

CHAPTER 2 LITERATURE REVIEW

2.1 Basics of Groundwater Contamination

The groundwater resource is attracting special attention due to its importance for our country's socioeconomic development. Although it is catering a majority of the demands of the domestic, irrigation and industrial sectors, its unplanned and accelerated development raises concerns among scientists, users and policymakers. Decreasing water levels and the depletion of Ground Water Table indicate a volumetric decline in water resources. The quality of groundwater is a major issue as it is the main source of drinking water in rural areas and a supplement in urban areas. In recent years, reports of ground water contamination from various chemical compounds from aquifers across the nation have increased (CGWB Report Faridabad, 2014).

It is becoming an increasingly important factor in research since water is one of the most essential commodities in life. Several investigations have been conducted by various researchers in other regions of the nation. According to a literature review, no systematic study has been conducted on the potability of ground water between the Mahi and Narmada rivers in Gujarat; hence, this study has been undertaken to provide a complete and appropriate assessment of ground water contamination and vulnerability problem in alluvial regions between the Mahi and Narmada rivers.

Here available literature is reviewed in six categories.

2.2 Groundwater Contamination Source Identification

2.2.1 “Identifying sources of groundwater contamination in a hard-rock aquifer system using multivariate statistical analyses and GIS-based geostatistical modeling techniques” published in Journal of Hydrology: Regional Studies by Machiwal and Jha (2015) in Elsevier B.V.

In this study, Box-Whisker plots are used to analyses the spatiotemporal fluctuations of fifteen groundwater quality metrics. Trends are found, quantified and a GIS-based groundwater quality index (GQI) is created. Principal component analysis (PCA) scores are coupled for the first time with GIS-based geostatistical modelling by following to a rigorous approach in a thorough manner to determine groundwater sources. The Udaipur district of Rajasthan was

chosen as the study area for this investigation. Box and whisker plots revealed that at the majority of aquifer system sites, groundwater hardness exceeds the permissible limits. HCA's findings divided 53 sites into two clusters. Fluoride, sodium, EC and TDS were the four parameters that showed significantly increasing trends ($p < 0.05$) at the majority of the sites, but significantly reducing trends in silica at 40% of the sites. Anthropogenic reasons, such as unsystematic and irregular groundwater withdrawals for home and irrigation uses, are blamed for the substantial trends' geographic dispersion. Comparatively to Cluster II, 12 metrics in Cluster I show increasing trends at 3–31% more sites.

2.2.2 “Spatial Variability of Ground Water Quality Using HCA, PCA and MANOVA at Lawspet, Puducherry in India” published by Suresh Nathan et al. (2017) in Computational Water, Energy and Environmental Engineering by Scientific Research.

An analysis of groundwater quality using multivariate statistical techniques such as Hierarchical Cluster Analysis, Principal Component Analysis, Factor Analysis and multivariate analysis of variance was conducted in Puducherry, India, to determine the principal factors influencing spatial variation and to evaluate source apportionment. The first known component that demonstrated the influence of human activity on ground water quality was created by PCA/FA and this dominant factor accounted for 82.79% of the total variance. The remaining four variables revealed geogenic and hardness elements. In contrast, other factor scores show high loading for HCO_3^- , Mg^{2+} , Ca^{2+} and TH (hardness and geogenic) in the north west and south west parts of the study area. The distribution of first factor scores shows high loading for EC, TDS, Na^+ and Cl^- (anthropogenic) in the south east and south west parts of the study area. In the southeast, K^+ and SO_4^{2-} (geogenic) are prominent. According to the MANOVA test, the significant mean differences between EC, TDS, HCO_3^- , Mg^{2+} , Ca^{2+} , TH, SO_4^{2-} , K^+ and Na^+ are statistically significant ($p < 0.005$). All physio-chemical parameters for Clusters 1, 2 and 3 are significantly different, as evidenced by their mean differences. In order to specify adaptive methods, researchers and decision-makers can use the geographical distribution maps that are produced based on Q-mode factor scores.

2.2.3 “Geo-environmental appraisal of groundwater quality in Bengal alluvial tract, India: a geochemical and statistical approach” published by Ghosh and Kanchan (2014) in Environmental Earth Science by Springer.

Based on groundwater samples collected across 5,324 km² area in the Bengal plain,

India, the present study examined groundwater quality. Arsenic, pH, total dissolved solids, electrical conductivity, iron, total hardness as calcium carbonate, Sulphate and Nitrite, as well as depth, such parameters that were examined. Multivariate statistical analysis was also conducted on the data set. Four components were identified via factor analysis, which accounted for 66.57% of the overall variability of the data. Factor 1 represented high positive loadings on electrical conductivity and total dissolved solids. Factor 2 showed a reduction process in groundwater and was connected to depth, arsenic and iron. A possible correlation between excessive groundwater extraction and groundwater Arsenic content was found. Aspects of Factor 3 and 4 were related to agricultural activities and geological conditions in the area. Four groups found using hierarchical cluster analysis also assisted to categorize the groundwater geochemistry of the area. The results and GIS made it easier to map and classify the groundwater quality.

2.2.4 “Multivariate statistical analysis for the assessment of groundwater quality under different hydrogeological regimes” published by Kazakis et al. (2017) in Environ Earth Science by Springer.

