These findings can guide policymakers, water resource managers, and local communities in making informed decisions to protect and manage groundwater resources effectively.

INTRODUCTION

Aim and Objectives of study

A variety of methodologies are used in this study, including identification of the source area and vulnerability of groundwater contamination in the study area, determining the relationship between groundwater quality and vulnerability parameters, as well as implementing management strategies to reduce public health risks in critical areas based on human health risk assessment (HHRA).

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 and Data Collection

The study area for the research is an alluvial region between Mahi and Narmada rivers, which are flowing through the central part of Gujarat state (Fig 1) the area coverage is six blocks of Vadodara, three blocks of Panchmahal and three blocks of Bharuch district above Narmada River. Total area of the alluvial region is 2750.15 km^2, residing between 72.51° to 73.64° Eastern longitude and 21.78° to 22.83° Northern latitude on a geographical basis.

The Vadodara district, sits on the banks of the Vishwamitri River, lies between 21º49’19” and 22º48’37” North latitude and 72º51’05” and 74º16’55” East longitude, with total area of 7550 km^2. The overall elevation ranges from 610 m in east to 20 m msl in south-west. The Vadodara is divided into 8 talukas namely Vadodara City, Vadodara Rural, Dabhoi, Karjan, Padra, Savli, Sinor and Waghodiya. Vadodara district sharing border with Alirajpur and Chhota Udaipur District to the East, Anand – Panchmahal and Kheda District to the North, Bharuch and Narmada District to the South.

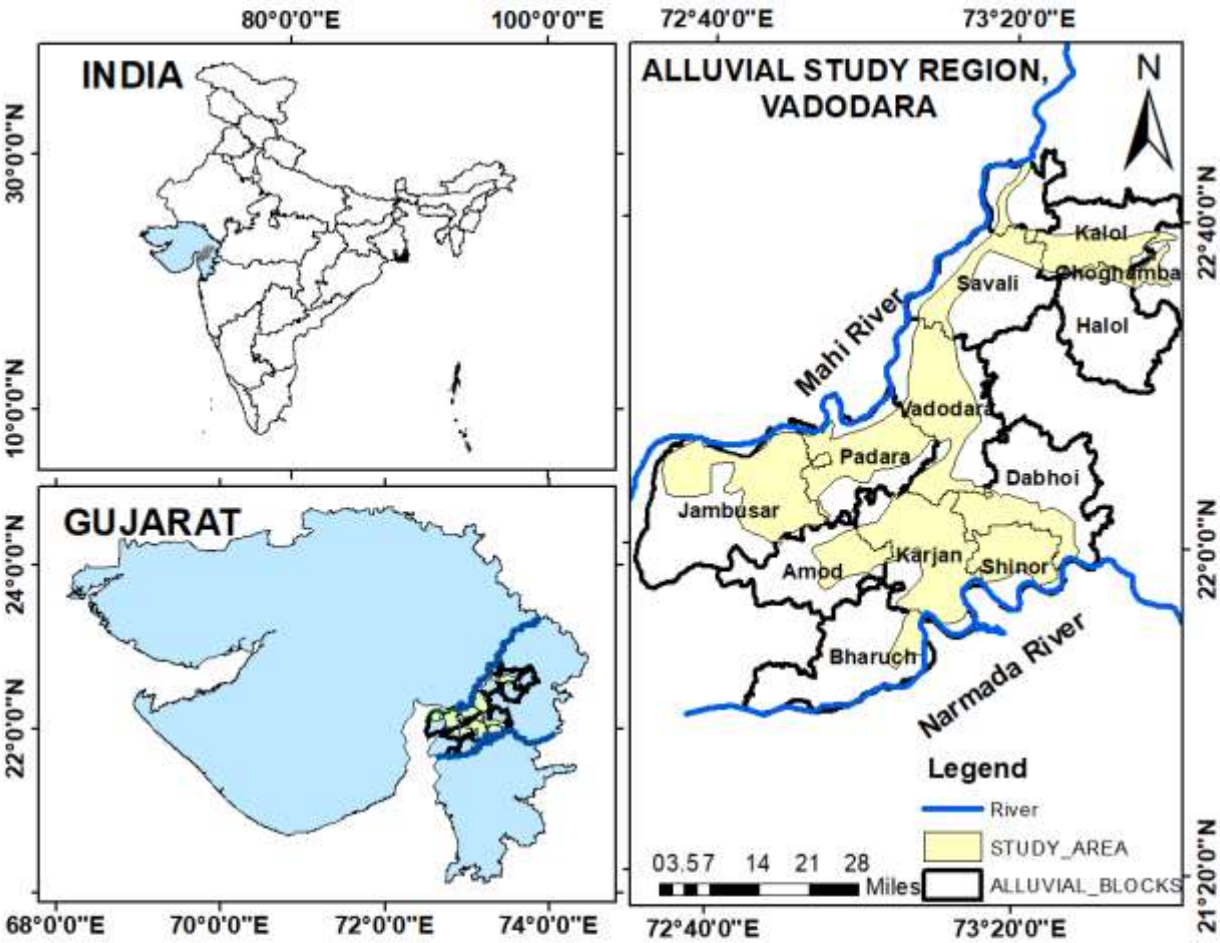

Fig 1: Alluvial study region, Gujarat, India

The Panchmahal district, sits on the banks of Mahisagar River, situated between 22º30’ and 23º30’ Latitudes and 73º15’ and 74º30’ Longitudes. With total area of 5210 km2, comprises 11 talukas at present namely Godhra, Halol, Kalol, Lunawada, Santrampur, Kadana, Jambughoda, Shahera, Morva-Hadaf, Khanpur and Ghoghamba. Panchmahal district sharing border with Aravalli district to the North, Kheda district to the west, Dahod district to the east and Vadodara and Chhota Udaipur district to the south. Panchmahal district is one of the important tribal districts of Gujarat State.

The Bharuch District, sits on the banks of Narmada River, Lies between 21º24’ to 22º17’ North latitude and 72º22’ and 73º31’ East longitude. Total area of Bharuch is 6527 km^2, divided into 7 talukas namely Jambusar, Amod, Vagra, Jhagadia, Anklesvar, Hansot and Valia and consist 21 towns and 663 villages. Bharuch District is sharing border with Anand and Vadodara districts to the North, Surat district to the South, Narmada district to the east.

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) (2018 Pre and Post 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) (Fig. 3.11)
2	SWDC, Ahmedabad	**For 'R':** Average Annual Rainfall (2000-2016) (Fig. 3.12) Canals, Tanks and Ponds, WCS polygons from google earth (Fig. 3.13) (Fig. 3.14)
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 (Fig. 3.16)
5	USGS Earth explorer	**For 'T':** SRTM Digital Elevation Map, Landsat 8 images, Land Use Land Cover (Fig. 3.15) (Fig. 3.17)
6	MOJS-DDWAS	**For 'FS':** Groundwater quality data (50 Wells) (2018 – Pre and Post monsoon) (Fig. 3.4 - 3.9) **For 'Model Validation':** (2018, 2019, 2020 – Pre and Post monsoon)
7	DIPS Reports (MSME)	**For 'EI':** Location and Type of Industries and STP Locations (Fig. 3.3)
8	Socioeconomic Data and Applications Center (SEDAC)	**For 'EI':** Villages Location and Population (Fig. 3.10)
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)
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	Groundwater quality samples (2021 Pre) (Fig. 3.18)
3	MOJS-DDWAS	Groundwater quality data (OS-50) (2018, 2019, 2020 – Pre & Post monsoon) Water use scenario, Population distribution

Table 1 shows the data requirement and collection. Groundwater quality data (50 Wells) of 2018 Pre and Post monsoon time period obtained from MOJS-DDWAS (Ministry of Jal Shakti – Department of Drinking Water and Sanitation) reports from the online portal were used to identify sources of groundwater contamination. Other hydrogeological data related to groundwater vulnerability and quality modelling have also been described in details in Table 1.

