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Research Article

An Evaluation of Groundwater Vulnerability Utilizing GIS-Based Model

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Abstract

Effective groundwater management requires assessing vulnerability to pollution. While the SINTACS method is widely used, it has limitations by not adequately considering hydrogeological parameters and supplementary data. To address SINTACS limitations, a modified approach (MSVILuLn) incorporates land use/cover and lineaments. Parameter weights were determined using analytic hierarchy process (MSVILuLn-AHP) and network process (MSVILuLn-ANP). Raster layers of nine parameters were analyzed in GIS to evaluate groundwater vulnerability index using SINTACS, MSVILuLn, MSVILuLn-AHP, and MSVILuLn-ANP. Nitrate concentrations from 48 wells were compared to validate results. MSVILuLn-ANP identified more very high/low vulnerability zones compared to others. It showed highest accuracy (91.7%) correlating vulnerability and nitrate levels. MSVILuLn-ANP offers a more comprehensive vulnerability assessment for groundwater management in Raipur city. Integrating SINTACS with GIS and objective weighting methods enhances spatial analysis of sensitive areas and prevents contamination.

Keywords: *SINTACS, Groundwater, Vulnerability, GIS, Water Quality Index, Raipur city.*

1. Introduction

Groundwater is the primary water source for Raipur city in Chhattisgarh. Rapid urban expansion poses risks to groundwater quality from pollution sources. Groundwater vulnerability assessment is needed to understand contamination risk and guide protection. Previous Indian studies have used models like DRASTIC and SINTACS in GIS, which integrate hydrogeological and land use factors. However, SINTACS does not consider lineaments that influence groundwater movement. Subjective weight assignment in existing models can affect accuracy. This research aims to modify SINTACS by including lineaments and applying AHP/ANP for objective reweighting. The modified SINTACS (Lu-Ln) will be compared to DRASTIC and original SINTACS. Vulnerability indices will be correlated with measured nitrate levels to validate the models. Identifying vulnerable zones through an improved assessment will facilitate scientifically-informed groundwater management in Raipur.

Various models and techniques have been developed over the years to assess groundwater vulnerability.

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An early approach was the DRASTIC model which used seven intrinsic hydrogeological parameters to evaluate vulnerability (Aller et al., 1987). Other index-based models include GOD, SINTACS, AVI etc. (Foster, 1987; Van Stempvoort et al., 1993; Vías et al., 2006).

In recent years, Geographic Information System (GIS) based techniques have become popular for groundwater vulnerability assessment due to their ability to integrate spatial data and modeling capabilities. Parameters influencing vulnerability can be mapped and overlaid in a GIS environment to produce vulnerability maps (Narasimhan et al., 2005). GIS models have been applied in different regions for vulnerability assessment, for example, Margat model in France (Margat and Van der Gun, 2013), COP method in Italy (Civita and De Maio, 2004) and SI method in Iran (Fijani et al., 2013).

In India, groundwater vulnerability has been studied for different states using GIS based models incorporating hydrogeological and land use data layers. Important studies include DRASTIC model application in Punjab (Gogoi et al., 2015), SI method for Gujarat (Jha et al., 2010) and modified DRASTIC model for Himachal Pradesh (Rai et al., 2015). However, there is limited research on groundwater vulnerability assessment specific to the city of Raipur. The current study aims to address this research gap by developing a GIS based model to evaluate groundwater vulnerability in Raipur city.

Rating methods and overlay and indexing techniques in GIS continue to be popular for groundwater vulnerability assessments. European Union funded projects such as REVEALS and GROWAM have established rating systems and procedures for member countries (Kunkel and Wendland, 2002; Tiktak et al., 2006).

Analytical hierarchy process (AHP), a multi-criteria decision analysis method, has also been integrated with GIS for groundwater vulnerability mapping. Factors are prioritized and weighted using AHP surveys before making the spatial overlay (Nusayba et al., 2014; Maleki et al., 2017).

Data driven statistical and machine learning techniques are gaining prominence in recent studies. Logistic regression and artificial neural network models have been developed and shown to have better predictive capability than traditional index methods (Kumar et al., 2015). Random forest classifier provided high accuracy for groundwater vulnerability mapping of Pernambuco state, Brazil (Rodrigues et al., 2019).

In India, state level geological surveys have mapped hydrogeological formations and parameters which help vulnerability modeling. For example, Central Ground Water Board reports aided modeling of Delhi and NCR regions (Jha et al., 2015; Mehta et al., 2019).

Urban-specific factors like landfill sites, sewage network and industrial zones need special consideration in city-scale assessment. This was done in vulnerability mapping of megacities like Delhi, Chennai and Kolkata (Lal et al., 2017; Singh et al., 2020; Mondal et al., 2021).

Remote sensing data is being combined with GIS to overcome limitations of field data collection. Land use/land cover, lineaments and soil maps from satellite imagery supported vulnerability evaluation in data scarce regions (Maheshwari et al., 2014; Kushwaha et al., 2018).

This literature review helps outline the state-of-the-art in groundwater vulnerability assessment methods and showcase applications relevant to the current study area and scale.

2. Methodology

Overlay and index methods are widely used for groundwater vulnerability assessments as shown in Fig. 1. They integrate ratings of factors like depth to water, recharge, soils, land use and management that impact contaminant transport to aquifers. This study assesses vulnerability in Raipur city, India using the SINTACS model. Data on geology, hydrology, land use etc. were obtained from agencies like CGWB. Layers for seven standard SINTACS parameters were prepared in GIS. The methodology was modified by adding land use/cover and lineaments, and weighting parameters using analytic hierarchy process (AHP) and analytic network process (ANP). Vulnerability indices from the models were validated against nitrate concentrations from groundwater samples to identify the most effective assessment for Raipur's vulnerable zones.

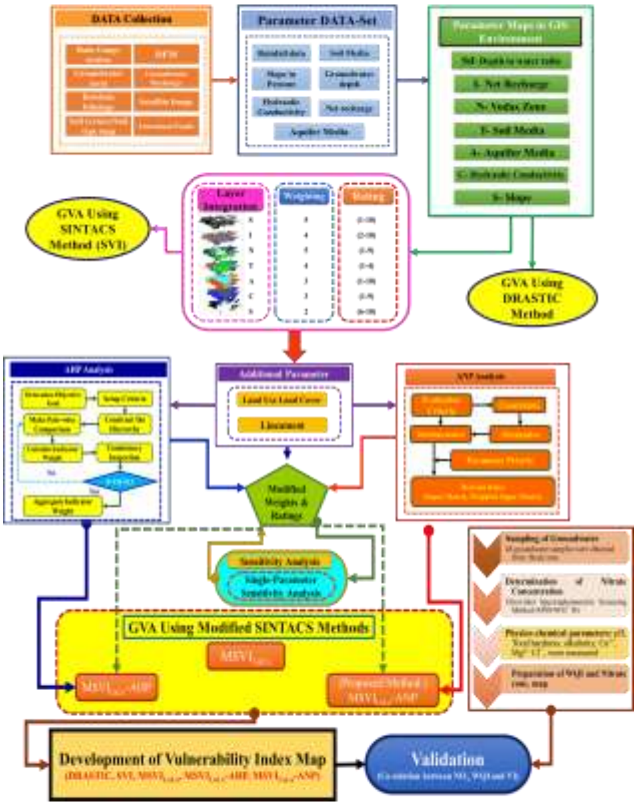

Fig. 1 Methodology

2.1 Study area

Raipur in Fig. 2, is the capital of Chhattisgarh state in central India covering 226 km2 between 21°10'-21°20'N and 81°35'-81°40'E. The population exceeds 1 million. The climate is warm year-round with average rainfall of 1460 mm mostly from June-October. The city lies in the Mahanadi basin near the Kharun River. The geology comprises Chandi and Gunderdehi limestone and sandstone formations, which are important aquifers with water depths of 5-30 mbgl. Industries like steel and cement are present. Raipur was chosen as 70% of the area has low slope and depth to water table, geological formations support infiltration. Groundwater is important for the city's water needs.