In this study, two techniques (factor and cluster analysis) were employed to analyses hydro-chemical data from three hydrological basins. The first location is the coastal region of the Eastern Thermaikos Gulf, where geothermal fluids and seawater intrusion have an impact on groundwater. The other two regions are the Gallikos and Perdikas inland basins, where industry and agricultural practices are the primary anthropogenic causes of groundwater pollution. The aforementioned techniques were initially used independently for each area and produced a distinct number of significant variables and clusters, while the spatial distribution of the natural and anthropogenic influences was identified for each area. Furthermore, factor and cluster analyses that combined data from all domains were used. In order to more clearly separate the effects of anthropogenic activities from the hydro-chemical processes, three key factors and five clusters were identified. It was concluded that salinization predominates in the coastal region, while high concentrations of NO_3 are primarily caused by agricultural operations and small livestock units in the Gallikos and Perdikas basins. However, this study has a few issues with multivariable statistical analysis when it comes to extremely high Cl and Na concentrations.

2.2.5 “Assessment of groundwater quality using multivariate statistical techniques in Hashtgerd Plain, Iran” published by Nosrati and Eeckhaut (2014) in Environ Earth Science by Springer.

To evaluate a large complex groundwater quality data set of the Hashtgerd Plain, multivariate statistical techniques were used, including cluster analysis (CA), factor analysis (FA) and principal component analysis (PCA). Groundwater was collected from 26 distinct wells and tested for 13 different criteria. Based on how similarly the groundwater quality characteristics varied among the 26 sampling sites, HCA divided them into two clusters. When FA based on PCA was applied to the data sets of the two distinct groups acquired by CA, it revealed three and five effective factors that, respectively, explained 79.56 and 81.57% of the total variance in the groundwater quality data sets of the two clusters. The major findings from FA show that the parameters affecting groundwater quality in the sampling sites in Hashtgerd Plain are mainly related to natural (dissolution of soil and rock), point source (domestic wastewater) and non-point source pollution (agricultural and orchard operations).

Brief overview on Current Practices, Research Gaps and Proposed Solutions on studies of Groundwater Contamination Source Identification

“Current practices” in groundwater contamination source identification employ a variety of multivariate statistical techniques and geospatial analyses to address the complexities of groundwater quality monitoring. Studies such as those by Machiwal and Jha (2015) and Kazakis et al. (2017) demonstrate the use of Box-Whisker plots, hierarchical cluster analysis (HCA), and principal component analysis (PCA) to reveal significant trends and clusters in groundwater quality metrics.

These techniques have been used across diverse geographical contexts, from the hard-rock aquifer systems of Udaipur to coastal region of E.T. Gulf highlighting critical factors such as anthropogenic impacts and geogenic influences. For instance, the research conducted in Puducherry and Hashtgerd Plain utilized multivariate methods to identify spatial variability and factors influencing groundwater quality, linking human activities to variations in key parameters like EC, TDS, and Na+.

However, despite the advancements, “gaps” remain in fully understanding the interaction between natural and anthropogenic factors across different hydrogeological settings and their long-term impacts on groundwater quality.

“Proposed solutions” include integrating advanced geostatistical modelling with multivariate statistical analyses and incorporating adaptive management strategies tailored to specific regional contexts. Further, specific anthropogenic sources can be investigated based on dominating groundwater quality parameters along with survey of location specific characteristics.

2.3 Approaches for Groundwater Vulnerability Assessment

2.3.1 “A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan” by Babiker et al. (2005), Published in Science of the Total Environment by Elsevier.

The purpose of this contribution is to estimate aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan, using the DRASTIC model and sensitivity studies to assess the relative significance of the model parameters. A further goal is to demonstrate how the DRASTIC and geographic information system (GIS) can be employed together to estimate the danger of groundwater pollution. To characterize the hydrogeological context and assess aquifer vulnerability, the DRASTIC model makes use of seven environmental parameters: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity.

The Kakamigahara aquifer's Western sector was defined by High vulnerability classes, while the Eastern portion was marked by Moderate vulnerability classes. The Kakamigahara's elevation North-eastern region showed low aquifer vulnerability. The integrated vulnerability map illustrates the high risk that intensive vegetable farming poses to the Eastern portion of the Kakamigahara aquifer. The more vulnerable Western part of the aquifer is, however, under a lower contamination risk. Land use appears to be a stronger indicator of Nitrate contamination of groundwater in Kakamigahara Heights. The soil media, topography, the vadose zone media and hydraulic conductivity all had a significant negative impact on the aquifer's underlying vulnerability. However, the net recharge parameter had the greatest impact.

2.3.2 “Assessing groundwater vulnerability using GIS-based DRASTIC model for Ahmedabad district, India” by Khakhar et al. (2017) Published in Environmental Earth Sciences by Springer.

With the help of the GIS platform, this research aims to determine the inherent vulnerability of groundwater to contamination. For the Ahmedabad district in Gujarat, India, the DRASTIC model is used in the research. The hydrogeology of the region is represented by the model using characteristics such as depth, recharge, aquifer, soil, topography, vadose zone and hydraulic conductivity. According to the research, the district's Northern portion has a 46.4% area that is considered having low vulnerability, the middle and Southern parts have a 48.4% area that is considered moderate vulnerability and the South-East of the district has a 5.2% area that is considered high vulnerability. Based on the study, the greater depth of the vadose zone, deeper water levels and the alluvial aquifer system with minor clay lenses may all contribute to the northern part's lesser vulnerability. The unconfined to semi-confined alluvial aquifer system, smaller vadose zone depths and greater volume of recharge from irrigation techniques may all contribute to the moderate and high vulnerability in the central and southern portions of the study area. In addition, the map removal and the single-parameter sensitivity analysis show that the vadose zone, recharge, depth and aquifer characteristics have a greater impact on the groundwater vulnerability index for the Ahmedabad region.

2.3.3 “Assessment of aquifer vulnerability in parts of Indo Gangetic plain, India” by Khan et al. (2010) published in International Journal of the Physical Sciences.