BRIEF RESEARCH METHODOLOGY

The following is a brief research methodology showed by figures 2a and 2b, explaining how each objective of present research has been achieved. After reviewing the available literature relevant to each objective, following are the line of action implemented:

1. The hydrogeological and physico-chemical data within the study area provide a comprehensive overview of groundwater contamination, highlighting the predominant parameters, including NO_3^-, TDS, and F^- concentrations in the groundwater.
2. The information presented above guides in identifying the origins and type of groundwater contamination, whether these sources are anthropogenic, geogenic or a combination of both.
3. Furthermore, study of literature pertaining to the assessment of groundwater vulnerability, including various approaches and their applicability, led us to choose an appropriate method, such as the DRASTIC analysis recommended by Linda Aller in 1987.
4. After understanding the way of implementation of DRASTIC approach, necessary data have been obtained from various state and central government agencies.
5. Using GIS tool, all required data input is done under the governing equation of conventional DRASTIC, to obtained Vulnerability Index in the form of raster image. Few operations are frequently used such as Spatial Analyst Tool, Interpolation, Extraction, Weighted sum, Modal Builder in GIS.
6. DRASTIC model is applied to assess the vulnerability in the study area.
7. This vulnerability index is validated using the Pearson correlation method with the dominant contaminant.
8. Conventional DRASTIC validation has revealed certain limitations as, (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. These weights are without any technical and logical base. (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.
9. In order to overcome these limitations area specific activities is introduced as the in terms of new parameter namely 'Factor Score (FS)' and 'External Influence (EI)'. Both parameters are representing various anthropogenic activities under different domain. Factor Score is based on actual polluted groundwater quality whereas External Influence

is based on influences by industrial activities, waste disposal from sewage treatment plant and rural sanitation effect by soak pit.

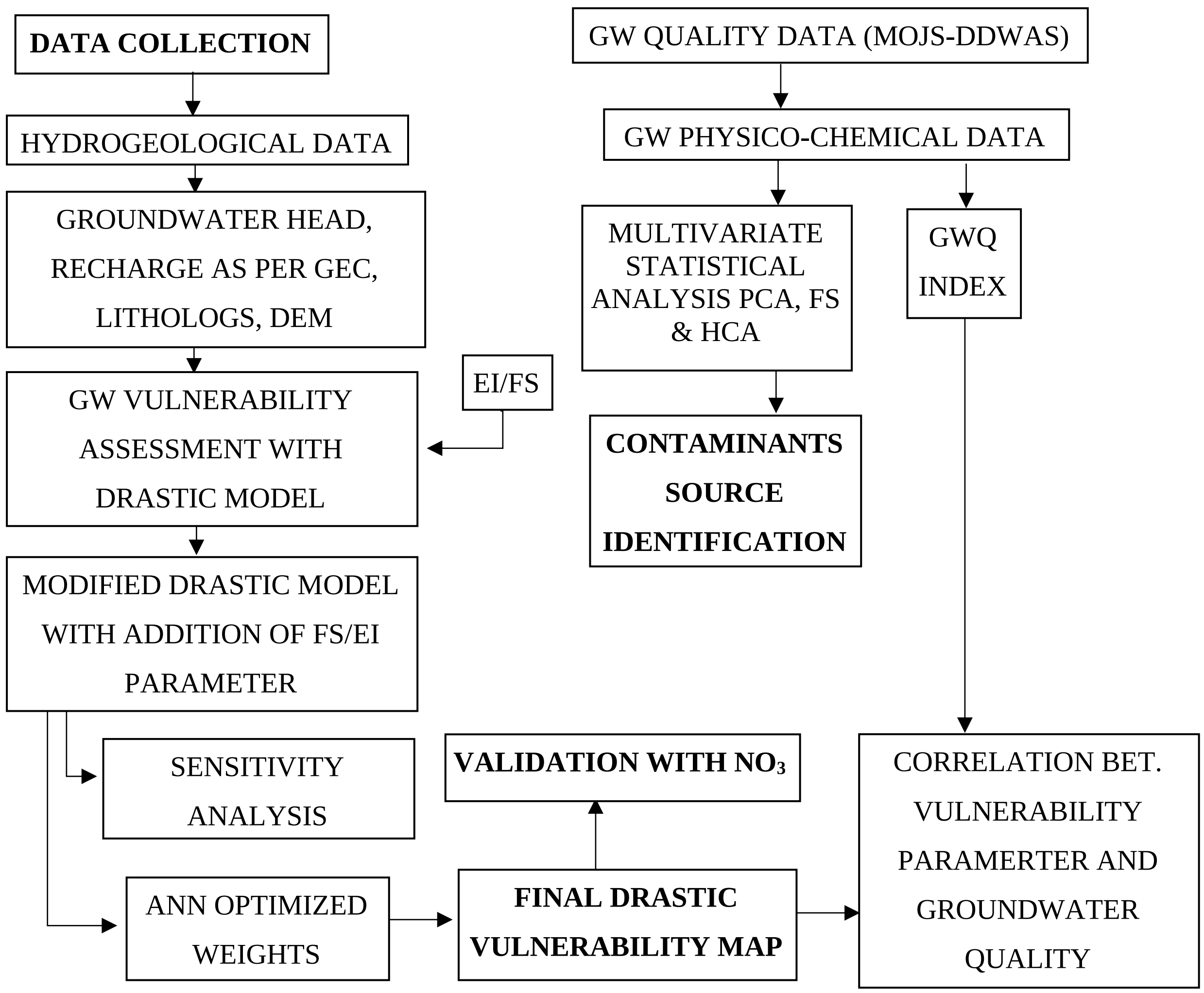

Fig 2a: A comprehensive flow chart of present research methodology

10. Initially model is run by the weights provided by Aller Linda. Initial weight for FS and EI parameter is five.
11. DRASTIC model is run using these weights and afterward the Single Parameter Sensitivity Analysis has been carried out for the calibration. As a result, effective weights are generated.
12. The weights generated through SPSA are based on theoretical recommendations by Linda Aller. To enhance their logical coherence, these weights are optimized using an Artificial Neural Network (ANN) with both dependent and independent variables.
13. Comparisons were made between the effective weights and ANN-optimized weights in order to evaluate the percentage error in it. The ANN-optimized weights have been

computed based on hydrogeological parameters which makes them logical, scientific and preferable.

14. The Modified DRASTIC model was developed in the ArcGIS environment for both pre and post-monsoon seasons, incorporating additional parameters and utilizing ANN-optimized weights. The model's performance was subsequently validated against the dominant contaminant.

