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Comparison of GIS-Based Intrinsic Groundwater Vulnerability Assessment Methods: DRASTIC and SINTACS

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ABSTRACT

The possibility of contaminants percolating and diffusing into the groundwater system is referred to as groundwater vulnerability. When groundwater once gets polluted it is very difficult to process/clean it so, measures must be taken to assess the vulnerability of the groundwater for effective groundwater conservation and management planning. This study aims to evaluate and map the vulnerability of Raipur city using the SINTACS and DRASTIC models and to compare their effectiveness between them. To assess the hydrogeological setting and evaluate aquifer vulnerability, each model includes seven environmental parameters (aquifer hydrogeologic features, effective infiltration, topographic slope, soil media, water table depth, unsaturated conditions, and hydraulic conductivity). The parameter data sets are evaluated in a Geographical Information system (GIS) environment to get the vulnerability index (VI), the index is categorized into five classes that show low to high vulnerability. The area under the low class for DRASTIC and SINTACS is 26.14% and 20.34% respectively whereas for the highly vulnerable class it is 15.54% and 22.54% respectively of the total area. By comparing the 15-groundwater sample value of nitrate concentration on the two vulnerability maps it was found that the SINTACS method result was shown to be significantly associated with the nitrate concentration with an accuracy of 86.7 percent.

INTRODUCTION

A good way to safeguard groundwater is vulnerability assessment since it identifies the locations that are most exposed to pollution. The actions of humans, such as farming, urbanization, and industry, have irreversibly damaged the quality of groundwater. Vulnerability is typically supposed as an "intrinsic" property of a groundwater system, determined by its sensitivity to environmental and/or human influences (Vrba & Zaporozec 1994). An aquifer's intrinsic vulnerability is the ease with which a pollutant deposited to the ground surface can reach and spread in groundwater. In the study area, the groundwater present in permeable aquifers provides the majority of water needed to meet demand. The coexistence of permeable aquifers, farming land, and industries, together with the excessive use of fertilizers in farming, effluent, and leakage from sewage has exacerbated nitrate contamination of groundwater. The amount of nitrate concentration in groundwater is regarded as a sign that the quality of the water is deteriorating.

Various methods mainly overlay/index statistical techniques, and process-based methods approaches were developed and then utilized for groundwater vulnerability assessment (GVA) (Tesoriero et al. 1998). As the information/data required for GVA is readily available over large areas, overlay/index approaches are frequently preferred (Shirazi et al. 2013). In overly and index approaches, elements (such as geology, soil, the impact of the vadose zone, etc.) that control the transport of pollutants from the ground surface into the saturated zone are mapped using existing and/or developed data. Each model depends mainly on the hydrogeological environment and aquifer characteristics. Then, each element is given a subjective numerical value (rating) based on how crucial it is for regulating the circulation of contaminants. The final vulnerability map of a region is created by linearly combining the rate maps. These techniques provide a qualitative and situational assessment of groundwater vulnerability.

DRASTIC and SINTACS are two of the most well-known and commonly utilized overlay/index approaches for evaluating GVA (Iqbal et al. 2012). The DRASTIC index model combines several thematic layers to generate vulnerability scores for various areas (Aller et al. 1987). The parameters characterization of vulnerability that was identified in the SINTACS approach is the same as those of the DRASTIC method (Civita & De Maio 1997). The key advantage of such methods is that they may be used for regional-scale evaluation since they allow for the assessment of some of the elements influencing the migration of pollutants over large areas. Geographic information systems (GIS) and Remote sensing (RS) methods were applied to collect and prepare the inputs parameter layer for the overlay/index models.

The objective of this study is to evaluate the Raipur city groundwater vulnerability using both DRASTIC and SINTACS overlay/index methods and compare the effectiveness of the method to the region. Also, it shows that combining the overlay/index method with a geographic information system (GIS) is a useful technique for determining groundwater pollution risk and managing water resources.

STUDY AREA

Raipur is the capital of Chhattisgarh state located in the central part of the state. The city is enclosed between 21°10’ to 21°20’ (N) latitudes and 81°35’ to 81°40’ (E) longitude (Fig. 1). It is around 290 m above sea level having an area of about approximately 226 km^2. According to Indian Metrological Department (IMD) Raipur, the region’s average rainfall is about 1460 mm. The city has a moist climate and is tropically dry, with warm temperatures all year. In the winter months of November to January, temperatures drop to 10°C, and in the summer months of March to May-June, temperatures can reach 48°C. The state experiences the rainy season from July to November, area depends on rain for irrigation and groundwater recharge as the main crop of the state is paddy (Rice), which is also known as the rice bowl of India. The water table depth of the city is found to be 3-40 meters below ground level (mbgl) (CGWB-Central Ground Water Board). The research region has mature soil types consisting of Inceptisols, Alfisols, and Vertisols and comes under the Seonath-Mahanadi alluvial plain. The Chandi and Gunderdehi formations can be found across the study region. The city is having many steel/iron and cement industries as the state is rich in iron ore and limestone which are raw materials for these industries.

