Assessment of groundwater vulnerability using GIS-based DRASTIC technology for the basaltic aquifer of Burhner watershed, Mohgaon block, Mandla (India)

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Groundwater (GW) vulnerability is foundation stone for evaluating the risk of GW contamination and developing management options to preserve the quality of GW. The concept of GW vulnerability is based on the assumption that the physical environment may provide some degree of protection for GW against human activities as well as natural contamination. The main objective of this study is to find out the GW vulnerable zones in Burhner watershed using the DRASTIC model in a geographical information system environment. Determination of DRASTIC index involves multiplying each parameter weight by its site rating and summing the total. On the basis of DRASTIC index values, a GW vulnerability map was prepared using Arc GIS 10 platform. Based on the results of the GW vulnerability assessment, the study area was divided into three zones: Low vulnerable zones ranging from 92 to 123 DRASTIC index with a geographical area of about 113.35 sq. km; moderate vulnerable zones ranging from 123 to 142 with 98.42 sq. km geographical area and high vulnerable zones with DRASTIC index ranging from 142 to 164 with 113.23 sq. km geographical area.

The term 'vulnerability of groundwater (GW) to contamination' was first used by Margat[1]. GW vulnerability to contamination was defined by the National Research Council (1993) as 'the tendency or likelihood of contaminants to reach a specified position in the GW system after introduction at some location above the uppermost aquifer'. GW pollution is nothing but artificially induced degradation of natural GW quality. GW vulnerability is a function of the geological setting of an area, as this largely controls the amount of time, i.e. the residence time of GW that has passed since the water fell as rain, infiltrated through the soil, reached the water table and began flowing to its present location[2].

Most of the population of the Mandla district, Madhya Pradesh, lives in the rural areas and depends on agriculture for its livelihood. Therefore, it is important that quality and quantity of GW should be of a desired level, but the study area does not meet the standards. GW is affected by high concentration of fluoride in many villages due to geogenic fluoride contamination. As farmers use fertilizers and pesticides to increase productivity, these chemicals also reach GW through irrigation. The DRASTIC model is useful for assessment of GW vulnerability zones in the study area. The objective of mapping aquifer vulnerability is to help planners to protect GW as an essential economic resource and to identify GW protection zones.

Several GW vulnerability assessment methods have been developed by researchers; but, all reports classify GW vulnerability assessment methods into three categories such as overlay and index methods, methods employing process-based simulation models and statistical methods[3,4]. The DRASTIC model[5], which belongs to the overlay and index category, is the most popular vulnerability mapping method and used as an important tool for GW planning and decision making. DRASTIC vulnerability index method is a GW quality model for evaluating the pollution potential of large areas using the seven hydrogeological factors of a region, which are a combination of geological, hydrogeological, geomorphological and meteorological characteristics of an aquifer[6,7].

The DRASTIC model can be a valuable tool for identifying GW supplies that are vulnerable to contamination using basic hydrogeological variables believed to influence contaminant transport from surface sources to GW[8].

The DRASTIC model[5] evaluates the intrinsic vulnerability of GW by considering factors including depth to water table, natural recharge rates, aquifer media, soil media, topographic aspect, impact of vadose zone media and hydraulic conductivity. Usually different ratings are assigned to each factor and then summed together with respective weights to a numerical value as the vulnerability index.

A vulnerability assessment defines the risk to an aquifer based on the physical characteristics of the vadose zone and aquifer and the presence of potential contaminant sources. These quotes illustrate the diversity in terminology.

GW vulnerability has been evaluated using DRASTIC model by various researchers in different parts of the world[9,10].

With the advent of remote sensing and GIS, DRASTIC model has been applied by various researchers for assessment of GW vulnerability[11–19].

Study area

The study area is situated in the Mandla district, East Central part of Madhya Pradesh, India (22°33′00″N to 22°51′00″N and 80°31′00″E to 80°41′00″E) and covering about 325 sq. km with uneven topography (Figure 1).