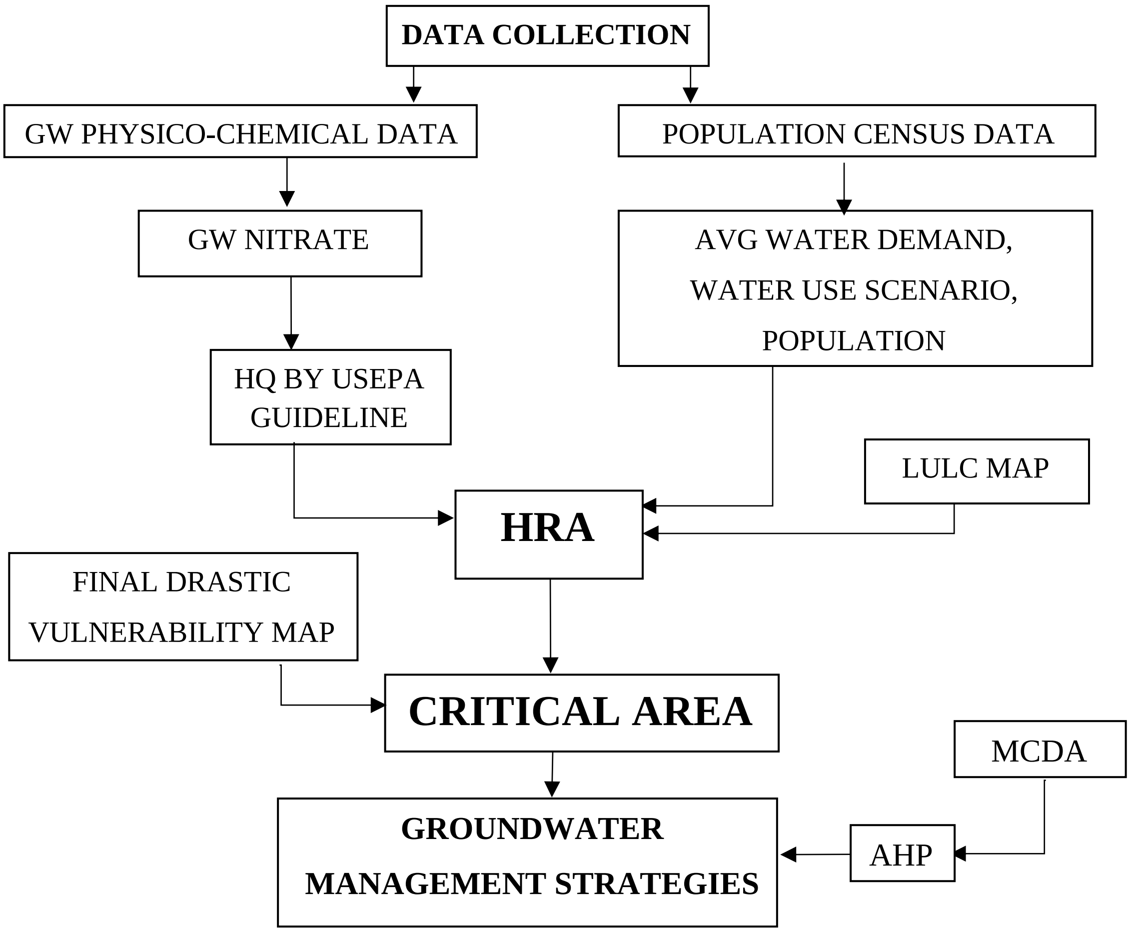

Fig 2b: A comprehensive flow chart of present research methodology

15. The Groundwater Quality Index (GWQI) was computed to assess the actual contaminant conditions within the study area. Additionally, GWQI was employed to establish correlations with vulnerability parameters using the Spearman correlation method, developed in the SPSS software. Further insights and interpretations based on these correlations will be provided.

16. Through the assessment of groundwater quality, we have identified the water quality

parameter with the highest contribution. Further it needs to recommend a suitable method for reducing its concentration in groundwater by AHP approach to minimize human health risk.

- To accomplish the above-mentioned objectives, the Hazard Quotient was initially calculated following the guidelines set by the standard USEPA.
- The health risk assessment has been obtained in form of raster map by individual layer of Hazard Quotient map, Land Use-Land Cover map, Population Distribution map and Water Use scenarios map.
- Subsequently, critical areas were identified through an overlay analysis of the health risk assessment output map and final vulnerability output map. This process pinpointed the critical zones within the study area where health risks are most pronounced.
- Following this, primary data was collected to confirm the presence of dominant contaminants within the identified critical zone.

17. Results from the primary data, revealed high concentrations of Nitrate (NO_3) in the majority of wells, the Nitrate reduction method was recommended at each well location using the Analytic Hierarchy Process (AHP) which is one of the Multi-Criteria Decision-Making (MCDM) technique.

KEY FINDINGS

Key Findings: Groundwater Contamination Source Identification

The multivariate statistical analysis methods, including Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA) and Factor Score (FS), have proven their efficiency in identifying contamination sources within a large dataset of groundwater quality parameters in the alluvial region. The application of PCA revealed three significant principal components, PC-1 (comprising TDS, NO_3, Cl, SO_4, Mg), PC-2 (consisting of F, ALK), and PC-3 (including pH, TH, Ca), all of which consistently pointed towards the same regions - the northern and central parts of the area. These areas exhibited high contamination levels originating from anthropogenic sources.

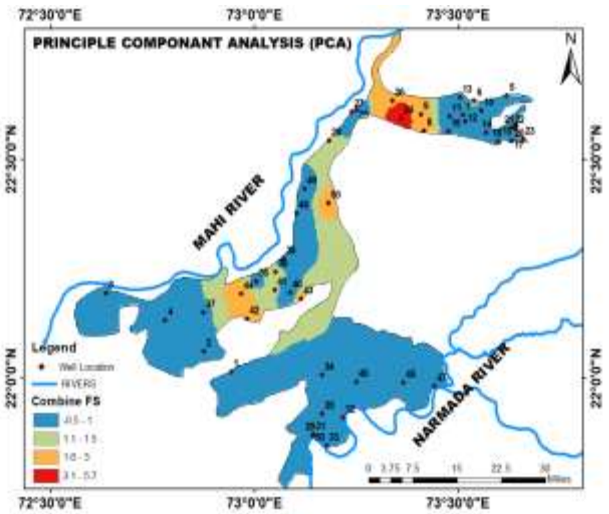

Fig 3: Composite PCA results

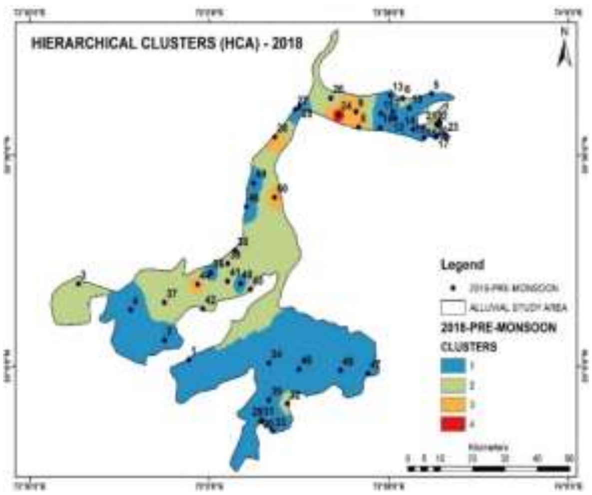

Fig 4: HCA Cluster map

Further analysis of individual PC maps highlighted the influence of the two main perennial rivers, Mahi and Narmada, flowing in the northern and southern parts of the alluvial region. Shallow groundwater depths (5 – 20 mbgl) towards these rivers correlated with a gradual decrease in factor scores (fig. 3), indicating the impact of these hydrological features on contamination patterns. Within the study area, there are a total of 50 well locations. Among these, 35 wells exhibit a factor score less than 1, indicating they are non-polluted. Additionally, there are 3 wells with factor scores ranging from 1 to 1.5, suggesting geogenic sources of contamination. Furthermore, there are 11 wells with factor scores between 1.5 and 3, primarily concentrated in the northern region of the study area. The highest factor score recorded is 5.68, predominantly found in the northern area of the study zone.

The categorization of well locations into clusters based on factor scores provided additional insights. Wells falling under cluster 3 and 4, characterized by factor scores higher than 1, indicated contamination from anthropogenic sources. Additionally, cluster 2 contained wells with positive factor scores greater than 1, signifying the need for ongoing monitoring due to combined geogenic and anthropogenic influences.

In the extensive analysis of 50 well locations, notable patterns have emerged across distinct clusters (fig. 4). Cluster 1 comprising 32 wells, predominantly situated in the southern and western regions of the alluvial area, represents negative factor scores and is deemed non-polluted.

