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Groundwater vulnerability mapping using modified DRASTIC ANP

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Research paper

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Groundwater vulnerability mapping using modified DRASTIC ANP

Groundwater vulnerable zones in phreatic aquifers of Nagpur city in India were evaluated using the modified DRASTIC method in the Geographical Information System (GIS) environment. In the present research, the ANP was applied for the first time to DRASTIC parameters for weight modification. Vulnerable groundwater zones obtained from various DRASTIC approaches were compared and validated using field data on nitrate concentration. A better correlation was established with the proposed Modified DRASTIC ANP procedure.

Key words:
AHP, ANP, DRASTIC, GIS, Groundwater Vulnerability, Nitrate

Znanstveni rad - Prethodno priopćenje

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Kartiranje osjetljivosti podzemnih voda pomoću modificiranog postupka DRASTIC ANP

Ocjenjivanje zona osjetljivosti podzemnih voda u freatskom vodonosniku grada Nagpura u Indiji provedeno je pomoću modificirane metode DRASTIC u okruženju geografskog informacijskog sustava (GIS). U ovom se radu proces ANP po prvi put primjenjuje za modificiranje pondera parametara u okviru metode DRASTIC. Zone osjetljivosti podzemne vode, dobivene na temelju raznih pristupa DRASTIC, uspoređuju se i potvrđuju pomoću terenskih podataka o koncentraciji nitrata. Bolja korelacija uspostavljena je primjenom predloženog modificiranog postupka DRASTIC ANP.

Ključne riječi:
AHP, ANP, DRASTIC, GIS, osjetljivost podzemne vode, nitrat

Forschungsbericht

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Grundwasserempfindlichkeitsdiagramm mithilfe des modifizierten DRASTIC ANP Verfahrens

Die Bewertung der Grundwasserempfindlichkeitszonen im unterirdischen Grundwasserleiter der Stadt Nagpura in Indien wurde mithilfe der modifizierten Methode DRASTIC in der Umgebung des geografischen Informationssystems (GIS) durchgeführt. In dieser Abhandlung wird der Arbeitsprozess ANP zum ersten Mal für die Modifizierung der Gewichtung der Parameter im Rahmen der Methode DRASTIC angewendet. Die Grundwasserempfindlichkeitszonen, die aufgrund unterschiedlicher Ansätze des DRASTIC erhalten wurden, werden verglichen und mithilfe der Felddaten über die Nitratkonzentration bestätigt. Eine bessere Korrelation wurde durch Anwendung des empfohlenen modifizierten Verfahrens DRASTIC ANP eingerichtet.

Schlüsselwörter:
AHP, ANP, DRASTIC, GIS, Grundwasserempfindlichkeit, Nitrat

1. Introduction

Groundwater is an important resource that resides within different stratigraphic layers below the earth surface. In addition to concerns about groundwater quantity, the overall quality of groundwater in aquifers is also a serious environmental issue. Due to increasing urbanization, the use of chemicals in daily activities negatively affects the quality of groundwater [1], as the disposal of the used water is operated at random. The use of groundwater is increasing significantly in the areas where the municipal water supply is limited in scope or is polluted. The primary concept that groundwater is non-vulnerable was inspired by the aquiclude characteristics that act as a protection filter [2]. Contaminants in water can be controlled at the source, before their infiltration, but once the contaminant has entered, the control of its properties is very difficult and sometimes even impossible [3].

With the growing awareness about importance of groundwater resources, attempts are being made to reduce, prevent and eliminate groundwater contamination [4]. Groundwater protection is essential for an effective management of groundwater resources. These protection goals can be achieved through assessment of groundwater vulnerability [5]. Attempts have been made by various researchers to map vulnerability of an area through combination of hydro-geological factors, anthropogenic influences and sources of contamination in the area under study [6].

Numerous methodologies are available in literature for estimation of groundwater vulnerability of an area. They include GOD [7], DRASTIC [8], SINTACS [9] etc., which are selected on the basis of availability of data. DRASTIC is one of the better known and extensively used overlay index methods that is applied worldwide for groundwater vulnerability assessment [10-12]. It was developed by the United States Environment Protection Agency (USEPA). In DRASTIC, seven hydrogeological parameters are used to assess groundwater vulnerability of an area, and the method is suitable for both karstic [13, 14] and porous aquifers [15]. The resulting vulnerability maps produced by DRASTIC are region specific, and so can not be used for various hydrogeological settings. To reduce the subjectivity of DRASTIC method and to enable better prediction of groundwater vulnerability, various modifications have been applied depending on the characteristics of the area under study. In recent studies some new important parameters, such as land use/land cover, lineament, etc., are included in the standard DRASTIC [2, 5] so as to permit better evaluation of groundwater vulnerability using these additional factors as well. DRASTIC rates and weights are modified depending on regional importance of the parameters. Various approaches have been used for modification, including the Wilcoxon Rank

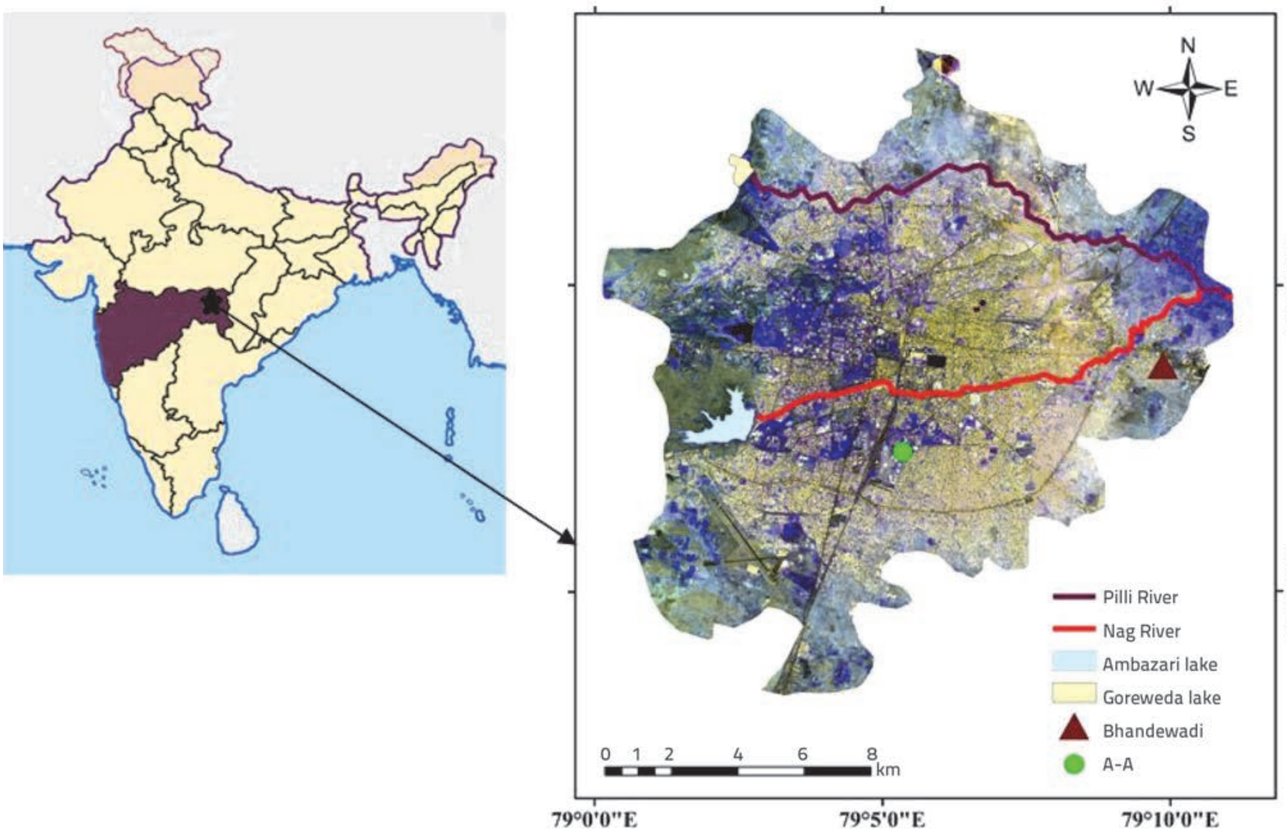


Figure 1. Location of the study area

Sum non-parametric statistical test [16], Analytical Hierarchy Process (AHP) [2, 17, 18], Discriminant Analysis [11], etc. The Single Parameter Sensitivity Analysis (SPSA) is used [19] to determine the influence of individual parameters on other parameters, and on the vulnerability index.