The Indo-Gangetic plain included a significant alluvial track with a multi-tiered aquifer system. Shallow groundwater regime was at risk of contamination as a result of aggressive development activities and agricultural advancement. In this study, the zones were divided up based on their vulnerability to contamination using the "DRASTIC" approach. In CGP, the land use pattern largely controlled the quality and quantity of shallow aquifers. Therefore, the widely used "DRASTIC" methodology was expanded to include land use pattern. The land use pattern was divided into various groups, such as industrial, agricultural and rural and a numerical rating was given for each group based on the potential of risk. The vulnerability indices calculated using the model's numerical basis and the resulting map shows that 5, 39, 33 and 23% of the area under study relate to low, moderate, high and extremely highly vulnerable zones, respectively.

2.3.4 “DRASTIC assessment of groundwater vulnerability to pollution in the Vistula floodplain in central Poland” by Krogulec and Trzeciak (2017) published in Hydrology Research by IWA.

In the Vistula River valley in central Poland, the DRASTIC approach was used to assess the vulnerability of groundwater to contamination. According to the study's findings, 31.2% of the studied area has a medium contamination potential, while 68.18% of it contains a low potential. To assess the relative significance of the characteristics for aquifer vulnerability, single parameter and map removal sensitivity analyses were carried out. According to the DRASTIC vulnerability index, the depth of the water table is by far the most significant parameter in central Poland. There is no high groundwater vulnerability in central Poland, even though the water table is shallow (less than 3 m below ground level) in more than 90% of the area.

2.3.5 “A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India” by Rahman (2008) published in Applied Geography by Elsevier.

Using the DRASTIC model in a Geographical Information System (GIS) context, this paper's primary goal is to identify the groundwater sensitive zones in shallow aquifers in Aligarh and its adjacent areas, one of the largest and fastest-growing towns in North India. The seven data layers that serve as the input for the model are the foundation of this model. Its letters stand for the first seven layers: topography, impact of the vadose zone, depth of water, net recharge, aquifer media, soil media and hydraulic conductivity. According to the study, more than 80% of Aligarh's groundwater has a medium to high vulnerability to water pollution, which is the biggest source of worry for the city's around 0.8 million residents. An effective tool for determining and analyzing the vulnerability to groundwater pollution has been made available by the GIS approach.

Brief overview on Current Practices, Research Gaps and Proposed Solutions on studies of Approaches for Groundwater Vulnerability Assessment

“**Current approaches**” to groundwater vulnerability assessment frequently utilize the DRASTIC model combined with GIS technologies to evaluate the risk of contamination across various regions. Studies such as those by Babiker et al. (2005) and Khakher et al. (2017) illustrate the application of the DRASTIC model to assess aquifer vulnerability in diverse geographical settings, including Japan, Poland and India. The model's seven parameters are used to create

vulnerability maps, revealing varying levels of risk from low to high across study areas. For instance, the research in the Ahmedabad district indicated that areas with deeper vadose zones and lower recharge rates have lower vulnerability, while regions with unconfined aquifers and higher recharge rates are more vulnerable. In contrast, the study of Vistula River valley, Central Poland found a predominance of low contamination potential despite shallow water tables, highlighting the importance of parameter sensitivity analysis.

Among various approaches to assess groundwater vulnerability, the DRASTIC analysis is more popular due to its hydrogeological parameters. However, the vulnerability assessment will be more precise with inclusion of location specific characteristics which is a major “**research gap**” need to be addressed.

The “**proposed solutions**” can be addition to the standard DRASTIC parameters (Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Hydraulic conductivity). It is crucial to address region-specific anthropogenic influences as individual parameters. These influences include the excessive use of fertilizers, urbanization, and the disposal of industrial effluents and wastewater from sewage treatment plants (STPs), which can significantly impact groundwater vulnerability in different study regions.

2.4 Limitations and Upgradation of DRASTIC Analysis

2.4.1 “An integrated approach for aquifer vulnerability mapping using GIS and rough sets: study from an alluvial aquifer in North India” by Khan et al. (2014) published in Hydrogeology Journal by Springer.

The characteristics of an area of the lower Kali watershed in western Uttar Pradesh, India, that are related to aquifer vulnerability were studied using a modified DRASTIC model in a GIS environment together with an information-analytic technique known as "rough sets." Topography (T) is eliminated as a potential control because the area is a level plain. The new model is named as DRASIC since it shares many other parameters with DRASTIC. The rough set technique is used to show how vulnerable certain administrative units (blocks) are in relation to each other within the study area. Three crucial metrics are determined using rough sets: strength, certainty and coverage. Strength describes the variation in vulnerability characteristics

across the entire area, certainty provides the proportions of low, medium and high vulnerability regions within a given block and coverage determines the prevalence of a certain vulnerability state across all blocks. The vulnerability index found ranging between 97 and 141. The findings demonstrate that several regions in the North and East of the study area show higher vulnerability. The South-Western region shows low to medium contaminant vulnerability. The majority of the central region and portions of the South-Eastern region shows moderate vulnerability.

2.4.2 “Groundwater vulnerability assessment using an improved DRASTIC method in GIS” by Neshat et al. (2014) published in Resources, Conservation and Recycling, Elsevier.