MATERIALS AND METHODS

A vulnerability assessment has been done for Raipur city using overlay/index-based methods that are DRASTIC and SINTACS. Each method uses seven parameters for the analysis, and this parameter layer is developed in a GIS system using some hydrogeological, precipitation, and satellite image data. With the use of the prepared layer, the vulnerability index was evaluated by applying both methods as illustrated in Fig. 2.

DRASTIC Method

The DRASTIC approach evolved through the offerings of the US Environmental Protection Agency’s (USEPA) services and is based on a parameter weighting and indexing system (Aller et al. 1987). The DRASTIC is the abbreviation of seven criteria that determine the vulnerability index: Depth to water (D); Recharge (R): effective recharge of the aquifer;

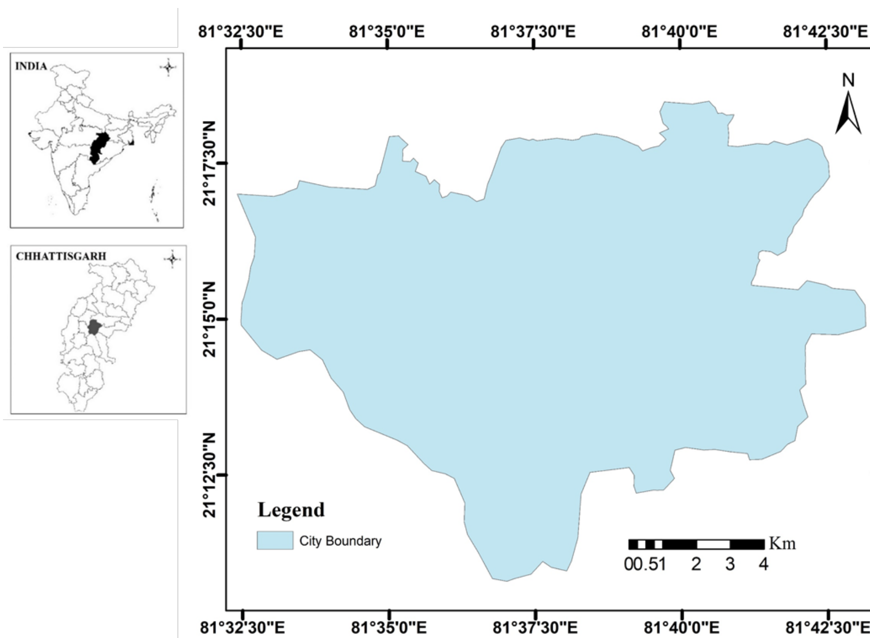

Fig. 1: The study area.

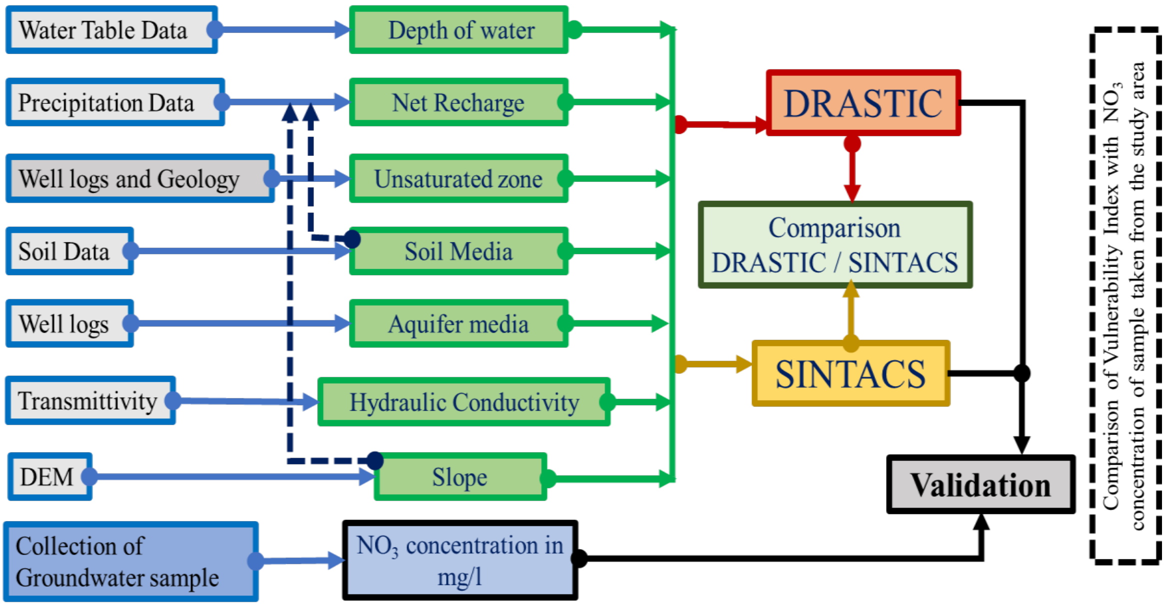

Fig. 2: Methodology flow chart.