As a highly urbanized city, Nagpur (Maharashtra state, India) is faced with the problem of over-exploitation and low quality of groundwater in various regions. The groundwater quality data from monitoring wells located within boundaries of the Nagpur Municipal Corporation (NMC) are investigated to analyse the actual condition of groundwater in urban settings. The data received from the Central Ground Water Board (CGWB) reveal that the monitoring wells of the city are affected by high nitrate concentrations. Other field parameters documented in the CGWB reports, such as pH, Total Hardness (TH), Total Dissolved Solids (TDS), etc., are well within permissible limits, except at several isolated pockets (areas).

The city is named after the Nag River (Figure 1), which is now becoming one of the major sources of pollution affecting quality of groundwater in the city area. Due to disposal of untreated sewage from households, poultry farms, small industries etc., the Nag River has been turning into a veritable sewage disposal drain since the last decade. The Nag River runs through the city from west to east. Chemical analysis results reveal that the higher nitrate contamination is present in the adjoining areas near the Nag River and in the eastern zone of the city near Bhandewadi (a waste disposal site) [20]. The solid waste collected from different localities of Nagpur city is dumped at Bhandewadi (Figure 1). The recharge through this site results in harmful contaminants that pollute the groundwater. Groundwater management and planning is very difficult due to its invisibility in nature, and it can be done more efficiently at regional levels, taking into account local parameters. The groundwater vulnerability assessment has to be made for Nagpur city so as to enable creation of effective local development policies.

On the basis of the aforesaid studies and available literature, it can be stated that no scientific study has so far been made using the Analytic Network Process (ANP) and the DRASTIC method for the purposes of groundwater vulnerability assessment. The aim of the present study is to assess groundwater vulnerability in Nagpur using the DRASTIC and its modification featuring the ANP algorithm.

2. Characterization of study area

The city of Nagpur is located at the geographical centre of India designated with the zero mile stone. It lies between 21°00' - 21°15' North and 79°00' - 79°15' East at an altitude of 310 m AMSL [21]. Nagpur is a centrally urbanized city occupying an area of about 218 sq. km, with a population of nearly 2,405,665. The city comprises a stratigraphy formed by Deccan Traps (57 %), Archeans Formation (23 %), Gondwana rocks (12 %) and Lameta Formation (8 %) [22]. Most of the aquifer can be identified within the bedrock having an appropriate water bearing capacity. The western part of the city is characterised by aquifers comprising gneiss, granite, etc. Sandstone aquifers are located in the north-east of the city that possesses both primary and secondary porosities, which increase its water bearing capacity. The central and north-south part of the city is covered by Lameta Formation. Geologically, the area is composed of basaltic flows of Deccan Traps origin, separated by Intertrappean Beds. Figure 2 shows lithological section marked in Figure 1, which gives a general idea about the strata in the study area. The city follows a steeper topography in the west and mild to flat in the east. The Nag River and the Pilli River are two major water bodies flowing through the urban setting of the city (Figure 1). The Nag River originates from Ambazari Lake and joins the Pili River originating from Gorewada Lake before joining the Kanhan River in Wainganga, sub-basin of Godavari. The city experiences extremely hot summers with temperatures rising up to 45°C, and cold winters with temperature falling to 12°C. The average annual rainfall in the area is nearly 1000 mm.

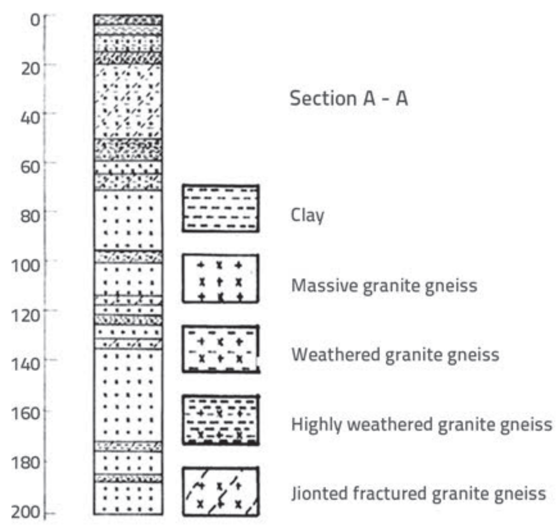


Figure 2. Lithological section A-A [23]

3. Materials and methods

3.1. DRASTIC

The DRASTIC overlay and index method is used to assess the intrinsic vulnerability of groundwater by considering known properties of the aquifers. The DRASTIC method considers the following parameters: Depth to water table (D), Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (V), and Hydraulic conductivity (C). The Delphi technique is used to assign the rates and weights of the parameters already documented in [8].

The parameters are classified into several subparameters depending on characteristics of an area. Each subparameter is rated on the scale of 1 to 10 on the basis of its relative effect on groundwater vulnerability. Weights are assigned to parameters from 1 to 5, depending on their importance for the assessment of groundwater vulnerability (Table 1). The vulnerability index (VI) is evaluated by linear combination of all parameters , Eq. (1):

$$VI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where, VI is the Vulnerability Index that is used to assess groundwater vulnerability, and the sub-scripts r and w indicate ratings and weights of the parameter, respectively.
All parametric and vulnerability maps were prepared by GIS technique using the ArcGIS 10 software. The block diagram shown in Figure 3 explains logical sequence of the method. The resulting vulnerability map of the study area is divided into five vulnerable zones showing vulnerability index for different areas. The Natural Breaks (Jenks) method is used for classification of vulnerability maps. The DRASTIC method can be adapted to various geological and hydrogeological contexts in order to obtain realistic output. Some new parameters can be added or several standard parameters can be removed depending on the area under study [5].
The controlling parameters of aquifers are used to assess vulnerability of the city of Nagpur using the DRASTIC approach. The data used for processing have been collected from different government agencies, authorised government web-sites, and previous research projects.

Depth to water table (D)
The depth to water level is the depth that a contaminant must travel to before reaching the groundwater. The greater the depth, the smaller are the chances of contamination, and vice versa. The data on 45 monitoring wells located at various locations within the city limits, provided by the Central Ground Water Board (CGWB), were used to form a thematic map. The collected data are a statistical discrete information. The Kriging interpolation tool in GIS was used to digitize the spatial variation of water level within city limits. The defined depth to water table map has 2x2 m resolution which varies from 0.7 m to 15.2 m below the ground level. The rating was made using the technique proposed in [8] (Figure 4).