In this work, the Kerman Plain's groundwater vulnerability was measured using modified DRASTIC technique using geographic information systems (GIS). To alter the DRASTIC rate changes, the Wilcoxon rank-sum nonparametric statistical test was used. The DRASTIC model, which was offered as an alternate solution for the imprecision demands, also used the analytical hierarchy process (AHP) method to analyses the validity of the criteria and sub-criteria of all its parameters. In comparison to the conventional method, the modified DRASTIC method efficiently determined the non-point source pollution. The vulnerability index and Nitrate concentration were related, as shown by the regression coefficient. The correlation coefficients between the Nitrate concentration and the AHP-AHP, DRASTIC-AHP and AHP-DRASTIC techniques were calculated to be 0.83, 0.81 and 0.45, respectively. Due to the distinct climatic and hydrogeological conditions in the area, the AHP-AHP technique outperformed all other models in terms of results.

2.4.3 “Applying a Modified DRASTIC Model to Assess Groundwater Vulnerability to Pollution: A Case Study in Central Poland” by Kozłowski and Sojka (2019) published in Polish Journal of Environmental Studies.

This paper examines the possibility for using the DRASTIC model as a helpful tool to assist in the process of planning local and regional development. The investigation was conducted in Central Poland, in the basin of the Stare Miasto Reservoir. The vulnerability of groundwater to contamination was assessed using the DRASTIC model in order to establish the policy to safeguard the reservoir and groundwater. The original model has been altered by the addition of the new variable "land use." The original and updated models were evaluated using the measured Nitrate concentrations. The study's findings demonstrated that the modified

DRASTIC model provided more precise predictions than the standard model. Due to the modification, the vulnerability index and Nitrate concentration were correlated with Pearson correlation coefficients of 0.56 and 0.69, respectively. The groundwater vulnerability map is required for local development planning and effect analysis.

2.4.4 “Assessment of groundwater vulnerability using modified DRASTIC model in Kharun Basin, Chhattisgarh, India” by Sinha et al. (2016) published in Arabian Journal of Geosciences by Springer.

In the field of hydrogeological science, the use of remote sensing and geographic information systems (GIS) has developed as one of the essential methods for evaluating, monitoring, preserving and managing groundwater resources. The groundwater vulnerable zone of the Kharun Basin has been assessed in the current study using a modified DRASTIC model. The modification was made by removing hydraulic conductivity and adding land use parameter. This study's objective is to identify the groundwater contamination zone by combining hydrogeological layers into a geographic information system (GIS). The resulting index value ranges from 86 to 191 and the zones are split into five classes, according to the final index map. The findings indicated that, of the entire area of 4191 km², about 8,197, 2730, 1229 and 27 km² are, respectively, located in very low, low, moderate and high vulnerability zones. This study also performs a sensitivity analysis, which demonstrates that compared to other parameters, the depth of the water table, land use and the topography all significantly affect the vulnerability index. Furthermore, it was revealed that topography and land use were more useful assessment factors for groundwater vulnerability than the original model had predicted. The DRASTI-LU index that results from model validation and the Nitrate sample are good correlated.

2.4.5 “A modified-DRASTIC model (DRASTICA) for assessment of groundwater vulnerability to pollution in an urbanized environment in Lucknow, India” by Singh et al. (2015) published in Environmental Earth Sciences by Springer.

In the current study, anthropogenic influence was introduced as a model parameter to a modified DRASTIC model called DRASTICA. An innovative methodology was used to characterize anthropogenic influence in Lucknow, the capital city of the state of Uttar Pradesh, in India, using satellite observations of nightlights from human settlements as a proxy and land-use/land-cover observations surrounding urbanization. A spatial integration of different parametric maps was performed using a geographic information system. According to the

groundwater vulnerability to pollution index, 8.2% of the total area is classified as low vulnerable, 24.5% as high vulnerable, 66.6% as moderately vulnerable and 0.7% as very high vulnerable. Groundwater Nitrate concentration was used to validate the results. Sensitivity analysis revealed that groundwater vulnerability to contamination was significantly influenced by anthropogenic impact and the depth of the water table, indicating that anthropogenic influence must be specifically considered in such research. The modified DRASTIC (DRASTICA) model brought out in this study can be useful in better classifying groundwater zones, prone to pollution where anthropogenic contamination is high, particularly in and near urban centers.

Brief overview on Current Practices, Research Gaps and Proposed Solutions on studies of Limitations and Upgradation of DRASTIC Analysis

“**Current research**” on improving the DRASTIC model for groundwater vulnerability assessment addresses various limitations by incorporating modifications and additional parameters to enhance its accuracy and relevance. For instance, Khan et al. (2014) and Neshat et al. (2014) have introduced new analytical techniques, such as rough sets and the Analytical Hierarchy Process (AHP), to refine vulnerability assessments incorporating specific regional conditions. The DRASIC model, which excludes less relevant parameters like topography, has also been adapted to improve its precision in diverse contexts, such as the alluvial aquifer in North India and the Kerman Plain in Iran. Further advancements are seen in the incorporation of land use and anthropogenic impacts into the model, as demonstrated by research in Poland and India (Sinha et al. 2016, Kozłowski and Sojka, 2019). These studies highlight the addition of parameters like land use and anthropogenic influence, which significantly enhance the model's predictive power for contamination risks. The modified DRASTIC model, including variables such as land use and hydraulic conductivity, has shown improved correlations with groundwater quality indicators like Nitrate concentrations. Research such as the DRASTICA model applied in Lucknow, India, highlights the importance of incorporating anthropogenic factors and using satellite data to refine vulnerability assessments in urban environments.

Despite these improvements, a significant "**research gap**" persists in addressing the calibration of weights assigned to each parameter, rather than relying on the theoretical weights recommended by the Delphi technique, as suggested by Aller L. et al. (1987). The use of these default weights may not accurately capture regional variations in groundwater vulnerability,

necessitating a more data-driven approach to fine-tune the weighting system based on local environmental conditions and anthropogenic influences.