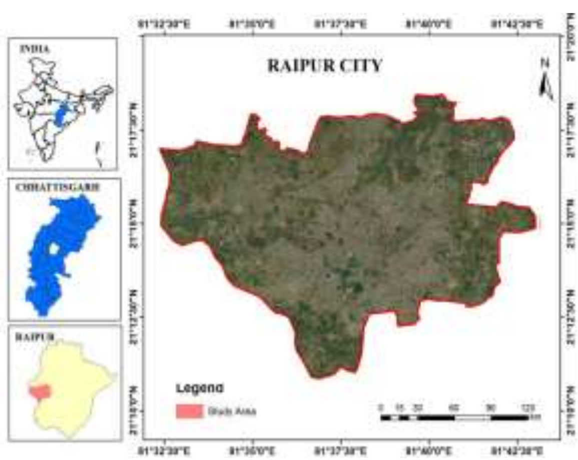

Fig. 2 Study area

2.2 SINTACS Method

The SINTACS method in Fig. 3, adapted the DRASTIC model for large-scale use in Italy due to its hydrogeological diversity. It is a parametric point count system where each factor has a score and weight. SINTACS was preferred for assessing Raipur's groundwater vulnerability due to its suitability, low cost, and use of relative, dimensionless properties dependent on aquifer and geological/hydrological characteristics. It uses seven parameters to determine the likelihood of contaminants reaching the aquifer through subsurface layers.

The parameters characterization of vulnerability that was identified in this approach are (Sd): Soggiacenza (depth of water table); (I): Infiltrazione (infiltration); (N): Not Azione del Satoru (depending on the unsaturated zone); (T): Tipologia della Copertura (soil); (A): Carratteri Idrogeologici dell 'Acquifero (hydrogeological characteristics of the aquifer); (C): Conductivity Idraulica (conductivity hydraulic). (S): Acclività Della Topographica area (average slope of the topographic surface)

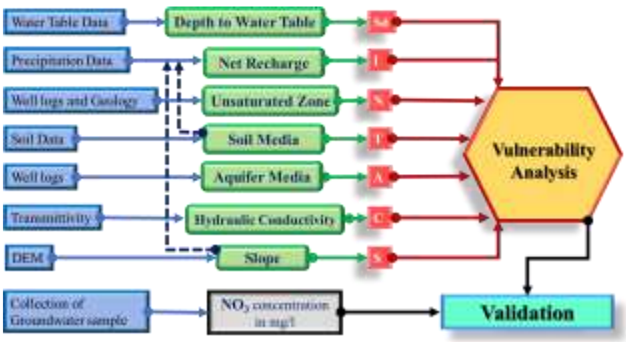

Fig. 3 SINTACS method

The SINTACS Vulnerability Index (SVI) was calculated using Equation 2, multiplying the weight of each parameter rating and adding the results. The seven GVA parameters in Table 1, used were: depth to water table (Sd), impact of vadose zone (I), net recharge (N), aquifer media (T), soil media (A), topography (C), and hydraulic conductivity (S). Criteria were rated from 1-5 and weighted from 1-10 based on relative importance to contamination. Weights were multiplied by ratings and summed to calculate the final SINTACS Vulnerability Index (SVI) by using Eq. 1.

$$SINTACS\ (SVI) = (SdrSdw) + (IrIw) + (NrNw) + (TrTw) + (ArAw) + (CrCw) + (Sr * Sw) \quad (1)$$

2.3 Preparation of parameter range, rating and index maps

Table 1 SINTACS rating and weight Given by Civita and De Maio

Parameters	Sub Parameter	*Rating	*Weight	Index Rating
Depth of water table (m) (Sd)	0-10 10-20 20-30 30-40 >40	10 7 5 3 1	5	50 35 25 15 5
Net recharge (I)	Very High (VH) High (H) Medium (M) Low (L) Very low (VL)	10 9 8 6 2	4	40 36 32 24 8
Impact of Vadose (N)	Stromatolitic dolomitic limestone with sandstone Stromatolitic dolomitic limestone Sandy clay loam Laterite Clay loam	9 8 3 2 1	5	45 40 15 10 5
Soil Media (T)	Sandy loam Sandy clay loam Gravelly sandy clay loam Clay sandy loam Clay loam Clay	4 3 3 2 2 1	4	16 12 12 8 8 4
Aquifer Media (A)	Stromatolitic dolomitic limestone with sandstone Stromatolitic dolomitic limestone Laterite	10 9 1	3	30 27 3
Hydraulic Conductivity (C) (m/day)	0.80 0.60 0.000864	9 8 1	3	27 24 3

2.4 Depth to Water Table

Depth to water Table 2, was determined from groundwater level data from 25 observation wells in 2019 from CGWB. IDW interpolation mapped the water table surface. Depth to water affects contaminant movement. Values were reclassified into SINTACS ratings using the Reclassify tool in GIS spatial analysis.

Table 2 Depth of water table at CGWB observed well locations

Well ID	Location Longitude (E)	 Latitude (N)	Name	Depth to water table (Meter)
W 01	81° 40'' 34'	21° 12'' 19'	Deopuri	18.28
W 02	81° 38'' 03'	21° 12'' 20'	Math Purena	10.82
W 03	81° 34'' 28'	21° 14'' 43'	Sarona	02.45
W 04	81° 36'' 07'	21° 15'' 05'	Kota	03.28
W 05	81° 37'' 14'	21° 14'' 20'	Ram Krishna Ashram	02.15
W 06	81° 37'' 30'	21° 14'' 17'	Amapara	08.84
W 07	81° 38'' 26'	21° 14'' 04'	Burapara	02.75
W 08	81° 35'' 42'	21° 16'' 37'	Sondongri	07.83
W 09	81° 36'' 39'	21° 16'' 14'	Gogaon	21.05
W 10	81° 38'' 58'	21° 14'' 42'	Indravati Colony	09.72
W 11	81° 35'' 02'	21° 14'' 21'	R.S. University	03.38

W 12	81° 38'' 51'	21° 15'' 43'	Sastri Nagar (Phapadih)	02.66
W 13	81° 39'' 47'	21° 14'' 45'	Sankar Nagar	04.61
W 14	81° 40'' 17'	21° 13'' 50'	Purena	20.11
W 15	81° 41'' 08'	21° 14'' 20'	Telibandha	29.02
W 16	81° 42'' 39'	21° 14'' 25'	Jora	02.08
W 17	81° 42'' 29'	21° 16'' 00'	Kachna	03.36
W 18	81° 42'' 29'	21° 13'' 12'	Dhrampura	02.87
W 19	81° 39'' 27'	21° 13'' 04'	Pachpedi naka	14.59
W 20	81° 39'' 02'	21° 14'' 52'	Raja Talab	03.21
W 21	81° 34'' 23'	21° 15'' 47'	Tatibandh	18.36
W 22	81° 34'' 27'	21° 16'' 36'	Jarwai	13.15
W 23	81° 34'' 27'	21° 17'' 27'	Tendua	13.85
W 24	81° 37'' 30'	21° 15'' 24'	Gudhiyari	02.88
W 25	81° 33'' 31'	21° 15'' 22'	MVM Tatibandh	10.60

2.5 Modified SINTACS Method by Including Two Parameters Like Lineaments and Land Use Land Cover

The modified SINTACS method (MSVILuLn) in Fig. 4, included land use/land cover (Lu) and lineaments (Ln) to assess Raipur's groundwater vulnerability. Lu from a 2019 image was classified and Ln mapped as lineament density.

$$MSVILuLn = (SdrSdv) + (IrIv) + (NrNv + (TrTv) + (ArAv) + (CrCv) + (SrSv) + (LurLuv) + (Lnr * Lnv) \quad (2)$$

Eq. 2, calculated the MSVILuLn index by linearly adding the standard SINTACS parameters and new Lu and Ln parameters weighted based on contamination importance. The final vulnerability map integrated all thematic maps in GIS.

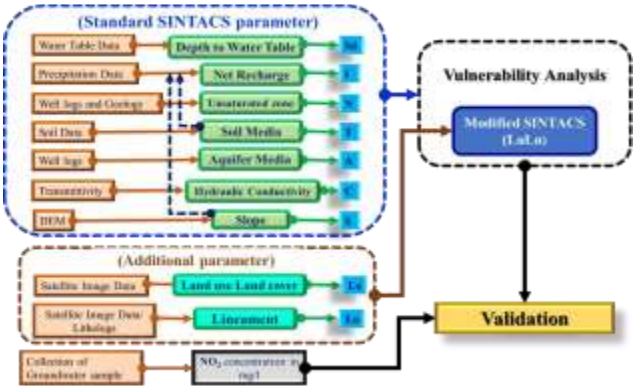

Fig. 4 Flow chart of MSVILuLn method

2.6 Modified SINTACS Method by Including Two Parameters and Using Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) approach was applied to ascertain the weight of all the parameters used in the Modified SINTACS Method by including two parameters, MSVILuLnAHP method Fig. 5, for the assessment of groundwater vulnerability and the results derived were used along with GIS methods (Santhosh and Sivakumar Babu, 2018; Soyaslan, 2020.

