CHAPTER 4 METHODOLOGY

4.1 Comprehensive Research Action Plan

The following is a comprehensive methodology that explains 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.

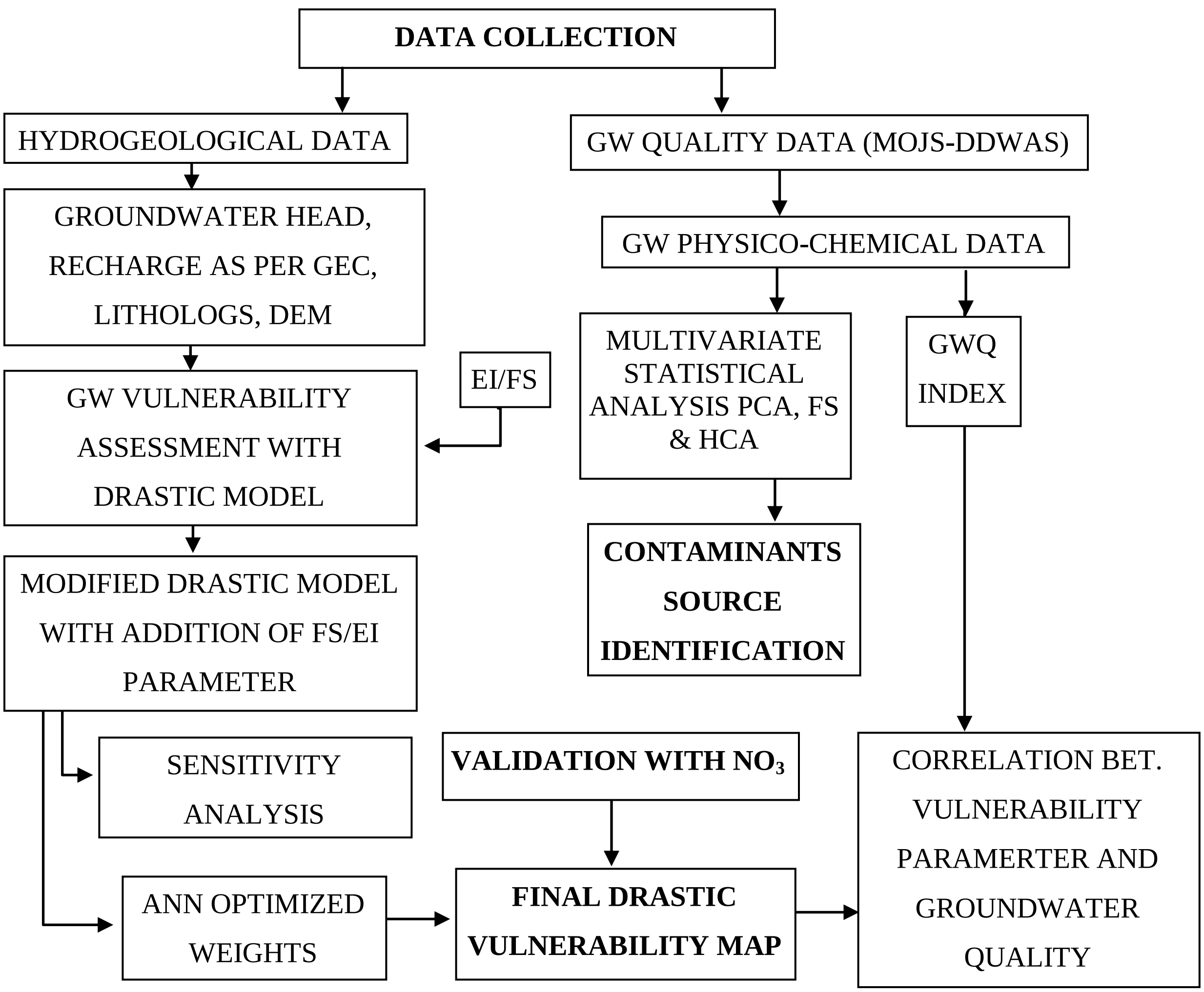

Fig 4.1 (a) A comprehensive flow chart of present research methodology

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) Delphi Committee suggested weights used by Aller Linda from 1 to 5 to vulnerability parameters D, R, A, S, T, I, C (in the year 1987). 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.
10. Initially model is run by the weights provided by Aller Linda (1987). 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 (1987). 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.
15. The Groundwater Quality Index (GWQI) was computed to assess the actual contamination 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.