Aquifer media (A); Soil media (S): refers to the type of soil; Topography (T): refers to the land's topographic slope; Impact of vadose zone (I): unsaturated zone; Hydraulic Conductivity of the aquifer (C).

The model generates a numerical index based on the weights and ratings applied to the seven parameters. The rate, evaluated on a 10 to 1 scale depending upon the relative effect on the vulnerability of groundwater, is represented by the significant media types or classes of individual parameters. After that, weights ranging from 1 to 5 are applied to the seven parameters to indicate their respective importance (Rahman 2008, Samey & Gang 2008, Prasad et al. 2011, Yin et al. 2013, Kazakis & Voudouris 2015, Baghapour et al. 2016). Each parameter rating for each interval was multiplied by a multiplier designated as weight, and the results were then added up to determine the final DRASTIC Vulnerability Index (DVI). The DVI is computed according to the subsequent equation (1) using ArcGIS software:

$$\text{DRASTIC VI} = (De*Dd) + (Re*Rd) + (Ae*Ad) + (Se*Sd) + (Te*Td) + (Ie*Id) + (Ce*Cd) \quad \ldots(1)$$

Table 1: Class distribution for DRASTIC method (Aller et. al 1987).

Degree of Vulnerability	Vulnerability Index
Very high	> 200
High	161 – 200
Average	121 – 160
Low	80 – 120
Very low	< 80

Where, 'd' is the weight of the parameter and 'e' is the rating, and D, R, A, S, T, I, and C are DRASTIC parameters.

SINTACS Method

SINTACS is a GVA method that employs the same parameters as DRASTIC (Rahman 2008). Using the same criteria as DRASTIC, the SINTACS approach was developed for typical Mediterranean climatic and hydrogeological environments. However, SINTACS has a more flexible rating and weighting process (Kapelj et al. 2013). The SINTACS is a tool for data and analysis optimization with a remarkable amount of versatility. It can function in a GIS setting, hence being utilized frequently in vulnerability analysis (Mali & Janža, 2005, Al Kuisi et al. 2006).

The five various weighing systems are influenced by the hydrogeological setting. The weighting systems show how important the parameters are concerning one another in various contexts, including normal, drainage, relevant, fissured, and karst. The characteristics used to evaluate vulnerability in this methodology are the same as those used in the DRASTIC method. SINTACS stands for (S)-depth of water, (I)- infiltration, (N)-unsaturated zone, (T)- soil, (A)-aquifer hydrogeological properties; (C)- hydraulic conductivity; (S)-the topographic surface's average slope (Civita & De Maio, 1997). The hydrological setting of a place is defined by the seven parameters listed above. According to the classification scale, these seven factors are further separated into ranges of 1 to 10, each of which represents a specific hydrological state (Kuisi et al. 2006, Sener & Davrez

Table 2: Weights attributed to parameters in the different scenarios of the SINTACS method (Civita 1990, Civita & De Maio 1997).

Parameter	Normal Impact	Important Drainage	Severe Impact	Cracked land	Karsts
S	5	4	5	3	2
I	4	4	5	3	5
N	5	4	4	3	1
T	4	2	5	4	3
A	3	5	3	4	5
C	3	5	2	5	5
S	2	2	2	4	5

2013). The rating given to each of these zones or ranges identifies their relative significance within each parameter in terms of increasing aquifer susceptibility. When assessing vulnerabilities, the seven characteristics are not thought to be equally significant. Weights from 1 to 5 are allocated to each of these criteria to indicate their relative importance (Table 4). The equation (2) is used to compute the SINTACS Vulnerability Index (SVI) (Al Kuisi et al. 2006, Guastaldi et al. 2014, Rutharvel Murthy et al. 2015, Al-Shatnawi et al. 2016, Jahromi et al. 2021)

$$\text{SINTACS VI} = (Se*Ss) + (Ie*Is) + (Ne*Ns) + (Te*Ts) + (Ae*As) + (Ce*Cs) + (Se*Ss) \quad ...(2)$$

Where S, I, N, T, A, C, and S are SINTACS parameters, ‘s’ and ‘e’ are the weights and rates allocated to each parameter.

Parameter Layer Preparation

Parameter layers for GVA are developed in GIS systems using precipitation, hydrogeological, and satellite data. The parameters are described below:

Depth to the Water Table

The depth of the water table is a measure of the distance between the ground’s surface and the top of the groundwater table. To acquire depth to the groundwater table layer parameter, the good data at different locations in the study region was interpolated using the Inverse Distance Weighted (IDW) method in the GIS environment (Fig. 3). The interpolation results obtained show that water depth in the area ranges from 3 to 41 meters below ground level (mbgl) Table 4. The lesser the depth of the water table from the ground more the threat of contamination from the pollutant present on the surface, in a view of its importance in GVA the weight given to the depth of water is 5.