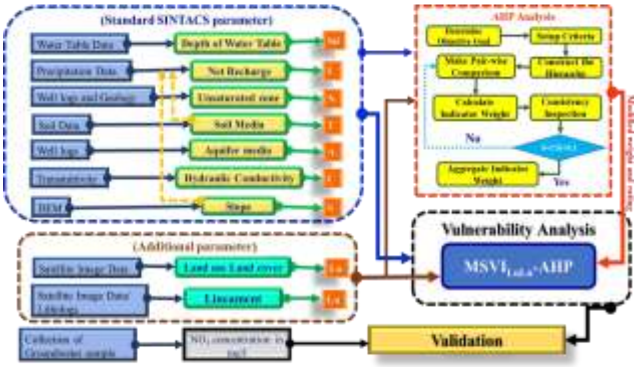

Fig. 5 Flow chart of MSVILuLn-AHP method.

3. Proposed Method

ANP is a MCDA in Fig. 6, that uses a holarchy network structure rather than a simple hierarchy. In ANP, criteria, sub-criteria and alternatives are equal nodes. The ANP solver software enters interrelationships to create matrices and determine weights accounting for internal and external parameter relationships, allowing better weight prediction for assessing groundwater vulnerability.

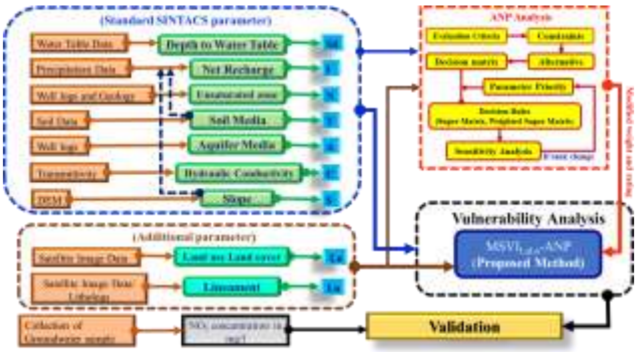

Fig. 6 Flow chart of MSVILuLn-ANP method

3.1 Comparitive Analysis of AHP and ANP

AHP uses a hierarchical structure while ANP allows complex interactions between decision elements. ANP considers direct and indirect dependencies between elements using pairwise comparisons to determine influence and dependence within a network as shown in Fig. 7. It provides a flexible representation of groundwater systems. ANP derives a supermatrix from clusters/elements, forms a weighted supermatrix using eigenvectors, transforms it into a limited supermatrix by raising it to a power, and finalizes priorities in the columns.

The MSVILuLn-ANP index was calculated using Equation 3:

$$MSVILuLn - ANP = (SdySdn) + (IyIn) + (NyNn) + (TyTn) + (AyAn) + (CyCn) + (SySn) + (LuyLun) + (Lny * Lnn) \quad (3)$$

Where the parameters were rated separately by SINTACS and ANP weights to obtain the result.

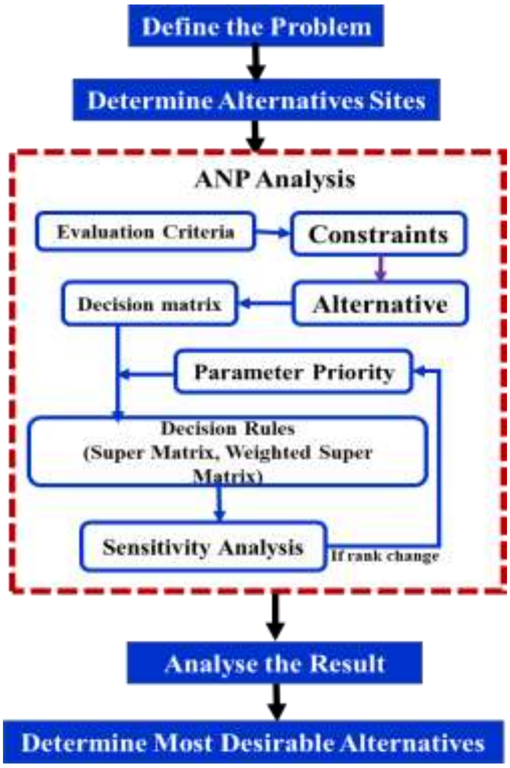

Fig. 7 Analytic network process flow chart

3.2 Single parameter sensitivity analysis (SPSA)

SPSA determines each parameter's effective weight in a vulnerability map. It identifies important parameters, improves model accuracy by refining influential ones, and prioritizes research by highlighting key parameters. SPSA was applied to indexes from SINTACS, Modified SINTACS(LuLn), Modified SINTACS(LuLn)-AHP, and Modified SINTACS(LuLn)-ANP.

The effective weight (W) for each cell was calculated using Equation 4:

$$W = (Pr * Pw / V) * 100 \quad (4)$$

Where W is the effective weight, Pr and Pw are the rating and weight of each parameter, and V is the final vulnerability index. The effective weight depends on the parameter value compared to the other eight parameters and its SINTACS weight.

3.3 Sampling and testing of ground water

48 groundwater samples were collected from wells in vulnerable zones to investigate validation. Samples were collected in sterilized PET containers and transported to the lab.

pH was measured using a pH meter. Hardness was determined by EDTA titration against standardized EDTA. Total hardness was calculated using Equation 5:

$$Total\ Hardness = (AB1000) / (ml\ of\ Sample) \quad (5)$$

Where A = ml EDTA used, B = mg CaCO3 equivalent to 1 ml EDTA. Calcium hardness was determined by EDTA titration with indicators. Magnesium was calculated by subtracting calcium from total hardness.

Alkalinity was measured by titrating with sulfuric acid and indicators. Phenolphthalein and methyl orange endpoints were determined. Nitrate was measured using a UV spectrophotometer in Table 3. Samples were acidified and absorbance at 220nm and 275nm were recorded. Concentration was calculated from a standard curve relating absorbance and concentration.
Chloride was determined by titrating samples with silver nitrate and an indicator. Tests helped validate vulnerability maps by comparing parameter concentrations in vulnerable zones identified as high, medium and low vulnerability to determine if concentrations matched predictions. The analyses aided in groundwater potential zone assessment as shown in Fig. 8 and Fig. 9.

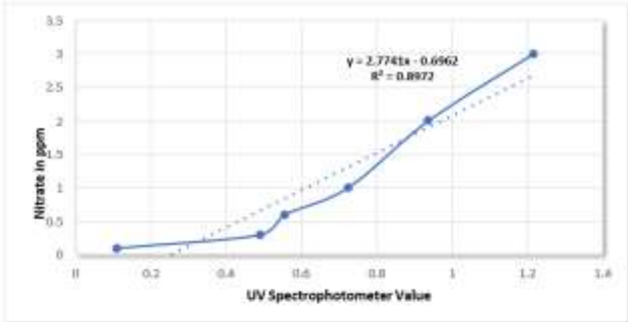

Fig. 8 The relationship between Nitrate solution to the test result value from UV-Spectrophotometer

Table 3 UV-Spectrophotometer experiment result data

Nitrate in ppm	UV-Spectrophotometer Value
0.1	0.108
0.3	0.49
0.6	0.555
1	0.723
2	0.937
3	1.216

4. Results & Discussions

4.1 Depth of Water Table

The depth to water table (Sd) in Fig. 9, significantly impacts vulnerability as deeper water tables allow more time for contaminant removal through soils. Water depth ranged from 3-41m below ground. Depths were classified by SINTACS and assigned rates from 1 (minimum impact) to 10 (maximum impact) on vulnerability.