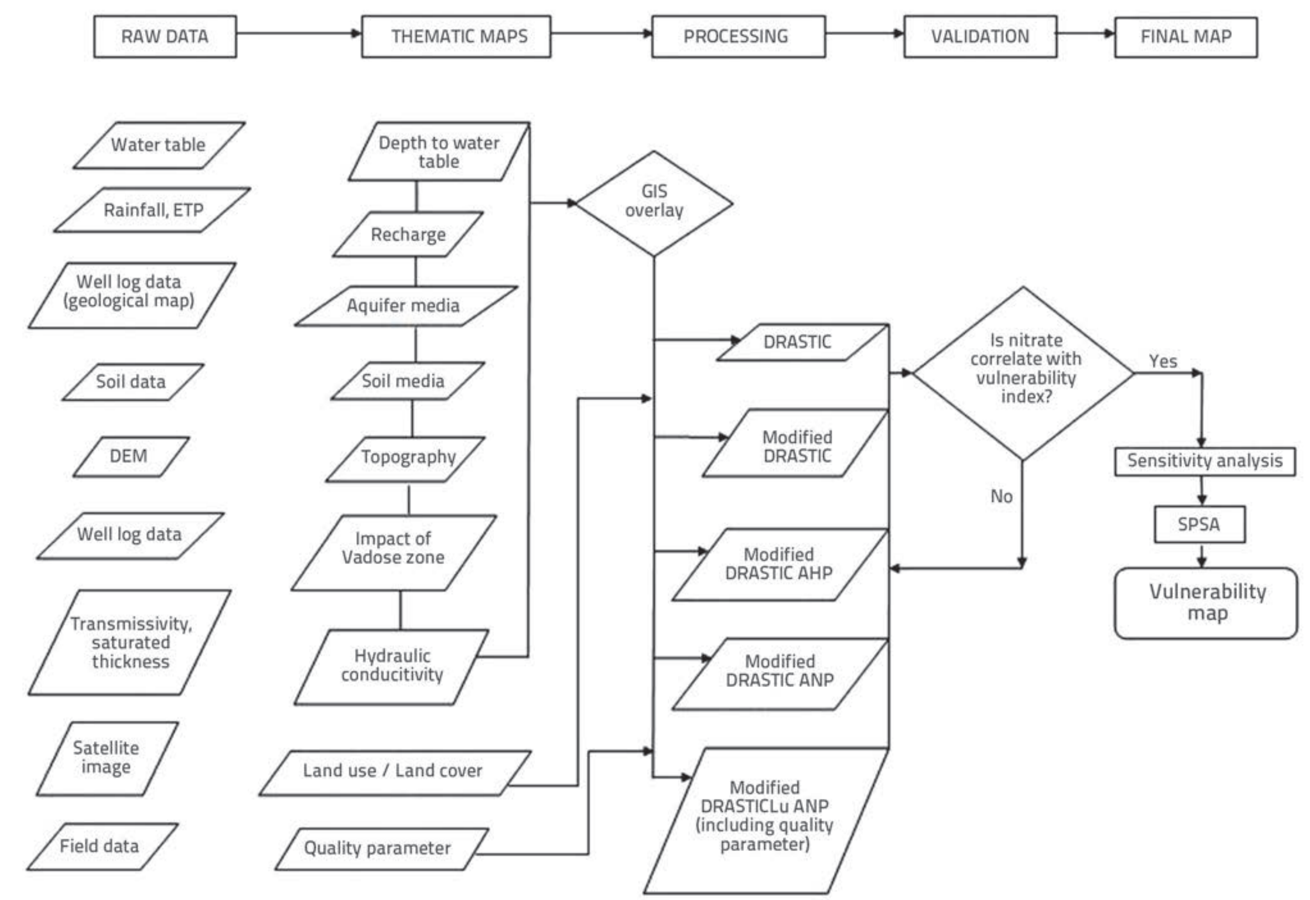
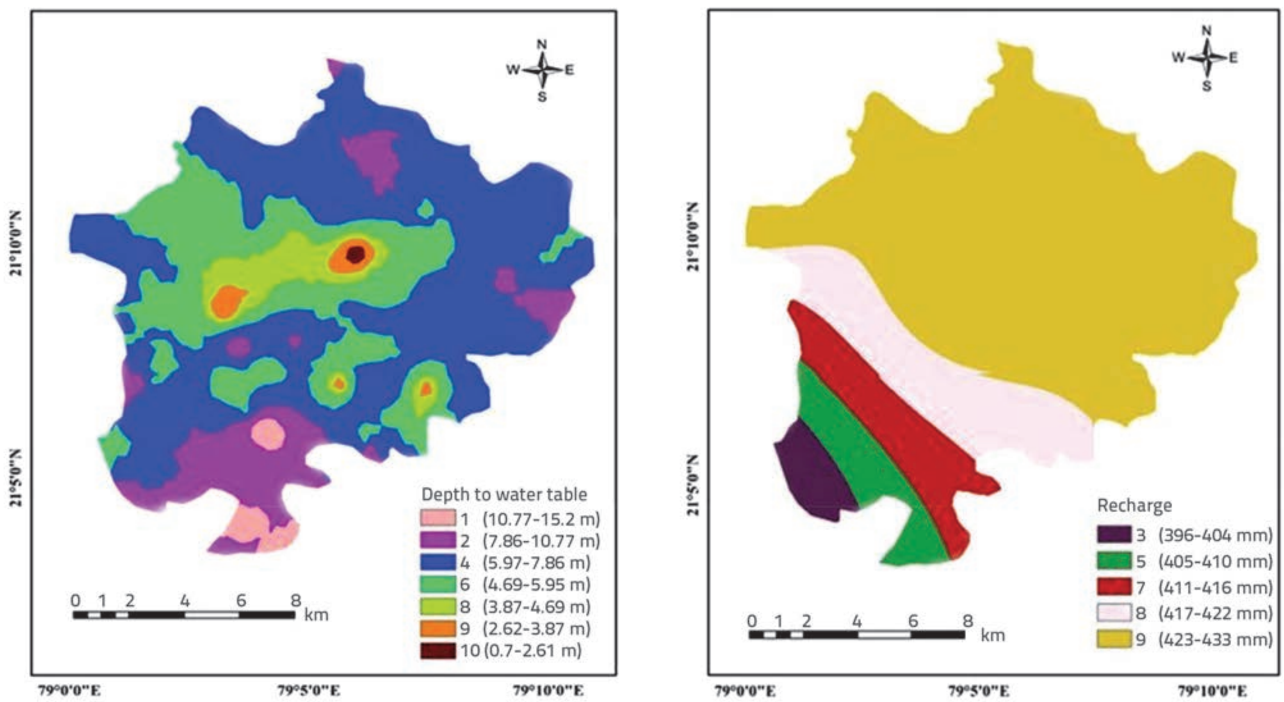


Figure 3. Methodology adopted in the present study



Depth to water table

Recharge

Figure 4. Maps showing subparameters and their assigned rates (D and R)

Recharge (R)

Rainfall is the major source of groundwater recharge in the area under study. The contaminants from the land surface move and infiltrate the aquifer through recharge occurring in the area. The average 5-year rainfall data from the nearby rain gauge stations, as obtained from the Indian Meteorological Department (IMD), were used as input for the calculation. For the current study, the effective infiltration was calculated by considering 30 - 40 % of the rainfall [10, 24] while the remainder was considered as loss due to evaporation, transpiration, etc., or runoff. The acquired recharge map of the area has a resolution of 2 x 2 m and varies from 396 mm to 433 mm in the study area. The rating was conducted as per [8] (Figure 4).

Aquifer media (A)

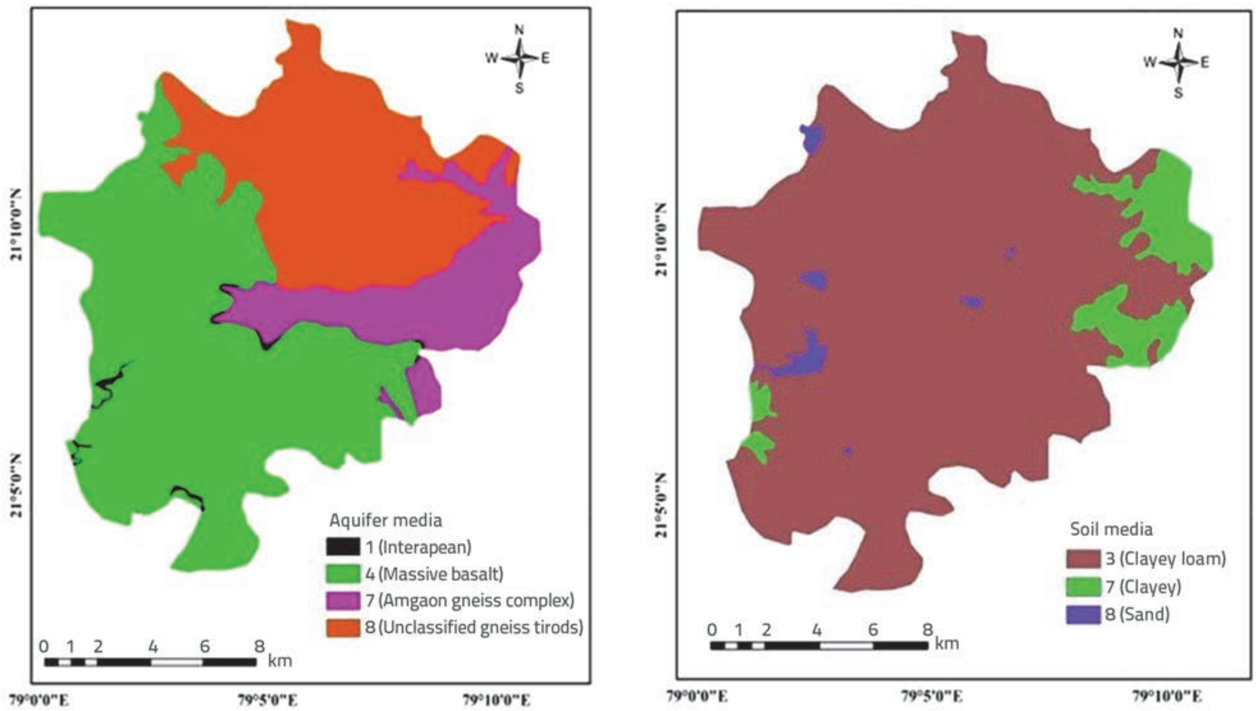
Aquifer media characterize the formation of rocks which can yield adequate quantity of water and represent the aquifer of the area. Since no maps or digital datasets were available, the first step was to employ a hydrogeologist to prepare a hydrogeological map using lithological data (CGWB) and topography. The map was digitized and registered to suitable coordinates system and then the data were converted to a raster (resolution 2 x 2 m) consistent with further procedure. The study area is mostly covered with hard rock formations such as Amgaon gneissic complex (metamorphic rock), Unclassified-gneiss-Tirodi gneissic complex (metamorphic rock), Massive basalt (Igneous rock) and Intertrappean beds. All the subparameters, rated as per [8], are shown in Figure 5.