Cluster 2, situated in central area, demonstrates a collective feature of high alkalinity across its 9 wells. The factor scores, surpassing a value of 1 in majority of wells, signify this pattern, with the origin of pollution linked to inadequate solid waste disposal practices. Cluster 3, which encompasses 8 wells in the northern upper zone, the examination common characteristics of Total Dissolved Solids (TDS) and Total Hardness (TH). Within this cluster, there is a notable presence of high Total Hardness, attributable to the proximity to industrial zones, consequently resulting in heightened Nitrate concentrations.

Cluster 4, specifically well number 24, manifests a highly contaminated zone in the northern part, validated by excessive Urea usage, animal husbandry practices, and improper domestic waste disposal near a pond. Lastly, a significant anthropogenic influence stems from the rapid expansion of Petroleum and Mineral-based industrial manufacturing units, coupled with improper waste disposal into small drains and the Mini River, notably in the northern reaches of the alluvial region. These findings emphasize the pressing need for targeted interventions and sustainable practices to preserve the groundwater quality and ecological integrity of the studied area. The combination of PCA, HCA and FS has effectively revealed contamination sources in the alluvial region's groundwater.

Key Findings: Groundwater Vulnerability assessment

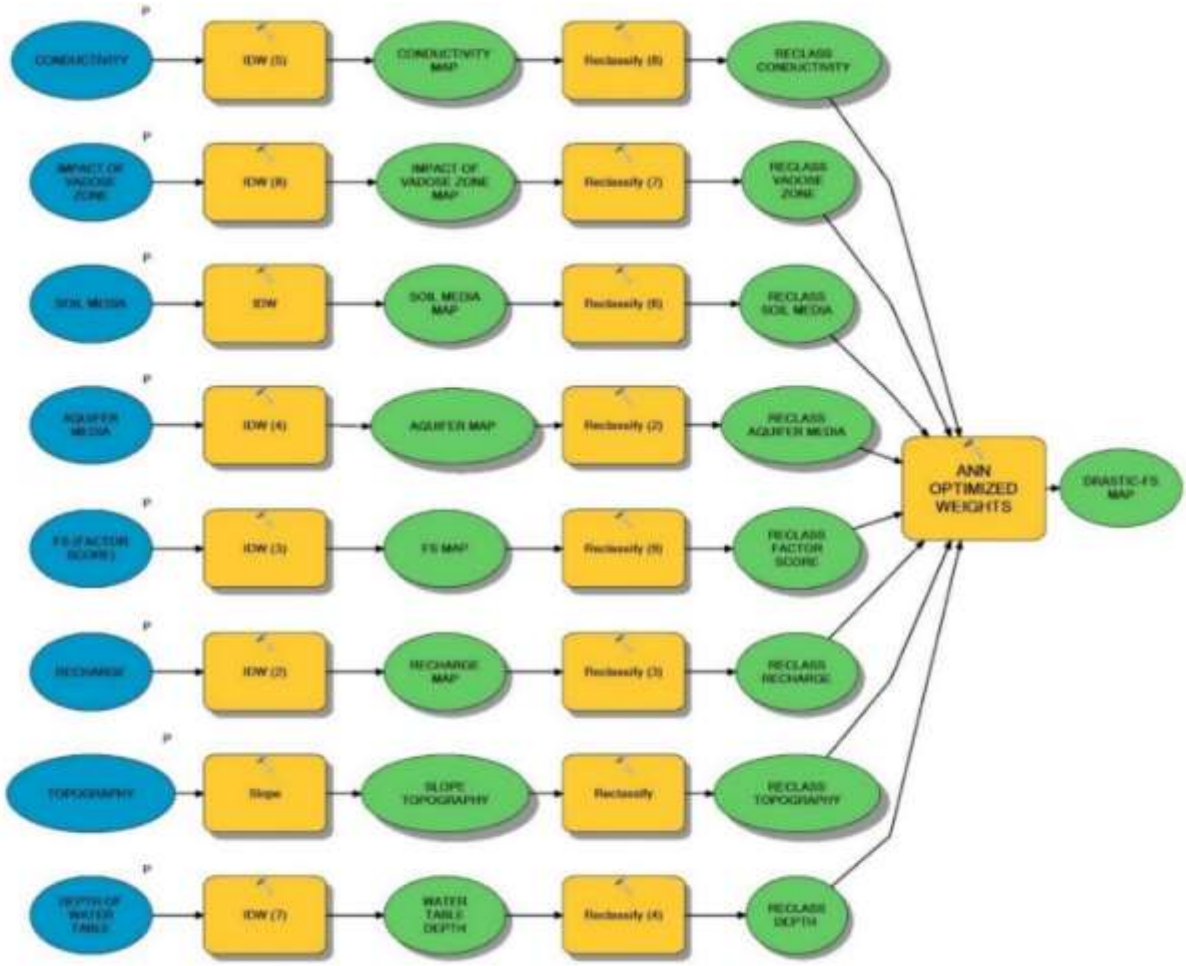

Fig 5: DRASTIC-FS Model Diagram

The above figure 5 represent DRASTIC-FS model development in GIS environment. Factor Score (FS) which identified groundwater contamination sources have been taken as a newly added parameter over the conventional DRASTIC approach. Final outcome of the DRASTIC-FS model comes in the form of a Vulnerability map classified in Sustainable, Less Vulnerable, Moderately Vulnerable, Highly Vulnerable and Severely Vulnerable classes. The DRASTIC-FS (ANN weights) model final vulnerability index (fig. 6 and 7) is mapped from 65 to 198 in that, sustainable (65-120), less vulnerable (120.1-140), moderately vulnerable (140.1-160), highly vulnerable (160.1-190) and severely vulnerable (190.1-198) are representative classes.

The distribution of study area (%) in each vulnerability class of the model (DRASTIC-FS) for both seasons (Pre and Post Monsoon) is shown below in table 2. The results from sustainable class show marginal decrease in percent (%) area for both the seasons. In pre monsoon season, less and moderately vulnerable classes show decrease and highly and severely vulnerable classes show increase in percent (%) area. In DRSTIC-FS post monsoon season, it has been observed that less and moderately vulnerable classes show increase in percent (%) area and highly vulnerable class show decrease in percent (%) area. This is because of higher infiltration rates and groundwater recharge in alluvial region resulting reduction of highly and severely vulnerable area significantly.