Groundwater Quality Index (GWQI) Calculation:

Step 1: Determine the Parameters:

Step 2: Consider the parameters such as pH, Total Dissolved Solids (TDS), Hardness, Chlorides, Sulfates, Nitrates, Fluoride, Calcium, Magnesium and Alkalinity.

Step 3: Calculate the Relative Weight (Wi):

Each parameter is assigned a weight based on its significance to drinking water quality.

Step 4: Calculate the relative weight for each parameter using:

$$\mathrm{Wi} = \frac{\mathrm{wi}}{\sum_{i=1}^{n} \mathrm{wi}}$$

where wi is the assigned weight for parameter i, and $\sum_{i=1}^{n}$ wi is the sum of all weights.

Step 5: Determine the Quality Rating (Qi):

Calculate the quality rating for each parameter using:

$$\mathrm{Qi} = \left(\frac{\mathrm{Ci}}{\mathrm{Si}}\right) * 100$$

where Ci is the concentration of the parameter, and Si is the standard acceptable limit for that parameter.

Step 6: Compute the Sub-Index (SIi): Calculate the sub-index for each parameter using:

$$SIi = Wi * Qi$$

Step 7: Calculate the Groundwater Quality Index (GWQI):

Sum the sub-indices to obtain the GWQI:

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

By following these steps, one can calculate the GWQI to assess the suitability of groundwater quality for drinking purposes (Mufid al-hadithi 2012).