Infiltration

The water that percolates from the surface, through the sub-surface into the water table (aquifer) is known as infiltration.

Table 3: Criteria for the vulnerability assessment in the SINTACS method (Civita & De Maio 1997).

Degree of Vulnerability	Vulnerability Index
Low	< 105
Average	105 – 186
High	186 – 210
Very high	> 210

Infiltration is crucial in evaluating the sensitivity of aquifers because it can introduce contaminants into groundwater through a variety of mechanisms, such as percolation and dilution from the saturated zone to the unsaturated zone. (Fig. 4). Formula established (Eq. 3) by Piscopo (2001) has been used for the evaluation of infiltration. A net recharge layer parameter was created using data on average rainfall (mm), soil permeability($m.day^{-1}$), and slope (%) percentage in a GIS framework (Table 4).

$$\text{Recharge value} = \text{Rainfall} + \text{Slope\%} + \text{Soil permeability} \quad ...(3)$$

Unsaturated Zone

The unsaturated zone is the area that is above the water table and below the typical soil horizon. Based on the interpretation of the lithological drilling data, the impact parameter of the unsaturated zone is evaluated. One of the most important factors in assessing susceptibility is the unsaturated zone parameter and hence the weight given to it is 5 according to its relative importance in evaluating the GVA (Fig. 5).

Soil

The topmost part of the unsaturated zone is referred to as the soil, which is also the primary layer of the physio-chemical

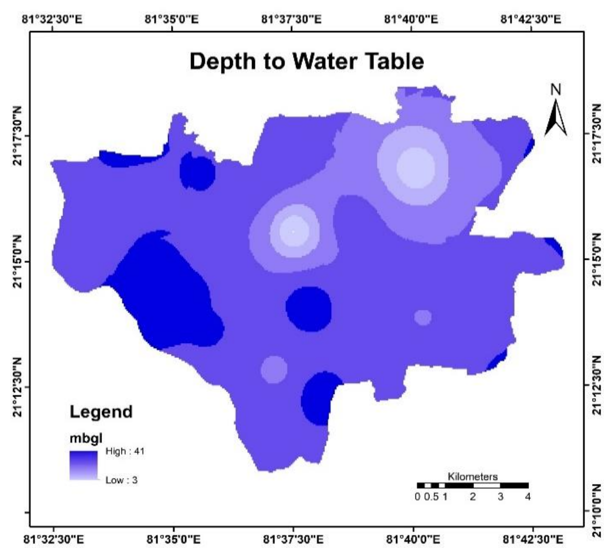

Fig. 3: Depth of the water table.

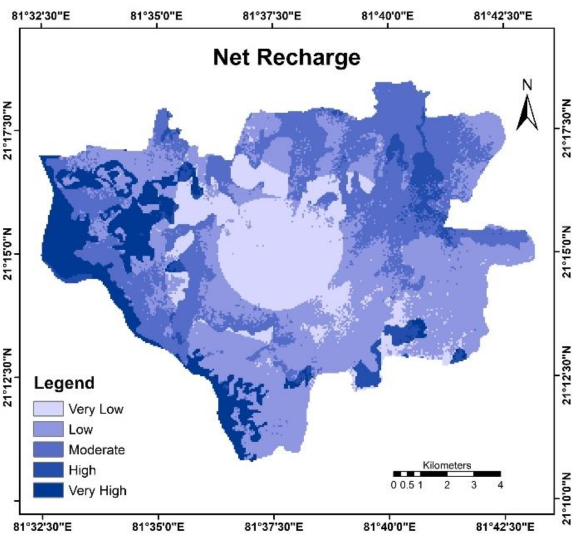

Fig. 4: Net recharge.

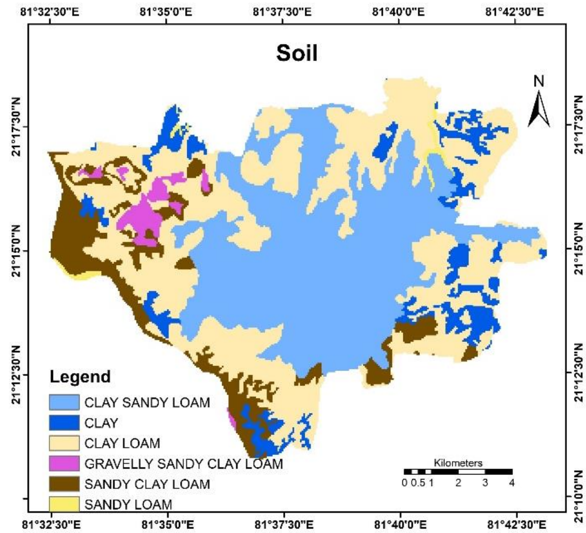

Fig. 6: Soil.