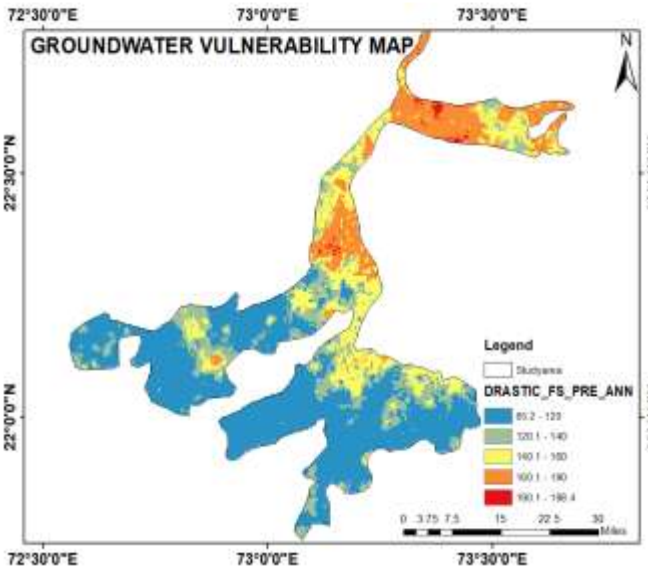

Fig 6: DRASTIC-FS Map Pre-Monsoon

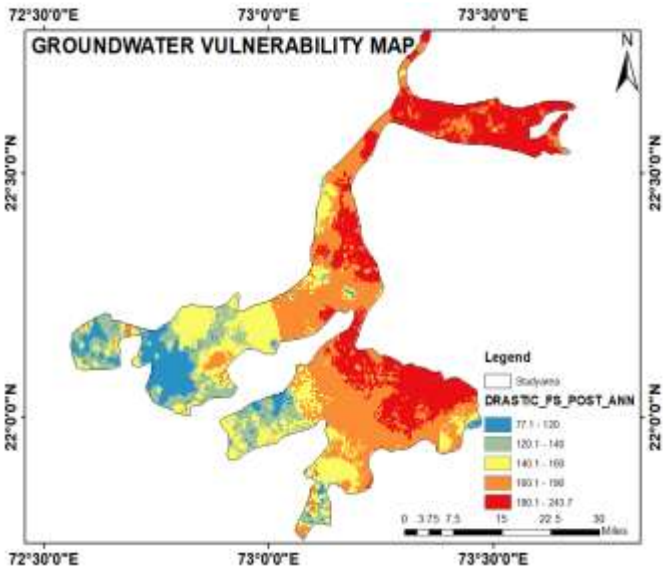

Fig 7: DRASTIC-FS Map Post-Monsoon

Table 2: Groundwater Vulnerability outcome in terms of % area

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

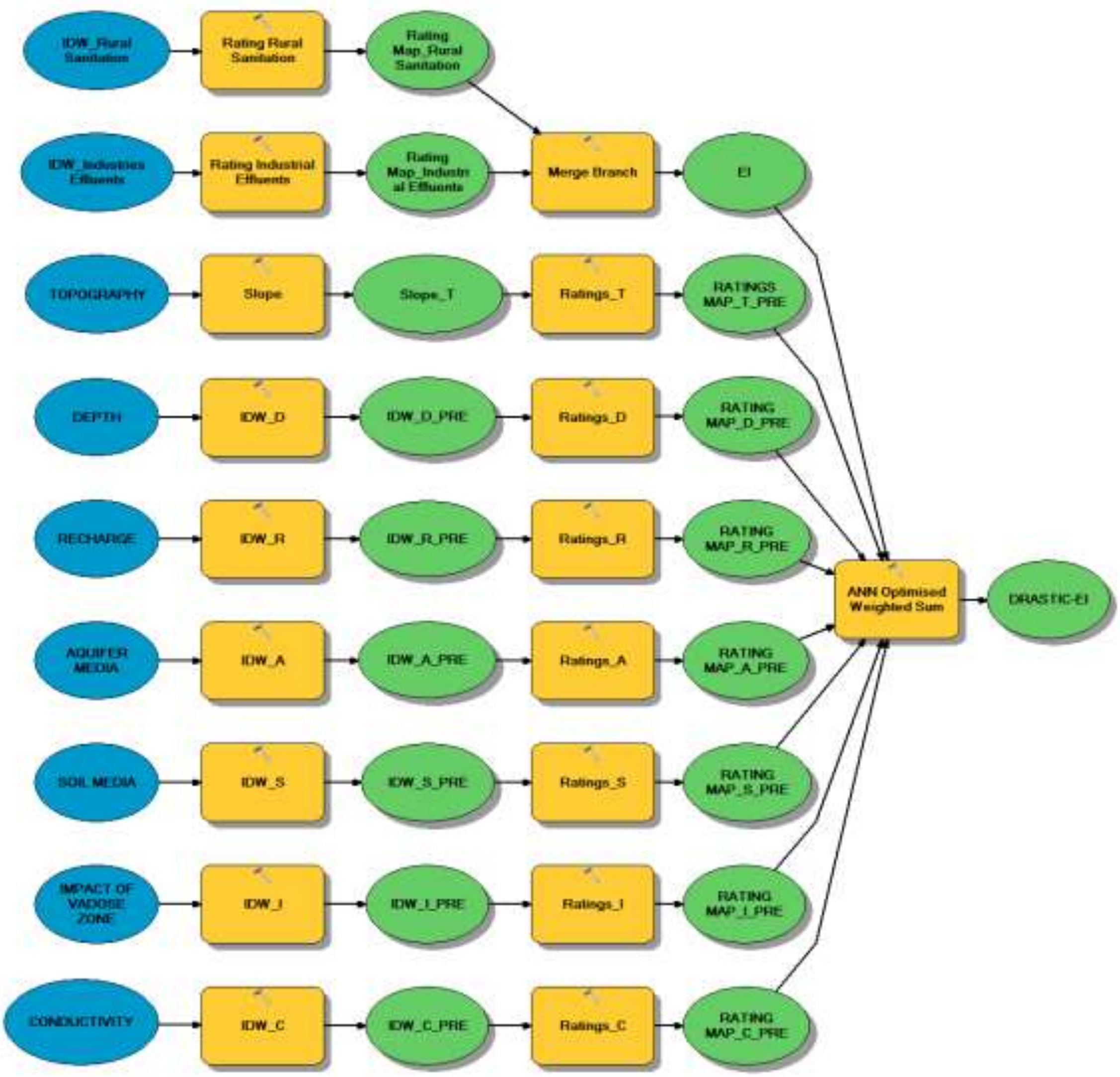

Fig 8: DRASTIC-EI Model

The above figure 8 represent DRASTIC-EI model development in GIS environment. External Influence (EI) representing a combination of industries and STPs locations as well as rural sanitation has also been taken as a newly added parameter over the conventional DRASTIC approach. The figures 9 and 10 show DRASTIC-EI pre and post monsoon maps of groundwater vulnerability respectively. Table 3 provides the distribution of the study area (%) across various vulnerability classes in the DRASTIC-EI model for both the Pre and Post Monsoon seasons. Notably, the sustainable class demonstrates a major decrease in area percentage during the post-monsoon period. In contrast, the pre-monsoon timeframe exhibits a decline in the percentage (%) area for the less and moderately vulnerable classes, while observing an increase in the highly and severely vulnerable classes.