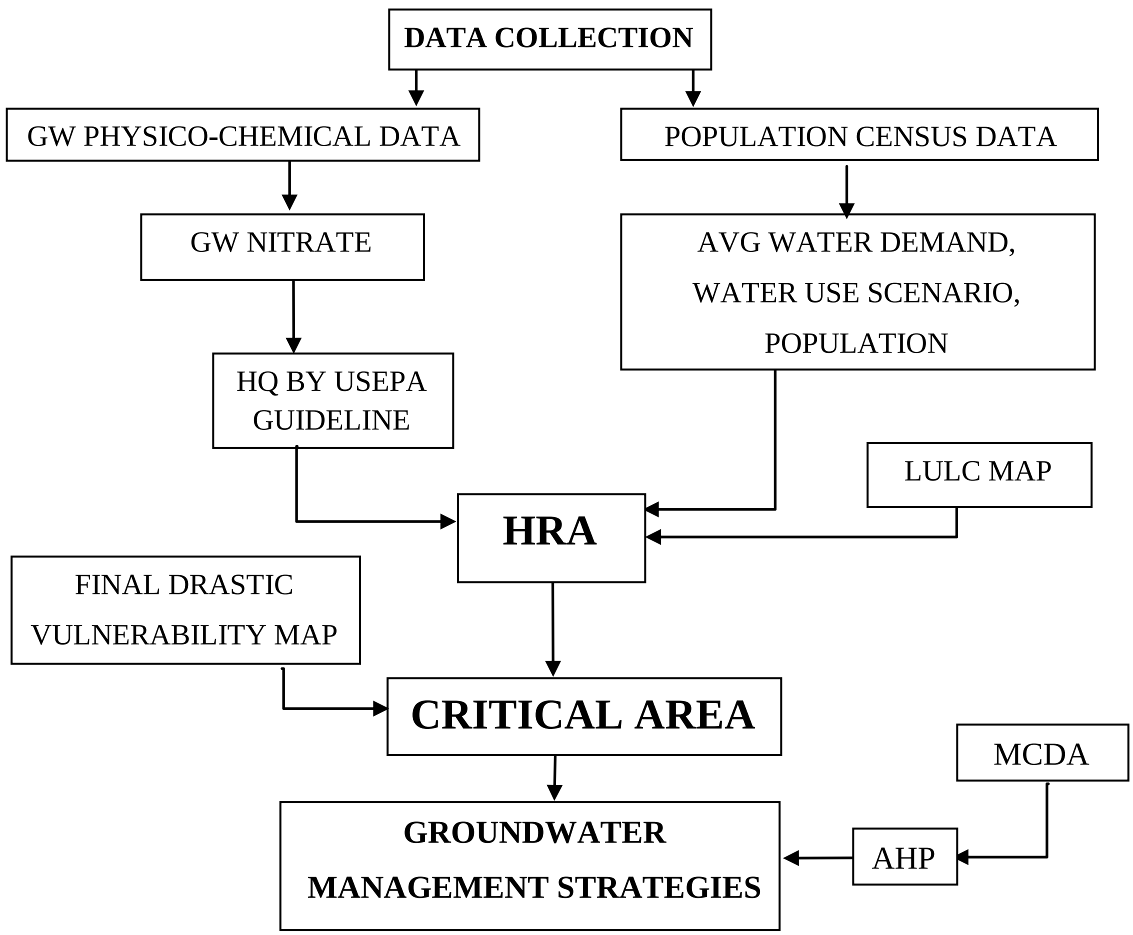

Fig 4.1 (b) A comprehensive flow chart of present research methodology

16. A comprehensive groundwater vulnerability assessment using a modified DRASTIC model revealed high Nitrate levels, posing significant health risks. The study area's diverse hydrogeological conditions require targeted Nitrate reduction strategies. By applying the Analytical Hierarchy Process (AHP), the most effective Nitrate reduction method can be

identified for each well location in a systematic manner as described below which reduce Nitrate concentrations and minimize health risks.

- **Hazard Quotient Calculation**: By using the standard USEPA guidelines to calculate the Hazard Quotient, the assessment ensures consistency and adherence to established protocols for evaluating health risks associated with groundwater contaminants.
- **Raster Map Health Risk Assessment**: Generating a health risk assessment in raster format allows for a detailed spatial analysis, integrating multiple layers like Hazard Quotient, Land Use-Land Cover, Population Distribution, and Water Use scenarios. This comprehensive approach provides a clearer understanding of potential health impacts across different scenarios and spatial distributions.
- **Overlay Analysis for Critical Areas**: Overlaying the health risk assessment output with the vulnerability map identifies areas where health risks are most critical. This method efficiently highlights zones requiring urgent attention by combining vulnerability and risk data.
- **Primary Data Collection**: Confirming the presence of dominant contaminants, specifically nitrate, through primary data collection ensures the accuracy of the risk assessment. Validating the findings from the spatial analysis with actual data makes the results more robust and reliable, enhancing the credibility of the health risk assessment and guiding effective management strategies.

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) techniques.

4.2 Source Identification of Groundwater Contamination

To identifying sources of contamination, initially a substantial dataset comprising groundwater quality information was gathered from the MOJS-DDWAS portal for the year 2018. This dataset covered both pre and post-monsoon seasons, providing a holistic view of groundwater conditions. At 50 selected well locations within the study area, a set of ten commonly monitored groundwater quality parameters, including pH, TDS, NO_3, F, Cl, SO_4, Ca, Mg, TH and ALK, were meticulously measured and recorded. To ensure consistency and facilitate comparative analysis, these parameter values were standardized using Z-scores, which transformed the raw data into a common scale.

Subsequently, Principal Component Analysis (PCA) was applied to this standardized dataset. PCA is a robust statistical technique that identifies patterns and correlations among variables, thus reducing dimensionality and simplifying complex data. Through PCA, Principal Components (PCs) were extracted, capturing the essential information within the dataset. Moreover, Factor Scores (FS) were calculated for each well location based on the PCA results, providing a quantitative representation of the groundwater quality at specific points.