Soil media (S)

Soil media consist of a part of the uppermost layers of the earth surface, which act as primary protection and restricts infiltration of pollutants through recharge and into the ground water. The soil map of the study area, scaled at 1/50000, was acquired from the National Bureau of Soil Survey (NBSS), Nagpur, India. The map was scanned, digitized, rasterized (resolution 2 x 2 m) and classified using an appropriate classification system supporting the DRASTIC method. The study area was classified as clayey (90.5 %), clay loam (8.0 %) and sand (1.5 %). These materials were rated according to [8] taking into account their influence in vulnerability assessment (Figure 5).

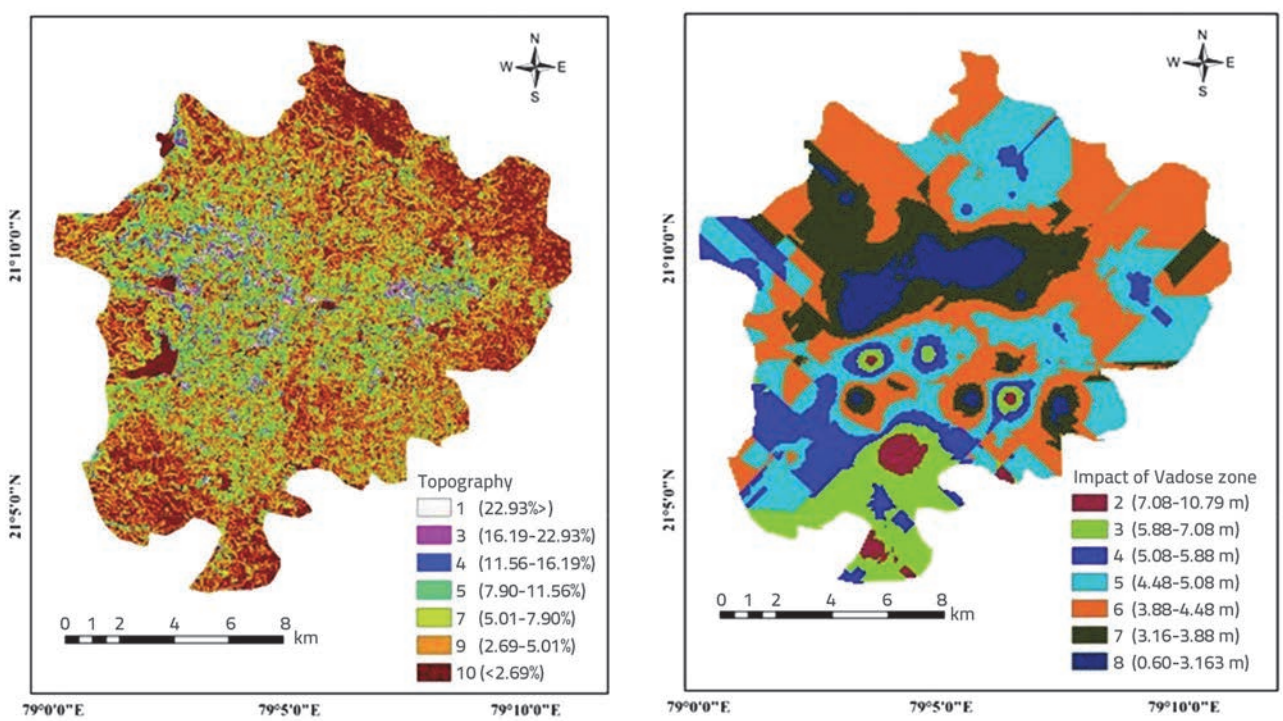
Topography (T)

Topography is specified as slope (%) as extracted from DEM (Cartosat). The DEM was downloaded from the authorized site (Bhuvan). The map is geo-referenced and rehabilitated in the slope format using the spatial analysis tool in Arc GIS; the detailed map resolution is 2 x 2 m. The contaminant will infiltrate or run off depending on the slope of the area. The steeper the slope the greater the runoff and smaller the infiltration, as time of detention is reduced, and vice versa for flat slopes. The slope in the study area is steep in the west zone and mild in the east zone, and it varies from 2.69 to 23



Aquifer media Soil media

Figure 5. Maps showing subparameters and their assigned rates (A and S)



Topography Impact of Vadose zone

Figure 6. Maps showing subparameters and their assigned rates (T and I)

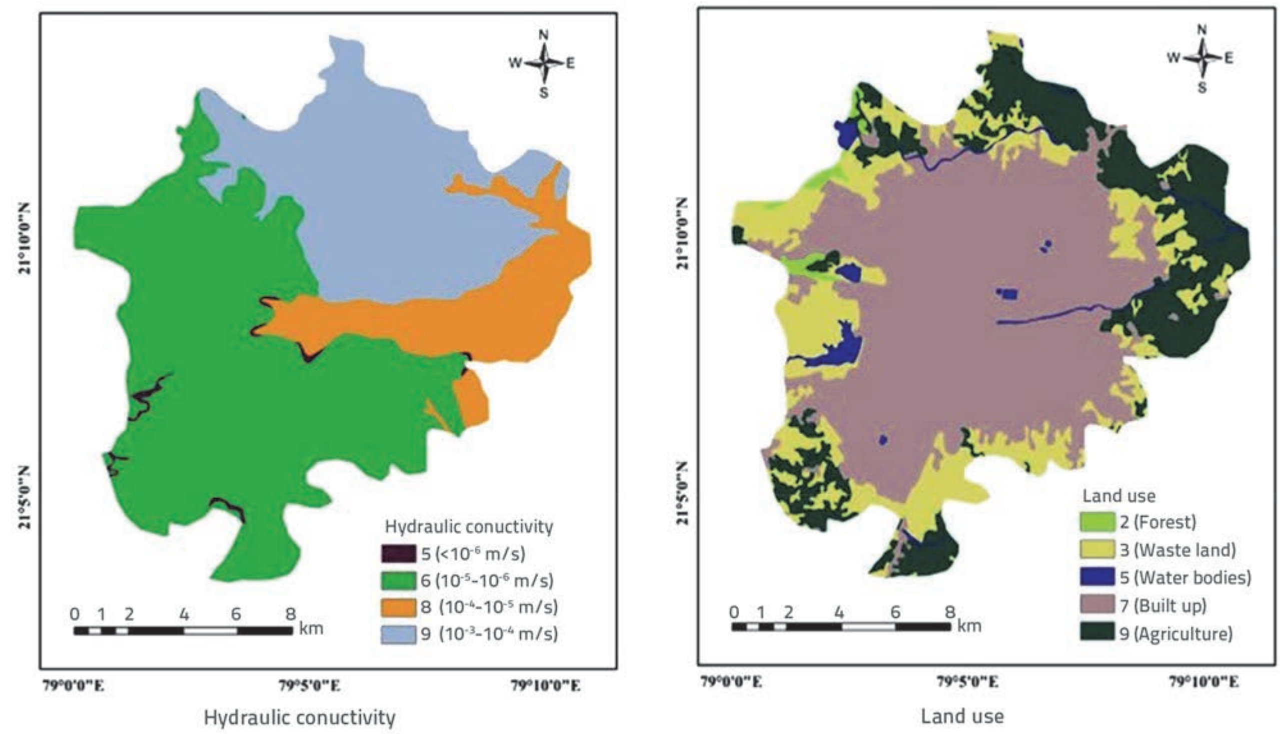


Figure 7. Maps showing subparameters and their assigned rates (C and Lu)

% (Figure 6). It was subsequently rated using the standard DRASTIC rating [8].