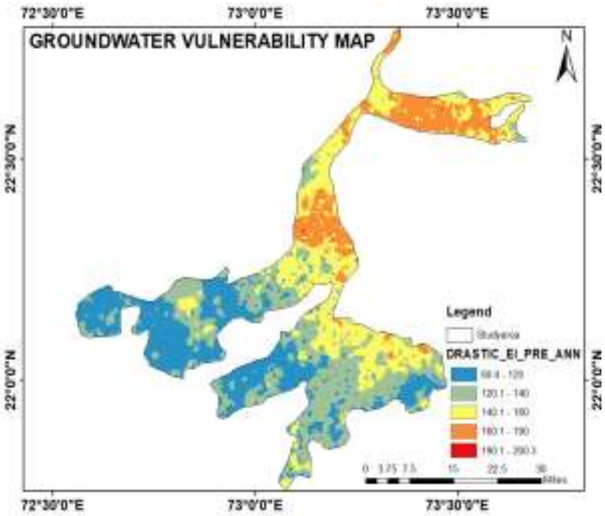

Fig 9: DRASTIC-EI Map Pre-Monsoon

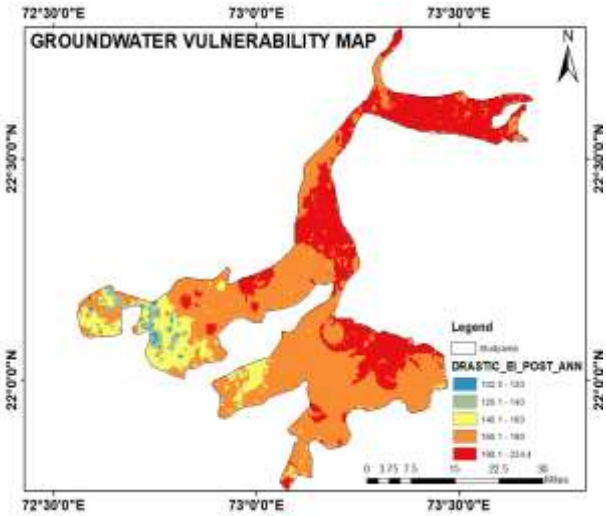

Fig 10: DRASTIC-EI Map Post-Monsoon

Table 3: Groundwater Vulnerability outcome in terms of % area

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

In study area, there is a significant problem with high Nitrate concentrations in the groundwater. This issue stems primarily from intense human activities, notably the excessive use of fertilizers in agricultural fields and high industrialization within the region. To assess the groundwater quality and vulnerability, a Factor Score (FS) and External Influence (EI) were employed, which likely takes into account various parameters, including Nitrate concentration. When the Factor Score and External Influence is high, it signifies poor groundwater quality, as high Nitrate levels often indicate contamination that renders the water unsafe for consumption. Moreover, areas with high Factor Scores and External Influence are also having more probability to further groundwater contamination, making them especially vulnerable. To validate these findings and the correlation between high Factor Scores, External Influence and Nitrate concentrations, spanning a three-year period from 2018 to 2020, for both pre and post monsoon season, has been studied.

This comprehensive validation ensures that the relationship between a high DRASTIC-FS Index, DRASTIC-EI Index and Nitrate concentrations remains consistent over time, underscoring the urgency of addressing this issue in the study area. High values of the DRASTIC-FS and DRASTIC-EI index matches with high Nitrate concentration within the study region and gives the good correlation. These findings validates the efficacy of the DRASTIC-FS and DRASTIC-EI model for the alluvial region situated between the Mahi and Narmada rivers in India.

Key Findings: Correlation of Vulnerability parameters with GWQI

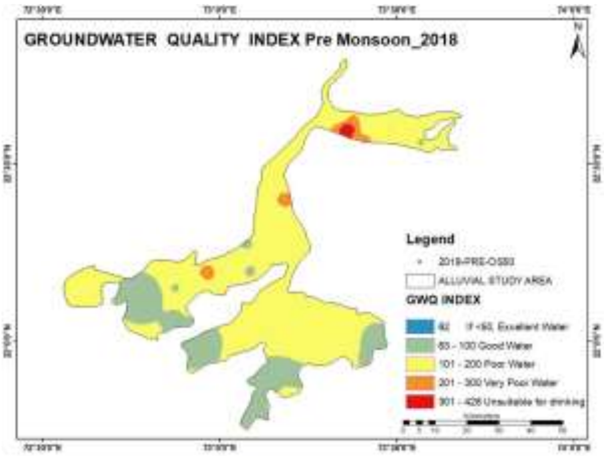

Fig 11: GWQI 2018 – Pre Monsoon

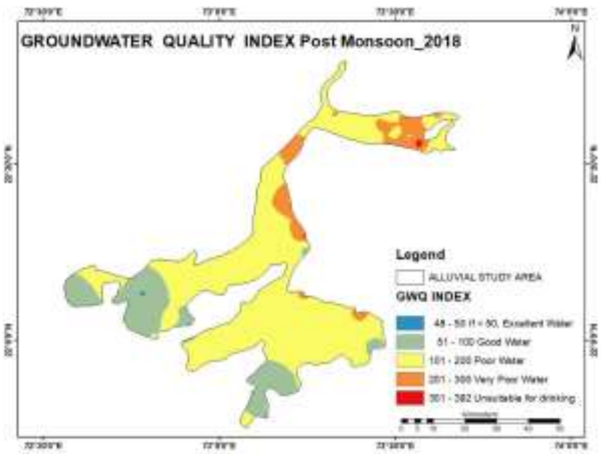

Fig 12: GWQI 2018 – Post Monsoon

Above figures (11 and 12) indicated groundwater quality index GWQI for pre and post monsoon seasons for 2018 time period which highlighted very less area (2.1%) having excellent quality of groundwater in post monsoon season. Approximately 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 season for the year 2018. The below table 4 show the correlation of vulnerability parameters with overall GWQI.

Table 4: Vul. Para. With GWQI

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

Recharge, 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 in traveling contaminate from surface to sub surface in Northern and Central region. Groundwater quality index has strong correlation with FS, EI, DRASTIC-FS and DRASTIC EI index which indicates aquifer system is vulnerable to contamination in Northern and Central region where groundwater quality is very poor.

According to the findings presented in table 4, it states that there is a significant increase in the correlation between the Groundwater Quality Index (GWQI) and the DRASTIC-FS and DRASTIC-EI parameters in the post monsoon season. These increasing correlation suggests, that recharge during the post-monsoon season plays a crucial role in the study area.

Key Findings: Reduction of Contaminant to Minimize Health Risk

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 (figure 13) 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 assessment (HRA).

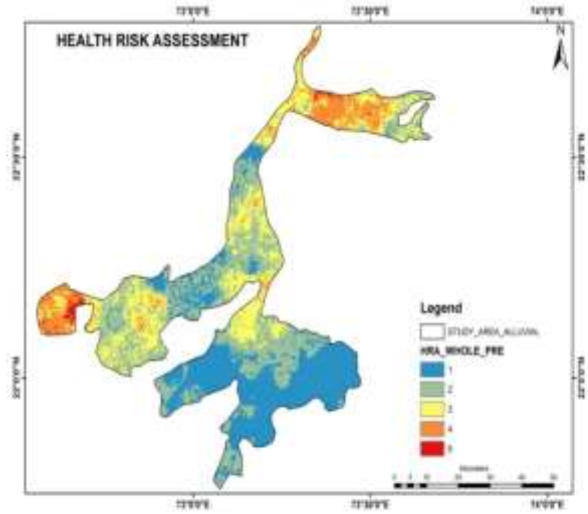

Fig 13: HRA – 2018-Pre Monsoon

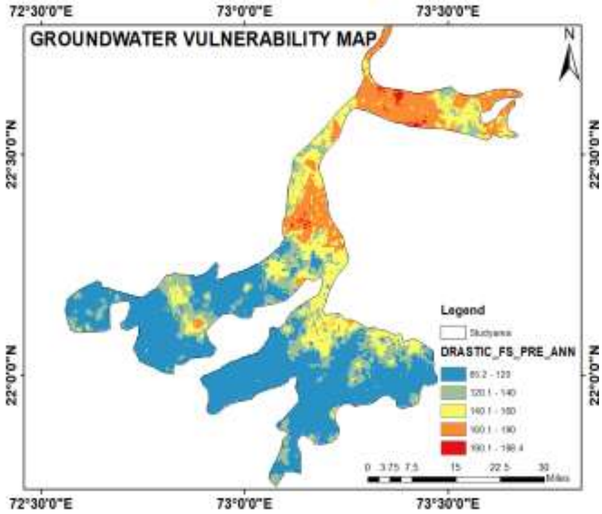

Fig 14: DRASTIC-FS Map Pre-Monsoon

Identification of Critical Area

The primary aim of this research is to propose effective remedial measures aimed at mitigating potential public health risks. In pursuit of this objective, various key parameters were examined, including the development of modified groundwater vulnerability (figure 14). These provide insights into the hydro-geological and physical characteristics of the study area. In order to pinpoint critical areas requiring immediate attention, upgraded DRASTIC maps and health risk assessment maps for the entire region was combined.

Analysis of groundwater vulnerability, using the modified DRASTIC method, revealed highly and severely vulnerable zones, particularly in the Northern, Central and Western region. The Health Risk Assessment (HRA) maps, encompassing the entire study area, indicated that health risks in the Northern and Western regions fall within the categories 4 and 5.