The area has a semi-arid climate with temperature of 41.3°C and mean daily minimum of 24°C. Average annual precipitation is 1182 mm. Sandy loam; loam and clay loam are the main soil types, which act as a natural filter to screen out many substances that mix with the water. Agriculture is the main occupation of the people. The northern and southern parts of the study area are hilly with 820 m elevation from mean sea level, a high linear ridge with moderate to steep slopes passes from east to west in the

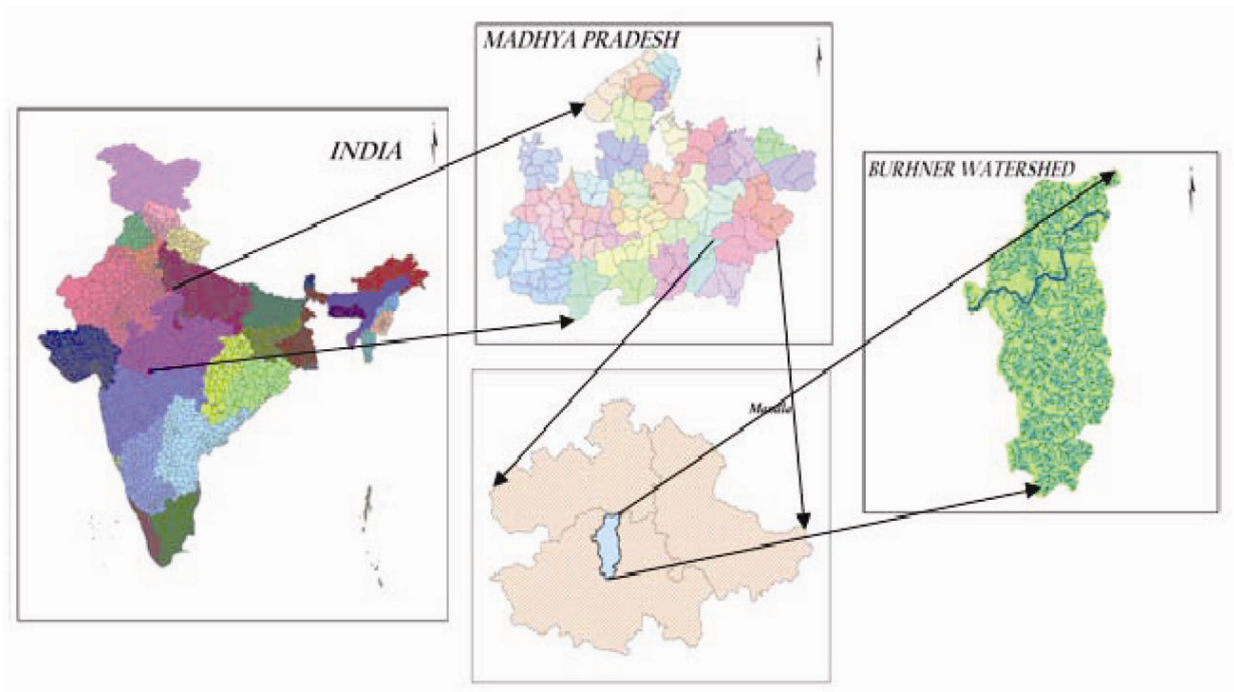

Figure 1. Location map of the study area.

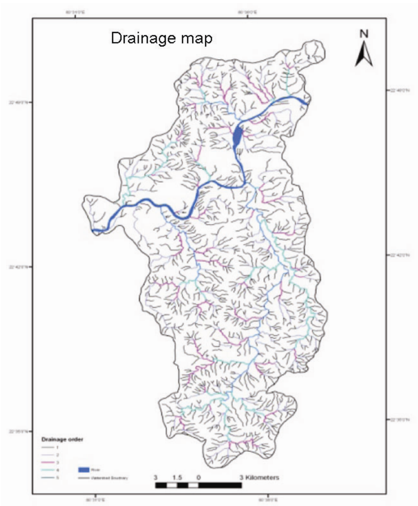

Figure 2. Drainage map of the study area.

middle of the watershed. The Budhner River is the main river flowing through the study area from east to west. Other tributaries contribute from the north and south. The drainage pattern is dendritic to sub-dendritic with fine to medium texture (Figure 2) reflecting the amount of precipitation, permeability, topography and structure in the area. The structure and lithology have played a major role in the evolution of the topography and drainage pattern.