The **proposed solution** includes weight optimization of modified DRASTIC approach based on advanced techniques such as ANN (Artificial Neural Network).

2.5 Groundwater Quality Assessment/Correlation Analysis

2.5.1 “Application of water quality index to assess suitability of groundwater quality for drinking purposes in Ratmao–Pathri Rao watershed, Haridwar District, India” by Al-Hadithi (2012) published in American Journal of Scientific and Industrial Research.

This study used the Water Quality Index to determine whether the groundwater quality in the Ratmao-Pathri Rao Watershed, Haridwar District, India, was suitable for drinking. This was accomplished by conducting a comprehensive physico-chemical analysis on 21 groundwater samples that were collected from eleven different sites. The WQI was determined by taking into account nine different factors, including pH, total hardness, calcium, magnesium, bicarbonate, chloride, Nitrate, sulphate and total dissolved solids. According to the calculated WQI, 48% of the water sample falls into the excellent and 48% into the good water categories. On the other hand, 4% of the sites in Teliwala village fall into the very poor categories. Such water is not suitable for drinking under normal conditions, so further salinity control measures are needed. Groundwater samples at this site have high TDS, Ca^{2+} , K^+ , Cl^- , HCO_3^- , NO_3^{2-} and SO_4^{2-} values, which explain the high WQI.

2.5.2 “Groundwater Quality assessment using Water Quality Index (WQI) in parts of Varanasi District, Uttar Pradesh, India” by Chaurasia et al. (2018) published in Journal of the Geological Society of India.

In the current study, sixteen groundwater samples were taken in May 2015 during the pre-monsoon season from the Southern Varanasi district in Uttar Pradesh, India. For the calculation of the water quality index, the following twenty two water quality parameters were taken into account: pH, electrical conductivity (EC), total hardness (TH), Total Dissolved Solid (TDS), alkalinity, sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), Nitrates (NO_3^-), bicarbonate (HCO_3^-), chlorides (Cl^-), sulphates (SO_4^-), fluorides (F^-), chromium (Cr), zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), nickel (Ni), lead (Pb) and cadmium (Cd).

The Bureau of Indian Standards (BIS 2012) has been referred when determining whether groundwater is fit for drinking and for calculating WQI. Significantly adverse correlations between several physicochemical parameters are also revealed by correlation studies. WQI classification shows that 20% of this study area falls into the non-drinkable water category and the remaining falls into good, moderate, poor, very poor categories.

2.5.3 “Correlation between Nitrate concentration in groundwater and parameters affecting aquifer intrinsic vulnerability” by Debernardi et al. (2008) published in Environmental Geology by Springer.

The purpose of this work is to assess the limitations and issues with aquifer vulnerability approaches used for groundwater Nitrate contamination prediction. The study area is the Piemonte plain region in Northern Italy, where an unrestricted Nitrate poisoning of the aquifer exists. The investigation included comparing the vulnerability classes determined by the GOD and TOT methods with the NO_3^- concentrations observed in the shallow aquifer in March and November 2004. Additionally, it compares NO_3^- concentrations to individual factors (depth to water table, land use and nitrogen input). There is an unclear relationship between groundwater Nitrate concentrations and depth to water table, land use and nitrogen input: in fact, these comparisons show wide ranges of possible Nitrate concentrations for each circumstance but also describe a phenomenon trend and highlight the maximum Nitrate concentrations for each circumstance. By comparing vulnerability indices with groundwater Nitrate levels, the same issue may be shown. These findings suggest that the complex mechanisms affecting Nitrate concentrations in soil, subsoil and groundwater cannot be well described by a single parameter or vulnerability technique (GOD or TOT). In particular, physical processes in aquifers like denitrification and Nitrate dilution are not examined by typical vulnerability analysis methodologies. A recent investigation in the shallow unconfined aquifer of the Piemonte plain indicates that dilution is the primary factor in groundwater Nitrate attenuation.

2.5.4 “Groundwater quality assessment using Water Quality Index (WQI) approach – Case study in a coastal region of Tamil Nadu, India” by Ganeshkumar and Jaideep (2011) published in International Journal of Environmental Sciences and Research.

The Indian state of Tamil Nadu includes places like Vedaranyam that are particularly sensitive to its enormous natural resources. The risk to water quality is particularly quite severe

because of its proximity to the unique accreting coastline. Using the water quality index (WQI) technique, an effort has been made in this paper to comprehend the ground water quality of Vedaranyam Taluka. From bore and tube wells, forty-four groundwater samples were taken. This sample collection was done both in the summer and post-monsoon. This study found that there are very few regions in the South-West of the study area that satisfy requirements for consumable water quality. According to the results of the research, the groundwater in the study area is being contaminated by both natural and artificial sources. However, an analysis of samples from 44 bore and tube wells shows that the majority of the ground water samples are not suitable for drinking, with the exception of those where the WQI values are within the permissible limit. This is accurate despite the existing salinization process and other human activities. In summary, this study shows that 29% of the groundwater in the summer and 66% of it during the post-monsoon season in Vedaranyam Taluka are unfit for drinking.

2.5.5 “Assessment and modelling of groundwater quality using WQI and GIS in Upper Egypt area” by Rabei (2018) published in Environmental Science and Pollution Research, Springer.