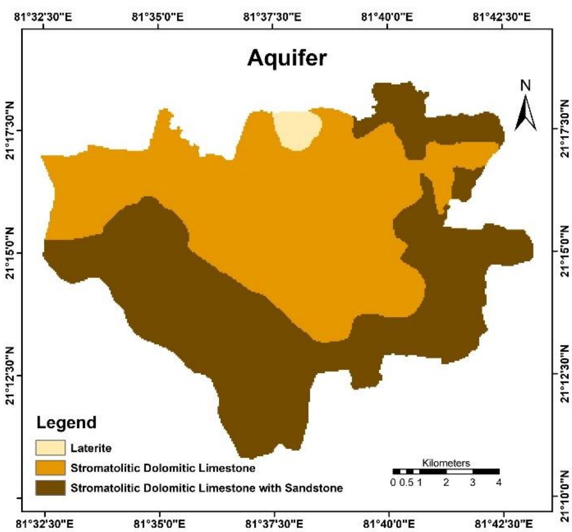

Fig. 5: Aquifer.

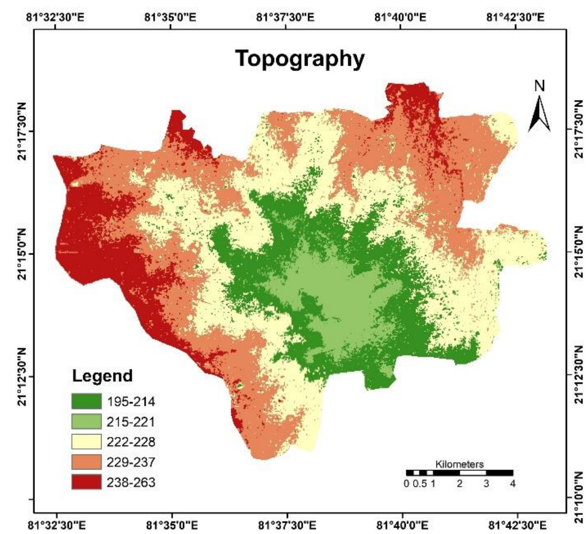

Fig. 7: Topography.

interface between potential pollutants and the subsoil (vadose zone). The soil significantly affects how much recharge can penetrate the groundwater and, as a result, how easily contaminants can travel into the unsaturated zone (Srinivasamoorthy et al. 2011). Additionally, where the zone of soil is sufficiently broad, the processes of volatilization, filtration, and sorption are highly important and are to be considered during analysis. The study area's soil is divided into six subgroups, as indicated in Fig. 6, including clay sandy loam, and clay loam and its rating and weights are depicted for both cases (DRASTIC and SINTACS) in Table 4.

Aquifer

An aquifer has enough saturated permeable material to produce a sizable amount of water for springs or wells. The drilling well records and geological map data of the basin were applied to develop the aquifer layer. The aquifer media in the study basin was divided into three regions (Mali & Janža 2005, Kumar et al. 2013, Busico et al. 2017). The study area contains mainly three aquifer types that are Stromatolitic Limestone with Sandstone, Stromatolitic Dolomitic Limestone, and Laterite as shown in Fig. 7, whereas its rating and weights are represented in Table 4.

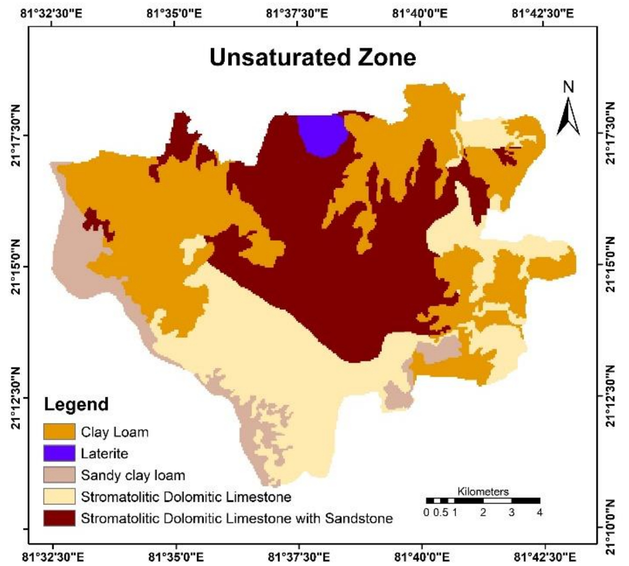

Fig. 8: Unsaturated zone.