Impact of vadose zone (I)

The vadose zone is the unsaturated zone extending between soil media to aquifer media. The thickness of the vadose zone is calculated using DEM and the depth to water level data [25]. The depth to water level map generated using interpolation methods does not include topographical variations. It can be improved by subtracting the interpolated depth level from the DEM of the area. The cell size of the generated raster map is 2x2 m, with the thickness varying from 0.6 m to 10.79 m, and the rating as suggested in [8]. It is shown in Figure 6. The flow in this zone is more or less vertical. The greater the depth, the lower the contaminant content. In the case of fractured rock, contaminants reach the aquifer very quickly through fissures.

Hydraulic Conductivity (C)

Hydraulic conductivity depends on the ability of the aquifer formation to transmit water. The hydraulic conductivity map was generated using the well log data, transmissivity, and saturated thickness. Contour lines of both data were digitized and the surface image was created. Then the resultant map was formed by dividing transmissivity by saturated thickness. The raster image was generated in the resolution of 2 x 2 m (Figure 7), which was then classified according to [8] into DRASTIC ranges.

Land Use/Land Cover (Lu)

The Lu map is used with other parameters in the modified DRASTIC approach. The land use map was prepared using the satellite data (LISS III) obtained from the authorized site (Bhuvan). The map was geo-referenced and a raster map with the resolution of 2 x 2 m was generated. The study area was divided into five classes: built-up area (56 %), agriculture (20 %), waste land (21 %), water bodies (2 %) and forest (1 %). Each class was rated on the scale of 1 to 10, based on its effect on groundwater vulnerability (Figure 7).

3.2 Modified DRASTIC

The groundwater vulnerability map evaluated using the standard DRASTIC approach considers only intrinsic characteristics of an aquifer, independently from actual anthropogenic activities on the surface [26]. To capture the effect of actual pollution, the source of pollutant is included as an additional parameter (Land Use/Land Cover (Lu)). The Modified DRASTIC Vulnerability Index was calculated using, Eq. (2), a linear combination of the standard VI, Eq. (1), and the new parameter (Lu).

$$MVI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w + Lu_r Lu_w \quad (2)$$

where, MVI is the Modified Vulnerability Index that is used to assess groundwater quality, while the sub-scripts r and w are the ratings and weights of the parameter, respectively.

3.3. Modified DRASTIC AHP

The Analytic Hierarchy Process (AHP) is a well-structured multiple decision-making tool, efficient for analysing complex decisions, and thus assisting the decision maker in the selection of the best possible option. Developed by Thomas Saaty in 1980 [27], this methodology has been applied to several fields. It was initially devised for the economics, and was later on extended to the environment [28-35]. The AHP tool was used to modify the weights of the parameters involved in the Modified DRASTIC method presented in the study. The derived weights were used, along with the rated parameters, for the groundwater vulnerability assessment. The parameters were compared on the basis of their significance for the assessment of groundwater vulnerability. The hierarchy was established by ranking parameters on a standardized nine-level comparison scale. The scale represents values from 1 for extremely unimportant parameters to 9 for extremely important parameters. The parameter comparison matrix was formed. Principal eigenvalues and the corresponding normalized eigenvectors helped in making the final decision. The consistency Ratio (CR) of the matrix is given by the ratio of Consistency Index (CI) to Random Consistency Index (RI). For matrix to be consistent, the value of CR should be less than or equal to 0.1. If it fails, then the answers to comparison are re-examined. The value of RI is well defined for different degrees of the matrix. The consistency index (CI) was estimated using Eq. (3):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

where, λ_{max} is the largest eigenvalue of the n order matrix.

3.4 Modified DRASTIC ANP

The Analytical Network Process (ANP) is the extension of the AHP method for the Multi-Criteria Decision Analysis (MCDA) proposed by Thomas L. Saaty. Here the use is made of the holarchy structure rather than a simplistic hierarchy structure [36]. The ANP consists of clusters of parameters, one cluster being connected with another cluster or the same cluster, while in the AHP all networks are evaluated in one direction [37]. The ANP is an arrangement aimed at organizing networks of criteria and subcriteria that control the interaction in the structure and network of influence between parameters and clusters, and so the AHP becomes a special case of the ANP. In the present study, a comparison similar to the AHP pair-wise comparison was made using the ANP with the scale of relative importance developed by Saaty (1980) [27]. All the parameters of the modified DRASTIC method were compared pair-wise in one direction, and the comparison was also made for individual parameters in order to obtain the most suitable weights, depending on the influence of parameters in the groundwater vulnerability assessment. All ANP operations were performed using the ANP solver 1.0.1 software [38]. The super matrix, the weighted super matrix, and the limit super matrix, were derived using the Saaty's methodology. The super matrix of a network is composed of priority vectors that are derived from a pair-wise comparison matrix. Each component of these priority vectors represents the influence of a given set of parameters in that component on any parameter in the network. The weighted super matrix is derived after formation of the super matrix. All components of the un-weighted super matrix are multiplied by their subsequent cluster weight to obtain the weighted super matrix. The limit super matrix is the converged matrix obtained from the power of raising the weighted super matrix several times, which indicates the priority vectors [36]. To verify the judgment criteria of matrices, the consistency ratio (the same as the AHP) should be less than or equal to 0.1 [39].

3.5. Sensitivity Analysis

The Sensitivity Analysis (SA) shows the influence of individual parameters on other parameters, as well as on the overall vulnerability assessment, which helps in the achievement of more appropriate results. A DRASTIC result varies under different hydrogeological conditions. Some previous research shows that groundwater vulnerability can be evaluated without considering all the documented DRASTIC parameters [4]. Depending on features of a specific area, some new parameters can be added and the less effective parameter can be removed for the respective study.

In the present study, the Single Parameter Sensitivity Analysis (SPSA) was performed using the modified DRASTIC method. The theoretical weight of a parameter is the weight assigned to each parameter using the standard approach suggested in [8]. The effective weight of a parameter is the outcome of the rate and weight assigned to individual parameter for groundwater vulnerability assessment [40]. The effective weights of all parameters are evaluated using eqn. (4) and compared with their respective theoretical weights.

$$W = \frac{P_r P_w}{MVI} \tag{4}$$

where, W is the effective weight of a parameter, Pr and Pw are the rating value and weight of a parameter, and MVI is the vulnerability index from the modified DRASTIC method.

Table 1. Standard and Modified weight values used in different DRASTIC approaches

Parameter	Weight			
	DRASTIC	Modified DRASTIC	Modified DRASTIC AHP	Modified DRASTIC ANP
Depth to water (D)	5	5	0.035	0.029
Recharge (R)	4	4	0.160	0.165
Aquifer media (A)	3	3	0.198	0.241
Soil media (S)	2	2	0.047	0.055
Topography (T)	1	1	0.089	0.106
Impact of vadose zone (I)	5	5	0.037	0.032
Hydraulic conductivity (C)	3	3	0.172	0.205
Land use / land cover (Lu)	-	5	0.262	0.166

3.6. Modification to the groundwater vulnerability map

The groundwater vulnerability of an area is evaluated using intrinsic parameters of an aquifer that include transport and attenuation process of contaminant [41], and an additional parameter land use/land cover which considers the source of contamination. The groundwater contamination occurrence depends not only on the source of contaminant, but also on the behaviour of the contaminant in strata of different hydrogeological properties [42]. Quality field data collected from monitoring wells are processed by the Kriging interpolation tool in the ArcGIS environment. The use of field data is essential in risk assessment analyses [43].

In the current study, the groundwater vulnerability map, obtained using intrinsic parameters and the land use parameter, was multiplied with the spatial variation of contaminant to consider the variation of contaminant concentration within the study area.

3.6.1. Data processing

The groundwater quality data from monitoring wells were provided by the CGWB Department Nagpur, India. The Kriging interpolation tool was used to form a surface map showing spatial variation of the Total Dissolved Solids (TDS). Before using the field parameter map for modifying the assessed groundwater vulnerability map, the Natural break (Jenks) (ArcGIS Software) method was used to classify the map into five zones varying from very high to very low concentration of contaminant depending on permissible limits. The map was then normalized so as to make the unit on a layer dimensionless and measurable using the same numerical scale. The final quality parameter map obtained after processing was used with the groundwater vulnerability map to evaluate areas that are more or less susceptible to contamination.