In this study, the quality of groundwater for irrigation and drinking was evaluated using 812 groundwater samples collected from the Sohag Governorate in the center of Upper Egypt. Each groundwater sample was examined for eleven water parameters (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , SO_4^{2-} , Fe^{2+} , Mn^{2+} , Cl^- , electrical conductivity and pH) in order to use them to assess the quality of the water. In order to assess the distribution of physicochemical parameters in the study area, traditional statistics were applied to the raw data. According to WQI results, only 1% of groundwater samples are unfit for consumption, whereas 75% of samples are OK for drinking and 20% of samples are good. Three indices are used to determine whether groundwater is suitable for irrigation: the sodium adsorption ratio (SAR), sodium percentage (Na%) and permeability index (PI). The findings indicate that most sampling sites are acceptable for irrigation, with less than 3% being unsuitable. Using GIS, the spatial distribution of the estimated values of the groundwater parameters WQI, SAR, Na%, PI were simulated.

2.5.6 “Groundwater quality assessment using water quality index” Patel and Vadodaria (2015) published in 20th International Conference on Hydraulics, Water Resources and River Engineering, HYDRO-2015, IIT Roorkee.

The purpose of this research is to determine whether the groundwater quality in Gujarat's

Mehsana district is suitable for drinking by collecting 63 water samples throughout the pre and post-monsoon seasons of 2013 and 2014. Different physicochemical parameters, such as pH, total hardness, Total Dissolved Solids, Calcium, Magnesium, Sodium, Bicarbonate, Sulphate and Chloride were studied. Based on the outcomes, the average groundwater WQI values for the study area were 221.14, 219.71, 233.20 and 229.36 for the pre and post-monsoon seasons of 2013 and 2014, respectively. According to the study, only about 22% of the water that is available in the study area qualifies into the "Good" category and can be used directly for drinking. There is a remaining 78 % of water that can only be used after it has been purified. This analysis was done in a GIS (geographic information system) framework. For improved planning and management of water resources, the index map offers decision-makers a thorough vision that is simple to understand.

Brief overview on Current Practices, Research Gaps and Proposed Solutions on studies of Groundwater Quality Assessment/Correlation Analysis

“**Current practices**” in groundwater quality assessment frequently utilize the Water Quality Index (WQI) to evaluate suitability for drinking and irrigation across diverse regions. Studies such as those conducted in Haridwar District, Varanasi, Tamil Nadu, and Upper Egypt have employed WQI to analyse water samples based on various physicochemical parameters, including pH, hardness, and Nitrate concentration. These studies have highlighted significant regional variations in water quality, with some areas showing excellent or good water quality, while others fall into poor or very poor categories, often due to high concentrations of contaminants or salinity. Studies in Northern Italy have shown that traditional vulnerability models may not fully capture the interactions between Nitrate levels and contributing factors like depth to the water table and land use.

The “**research gap**” is lack of understanding of strong correlation among groundwater quality parameters and vulnerability parameters to verify dominating contaminants for further remedial measures.

To address these gaps, “**proposed solutions**” include calculating the correlation using Spearman’s method, between the ranked values of groundwater quality indicators (e.g., Nitrate

concentration, pH) and different vulnerability parameters, to identify which parameters (e.g., depth to water, recharge) have the most significant impact on water quality.

2.6 Public Health Risk Assessment

2.6.1 “Assessment of human health risk associated with high groundwater fluoride intake in southern districts of Punjab, India” Ahada and Suthar (2017) published in Exposure and Health by Springer.

This research examined into the health concerns connected with groundwater Fluoride levels among residents of Punjab's Southern districts in India. In the Malwa region of Punjab, a total of 76 groundwater samples were collected and these samples were further tested for chemical characteristics. A range of 0.60 to 5.07 mg/l of fluoride was found, according to the results. The majority of sites had groundwater fluoride concentrations that above the WHO-recommended and permitted limit of 1.0 mg/l. The values of Chronic Daily Intake (CDI) and Hazard Quotient (HQ_{Fluoride}) revealed that excessive use of groundwater that is high in Fluoride exposes local populations at a high risk of non-carcinogenic health risks. For all sampling locations, the HQ_{Fluoride} was calculated to be between 0.29 and 2.41 for adults and 0.67 to 5.63 for children, showing a much higher risk than the permitted levels (> 1). Site-7 (villages in the Barnala district) is the location with the highest health risk for both adults and children. However, according to HQ data, Site-6 (for adults) and Site-4 (for children) are the most contaminated places with a high risk of adverse impacts on human health.

2.6.2 “Groundwater Nitrate contamination and associated human health risk assessment in southern districts of Punjab, India” by Ahada and Suthar (2018) published in Environmental Science and Pollution Research by Springer.

This study aimed to assess the levels of NO_3 in the groundwater of 14 densely populated districts in Malwa Punjab, India and any potential health risks to the local populations. Over 92% of the 76 sites sampled exhibited NO_3 concentrations that were higher above the permissible limits set by the Bureau of Indian Standards (45 mg/l) and the World Health Organization. The concentration of NO_3 ranged from 38.45 to 198.05 mg/l (50 mg/l). The USEPA's human health risk assessment (HHRA) model was used to calculate the potential health risks of high NO_3 intake for both adults and children. The findings of this study indicated that the Chronic Daily Intake (CDI) for the adult and children population in this region, respectively, fell within the

ranges of 1.09-5.65 and 2.56-13.20. In the majority of sampling sites, the hazard quotient (HQ_{Nitrate}) value ranged from 1.09 to 6.65 for the adult population of Malwa and from 2.56 to 13.20 for the population of children. According to this study, the Malwa's adult and young populations both are at an increased risk of chronic toxicity due to excessive NO_3 intake.

2.6.3 “Health risk assessment of groundwater nitrogen pollution in Songnen Plain” by Wu et al. (2021) published in Ecotoxicology and Environmental Safety by Elsevier.