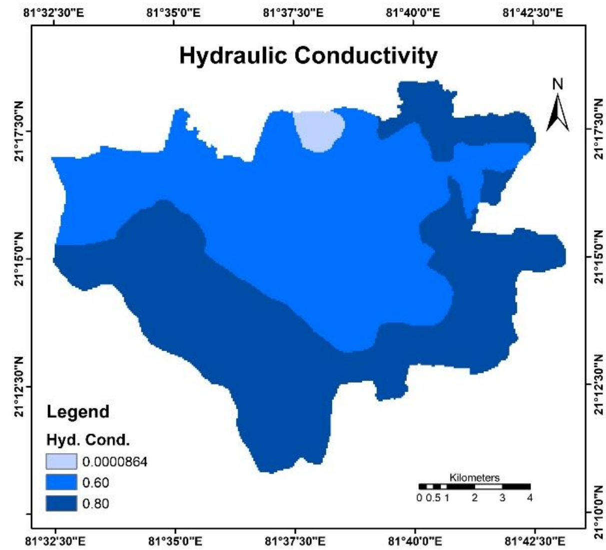

Fig. 9: Hydraulic Conductivity.

Topography

In terms of vulnerability assessment, the slope of the bed or topography influences whether water and contaminants will preferentially drain off or stay on the surface for enough time to penetrate (Kapelj et al. 2013). If the slope is low the runoff rate will be low and the deposition of water will be there which will ultimately lead to an aquifer through the subsurface layer. Using the CartoSAT Digital Elevation Model (DEM), which has a resolution of 30m, it is possible to determine the topographical slope in the GIS environment. Fig. 8 demonstrates the area's gradient, weight, and rate for both methods are shown in Table 4.

Hydraulic Conductivity

The hydraulic conductivity of the aquifer is a gauge of its water-carrying capacity. This property controls how quickly groundwater will flow when subjected to a particular hydraulic gradient; higher conductivity levels often equate to high sensitivity to pollutants (Fig. 9). The parameter layer was prepared using the data obtained from CGWB through GIS analysis.

RESULTS AND DISCUSSION

The seven parameter layers were put together using Equations (1) and (2) to calculate the DRASTIC and SINTACS vulnerability index of Raipur city. The Vulnerability index of DRASTIC for the region of study is 70 to 207 as the vulnerability index of the SINTACS method ranges from 84 to 215 (Fig. 10 and 11).

The acquired vulnerability map illustrates the different levels of aquifers' sensitivity to contamination. The result is standardized and divided into five classes. Both DRASTIC and SINTACS-based categories are termed as low, very low, high, very high, and moderate vulnerability (Fig. 10 and 11). The result obtains from the DRASTIC method shows that 26.14% i.e 59.08 km^2 of the complete region demonstrate low susceptibility, 42.75% 96.62 km^2 indicates moderate vulnerability and 10.25% that is 23.17 km^2 of the study region is having vulnerability in the very-high range (Table 5). The outcome of SINTACS VI shows that out of 226 km^2 area 20.34% which is 45.97 km^2 contributes to low vulnerability, 36.4% which is 82.26 km^2 of the entire area indicates moderate vulnerability and 12.26% which is 27.71km^2 of the section is demonstrating vulnerability in a very high zone (Table 5).

To identify areas that belonged to the same or different categories of vulnerability classes, the findings from the DRASTIC and SINTACS models were compared.VI obtained from each model are compared pixel by pixel for the five-vulnerability class done in ArcGIS. Fig.-12 represents the difference in vulnerability classes in both methods. The comparison result is categorized into 3 groups, the pixel with no difference in VI is placed under the No difference class, with ±10 change in pixel value kept under slight difference whereas if the change is between 10 to 24 it is kept under moderate. According to the analysis, there is only a slight difference between low (DVI) and low (SVI) classes, and moderate (DVI) to moderate (SVI) classes, although there is an average difference between higher classes.

Table 4: The DRASTIC and SINTACS models' rating and weighting of each parameter (Aller et al. 1987, Civita & De Maio, 1997).

Parameters	Sub-Parameter	DRASTIC			SINTACS		
		Rating	Weight	Index rating	Rating	Weight	Index rating
Groundwater depth	0-10	10	5	50	10		50
[m] [Sd]	10-20	8		40	7	5	35
	20-30	6		30	5		25
	30-40	3		15	3		15
	>40	1		5	1		5
Net recharge (I)	Very-high	10		40	10		40
	High	9		36	9	4	36
	Medium	7	4	28	8		32
	Low	5		20	6		24
	Very-low	2		8	2		8
Impact of Vadose (N)	Stromatolitic lime and dolomite with flaggy limestone	9	5	45	9	5	45
	Stromatolitic limestone and dolomite	7		35	8		40
	Sandy clay loam	3		15	3		15
	Laterite	2		10	2		10
	Clay loam	1		5	1		5
Soil Media (T)	Sandy loam	5		10	4		16
	Gravelly sandy Clay loam	3	2	6	3	4	12
	Sandy clay loam	3		6	3		12
	Clay sandy loam	2		4	2		8
	Clay loam	2		4	2		8
	Clay	1		2	1		4
Aquifer Media (A)	Stromatolitic limestone with Sandstone	10	3	30	10	3	30
	Stromatolitic dolomitic lime-stone	9		27	9		27
	Laterite	1		3	1		3
Hydraulic	0.80 $m.day^{-1}$	9		27	9		27
Conductivity (C)	0.60 $m.day^{-1}$	8	3	24	8	3	24
	0.000864 $m.day^{-1}$	1		3	1		3
Slope (S)	Very low	10		10	10		20
	Low	9	1	9	9	2	18
	Moderate	7		7	8		16
	High	6		6	7		14
	Very High	5		5	6		12