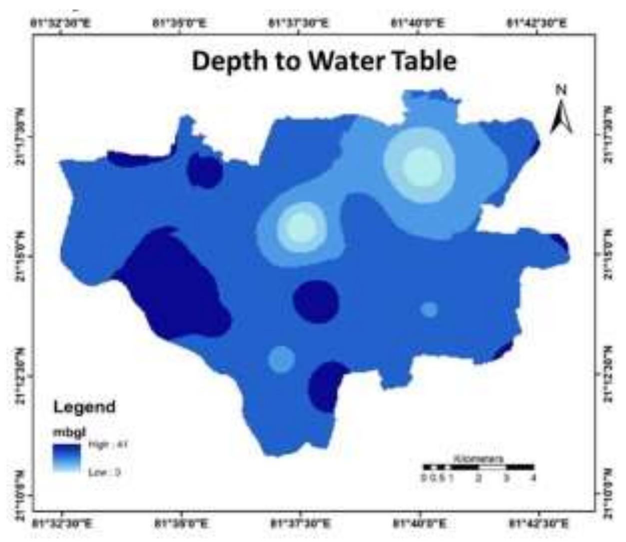

Fig. 9 Depth to water table

4.2 Net Recharge

Effective infiltration (I) represents recharge reaching the water table, transporting contaminants. Greater recharge increases pollution potential. Raster maps of slope, rainfall, soil permeability with different dimensions were reclassified per standard ratings and weights to add the quantities and determine net recharge. Recharge was classified into very high, high, moderate, low and very low groups as shown in Fig. 10.

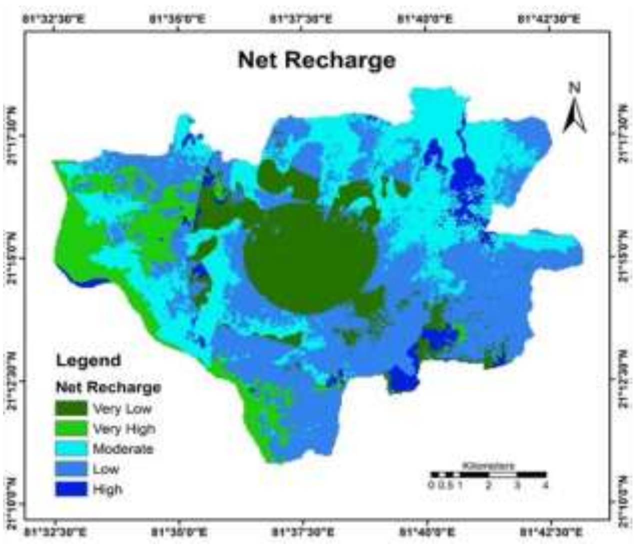

Fig. 10 Net recharge

4.3 Impact of Vadose Zone

A vadose zone media (N) map of Raipur city in Fig. 11, was developed from CGWB lithologic well data. Following guidelines, the raster map showed most areas with Stromatolitic dolomitic limestone, sandstone and clay loam. As the unsaturated zone significantly impacts vulnerability, it was given a weight of 5.

Fig. 11 Unsaturated (Vodas) zone

4.4 Soil Media

The soil media (T) in Fig. 12, significantly influences recharge. Soils in the area included gravelly sandy clay loam, sandy loam, sandy clay loam, clay, clay loam, clay sandy loam. Clay soils received the lowest rating since they decrease permeability and restrict contaminant migration. Soil was given a weight of 4.

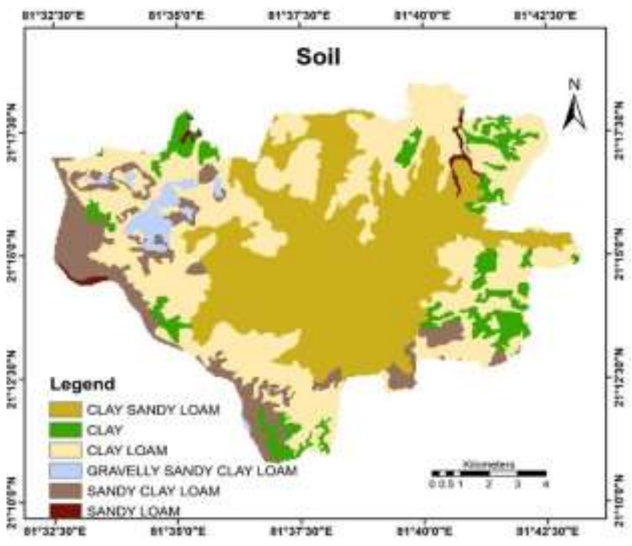

Fig. 12 Soil media

4.5 Aquifer Media

Limestone and dolomite are the main aquifer formations. The Chandi formation contains cavernous limestone. Alluvium alongside rivers also stores groundwater. Using CGWB data, an aquifer media map was generated. Dolomite and limestone have high permeability as karstic rocks. SINTACS rated laterite as 1 and stromatolitic dolomitic limestone/sandstone as 10 for the aquifer media (A) parameter, given a weight of 3 as shown in Fig. 13.

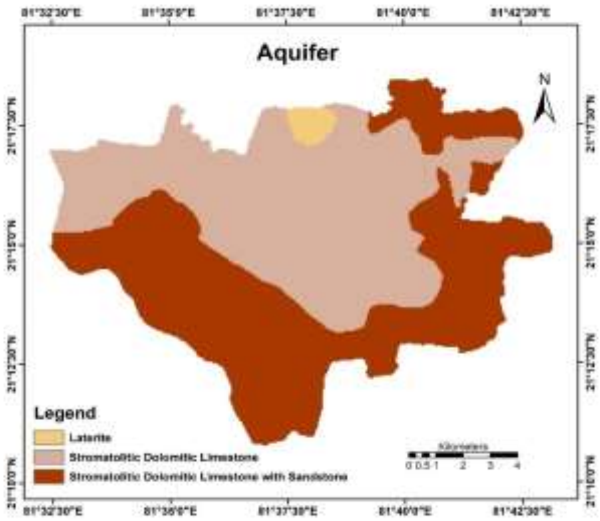

Fig. 13 Aquifer media

4.6 Hydraulic Conductivity

Contamination depends on groundwater flow rate. Hydraulic conductivity (C) in Fig. 14, data from pumping tests were used to map values for the study area using CGWB data. Conductivity in the Chhattisgarh Chandi formation ranged from 0.02-1.1 m/day and overall 0.000864-0.80 m/day. Civita and De Maio categorized values into three zones rated 1, 8, and 9 for the map, given a weight of 3.

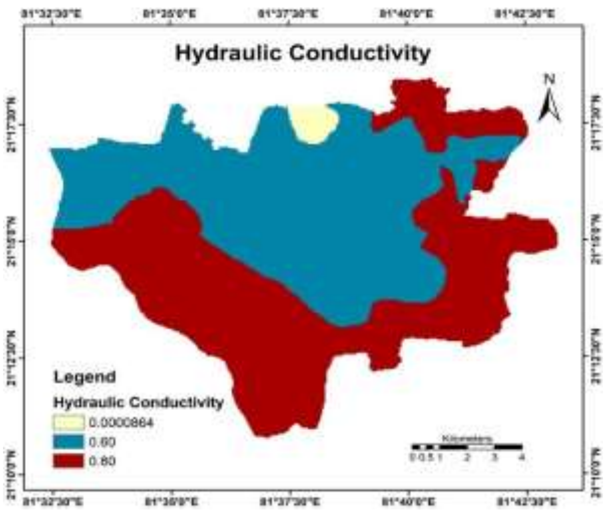

Fig. 14 Hydraulic conductivity

4.7 Topography

The slope layer was prepared using 30m NRSC CartoDEM data. Low slopes allow more infiltration while high slopes allow less. Slope values (S-parameter) were assessed on a 1-10 scale using SINTACS, with 1 as the lowest slope and 10 the maximum. Fig. 15 shows altitude decreasing from the central high area to the outer boundary. Slope was given a weight of 2 as per SVI.