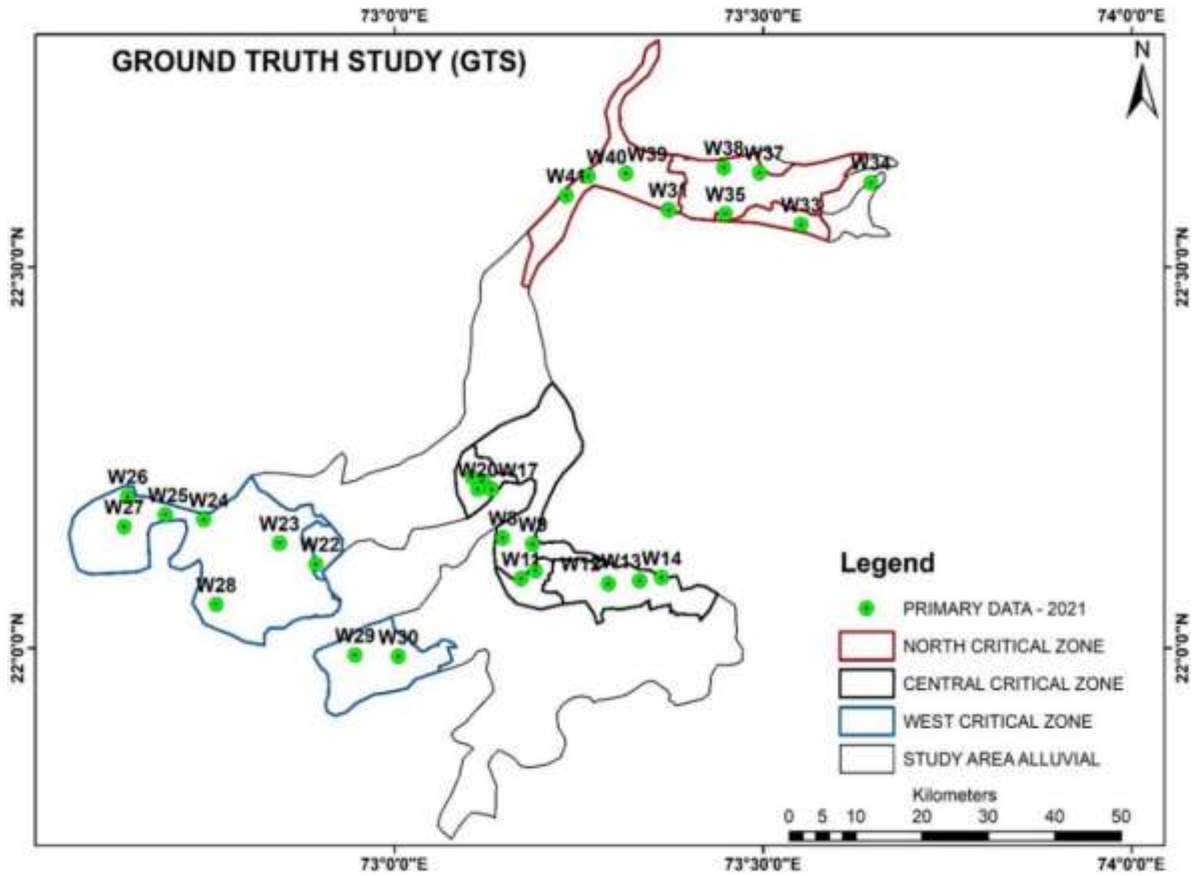

Fig 15: Identify the critical zones and sample collection in study area

Subsequently, by integrating the necessary raster files using the overlay tool in ARC-GIS, fig 15 was generated, which serves as a visual representation of the critical areas within the study region. Each highlighted polygon on this map signifies a critical area deserving special attention and targeted remedial actions.

Suitable method to reduce Nitrate in groundwater with AHP

The present research has placed its emphasis on evaluating eight fundamental criteria, consisting of four non-technical aspects: Initial Cost (IC), Operation and Maintenance Cost (OMC), Remedial Time (RT), and Removal Rate (RR) and four technical considerations: Ground Water Table (GWT), Aquifer Material (AM), Location Specific Characteristic (LSC), and Contamination Level (CL). These criteria were employed to assess the performance of five distinct groundwater remediation alternatives, namely phytoremediation (PHYTO), pump and treat (PAT), pump and fertilize (PAF), permeable reactive barrier (PRB) and chemical reduction (CHEM).

In proposing specific Nitrate reduction method for addressing high Nitrate concentrations at specific well sites, there have taken into account a range of hydrogeological criteria, including Location-Specific Characteristics, Aquifer Material, Contamination Level and Groundwater Table. Additionally, four non-technical criteria such as Initial Cost, Operation and Maintenance Cost, Removal Rate, and Remediation Time have been included in the approach of Analytical Hierarchy Process of MCDM. To minimize the public health risk due to high Nitrate concentration specific Nitrate reduction method for 24 wells have been determined using the AHP method and the results are presented in Table 5. For well no 1 of urban region the values of global weight obtained on which the preference of remedial method is recommend as CHEM = 0.228, PAT = 0.217, PHYTO = 0.213, PRB = 0.182, PAF = 0.161. Similarly, all remaining well individual AHP matrix have been computed based on which these below table has been prepared.

Table 5: Groundwater Nitrate from primary data collection and sample location specific characteristics

Sr.	Zone	Block	Village	Location	NO_3	Ground Water Level (fbgl)	Aquifer Material	Suitable Remedial Strategy
W1	Central	Vadodara	Panigate	Bauchawad, Yakutpura,Panigate	73.76	05 – 20	Aggregated Clay	CHEM
W3	Central	Vadodara	Kevdabaug	Batuk Mandir, Kevdabaug	140.83	05 – 20	Sandy Loam	PAT
W7	Central	Vadodara	Tarsali-2	Bhathiji Mandir, Tarsali	93.01	05 – 20	Loam	CHEM
W9	Central	Vadodara	Por	Icici Bank Building, Por Village	124.13	> 50	Sandy Loam	PAT
W10	Central	Karjan	Bamangam	Bhathiji Maharaj Temple	108.35	35 – 50	Sand	PAT
W11	Central	Karjan	Manglage	Varahi Mata Temple	112.11	35 – 50	Sandy Loam	PAT
W12	Central	Dabhoi	Parikha	Ramdev Mandir, Opp. Gram Panchayat	55.23	35 – 50	Aggregated Clay	PAF
W13	Central	Dabhoi	Mandala	Near RangaiKaansh, Mandala	68.53	35 – 50	Clay	PAF
W16	Central	Padra	Chansad-1	Opp. Baps Shree Swaminarayan Mandir	155.96	20 – 35	Sand	PAT
W17	Central	Padra	Chansad-2	Opp. Panchayat Karyalay, Chansad	140.83	20 – 35	Sand	CHEM
W19	Central	Padra	Darapura	Farm near entrance of Darapura Village	122.66	> 50	Sandy Loam	PAT
W22	Central	Padra	Kanzat	Near Amba Mata Temple and Pond	62.94	35 – 50	Aggregated Clay	PAF
W25	West	Jambusar	Nahar	Near Bhathiji Temple and Pond	95.5	5 – 20	Clay Loam	PHYTO
W27	West	Jambusar	Hamdpor	Village Vasahat, near large Pond	69.36	35 – 50	Clay Loam	PAF
W30	West	Amod	Suthodara	Village Vasahat near Pond	46.97	35 – 50	Clay Loam	PAF
W31	North	Savli	Tulsipura	Near Pond and VillaeVasahat	167.61	5 – 20	Sand	PAT
W31a	North	Savli	Tulsipura	Near Pond and VillaeVasahat	204.22	20 – 35	Sand	PAT
W32	North	Halol	Dharampuri	Masonry Well in Farm, Village Vasahat	129.91	20 – 35	Sand	CHEM
W33	North	Halol	Muladhari	Rameswar Temple, Panigate	78.72	5 – 20	Clay Loam	PHYTO
W34	North	Ghoghamba	Raveri	Near Karad Canal, Ghoghamba Village	48.62	5 – 20	Gravel	CHEM
W35	North	Kalol	Madhvas	Muvla area Opp. Mahvir Park	67.61	35 – 50	Clay Loam	CHEM
W36	North	Kalol	Kalol City	Private Farm of Virendra Patel in Kalol	102.94	20 – 35	Sand	CHEM
W37	North	Kalol	Delol	Near Panchvati Lemon farm, Delol	116.7	> 50	Gravel	CHEM
W39	North	Savli	Mevli	Farm near Mevli Village Vasahat	133.49	> 50	Peat	PRB