4. Results

4.1. DRASTIC

The Groundwater Vulnerability Map of the study area was obtained based on seven rated controlling parameters suggested by DRASTIC [8] (Table 1). The final result is the overlay analysis of the chosen parameters, Eq. (1). The vulnerability map was classified into different vulnerability zones using the Natural break (Jenks) method in the Arc GIS environment. The city is mainly divided into five zones showing very high (14.20 %), high (49.30 %), moderate (19.02 %), low (10.09 %) and very low (7.39 %) vulnerability areas (Figure 10). The resultant Groundwater Vulnerability Map (Figure 8.a) shows that the north and north-east regions of the city are under high risk of contamination, as revealed by very high to high vulnerability indices. The central region of the city shows moderate vulnerability, while the south and south-west parts of the city are safe from contamination as confirmed by the lowest vulnerability index.

4.2. Modified DRASTIC

An additional parameter considering local factors affecting groundwater, i.e. the Land Use/Land Cover (Lu) parameter, was added to standard DRASTIC parameters to enable better groundwater vulnerability assessment. The groundwater vulnerability index map of the area was evaluated by means of all eight rated parameters and standard weights (Table 1) using Eq. (2). Using a similar procedure, the resultant map was classified into several vulnerability zones varying from very low to very high. Compared to the resultant standard DRASTIC method, the results obtained using the modified DRASTIC approach show that the area described as the very high vulnerability zone is increased by 10.48 %, high vulnerability zone is decreased by 17.31 %, moderate vulnerability zone is increased by 4.66 %, low vulnerability zone is increased by 10.48 %, and the very low vulnerability zone is decreased by 1.80 % (Figure 10). Close

Table 2. Statistical summary and SPSA results

Parameter	Column 1			Column 2		Column 3		
	Statistical summary			Theoretical weight	Theoretical weight [%]	Effective weight [%]		
	Min.	Mean	Max.			Min.	Mean	Max.
D	1	4.47	10	5	17.86	3	13.71	29
R	2	6.94	8	4	14.28	5	17.12	28
A	3	5.69	8	3	10.71	4	10.33	17
S	2	5.63	6	2	7.14	1	2.37	10
T	1	8.22	10	1	3.57	0	4.95	12
I	2	5.51	8	5	17.86	7	17.04	30
C	5	5.69	8	4	10.71	4	10.33	17
Lu	2	6.49	9	5	17.86	6	20.28	43

*Min. = Minimum, Max. = Maximum

inspection of the modified DRASTIC vulnerability map shows that the central to north-east areas of the city are situated in the high to very high groundwater vulnerability zone (Figure 8(b)). The south region of the city is found to be safe from contamination, with the lowest vulnerability levels exhibited in both standard DRASTIC and modified DRASTIC methods.

4.3. Sensitivity analysis

The sensitivity analysis was conducted using the modified DRASTIC parameters to determine their impact on the resultant groundwater vulnerability. The contribution of an individual parameter to the vulnerability index is examined by comparing mean values of the parameters. The results presented in Table 2 (Column 1) reveal that the topography, recharge and land use show the highest contribution to the vulnerability index, while contribution is lower for other parameters viz. aquifer media, hydraulic conductivity, soil media, impact of vadose zone, and depth to water table.

The Single Parameter Sensitivity Analysis (SPSA) was performed to identify the most effective parameters for groundwater vulnerability assessment, and this by comparing theoretical weight with the respective effective weight of parameters. The theoretical weight, presented in Table 2 (Column 2), is the weight assigned to parameters during the groundwater vulnerability assessment. The effective weight of the parameters is evaluated using Eq. (4). The corresponding results are given in Column 3 of Table 2. The SPSA results (Table 2) reveal that the recharge, land use, and topography, are the most effective parameters as their effective weights are higher than their respective theoretical weights, and as they cause a significant impact on vulnerability assessment. It was observed that all other parameters show lower effective weights compared to theoretical weights, with moderate impact on groundwater vulnerability of the study area. In the study area, the recharge and topography were found to be major contributing parameters for groundwater vulnerability assessment. As the recharge in the study area is nearly constant, it is one of the factors that increases groundwater contamination. Topography of the area is heterogeneous, steeper in the west and milder in the east, thus concentration of contaminants is higher in the east part of the city.

4.4. Modified DRASTIC AHP

The Analytical Hierarchy Process (AHP) is the Multi-Criteria Decision Analysis (MCDA) method that was used in the paper to revise weights of the modified DRASTIC parameters. The groundwater vulnerability was evaluated by means of input parameters rated using the standard Delphi approach. Modified weights were obtained from the AHP (Table 1). The resultant vulnerability map was classified into different classes, from very low to very high vulnerability indices, using the Natural break (Jenks) method. The percentages of areas included in different vulnerability zones are: very high (36.03 %), high (20.69 %), moderate (27.51 %), low (10.48 %), and very low (5.28 %) (Figure 10). The central, north and north-east regions of the city were once again found to be the areas of very high to high vulnerability with higher vulnerability indices, while the south region is considered to be a safer zone exhibiting the moderate vulnerability to lowest vulnerability indices (Figure 8.c).

4.5. Modified DRASTIC ANP

The Analytic Network Process (ANP) was used to modify weights using the pair-wise comparison of clusters of parameters, one cluster being connected with another cluster or with the same cluster. The groundwater vulnerability was evaluated using all eight parameters, and the rating was made using the standard approach and modified weights through ANP (Table 1). The percentages of areas included in individual vulnerability zones are: very high (20.70 %), high (19.26 %), moderate (26.30 %), low (22.82 %) and very low (10.91 %) (Figure 10). The central to south and west regions of the city exhibit moderate to very low vulnerability, whereas the central to north and north east regions are high risk zones showing very high to high vulnerability (Figure 8.d).

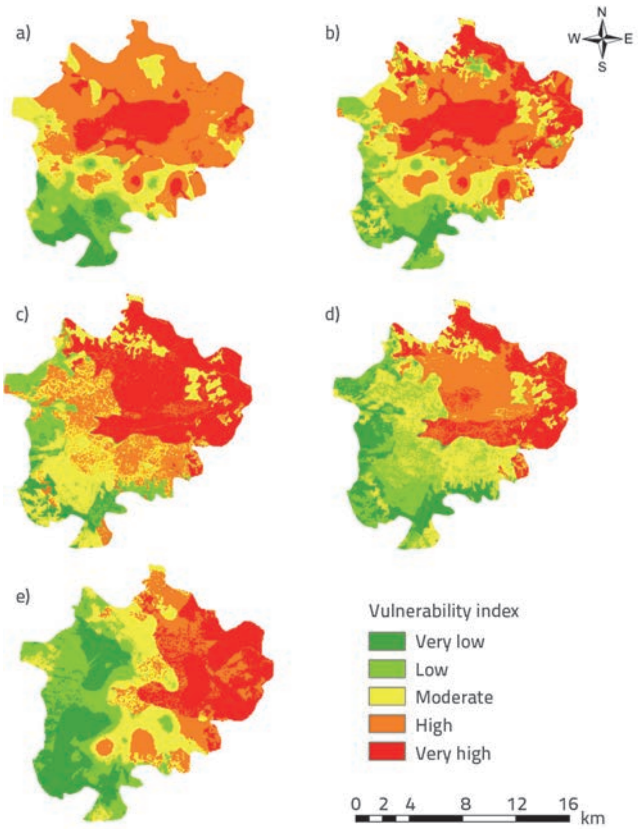


Figure 8. Groundwater vulnerability maps based on: a) DRASTIC; b) Modified DRASTIC; c) Modified DRASTIC AHP; d) Modified DRASTIC ANP; e) Modified DRASTIC ANP (Including the quality parameter)

4.6. Validation

The Groundwater Vulnerability Maps generated for the city of Nagpur via DRASTIC approaches include a variety of parameters and are unique due to specific hydrogeology; hence they need to be validated. The Nitrate field data collected in the study area were used for validation of the resultant groundwater vulnerability map (Figure 9.b). The concentration of nitrate is negligible under natural groundwater conditions, and its presence is mainly due to anthropogenic activities. The resultant vulnerability maps obtained using the DRASTIC method and its modification were validated with regard to nitrate concentration using different correlation methods (Table 3). The results given in Table 3 show the higher correlation of the modified DRASTIC ANP vulnerability map with nitrate concentrations, compared to other methods applied in the study. If the resultant groundwater vulnerability map does not show good correlation with the field data (nitrate), further modifications can be applied such as revising the weight of parameters or involving new parameters for better prediction of vulnerable zones.