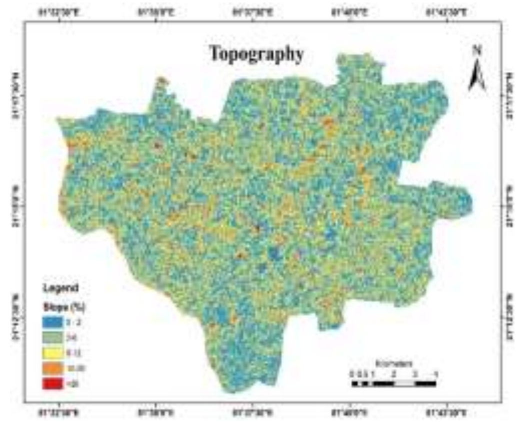

Fig. 15 Topography

4.8 Modified SINTACS method by including two parameters like lineaments and land use land cover

An improved SINTACS approach was adopted, integrating land use/cover (Lu) and lineaments (Ln) as additional parameters. Standard SINTACS uses 7 parameters, but this was modified.

LuLc mapping from satellite data identified agriculture, built up, vegetation, open land and water bodies areas. Built up and agriculture affect vulnerability as major pollutant sources.

Lineament density mapping from 0-2.12 km2 was classified into 5 categories using natural breaks. Higher density areas were given lower ratings, reflecting fracture influence.

Results showed in Table 4, that very high, low and very low vulnerability areas increased while moderate and high decreased compared to standard SINTACS. The additional Lu and Ln parameters accounted for local influences, providing a more accurate vulnerability assessment as shown in Fig. 16.

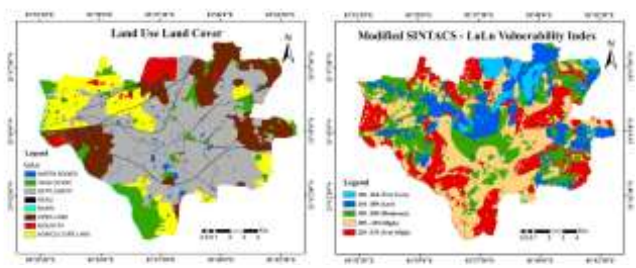

Fig. 16 SINTACS vulnerability index map and land use land cover

Table 4 Criteria for the vulnerability assessment in the MSVILuLn method.

Degree of Vulnerability	Vulnerability Index
Very low	<164
Low	164-189
Average	189-209
High	209 – 229
Very high	>229

4.9 Modified SINTACS method by including two parameters and using analytic hierarchy process

AHP, an MCDM method, was used to modify weights and ratings in Modified SINTACS for better local assessment. Table 5 shows the modified AHP weights and ratings. Vulnerability was derived using Eq. (3.7). The index ranged from 20-35. In the SINTACS-AHP map, areas under very low, low, moderate, high and very high vulnerability classes were 17.11%, 20.15%, 30.34%, 24.04% and 8.36% respectively as shown in Figure 4.13.

Table 5 Rating and weights of each parameter of MSVILuLn-AHP method for GVA.

Parameters	Sub-Parameter	Rating	AHP Weight
	0-10	10	
	10-20	7	
Depth of water table (m) (Sd)	20-30	5	0.205
	30-40	3	
	>40	1	
	Very High	10	
	High	9	
Net recharge (I)	Medium	8	0.111
	Low	6	
	Very low	2	
	Stromatolitic Dolomitic Limestone with Sandstone	9	
	Stromatolitic Dolomitic Limestone	8	
Impact of Vadose (N)	Sandy clay loam	3	0.182
	Laterite	2	
	Clay loam	1	
	Sandy loam	4	
	Gravelly sandy Clay loam	3	
	Sandy clay loam	3	
Soil Media (T)			0.057
	Clay sandy loam	2	
	Clay loam	2	
	Clay	1	
	Stromatolitic Dolomitic Limestone with Sandstone	10	
Aquifer Media (A)	Stromatolitic Dolomitic Limestone	9	0.061
	Laterite	1	
	0.80 m/day	9	
Hydraulic Conductivity (C)	0.60 m/day	8	0.107
	0.000864 m/day	1	
	Very low	10	
Slope (S)			0.035
	Low	9	
	Moderate	8	
	High	7	
	Very High	6	
	Agriculture Filed	9	
	Settlement	7	
Landuse-	Vegetation	5	0.181
Landcover (Lu)			
	Water Bodies	3	
	Open land	2	
	0-1.05	9	
	1.05-1.3	7	
Lineament (Ln)	1.3-1.5	5	0.062
	1.5-1.8	3	
	1.8-2.12	1	

4.10 Sensitivity Analysis of Modified SINTACS Method by Including Two Parameters and Using Analytic Hierarchy Process

A pairwise comparison in Fig. 17, was done between cases of different parameters: depth of water, land use, unsaturated zone, lineament and topography. Differences in alternative weights and criticality degrees of criteria that cause rank changes were observed. Sensitivity coefficients showed the unsaturated zone as the most sensitive parameter in Table 6, causing a rank reversal between depth of water and land use land cover. Overall, sensitivity analysis showed in Fig. 18, the final vulnerability assessment decision was consistent and reliable.

Table 6 Critical and Sensitivity Degree of Coefficient for rank reversal

The difference in weight of the alternative (k)	Criticality degree of criterion (Dk)	sensitivity coefficient of criterion (Sk)=1/Dk
Case V1	-	-
(Case V2) 0.042	26.85	0.037
(Case V3) 0.026	34.69	0.029
(Case V4) 0.051	47.79	0.021
(Case V5) 0.032	42.46	0.024

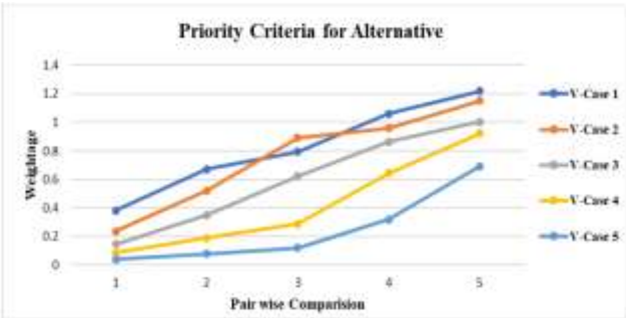

Fig. 17 Priority/Rank Criteria for alternative cases using sensitivity analysis

Table 7 Criteria for the vulnerability assessment in the MSVILuLn-AHP method

Degree of Vulnerability	Vulnerability Index
Very low	<20
Low	21-25
Average	26-30
High	31-35
Very high	>35

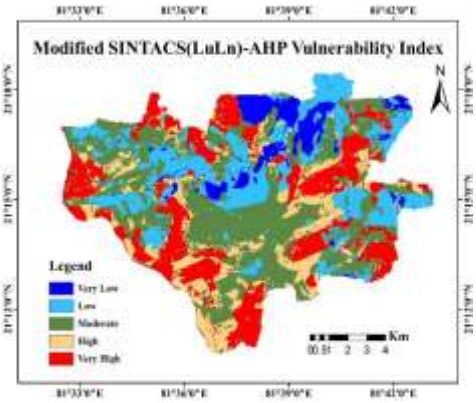

Fig. 18 Modified SINTACS-AHP vulnerability index map

ANP was used to revise Modified SINTACS weights. Parameters and sub-parameters were organized into clusters and nodes. ANP allowed comparisons between all parameters instead of just within clusters. Pairwise matrices between parameters and sub-parameters were formed to derive priorities. CR was checked to verify judgments.

The supermatrix incorporated pairwise results into frames based on parameter/sub-parameter comparisons. The weighted supermatrix multiplied this by cluster weights. Column normalization yielded the limited supermatrix with final weights.

Modified ANP weights and standard SINTACS rates were applied in Modified SINTACS(LuLn)-ANP in Fig. 19. Results showed in Table 8, very low to very high vulnerability zones of 18.24%, 16.62%, 28.12%, 26.48%, 10.54% respectively, with central/SW zones very high to high and central/NE zones moderate to very low.

Table 8 Rating and weights of each parameter of MSVILuLn-ANP method for GVA.