CONCLUSIONS

1. The multivariate statistical analysis methods PCA, FSA and HCA and 10 parameters are used on a large study area to determine 3 PCs based on the inter correlation of water quality parameters. A composite PC map reveals that majority of the well having factor scores higher than 1 are located in cluster 2, 3 and 4, indicating part of Kalol and Savli Taluka are affected by anthropogenic sources.
2. Among 50 well location, 32 wells fell under cluster 1 having negative factor scores being considered as non-polluted. These wells are located in Southern and Western parts of the alluvial region.
3. Cluster 2 primarily covers the central region of the study area, with the 9 wells exhibiting a shared characteristic of high Alkalinity indicated by Factor Scores greater than 1 in majority of the wells in this area. The contamination source in this area has been attributed to the substantial presence of improper solid waste disposal activities.
4. Cluster 3 predominantly comprises upper North zone of the study area having 8 wells. Hierarchical Cluster Analysis (HCA) indicates that the primary component influencing cluster 3, includes variables Total Dissolved Solids (TDS) and Total Hardness (TH). It was also observed that the 8 wells in cluster 3 share a common characteristic of high Total Hardness direct indicative of influence of its proximity to industrial areas. Significant number of these wells exhibit high levels of Nitrate concentration also.
5. Well number 24 of Cluster 4, exhibit a highly contaminated zone in the Northern part. This contamination has been verified by actual causes of excessive usage of Urea, coupled with practices related to animal husbandry and disposal of domestic waste in nearby pond.
6. 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 is another key anthropogenic source of contamination.
7. Based on the validation outcomes, it became evident that the conventional DRASTIC model is not entirely effective in assessing the groundwater vulnerability in the study area.To enhance these model, two separates' models, namely DRASTIC-FS and DRASTIC-EI have been proposed by introduction of new parameters, Factor Score (FS) and External Influence (EI) respectively.
8. DRASTIC-FS and DRASTIC-EI analysis, reveals that each model operates on a distinct conceptual framework relating anthropogenic activities. Hence, it is essential to recognize

that no direct comparison can be drawn between these two models due to their fundamentally different approaches and objectives. DRASTIC-FS gives idea about level of susceptibility to contamination by indirect way of assessment using integrated effect of various causes of ground water quality deterioration. DRASTIC-EI gives susceptibility to contamination by direct integration and analysis of apparent sources like high industrialization and urbanization.

9. From the study it is concluded that the weights of variable parameters (D, R, I, C, FS, EI) can be determined more accurately using ANN technique, instead of accepting its values recommended by Delphi committee of Aller Linda et. al. in 1985. Delphi committee's weights were recommended without any technical base where as these ANN weights are optimized based on hydrogeological criteria and technical base which make the ANN weights more accurate and appropriate to the conventional weights given by Aller Linda.
10. This study successfully validated the DRASTIC-FS and DRASTIC-EI models against Groundwater Nitrate concentration data for three consecutive years (2018, 2019, 2020) using Pearson correlation analysis. The results consistently showed reasonably higher correlation coefficients ('r') ranging between 0.54-0.63 for DRASTIC-EI and 0.50-0.69 for DRASTIC-FS compared to the Conventional method. This leads to conclude that conventional DRASTIC is not proper approach for assessment of vulnerability and for accurate assessment of vulnerability conventional DRASTIC should be modified considering influences of local significant factors and using calibrated weights of different parameters.
11. 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 making the groundwater vulnerable.
12. The vulnerability index, indicates considerable increase in its values during the post-monsoon season which is contradicting conventional understanding of improvement of water quality in post monsoon period due to dilution of concentrations of contaminants. The main reason for this is rise of groundwater levels during post monsoon period and the recharge from industrial wastewater which plays significant role in increasing vulnerability of the groundwater to potential contamination. This suggests the need for severe management practices and monitoring measures to safeguard groundwater quality and prevent adverse environmental impacts associated with industrial discharge.

13. 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 indicating showed high health risk.
14. The AHP approach in Multi-Criteria Decision Analysis (MCDA) is based on eight key evaluation criteria. To enhance the effectiveness of the AHP analysis, additional criteria related to hydrogeological variables are introduced. These includes groundwater table (GWT), aquifer material (AM), location-specific characteristics (LSC) and contamination level (CL). Because of inclusion of these hydrogeological considerations AHP outcomes for each well works out to be more accurate both logical and scientifically.
15. Majority of population in the Northern region, is involved in agricultural activities. Also some industries are located nearby Kalol city area, groundwater table is between of 30 to 50 ft (fbgl) and soil is mostly sand or clay hence use of Chemical Reduction (CHEM)is the most suitable method for denitrification in this part of the study area.
16. 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 aquifer of this region mainly consist clay formation and also mostly part is cover with clay and also groundwater level is near to the surface hence combination of Pump And Fertilizer (PAF) and Phytoremediation (PHYTO) are recommended methods for denitrification for this part of the study area.
17. The Central region consists Makarpura industrial area and sub-urban area of Vadodara city, Danteshwar, Tarsali having high density of population. Groundwater level in these area is also high between 15 to 75 (fbgl) hence Chemical Reduction (CHEM) and Pump And Treat (PAT) methods are suggested for denitrification of groundwater. Efficiency of Pump and Treat (PAT) method can be increased by the cost-benefit analysis.
18. The spatial distribution of Nitrate concentration in study area shows the groundwater is highly contaminated in the Northern region as well as in upper part of central region. 22.22 % of these area is contaminated due to Nitrate concentration. Vulnerability index obtained by DRASTIC-FS indicates 32.49 % of Northern, Central and Western Zone are highly and severely vulnerable to contamination. From this it is concluded that remaining 10.27 % area is highly susceptible to contamination with passage of time if proper remediation strategy for reduction of Nitrate concentration is not adopted.

RECOMMENDATIONS

1. **Strengthen Waste Management and Industrial Effluent Controls**: Implement stricter regulations for solid waste disposal and industrial effluent treatment, particularly in contaminated areas to mitigate groundwater pollution from anthropogenic sources.

2. **Adopt and Enhance Groundwater Vulnerability Models**: Use the modified DRASTIC-FS and DRASTIC-EI models for more accurate groundwater vulnerability assessments, incorporating Artificial Neural Networks (ANN) to refine parameter weights based on local hydrogeological factors.

3. **Region-Specific Remedial Measures**: Implement tailored remediation strategies such as Phytoremediation, Chemical Reduction, Pump and Treat etc., in regions with high nitrate contamination with due focus on local characteristics like soil type and groundwater depth.

4. **Continuous Monitoring and Proactive Management**: Establish long-term monitoring systems, especially in post-monsoon, to manage groundwater recharge and contamination, and develop proactive remediation strategies for high-risk areas based on the vulnerability index and nitrate concentration data.

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