This study explored Nitrogen pollution, estimated its potential danger to human health for local communities in the Songnen Plain of Northeast China and recognized parameter uncertainties using a land use methods, geostatistical analysis and triangular random models. The study revealed more than 72.35% of the samples exceeded the Grade III threshold (20 mg/l of N) according to China's standard. Nitrate Nitrogen content is greater than 20 mg/l accounted for about 60% of the study area, which is primarily distributed in the Eastern and Central high plain area. Nitrate concentrations in groundwater ranged from 0.01 to 523.45 mg/l. Two land uses had non-carcinogenic hazards (HI) that were higher than the safe limit ($HI > 1$), indicating that groundwater Nitrate would have serious health consequences on the age groups and further endanger children. In this study, Nitrate-nitrogen was the dominating contaminant, with a maximum value of 523.45 mg/l and a sample rate exceeding the standard rate of 72.35 percent. 60% of the overall area had Nitrate-nitrogen concentrations above the standard (20 mg/l), which was mostly concentrated in the Eastern and Central plateau regions. Town property was ranked above rural area in terms of non-carcinogenic dangers for both adults and children. The townland's risk value was almost twice that of agricultural land. The non-carcinogenic health risks were significantly higher than 1 % safety threshold in both the land use types. Drinking groundwater raises increased risks to children and could be physically harmful to adults.

2.6.4 “Hazard and risk assessment of pollution on the groundwater resources and residents’ health of Salfit District, Palestine” by Aliewi and Al-Khatib (2015) published in Journal of Hydrology: Regional Studies by Elsevier.

The Salfit District in the Northern West Bank of Palestine was the subject of the study. The primary goal of this study is to evaluate groundwater contamination and estimate the vulnerability, hazards and risks of pollution on groundwater resources and on the health of residents as these aquifers serve as the district's primary sources of drinking water. Using a

Durov diagram, it was determined that the water sources were contaminated, directly adversely impacting the health of the Salfit District's population. It was found that chlorination procedures were typically effectively implemented by the majority of the municipalities with water network systems, but disinfection was almost absent in cisterns. Additionally, it was determined that the drinking water supplies and resources were contaminated by sewage, which is considered to be the cause of the spread of several water-related illnesses including eye and diarrhoeal diseases as well as vomiting that have been reported in clinics in the Salfit District.

2.6.5 “Assessment of Groundwater Quality and Associated Health Risks: A case study of Ranchi city, Jharkhand, India” by Tirkey et al. (2017) published in Groundwater for Sustainable Development, Elsevier.

Since the establishment of the state of Jharkhand, Ranchi's urbanization rate has accelerated. A study was carried out to assess the state of groundwater quality in Ranchi's peri-urban agglomeration. In the monsoon season, samples were taken at 44 locations throughout the city's rural, peri urban, urban, industrial and commercial zones. Along with the physico-chemical properties, they were also tested for 10 heavy metals, including As, Mn, Ni, Se, Fe, Cu, Cd, Co, Cr and Pb. All of the other elements, with the exception of As, Mn, Ni and Se, were below detection levels. The concentrations (ppb) of the very hazardous elements As, Ni, Mn and Se, which are above the BIS/WHO criteria for drinking water, varied from 0.0 to 200, 0.0 to 80, 0.0 to 4200 and 30 to 140, respectively. Industrial and commercial zones have worse water quality than rural, peri-urban and urban zones, according to zonal variation. According to the Water Quality Index, just 9% of the 44 sampling locations have high water quality, with 80% of places having low water quality, 7% having extremely bad water quality and 4% being unsafe for drinking. Based on health risk assessment, it is concluded that there are greater number of residents within the study area who are likely to be exposed to noncarcinogenic effects than to carcinogenic effects due to Arsenic and Selenium.

Brief overview on Current Practices, Research Gaps and Proposed Solutions on studies of Public Health Risk Assessment

“The current state” of public health risk assessment in relation to groundwater quality reveals significant concerns across various regions across the world. Studies have consistently

identified high levels of contaminants, such as Fluoride and Nitrate, in groundwater sources, which pose serious health risks to local populations. For example, research in Punjab, India, highlighted that elevated Fluoride and Nitrate levels exceed safe limits, leading to high non-carcinogenic health risks, especially for children. Similarly, in Northeast China and Palestine, studies have shown that groundwater contamination by Nitrates and sewage, respectively, results in adverse health impacts, including increased risks of chronic toxicity and waterborne diseases. In urban areas like Ranchi, India, industrial and commercial activities have exacerbated the problem, with heavy metals like Arsenic and Selenium posing significant health hazards.

The “**research gaps**” observed that HRA based on USEPA guidelines considering only the Hazard Quotient, does not comprehensively address the public health risk.

“**Proposed solutions**” is to involve addition of location specific characteristics such as LULC pattern, water use scenario, population distribution and groundwater vulnerability in identification of critical area. Such critical area should be prioritized for effective groundwater remediation.

2.7 Groundwater Management Strategies

2.7.1 “Source area management practices as remediation tool to address groundwater Nitrate pollution in drinking supply wells” by Bastani and Harter (2019), published in Journal of Contaminant Hydrology (2019) by Elsevier.