Parameters	Sub Parameter	ANP Weight	ANP Rating
	0-10		2.38
	10-20		1.666
Groundwater depth (m) (Sd)	20-30	0.238	1.19
	30-40		0.714
	>40		0.238
	Very High		1.180
	High		1.062
Net recharge (I)	Medium	0.118	0.944
	Low		0.708
	Very low		0.236
	Stromatolitic Dolomitic Limestone with Sandstone		1.818
	Stromatolitic Dolomitic Limestone.		1.616
Impact of Vadose (N)		0.202	
	Sandy clay loam		0.606
	Laterite		0.404
	Clay loam		0.202
Soil Media (T)	Sandy loam	0.042	0.168
	Gravelly sandy Clay loam		0.126
	Sandy clay loam		0.126
	Clay sandy loam		0.084
	Clay loam		0.084
	Clay		0.042
	Stromatolitic Dolomitic Limestone with		0.630
Aquifer Media (A)	Sandstone. Stromatolitic Dolomitic Limestone.	0.063	0.567
	Laterite		0.063
	0.80 m/day		0.738
Hydraulic Conductivity (C)	0.60 m/day	0.082	0.656
	0.000864 m/day		0.082
	0-2		0.280
	02-06		0.252
Slope (S)	06-12	0.028	0.224
	12-20		0.196
	>20		0.168
	Agriculture Filed		1.485
	Settlement		1.155
Land use Land cover (Lu)	Vegetation	0.165	0.825
	Water Bodies		0.495
	Open land		0.330
	0-1.05		0.558
	1.05-1.3		0.434
Lineament (Ln)	1.3-1.5	0.062	0.310
	1.5-1.8		0.186
	1.8-2.12		0.062

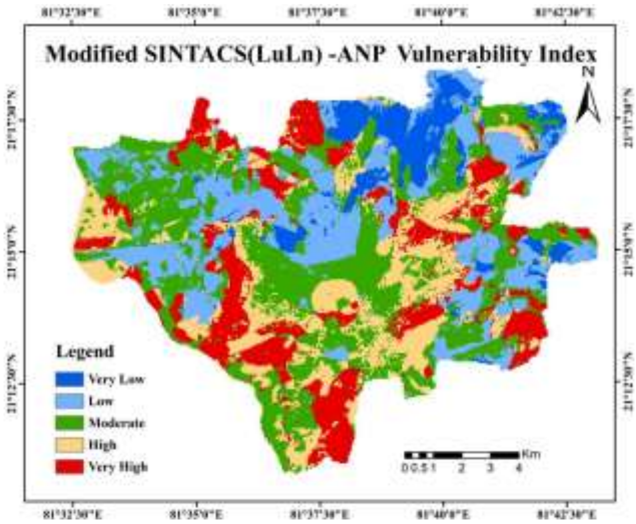

Fig. 19 Modified SINTACS-ANP vulnerability index map

Table 9 Criteria for the vulnerability assessment in the MSVILuLn-ANP method.

Degree of Vulnerability	Vulnerability Index
Very low	<7
Low	8-13
Average	14-18
High	18-22
Very high	>23

4.11 Single Parameter Sensitivity Analysis

Single parameter Sensitivity Analysis (SPSA) was applied to assess the groundwater vulnerability indexes from the 3 methods. SPSA involves varying each input parameter individually while keeping others constant to assess sensitivity and identify influential parameters and understand their impact.

The effective weight was determined by comparing a single parameter's value to the other eight parameters in Table 10, as well as the weight and rating assigned by SINTACS Vulnerability analysis (Babiker et al., 2005; Neshat et al., 2014a). The effective weight of each cell in the assessment area is calculated using Eq. 6:

$$Weffective = Px * Rx * Wx / \Sigma(Px * Rx * Wx) \quad (6)$$

Where, Weffective is the effective weight of parameter x, Px is the parameter value, Rx is the rating and Wx is the theoretical weight.

SPSA revealed depth to water, unsaturated zone, topography, hydraulic conductivity, land use, and lineament as most effective parameters with higher mean effective weights compared to their theoretical weights, showing some deviation. This indicated these parameters have more influence on the vulnerability assessment results.

Table 10 Sensitivity analysis of proposed method

Parameter	Theoretical		Min	Max	SD	Effective	
	Weight	Weight%				Weight	Weight %
Depth to water table (m) (Sd)	5	14.7	7.9	23.7	3.49	0.205	15.80
Net recharge (I)	4	11.76	5.1	13.2	3.16	0.111	11.21
Impact of Vadose (N)	5	14.7	10.2	20.1	3.64	0.182	15.15
Soil Media (T)	4	11.76	6.9	10.3	1.048	0.057	7.85
Aquifer Media (A)	3	8.82	4.2	12.4	4.23	0.061	8.34
Hydraulic Conductivity (C)	3	8.82	3.9	15.7	4.15	0.107	9.82
Topographic Slope (S)	2	5.88	2	13.9	1.58	0.035	6.95
Land use land cover (Lu)	5	14.7	4.5	21.3	2.86	0.181	15.04
Lineament (Ln)	3	8.82	4.8	12.2	2.58	0.062	9.84

4.12 Comparison of vulnerability index area between applied methods

Vulnerability zone distributions and areas using different methods (MSVILuLn, MSVILuLn-AHP, MSVILuLn-ANP) were compared based on vulnerability index and area as shown in Fig. 20, and Table 11. Very high, low and very low zones increased for MSVILuLn compared to SVI, and increased for MSVILuLn-AHP compared to MSVILuLn. For MSVILuLn-ANP, very high and very low zones increased while high, moderate, and low zones decreased compared to MSVILuLn-AHP.

Table 11 Area falling under different classes.

Vulnerability Classes	SINTACS		Modified SINTACS-LuLn		Modified SINTACS(LuLn)- AHP		Modified SINTACS (LuLn)-ANP (Proposed Method)	
	Area Sq. km	Area in%	Area Sq. km	Area in%	Area Sq. km	Area in%	Area Sq. km	Area in%
Very High	29.89	13.23	16.77	7.42	18.89	8.36	23.82	10.54
High	42.49	18.80	46.22	20.45	54.33	24.04	59.84	26.48
Moderate	41.61	18.41	53.25	23.56	68.57	30.34	63.55	28.12
Low	35.55	15.73	59.90	26.51	45.54	20.15	37.56	16.62
Very Low	76.45	33.83	50.06	22.15	38.67	17.11	41.22	18.24

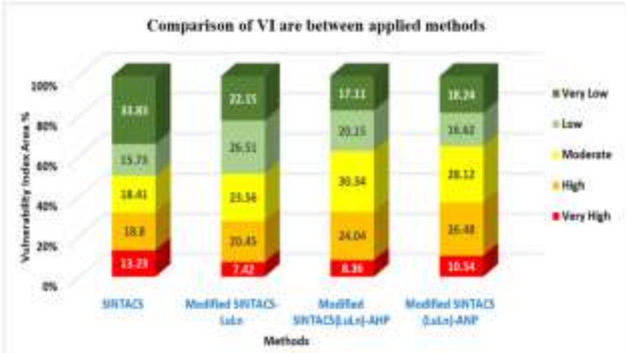

Fig. 20 Comparison of four different vulnerability index

4.13 Validation Using Nitrate Concentration

Nitrate contamination validation was done as it is a major groundwater pollutant. 48 samples from vulnerable zones were tested using UV spectrophotometer. Nitrate ranged from 8-125 mg/L, with 45mg/L the drinking limit as shown in Fig. 21.

Highly vulnerable zones showed 40-125mg/L nitrate, moderately vulnerable 15-40mg/L, and low vulnerability <15mg/L. High nitrate levels correlated with high-very high vulnerability areas.

Sample point locations in Table 12, were overlaid on vulnerability maps from different methods for comparison. This validated the effectiveness of the models in assessing contamination vulnerability. The modified SINTACS method is shown in Fig. 22.