The FS values obtained were then integrated into an Arc-GIS environment. GIS technology allowed for the visualization and mapping of the spatial distribution of these Factor Scores across the study area. This spatial representation offered valuable insights into how groundwater quality varied across different locations within the region. Furthermore, Hierarchical Cluster Analysis (HCA) was applied to classify the well locations into distinct clusters based on their groundwater quality characteristics. The results of HCA were presented in the form of a Dendrogram, which visually illustrated the grouping of wells with similar groundwater quality profiles. This clustering analysis served to identify spatial patterns and potential areas of concern.

4.3 Assessment of Groundwater Vulnerability

The groundwater vulnerability assessment undertaken in this study follows a comprehensive approach that involves multiple interconnected steps to evaluate the vulnerability of the study area to potential contamination.

In the initial phase, hydrogeological data is collected and examined to serve as the foundation for developing the DRASTIC model. Each parameter chosen for this model represents a crucial part of groundwater vulnerability. These parameters include groundwater depth (provides insights into the accessibility of groundwater), average annual rainfall and the presence of water conservation structures (influence the recharge potential), and reference data for recharge and extraction, essential for net recharge calculations. Additionally, data related to the lithology of the aquifer, soil characteristics, hydraulic conductivity, topography, land use and land cover, collectively create a comprehensive understanding of the region's hydrogeological conditions. Besides, information on anthropogenic activities, such as the location and type of industries, Sewage Treatment Plants (STPs) and village populations, is incorporated into the assessment to account for potential contamination sources.

An essential step in this process is recognizing and studying the inherent limitations in the DRASTIC analysis. This careful examination allows to better understand the model's constraints and potential biases, ensuring a more accurate and reliable assessment. To execute the vulnerability assessment, a Geographic Information System (GIS) is employed. Various GIS tools and operations, such as spatial analysis, interpolation techniques, weighted sum calculations and model building, are applied to integrate all the collected data into the DRASTIC model equation. This process results in assigning appropriate weights to each parameter based on recommendations by Aller Linda (1987).

DRASTIC Model description:

The DRASTIC model for assessing groundwater vulnerability was developed in the United States in 1987 by Aller, L. (Linda), Bennett, T., Lehr, J. H., Petty, R. J., and Hackett, G. The acronym "DRASTIC" stands for the seven key parameters used in this model: Depth to Water, Recharge, Aquifer Media, Soil Media, Topography, Impact of the Vadose Zone, and Conductivity of the Aquifer. This model has gained widespread recognition in the field of groundwater protection and management, as each of these parameters plays a critical role in determining an area's susceptibility to groundwater contamination.

Depth to Water refers to the distance between the ground surface and the water table. Areas with a shallow water table are more vulnerable to contamination because pollutants can more easily reach the groundwater. Recharge is the process by which water infiltrates the ground and replenishes the aquifer; higher recharge rates can facilitate the movement of contaminants into the groundwater.

Aquifer Media and Soil Media describes the types of geological and soil materials present in the ground, as different materials have varying capacities to filter and block contaminants. Topography, or the shape of the land, affects how water flows over the surface and how contaminants are transported. The "Impact of the Vadose Zone refers to the influence of the unsaturated zone above the water table on contaminant movement.

Lastly, Conductivity of the Aquifer measures how easily water can flow through the aquifer material, which influences the speed at which contaminants can travel through the ground and reach the groundwater. The DRASTIC model assigns specific weights and ratings to each of these factors, which are then combined to create a vulnerability index. This index categorizes areas into different levels of vulnerability, such as low, moderate, high, or very high.

The DRASTIC index for groundwater vulnerability is calculated using the following equation:

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

Where, D = Depth to water level, R = Net recharge (inches), A = aquifer media, S = Soil media, T = Topography, I = Impact of vadose zone and C = Hydraulic conductivity, r = parameter Rating, w = parameter Weight

Each thematic layer associated with the DRASTIC index is assigned a weight (W) and an appropriate rating (R). The sum of the products of these ratings and weights for each layer at a specific location represents the vulnerability index.