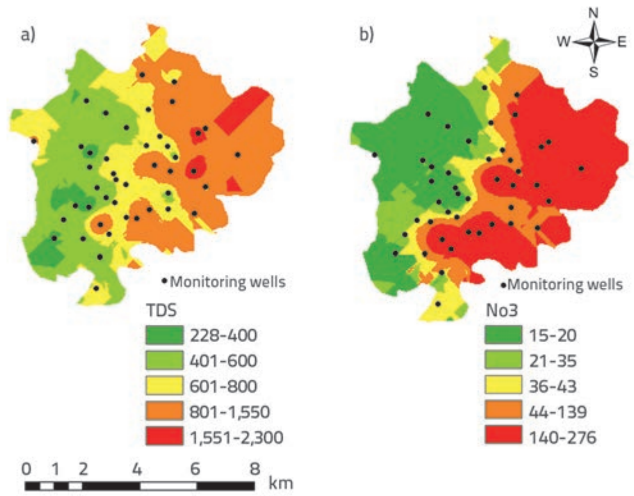


Figure 9. Groundwater quality maps: a) Total Dissolved Solids (TDS); b) nitrate (No_3)

4.7. Modification of groundwater vulnerability map

The groundwater vulnerability map acquired using the modified DRASTIC ANP approach shows better correlation with the nitrate concentration of the city compared to other approaches considered in the study. The resultant groundwater vulnerability map was further modified using the field quality data. The quality parameter (TDS) shown in Figure 9.a was multiplied with the resultant vulnerability map (Modified DRASTIC ANP) of the area to form a more realistic map considering spatial variation of contaminants within city limits.

Table 3. Correlation between groundwater vulnerability maps and nitrate concentration

Vulnerability map	DRASTIC	Modified DRASTIC	Modified DRASTIC AHP	Modifiedk DRASTIC ANP	Modified DRASTIC ANP (Including quality parameter)
Pearson coefficient	0.249	0.310	0.497	0.553	0.736
Kendall's coefficient	0.130	0.154	0.333	0.394	0.691
Spearman coefficient	0.174	0.215	0.462	0.530	0.846

The resultant map (Figure 8.e) shows that the vulnerability of the area is very high to high in the north-east zone. Central to north zones exhibit moderate vulnerability, while the south-west and south regions are considered to be safe as their vulnerability indices are very low to low. The areas included in individual vulnerability zones are shown in Figure 9. The groundwater vulnerability map (Figure 8.e) obtained using the Modified DRASTIC ANP (Including the quality parameter) shows higher correlation with nitrate concentration, compared to other DRASTIC approaches (Table 3).

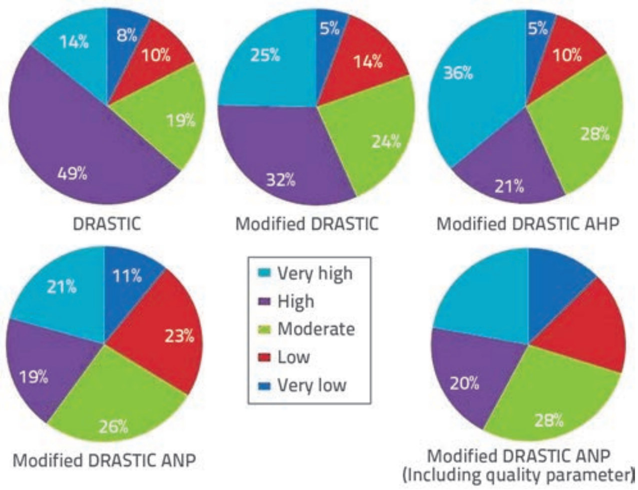


Figure 10. Vulnerability areas vis-a-vis applied methods

The resultant groundwater vulnerability maps show that various areas of the city lie in the high to very vulnerability zones. In practice, several policies can be applied so as to reduce groundwater contamination in the city. The solid waste collected from different zones of the city should be dumped into a dumping site, away from human habitations, in the zone that is less vulnerable to contamination especially from the aspect of its hydrogeology. The capacity of the existing sewage treatment plant should be increased so that it can effectively handle waste generated by the city. Scientific rainwater harvesting practices can be adopted to recharge the groundwater, which would help in the dissolution of contaminants.

5. Conclusions

The DRASTIC approach and its modification were used to evaluate vulnerability of groundwater in the city of Nagpur. An additional land use parameter and revised weights of the parameters were applied using the MCDA approach. The ANP and AHP were used for refining the groundwater vulnerability assessment. The results can be summarized as follows:

- The Groundwater Vulnerability Map obtained using Modified DRASTIC ANP provided more appropriate result compared to Modified DRASTIC AHP, Modified DRASTIC and DRASTIC for the study area.
- Sensitivity analysis results show that the topography, recharge and land use are the parameters that contribute more to the groundwater vulnerability assessment of the study area.
- The modification applied to the resultant groundwater vulnerability map (Modified DRASTIC ANP), based on the quality field data, helped in the realization of a more reliable map, with better definition of the areas that are more or less susceptible to contamination; it shows good correlation with the observed nitrate concentration.

In order to increase accuracy in the determination of groundwater vulnerability zones, it is felt that a larger study area can be selected for the study, which would include the effect of neighbouring hydro-geological properties and anthropogenic activities on the groundwater of the city of Nagpur.

REFERENCES

[1] Driscol, M.O., Clinton, S., Jefferson, A., Manda, A., McMillan, S.: Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States. Water, 2 (2010), pp. 605-648, https://doi.org/10.3390/w2030605.

[2] Umar, R., Ahmed, I., Alam, F.A.: Mapping Groundwater Vulnerable Zones Using Modified DRASTIC Approach of an Alluvial Aquifer in Parts of Central Ganga Plain, Western Uttar Pradesh, Journal Geological Society of India, 73 (2009) 2, pp. 193-201, https://doi.org/10.1007/s12594-009-0075-z.

[3] Johnson, C.C.: Land application of water-an accident waiting to happen, Ground Water. Earth science, 17 (1979) 1, pp. 69-72, https://doi.org/10.1111/j.1745-6584.1979.tb03277.x.

[4] Rahman, A.: A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India, Applied Geography, 28 (2008) 1, pp. 32-53, https://doi.org/10.1016/j.apgeog.2007.07.008.

[5] Sener, E., Davraz, A.: Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Egirdir Lake basin (Isparta, Turkey), Hydrogeology Journal, 21 (2013) 3, pp. 701-714, https://doi.org/10.1007/s10040-012-0947-y.

[6] Abdulla, M.A., Nadhir, A.A., Ahmed, A.A., Fadi, L.A., Sven, K.: Modeling the Risk of Groundwater Contamination using Modified DRASTIC and GIS in Amman-Zerqa Basin, Jordan. Central European Journal Engineering, 4 (2014) 3, pp. 264-280, https://doi.org/10.2478/s13531-013-0163-0.

[7] Foster, S.: Fundamental concept in aquifer vulnerability pollution risk and protection strateg, Proceedings and Information, pp. 69-86, 1987.

[8] Aller, L., Lehr, J., Petty, R., Bennett, T.: A standardized system to evaluate Groundwater Pollution using Hydrogeologic setting, Journal of the Geological Society of India, 29 (1987) 1, pp. 23-37.

[9] Civita, M., De Maio, M.: Un sistema parametrico per la valutazione e la cartografia della vulnerabilita' degli acquiferi all'inquinamento,Bologna: Pitagora Editrice. 1997.

[10] Gupta, N,: Groundwater Vulnerability Assessment using DRASTIC Method in Jabalpur District of Madhya Pradesh. International Journal of Recent Technology and Engineering, 3 (2014) 3, pp. 36-43, https://doi.org/10.4236/ijg.2016.74043

[11] Jang, C.S., Lin, C.W., Liang, C.P., Chen, J.-S.: Developing a reliable model for aquifer vulnerability, Stochastic Environment Research and Risk Assessment, 30 (2015) 1, pp. 175-187, https://doi.org/10.1007/s00477-015-1063-z

[12] Sadeghfam, S., Hassanzadeh, Y., Nadiri, A.A., Zarghami, M.: Localization of Groundwater Vulnerability Assessment Using Catastrophe Theory. Water Resources Management, 30 (2016), pp. 4585-4601, https://doi.org/10.1007/s11269-016-1440-5.