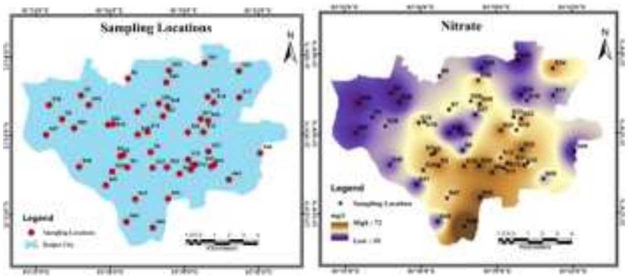

Fig. 21 Location of groundwater sample and nitrate

Table 12 Groundwater sample location points with Nitrate concentration

Sample No.	Nitrate sample (Conc. mg/l)	Sample No.	Nitrate sample (Conc. mg/l)
S1	39.72	S25	48.55
S2	36.74	S26	29.35
S3	42.15	S27	20.53
S4	20.43	S28	36.34
S5	13.5	S29	14.3
S6	25.06	S30	38.02
S7	31.32	S31	26.05
S8	21.03	S32	43.72
S9	45.77	S33	46.05
S10	42.65	S34	38.46
S11	40.87	S35	35.12
S12	41.09	S36	12.38
S13	29.09	S37	14.21
S14	10.28	S38	24.08
S15	14.02	S39	12.03
S16	28.27	S40	20.09
S17	21.05	S41	18.02
S18	23.05	S42	10.14
S19	27.69	S43	48.22
S20	13.39	S44	14.12
S21	25.32	S45	25.26
S22	40.26	S46	72.34
S23	42.06	S47	32.04
S24	35.65	S48	20.92

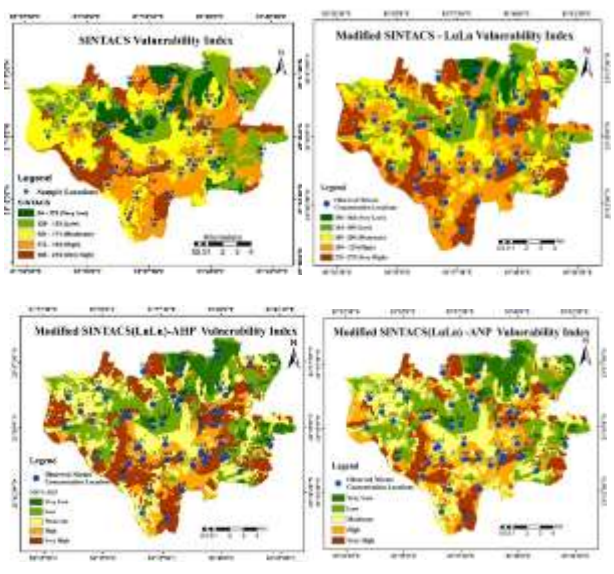

Fig. 22 Modified SINTACS

Table 13 Accuracy of the applied method using Nitrate concentration of sample point location.

	SVI	MSVILuLn	MSVILuLn-AHP	MSVILuLn-ANP (Proposed Method)
Nitrate sample	S1, S2, S6, S8,	S1, S8, S13, S17,	S8, S13, S17, S28,	S17, S35, S41, and
(Which does not	S17, S21, S25, S28,	S20, S24, S28,	S38, S41, and S45	S45
have similarities)	S34, S37, S38, S41,	S30, S34, S38, and		
	and S45	S41		
Accuracy% (similarities /total sample)	72.92	77.08	85.42	91.67

Sample points S14, S15, S21, S26, S29 showed high nitrate and vulnerability in all methods, while S4, S5, S22, S30 showed low values. S2, S7, S12, S25 were moderate.

Most high nitrate regions were agricultural, indicating fertilizers as the primary contamination source since no geological sources exist.

Correlations between vulnerability and nitrate concentration Table 13, showed:

- SINTACS accuracy was 73.4%
- Modified SINTACS was 76.7%
- MSVILuLn-AHP was 86.6%
- MSVILuLn-ANP was 90%

Modified SINTACS correlated better than SINTACS due to adding land use and lineaments. MSVILuLn-ANP correlated best as ANP weighted parameters by relative importance in the study area. Results demonstrate model efficacy and validate vulnerability assessments.

4.14 Validation Using Water Quality Index

Chloride in excess imparts a salty taste and causes laxative effects in sensitive people (Anitha et al.2011; Sadat-Noori et al. 2014). In the study area chloride concentration ranges from 30.12 mg/l to 269.77 mg/l.
Hardness is mainly due to Ca and Mg ions originating from soil and rock formations (Arumugam 2010). In the study area hardness ranges from 80.41 mg/l to 549.31 mg/l. The spatial distribution map shows 2.70 sq km exceeding the maximum desirable limit and 148.30 sq km exceeding the maximum permissible limit.

Where, C = concentration of the ion in water (mg/l), T = total hardness of water (mg/l as $CaCO3$), Ca = calcium hardness of water (mg/l as $CaCO3$), Mg = magnesium hardness of water (mg/l as $CaCO3$).
Mg concentration ranges from 4.42 mg/l to 62.47 mg/l. The spatial distribution map shows around 70.26 sq km and 156.32 sq km areas within the maximum

desirable and permissible limits respectively. The quality parameters of water is shown in Table 14,15.

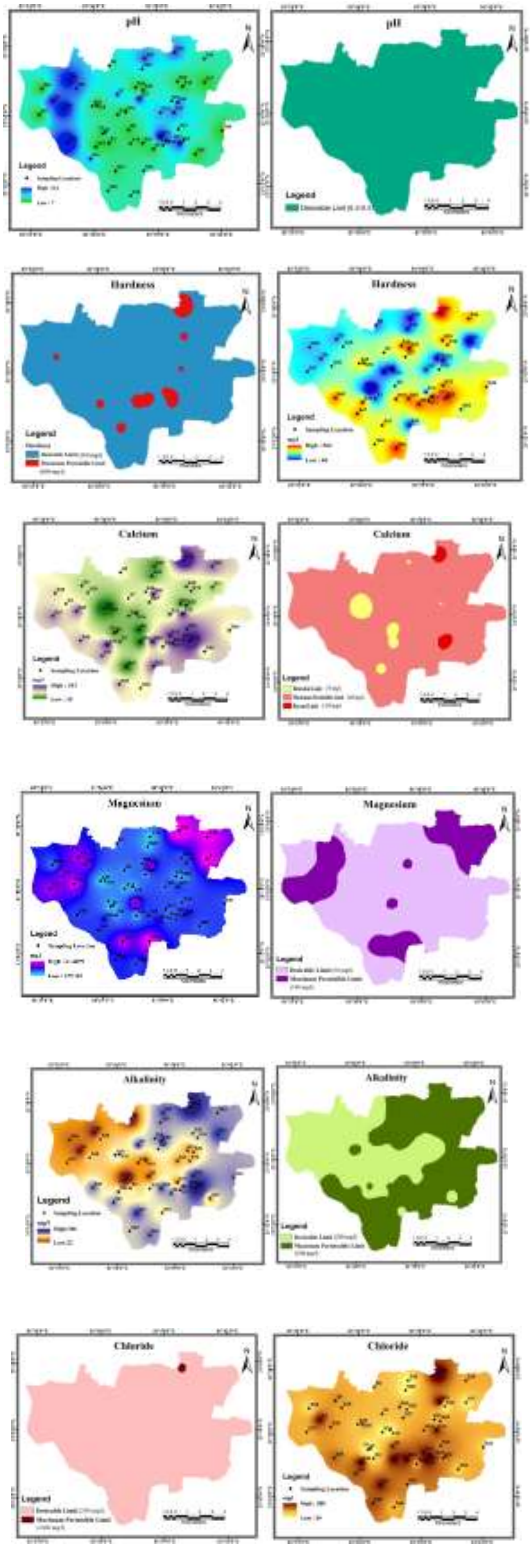

Fig. 23 Validation using water quality index

Table 14 Status of groundwater quality parameters as prescribed by BIS (2009) for drinking purpose in the Raipur city.

Parameter	BIS Standard		Suitability for drinking (Area in Km2)		Total area (Km2)
		Maximum Desirable	Maximum Permissible	Beyond Limit	
pH	6.5-8.5	7	-	-	226
Alkalinity	200-600	85.74	140.25	-	226
Hardness	200-600	2.7	148.30	-	226
Chloride (Cl)	250-1000	224.08	1.92	-	226
Calcium (Ca)	75-200	7.48	215.57	2.84	226
Magnesium (Mg)	30	156.32	70.26		226

Table 15 Normal statistics of water quality parameters of groundwater samples.

Parameters		Sample		
	Min	Max	A-Mean	Std. Dev.
pH	7	8.3	7.28	0.32
Alkalinity	23.6	394.36	203.08	71.28
Hardness	84.32	524.68	347.40	135.37
Chloride (Cl)	34.28	268.42	141.33	61.22
Nitrate	10.14	72.34	29.49	13.13
Calcium (Ca)	34.75	242.8	127.38	51.71
Magnesium (Mg)	8.96	61.74	24.62	13.10

Note: All units except pH and Electrical conductivity are in mg/l, Min-Minimum, Max-Maximum, AM- Arithmetic mean, SD-Standard deviation, CV-Coefficient variation.