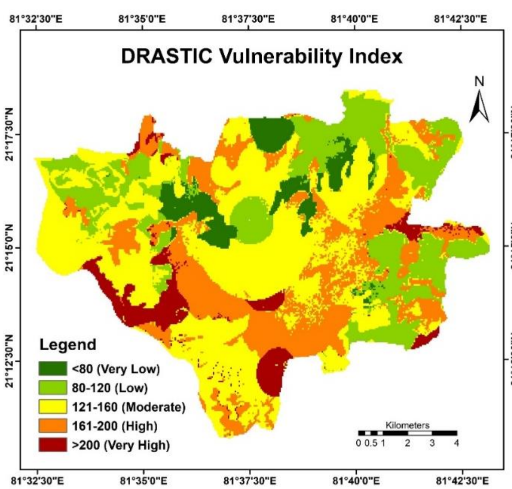

Fig. 10: DRASTIC Vulnerability Index.

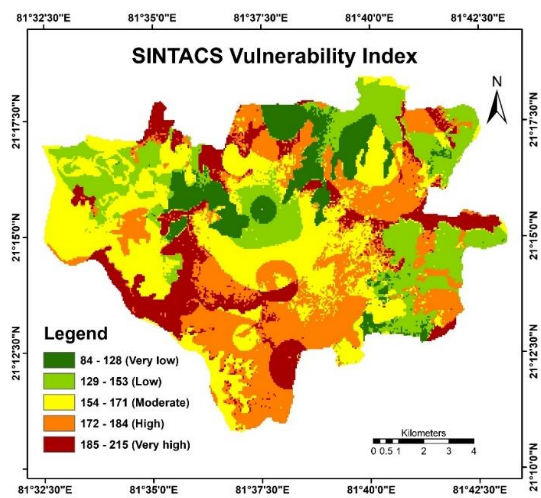

Fig. 11: SINTACS Vulnerability Index.

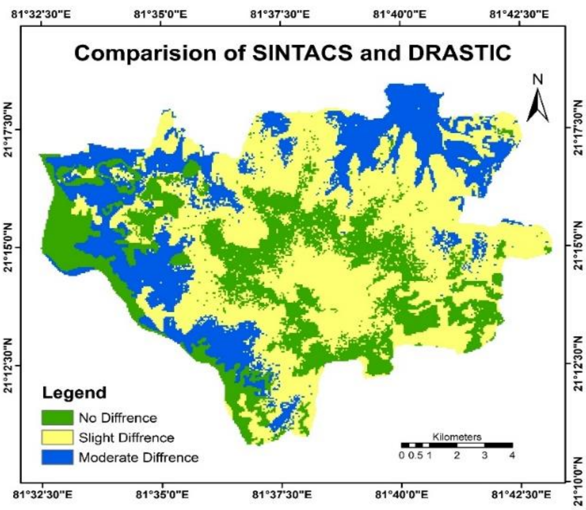

Fig. 12: Comparison of SINTACS, DRASTIC vulnerability index.

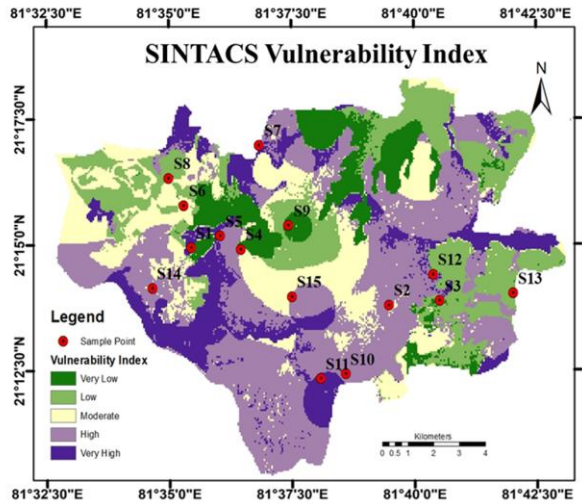

Fig. 13: Nitrate sample point location.

Table 5: Vulnerability index range categorization.

Classes	DRASTIC		SINTACS	
	Area [%]	Area [km^2]	Area [%]	Area [km^2]
Very Low	5.32	12.02	8.46	19.12
Low	26.14	59.08	20.34	45.97
Moderate	42.75	96.62	36.4	82.26
High	15.54	35.12	22.54	50.94
Very High	10.25	23.17	12.26	27.71

VALIDATION

For a more accurate evaluation, the vulnerability index maps generated by the overlay and index method (DVI and SVI) can be compared and validated with the field measurements of the physical and chemical properties of groundwater. Nitrate concentrations in groundwater are viewed as a warning that the water's quality is declining. The level of nitrate discovered in the region, which is one of the main groundwater pollutants, validated the

Table 6: Nitrogen concentrations at various sample sites and their associated vulnerability index.