[13] Mimi, Z.A., Mahmoud, N., Madi, M.A.: A Modified DRASTIC Model for Intrinsic Vulnerability Mapping for Karst Aquifers: A Case Study. Environmental Earth Sciences, 66 (2012) 2, pp. 447-456, https://doi.org 10.1007/s12665-011-1252-0.

[14] Bartzas, G., Zaharaki, D., Hernández-Fernández, M.T., Ortego, J.L., Komnitsas, K.: Assessment of Aquifer Vulnerability in an Agricultural Area in Spain Using the DRASTIC Model. Environmental Forensics, 16 (2015) pp. 356-373, https://doi.org/10.1080/15275922.2015.1091407.

[15] Kazakis, N., Voudouris, K.S.: Groundwater vulnerability and pollution risk assessment of porous aquifers to nitrate: Modifying the DRASTIC method using quantitative parameters. Journal of Hydrology, 525, (2015), pp. 13-25, https://doi.org/10.1016/j.jhydrol.2015.03.035.

[16] Neshat, A., Pradhan, B., Pirasteh, S., Mohd Shafri, H.Z.: Estimating groundwater vulnerability to pollution using a modified DRASTIC model in the Kerman agricultural area, Iran, Environmental Earth Science, 71 (2013) 7, pp. 3119-3131, https://doi.org/10.1007/s12665-013-2690-7.

[17] Agarwal, R., Garg, P.: Remote Sensing and GIS Based Groundwater Potential & Recharge Zones Mapping Using Multi-Criteria Decision Making Technique, Water Resources Management, 30 (2016) 1, pp. 243-260, https://doi.org/10.1007/s11269-015-1159-8.

[18] Jaiswal, R., Thomas, T., Galkate, R., Ghosh, N.C., Singh, S.: Watershed Prioritization Using Saaty's AHP Based Decision Support for Soil Conservation Measures, Water Resources Management, 28 (2014) 2, pp. 475-494, https://doi.org/10.1007/s11269-013-0494-x.

[19] Wu, W., Yin, S., Chen, H.L.: Groundwater Vulnerability Assessment and Feasibility Mapping Under Reclaimed Water Irrigation by a Modified DRASTIC Model, Water Resources Management, 28 (2014) 5, pp. 1219-1234, https://doi.org/10.1007/s11269-014-0536-z.

[20] Jain, S.K., Sharma, V.: Contamination of Ground Water by Sewage. Faridabad: Central Ground Water Board, 2011.

[21] Mandal, D.N.: Government of India Ministry of Water Resources Central Ground Water Board. Nagpur: CGWB, 2011.

[22] Dhiman, S.C., Kunar, S.: Ground water scenario in major cities of india. Faridabad: Central Ground Water Board, 2011.

[23] Ranjan, B.: Basic Report of exploratory well (1079/BDR/2001). Nagpur, CGWB, 2002

[24] Baalousha, H.: Vulnerability assessment for the Gaza Strip, Palestine using DRASTIC, Environmental Geology, 50 (2006) 3, pp. 405-415, https://doi.org/10.1007/s00254-006-0219-z.

[25] Li, R., Zhao, L.: Vadose Zone Mapping Using Geographic Information Systems and Geostatistics A case study in the Elkhorn River Basin, Nebraska, USA. International Symposium on Water Resource and Environmental Protection, IEEE pp. 3177-3179, 2011.https://doi.org/10.1109/ISWREP.2011.5893555.

[26] Leone, A., Ripa, M., Uricchio, V., Deak, J., Vargay, Z.: Vulnerability and risk evaluation of agricultural nitrogen pollution for Hungary's main aquifer using DRASTIC and GLEAMS models, Journal of Environmental Management, 90 (2009), pp. 2969-2978, https://doi.org/10.1016/j.jenvman.2007.08.009.

[27] Saaty, T.: The Analytic Hierarchy Process, New york, McGraw-Hill 1980.

[28] Triantaphyllou, E., Mann, H.S.: Using the analytic hierarchy process for decision making in engineering applications: some challenges, International Journal of Industrial Engineering, Applications and Practice, 2 (1995) 1, pp. 35-44,

[29] Ramanathan, R.: A note on the use of the analytic hierarchy process for environmental impact assessment. Journal of Environmental Management, 63 (2001), pp. 27-35, https://doi.org/10.1006/jema.2001.0455.

[30] Sipahi, S., Timor, M.: The analytic hierarchy process and analytic network process: an overview of applications. Management Decision, 48 (2010) 5, pp. 775-808, https://doi.org/10.1108/00251741011043920.

[31] Thirumalaivasan, D., Karmegam, M., Venugopal, K.: AHP-DRASTIC software for specific aquifer vulnerability assessment using DRASTIC model and GIS. Environmental Modelling & Software, 18 (2003) 7, pp. 645-656, https://doi.org/10.1016/S1364-8152(03)00051-3.

[32] Gangadharan, R., Nila Rekha, P., Vinoth, S.: Assessment of groundwater vulnerability mapping using AHP method in coastal watershed of shrimp farming area. Arabian Jornal of Geoscience, 9 (2016) 107, https://doi.org/10.1007/s12517-015-2230-8.

[33] Suhua, Z., Guangqi, C., Ligang, F., Yunwen, N.: GIS-Based Integration of Subjective and Objective Weighting Methods for Regional Landslides Susceptibility Mapping, MDPI Sustainability, 8 (2016) 334, https://doi.org/10.3390/su8040334.

[34] Achour, Y., Boumezbeur, A., Hadji, R.: Landslide susceptibility mapping using analytic hierarchy process and information value methods along a highway road section in Constantine, Algeria. Arabian Journal of Geoscience,10 (2017) 194, https://doi.org/10.1007/s12517-017-2980-6.

[35] Calligaris, C., Tariq, S., Khan, H., Poretti, G.: Landslide susceptibility analysis in Arandu area Shigar valley, CKNP (Gilgit-Baltistan-Pakistan). Advancing Culture of Living with Landslides, pp. 909-916, 2017. https://doi.org/10.1007/978-3-319-53498-5_103.

[36] Afzali, A., Sabri, S., Rashid, M., Samani, J.M., Ludin, A.N.: Inter-Municipal Landfill Site Selection Using Analytic Network Process, Water Resources Management, 28 (2014) 8, pp. 2179-2194, https://doi.org/10.1007/s11269-014-0605-3

[37] Saaty, T.L.: Applications of Analytic Network Process in entertainment, Iranian Journal of Operational Research, 1 (2009) 2, pp. 41-55.

[38] ANP Solver, http://kkir.simor.ntua.gr/anpsolver.html, 22.04.2016

[39] Saaty, T.L.: Decision making with dependence and feedback: The Analytic Network Process, Second edition, Pittsburgh, USA, RWS Publications, 2001.

[40] Babiker, I.S., Mohamed, M.A., Hiyama, T., Kato, K.: A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan, Science of the Total Environment, 345 (2005) 1-3, pp. 127-140, https://doi.org/10.1016/j.scitotenv.2004.11.005

[41] Kaddour, K., Houcine, B., Smail, M.: Assessment of the vulnerability of an aquifer by DRASTIC and SYNTACS methods: Aquifer of BazeGeult Zerga area (northeast Algeria). Journal of Environmental Research and Management, 5 (2014) 9, pp. 169-179.

[42] Wang, J., He, J., Chen, H.: Assessment of groundwater contamination risk using hazard quantification, a modified DRASTIC model and groundwater value, Beijing Plain, China. Science of the Total Environment, 432, (2012), pp. 216-226, https://doi.org/0.1016/j.scitotenv.2012.06.005.

[43] Jafari, F., Javadi, S., Golmohammadi, G., Mohammadi, K., Khodadadi, A., Mohammadzadeh, M.: Groundwater risk mapping prediction using mathematical modeling and the Monte Carlo technique. Environmental Earth Science, 75 (2016) 491, https://doi.org/10.1007/s12665-016-5335-9.