It is generally recognized that the primary cause of groundwater Nitrate contamination of rural residential and urban public water supply wells in farming regions is agricultural activity. Improved nutrient management techniques and "pump and fertilize" using irrigation wells that are Nitrate-affected are two management strategies that have been suggested to lower the quantity of Nitrate in groundwater. The Central Valley aquifer system in California's Modesto basin was the site of the development of a numerical model of Nitrate fate and transport. Business as usual, alternative low-impact crops and Ag-MAR at the source area of the public supply well are some of the model scenarios that have been implemented. The area between farming and the public supply well which requires remediation and alternative nutrient management and recharge techniques are used. It has been demonstrated that enhancing farming source area management techniques is a useful tool for remediating ambient groundwater while maintaining or even improving groundwater quality in the targeted supply well. The best

outcomes are obtained by simultaneously reducing the Nitrate load and enhancing recharging in the source area. In comparison to the "business as usual" scenario, this one lowered the amount of Nitrate in the supply well's drinking water by 80%. Between the farmlands in the source area and the supply well, it also treated the ambient groundwater utilized by domestic wells and after 60 years of usage, the Nitrate level was reduced by 60% more. The initial reaction time (five years) was shortened as the recharge rate increased and this effect was the most long-lasting.

2.7.2 “Risk assessment framework for Nitrate contamination in groundwater for regional management” by Teng et al. (2019) published in Science of the Total Environment, Elsevier.

The contamination of groundwater with Nitrates is currently regarded as one of the most important environmental problems in the world. As a result, the source-pathway-receptor-response model has been used to suggest a unique method for screening and evaluating the risk of groundwater Nitrate contamination. The methodology includes human health risk assessments (HHRAs), groundwater contamination risk assessments (CRAs) and Groundwater Relative Risk Models (RRMs). It is used in North-East China's lower Liaohe river basin plain. The results showed that RRM had successfully identified the focal regions in the study region with the highest relative groundwater risk. About 9.9% of the extremely high relative risk (V class) zones identified as priority locations for contamination risk assessments in the Liaohe River plain. The majority of the region's 16.9% (3978 km²) in the northeast is made up of high relative risk areas (IV class). The primary cause of groundwater contamination was found to be agricultural applications, whereas hydrogeological factors were to blame for high sensitive zones. According to health risk evaluations, Nitrate in groundwater poses significant non-carcinogenic threats to the population in particular zones, particularly to children and those residing in the most severely contaminated areas.

2.7.3 “A multi-level method for groundwater remediation management accommodating non-competitive objectives” by Lu et al. (2019) published in Journal of Hydrology, Elsevier.

There have been no attempts to deal with a group of non-competitive goals when carrying out the best groundwater cleanup management. When goals need to be met at various levels, this

work proposes a multi-level nonlinear simulation-optimization (ML-NSO) model for groundwater remediation management. In order to develop this model, a generic framework was used to integrate health-risk assessment (at the level of residential worry), energy evaluation (at the level of energy concern) and contamination predictions (at the level of environmental concern). A case study from a real-world setting in the Canadian Saskatchewan town of Cantuar serves as an illustration of the model's potential and effectiveness. The study results support in (a) coming up with non-compromised solutions in connection with the best methods for injecting and extracting groundwater, (b) displaying the distribution of contaminant concentration and carcinogenic risks for human health and estimating the corresponding energy consumption. Results indicate that the ML-NSO model would give the residential and environmental concerns a higher priority by tolerating a little increase in energy costs. The ML-NSO model would offer more comprehensive and systematic policies while taking the system's leader-follower relationship into consideration. The ML-NSO model offers relatively lower benefits compared to MO-NSO, but it is generally accompanied by better benefits for the environment and health risks. A lower level of health risk and a better environmental quality can be obtained while sacrificing some economic benefits.

2.7.4 “A coupled optimization of groundwater remediation alternatives screening under health risk assessment: An application to a petroleum-contaminated site in a cold industrial region in Northeastern China” by Chen et al. (2021) published in Journal of Hazardous Materials, Elsevier.

Contaminated sites pose serious social and environmental challenges and have attracted worldwide attention. A novel method for assessing health risks (HRA) and demonstrating a multicriteria decision analysis (MCDA) using this method were the main objectives of this study to select the most appropriate remediation alternatives of groundwater and to prioritize contaminated sites management. Longtan, a typical contaminated site in Jilin province, China, was used to demonstrate HRA and MCDA. According to the study's findings, the vanillin facility to the site's North was the primary source of pollution, while Benzene (PhH) and 1,2-dichloroethylene (1,2-DCE) were the principal organic pollutants. The health risk range increased significantly in the winter compared to the summer as a result of pollution that moved from the North to the South. Based on the HRA results, four remedial options were suggested.

According to the MCDA findings, PRB is the technology best suited for integrating the relevant environmental, social, economic and technological components needed for remediation.

Brief overview on Current Practices, Research Gaps and Proposed Solutions on studies of Groundwater Management Strategies

“**Current practices**” of source area management, which includes improving nutrient management and using techniques like "pump and fertilize," have been shown to reduce nitrate levels significantly, as demonstrated in California's Central Valley. Risk assessment frameworks help prioritize areas for remediation based on contamination risk and health impact, as seen in northeast China's Liaohe River basin. Multi-level management models address non-competitive objectives, balancing health risk, environmental concerns, and energy use, with case studies indicating their potential for comprehensive management strategies. Furthermore, coupled optimization methods of assessment of health risks and remediation alternatives, illustrated by the petroleum contamination site in Jilin, China, suggested the importance of integrating environmental, social, and economic factors into decision-making.

The “**research gap**” observed is the necessity to include more criteria based on hydrogeological parameters in addition to economic criteria while performing MCDA.

“**Proposed solutions**” suggested addition of groundwater table (GWT), aquifer media (AM), location specific characteristics (LSC) and Contaminant level (CL) as hydrogeological criteria in MCDA. Further variation of these parameters at each well location can precisely prescribe suitable remedial method.

To achieve the main objective of this study, a literature review has been conducted. Based on the papers reviewed, a list of data to be collected has been outlined in chapter-3 (Study Area and Data Collection).