4.15 Water Quality Index Model

Calculation of unit weight (Wn) by using Eq. 7, For various water quality parameters is inversely proportional to the recommended standards Sn for the corresponding parameters.

$$Wn = \frac{K}{Sn} \qquad (7)$$

where: Wn = unit weight for the nth parameters; Sn = standard value for nth parameter;

K = constant for proportionality [k=1(∑1/Sn)].

Calculation of sub index of quality rating (Qn): Let (n) there be the water quality parameters and (qn) the quality rating or sub-index corresponding to nth parameter is a number reflecting the relative value of this parameter in the polluted water with respect to its standards permissible value). The qn value of is calculated using the following Eq. 8.

$$Qn = 100\,[(Vn - Vi)\,/\,(Sn - Vi)] \qquad (8)$$

where: qn = quality rating for the nth water quality parameter; Vn = estimated value of the nth parameter at a given sampling station; Sn = standard permissible value of the nth parameter; Vi0 = ideal value of nth parameter in pure water.

$$WQI = \Sigma qnWn/\Sigma Wn \quad (9)$$

The overall water quality index was calculated by aggregating the quality rating with unit weight linearly as shown in Table 16.

Table 16 Unit weight calculation

Parameters	BIS Standards (Sn)	1/sn	∑ 1/Sn	k=1(∑1/Sn)	Wn=k/Sn	ideal value (Vo)	mean conc. Value (Vn)	Vn/Sn	Qn=Vn/Sn *100	Wn*Qn
pH	8.5	0.117	0.201	4.98	0.58	7	7.2	0.13	13.33	7.82
Alkalinity	200	0.005	0.201	4.98	0.024	0	214.72	1.07	107.36	2.67
Hardness	200	0.005	0.201	4.98	0.024	0	392.48	1.96	196.24	4.89
Chloride (Cl)	250	0.004	0.201	4.98	0.019	0	180.64	0.72	72.25	1.44
Nitrate	45	0.022	0.201	4.98	0.110	0	20.92	0.46	46.48	5.15
Calcium (Ca)-mg/l	75	0.013	0.201	4.98	0.066	0	146.78	1.95	195.70	13.01
Magnesium (Mg)	30	0.033	0.201	4.98	0.166	0	24.62	0.82	82.06	13.64
		0.201		Sum=	1.000				WQI (1)=	48

Table 17 Water quality parameter standards and relative weights

Chemical parameters	Indian Standards	Relative weight (Wn)
pH	6.5-8.5	0.587
Total hardness (TH)	300-600	0.025
Calcium	75-200	0.025
Magnesium	30-100	0.020
Alkalinity	200-600	0.111
Chloride	250-1,000	0.066
Nitrate	45-100	0.166

Water Quality Index range distribution in five range as excellent, good, poor, very poor and unfit for drinking are presented in Table 17,18. Spatial distribution of WQI is presented in Fig. 24.`

Table 18 Water quality index range of the study area

WQI Range	Water Quality	2 Area in km	Area in%
<25	Excellent	30.82	20.64
25-50	Good	69.64	46.64
50-75	Poor	39.92	26.74
75-100	Very Poor	8.93	5.98
>100	Unfit for Drinking	0.012	0.01

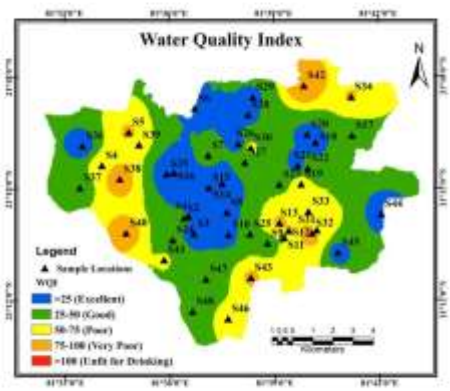

Fig. 14 Water quality index

Table 19 Accuracy of the applied method using WQI of sample point location.

	SVI	MSVILuLn	MSVILuLn-AHP	MSVILuLn-ANP (Proposed Method)
WQI (Which does not have similarities)	28	31	35	38
Accuracy% (similarities/total sample)	58.34%	64.58%	72.92%	79.16%

In the MSVILuLn-ANP method, not only the parameters are considered for comparison but also the sub-parameter effects on other parameters and the same parameter are assessed. Comparative analysis of all the approaches reveals that the city's best correlation of WQI is obtained with MSVILuLn-ANP Table 19. The overall analysis involved in ANP for modifying the parameters' weight helps better assess groundwater vulnerability in the study area.

The correlation between the methods and the validation with nitrate and the WQI index varied across different areas of the city. It was observed that specific areas within the city exhibited a strong correlation between the vulnerability assessment methods, the nitrate concentrations and WQI. Sample no. S3, S9, S10, S12, S14, S15, S16, S18, S19, S22, S26, S27, S29, S31, S39, S40, S43, and S46 shows strong correlation between the methods and good validation with Nitrate and WQI index on comparing. These areas indicated a higher level of vulnerability to groundwater contamination, as reflected by both the vulnerability index and the presence of elevated nitrate levels. This finding emphasizes the importance of incorporating multiple parameters and conducting comprehensive validation to accurately identify and assess groundwater vulnerability in different regions.

Although nitrate isn't naturally found in Raipur's city but it infiltrates the aquifer system as a result of mainly: Agricultural practices that use excessive fertilizers, Waste coming out of industries and sewages from densely populated and urbanized locality, contributing to the high vulnerability. Sample No. S3,

S9, S10, S11, S12, S17, S23, S24, S32, S33, S41, S43, S46 are having high vulnerability as these sample are distributed and mainly present either on the densely populated zone, industrial zone or agriculture land near the kharun river.

For the study region, the SVI ranges from 84 to 215 values. The resulting SINTACS Index map for the study region shows that the majority of the territory area, 33.83% is in very high vulnerability zone. The moderate vulnerability area contains 18.41% of the entire region, while the low vulnerability zone covers 13.23%. The vulnerability index map for the region in the MSVILuLn Index ranges from 106 to 275. The very high vulnerability region includes 22.15% of the total area. The moderate while the low vulnerability zone covers 7.42%.. The MSVILuLn- AHP ranges from 19.91 to 33.52 values. The resulting MSVILuLn-AHP method, index map for the study region shows that the very high vulnerability area contains 18.89% of the entire region, while the low vulnerability zone covers 8.36%. The vulnerability index map for the region in the MSVILuLn-ANP method, index ranges from 6.48 to 24.86. The very high vulnerability region includes 18.24% of the total area. The moderate vulnerability zone covers 28.12% of the area, while the very low vulnerability zone covers 10.54 %. The result shows that the areas in the very high, and very low vulnerable zones of MSVILuLn-ANP method increase by 1.61%, and 2.38%. whereas the regions of high, moderate and low vulnerable zones of MSVILuLn-ANP decrease by 0.58%, 2.22%, and 1.19% when compared to the MSVILuLn- AHP method. The change in the VI is mainly due to the consideration of the parameter land use land cover and the weightage given to parameters as per the hydrogeological condition of study area.

Conclusions

The groundwater vulnerability index (GVI) was evaluated using SINTACS (SVI), MSVILuLn, MSVILuLn-AHP, and MSVILuLn-ANP models. Results were validated using nitrate concentrations and water quality index (WQI) from 48 sampling locations.

The MSVILuLn-AHP method showed 85.42% accuracy correlating GVI and nitrate levels, and 72.92% accuracy for GVI and WQI. MSVILuLn-ANP achieved 79.12% accuracy for GVI vs. WQI. Remarkably, it showed 91.67% accuracy between GVI and nitrate concentrations, the highest of all methods.

Nitrate infiltration in Raipur's aquifer results from fertilizer use, industrial/sewage waste in densely populated areas. Central areas have low-moderate vulnerability due to less groundwater recharge. Eastern/northern parts near industries are moderately-highly vulnerable. Southeast, south and southwest agricultural regions are slightly highly vulnerable due to surface runoff accumulation.

MSVILuLn-ANP most precisely evaluated Raipur's groundwater sensitivity zones by incorporating important hydrogeological parameters like land use/cover and lineaments. SINTACS coupled with GIS provides a highly accurate spatial analysis approach.

This study aids sustainable groundwater management by identifying sensitive areas and preventing contamination through informed decision making. MSVILuLn-ANP offers a robust vulnerability assessment technique for planners and managers.

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