The model is enhanced with an additional layer 'Factor Score (FS)' and 'External Influence (EI)', referred to as DRASTIC-FS (Factor Score) or DRASTIC-EI (External Influence), to account for the impact of anthropogenic activities. This layer allows for a more comprehensive assessment by considering the Factor Scores or External Influence related to these activities. Artificial Neural Networks (ANNs) are introduced into the methodology to optimize the weights of individual vulnerability parameters scientifically. This step overcomes the limitations of conventional DRASTIC analysis by refining the weight assignment process.

The revised DRASTIC-FS or DRASTIC-EI model, incorporating the modified equations based on the ANN-optimized weights, is created within the GIS environment. The output of this model is represented as a raster map, providing a spatial visualization of vulnerability across the study area. A sensitivity analysis, specifically the Single Parameter Sensitivity Analysis (SPSA) method, is applied to calibrate the theoretical weights against effective weights and ANN-optimized weights.

The modified vulnerability output of the model is subjected to validation using a dominant water quality parameter, Nitrate (NO_3), for multiple successive years (2018, 2019 and 2020). This rigorous and systematic approach results in a comprehensive understanding of groundwater vulnerability within the study area, encompassing both natural and anthropogenic factors, and is invaluable for making informed decisions regarding groundwater resource management and protection.

4.4 Groundwater Quality Index and Correlation Analysis

The groundwater quality index is a scale evaluating the condition of groundwater in unconfined aquifers. It begins by selecting specific types of well samples from the aquifer, focusing the analysis on particular groundwater sources. Subsequently, a Groundwater Quality Index (GWQI) is computed, consolidating information from various water quality parameters into a single index. Data collected from each well location, and vulnerability parameters like Depth to Water (D), Rainfall (R), Aquifer properties (A), Soil characteristics (S), Topography (T), Impact of anthropogenic activities (I), Climate (C), as well as Factor Scores (FS) and External Influence (EI), are organized in a tabular format for systematic analysis. Statistical correlation analysis, specifically Spearman's Rank-Order Correlation, is then employed to uncover relationships between vulnerability parameters and water quality parameters, along with the GWQI. The results of this analysis provide valuable insights into how changes in vulnerability parameters may impact groundwater quality. Ultimately, the assessment's outcome is interpreted to derive meaningful conclusions and recommendations, guiding future actions and decisions related to groundwater management and protection.

4.5 Strategy for reduction of Nitrate concentration to minimize the health risk

This comprehensive study was conducted to address groundwater contamination concerns arising from high Nitrate concentrations in the study area. Initial investigations revealed Nitrate levels are reaching as high as 284 mg/l, indicating a significant environmental and health risk. To assess these risks, Hazard Quotients (HQ) were computed for both adults and children using USEPA methodology, taking into account factors like chronic daily intake (CDI) from drinking water and a reference dose (RfD) for non-carcinogenic health risk assessment.

Further refinement was done by integration of logical components, including Land Use-Land Cover (LULC), water use scenarios and population distribution, into a Health Risk Assessment (HRA) map generated using Arc-GIS tools. This map assigned varying ratings to different areas based on the amalgamation of these components. Investigation was then carried out in these critical areas, referred to as Ground Truth Study (GTS), to verify the presence of high Nitrate concentrations and collect primary data. This data served as the foundation for proposing remedial strategies for specific well locations within these critical areas.

In total, 24 out of 41 sampled well locations were identified as exhibiting high Nitrate levels in groundwater. Various strategies, including PHYTO (phytoremediation), PAF (passive adsorption filter), PRB (permeable reactive barrier), CHEM (chemical treatment), and PAT (public awareness and training), were recommended to address the Nitrate contamination issue effectively and mitigate associated health risks, providing a comprehensive approach safeguarding groundwater quality in the study area.