Location (Latitude) E	(Longitude)N	Sample number	Nitrate concentration [mg.L^{-1}]	class	DRASTIC Vulnerability Index	SINTAC Vulnerability Index
81.5884	21.2527	S-1	48.12	h	H(Similar)	H(Similar)
81.6058	21.2522	S-2	64.34	h	H(Similar)	H(Similar)
81.5986	21.2565	S-3	14.20	l	M(Dissimilar)	M(Dissimilar)
81.5805	21.2752	S-4	10.86	l	L(Similar)	L(Similar)
81.6224	21.2600	S-5	32.45	m	H(Dissimilar)	M(Similar)
81.6422	21.2124	S-6	21.64	m	M(Similar)	M(Similar)
81.6336	21.2108	S-7	52.36	h	H(Similar)	H(Similar)
81.6731	21.2442	S-8	29.3	m	L(Dissimilar)	M(Similar)
81.5746	21.2396	S-9	9.2	l	L(Similar)	L(Similar)
81.6237	21.2371	S-10	24.46	m	H(Dissimilar)	M(Similar)
81.6338	21.2107	S-11	68.26	h	H(Similar)	H(Similar)
81.6730	21.2443	S-12	84.34	h	H(Similar)	H(Similar)
81.7010	21.2384	S-13	12.52	l	L(Similar)	L(Similar)
81.5748	21.2398	S-14	40.62	m	M(Similar)	H(Dissimilar)
81.6237	21.2371	S-15	10.34	l	M(Dissimilar)	L(Similar)

Note: 1. DVI and SVI- (L = low, M = moderate, H = high); 2. Nitrate Conc.- (l = low, m = moderate, h = high)

Table 7: Accuracy of the applied methods using Nitrate concentration of sample point location**.**

	DRASTIC	SINTACS
Nitrate sample (Which does not have similarities)	S5, S8, S10, and S15	S3 and S14
Accuracy % (similarities/total sample)	73.4	86.7

delineated groundwater-sensitive zones (Ramesh & Elango 2012, Kumar et al. 2013, Neshat & Pradhan 2017, Noori et al. 2018). Although nitrate is not naturally present in groundwater, excessive fertilizer uses in agricultural practices, leakage from the septic tank and sewage, and effluent from industries cause it to contaminate the aquifer system. To determine the model's efficacy in determining groundwater vulnerability to pollution, the association between the GVA model (DRASTIC, SINTACS), and groundwater nitrate levels was examined (Table 6). In the study area's identified groundwater risk zones, 15 groundwater samples were therefore collected from the various wells (Table 6). The Ultraviolet Spectrophotometric Screening Method (4500-NO3-B) was used to evaluate the nitrate concentration (Fig. 13). The results of the chemical analysis show that NO3 concentrations for all groundwater samples range from 9 $mg.L^{-1}$ to 125 $mg.L^{-1}$. Given that according to (IS:10500) Drinking Water Standards, the highest permissible and most acceptable nitrate limit that is suitable for human consumption is 45 $mg.L^{-1}$. Groundwater with nitrate concentrations over that level is dangerous for human consumption. In comparing the concentration of nitrate found at the location and the VI obtain from the analysis, the SINTACS method shows better accuracy (Table 7).

CONCLUSION

The overlay/index method combined with GIS is a highly precise way of determining how sensitive groundwater is to contamination. The study region's following DRASTIC and SINTACS maps show that the majority of the area; 42.75 percent and 36.4%, respectively are in the intermediate vulnerability zone. The yearly net recharge, which is 250+mm, is the main cause of the extremely high vulnerability with a high rate near industrial areas (chemical pollutants and wastewater) and the agricultural land (use of pesticides for farming) are the major reason for the high VI of those particular regions. In addition, the Unsaturated/ Vodas zone is also a factor contributing to vulnerability most of the area contains limestone with Sandstone making it simpler for water to infiltrate into the ground. The results obtained from the DRASTIC and SINTACS models were compared to pinpoint regions that fell into the same or different categories of vulnerability classes. From the analysis, it is found that there is a slight difference in the low (DVI) to low (SVI) class and moderate (DVI) to moderate (SVI) class, whereas it is an average difference in a higher class.

On comparing the 15-groundwater sample value of Nitrate concentration on the two maps we find that the SINTACS model gives the best result and more than 60% of the area comes under the low and moderate vulnerability class. The SINTACS results were shown to be significantly associated with the nitrate concentration of groundwater sample collected from the study area, with an accuracy of 86.7 percent, and is more suitable for evaluating Raipur's groundwater-sensitive zones.

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