Materials and methodology

The DRASTIC model is based on seven parameters, corresponding to seven layers to be used as input parameters for modelling. Required information was obtained from various government and semi-government agencies at the described scale. The acronym DRASTIC corresponds to the initials of the seven base maps.

- Depth to water
- Net recharge
- Aquifer media
- Soil media
- Topography
- Impact of the vadose zone
- Hydraulic conductivity

The DRASTIC model evaluates the intrinsic vulnerability (IV) of GW by considering factors including depth to water table, natural recharge rates, aquifer media, soil media, topographic aspect, impact of vadose zone media and hydraulic conductivity. Usually different ratings are assigned to each factor and then summed together to a numerical value as the vulnerability index.

$$\text{DRASTIC index (IV)} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw, \quad (1)$$

where D the is depth to water table, R the net recharge, A the aquifer media, S the soil media, T the topography, I the impact of vadose zone, C the (hydraulic) conductivity of the aquifer, r the rating value assigned to units of parameters and w is the weight assigned to each parameter.

The numerical weights and ratings, which were established using the Delphi technique[6], are well-defined and have been used worldwide[20–22]. Weight of the parameter (normally from 1 to 5) is used for DRASTIC model development. The weight is a function of value of the single parameter with regard to the other six parameters as well as the weight assigned to it by the DRASTIC model[23].

Standard values for all parameters regarding their weight and rating are given in Tables 1–3. List of databases of hydrological parameters used in the study is given in Table 4. Details of each parameter and their maps with their ratings and weights are given sequentially afterwards. The flow chart of methodology for GW vulnerability analysis is given in Figure 3.

Preparation of parameter range, rating and index maps

Maps have been prepared by entering the values of various parameters in GIS

Table 1. Standard assigned ratings and weights for DRASTIC parameter ranges (ref. 7)

Depth of water (ft)		Net recharge (inches)			Aquifer media	
Range	Rating	Type of land use classes	Range	Rating	Range	Rating
<5	10	Barren lands/open plots with vegetation	0–2	1	Massive shale	2
5–15	9	Water bodies/wet lands	2–4	3	Metamorphic/igneous	3
15–30	7				Weathered metamorphic/igneous thin bedded sandstone, limestone shale sequence	4
30–50	5				Shale sequences	6
50–75	3				Massive sandstone	6
75–100	2				Massive limestone	6
>100	1				Sand and gravel	8
					Basalt	9
					Karst limestone	10
Weight 5		Weight 4			Weight 3	

Soil media		Topography		Impact of the vadose zone		Hydraulic conductivity	
Range	Rating	Slope range	Rating	Ranging	Rating	Ranges (GPD/ft^2)	Rating
Thin or absent	10	0–2	10	Silt/clay	1	1–100	1
Gravel	10	2–6	9	Shale	3	100–300	2
Sand	9	6–12	5	Limestone	6	300–700	4
Peat	8	12–18	3	Sandstone	6	700–1000	6
Shrinking and /or aggregated clay	7	>18	1	Bedded limestone, sandstone, shale	6	1000–2000	8
Sandy loam	6			Sand and gravel with significant silt and clay	6	>2000	10
Loam	5			Metamorphic/igneous	4		
Silty loam	4			Sand and gravel	8		
Clay loam	3			Basalt	9		
Muck	2			Karst limestone	10		
Non shrinking and non aggregated clay	1						
Weight 2		Weight 1		Weight 5		Weight 3	

Table 2. Standard range and rating for rainfall and soil[24]

Rainfall		Soil permeability	
Range (mm)	Rating	Range	Rating
>850	4	High	5
700–850	3	Moderate to high	4
500–700	2	Moderate	3
<500	1	Slow	2
		Very slow	1

environment and these values are converted into shape files, which were converted into raster files to prepare the respective parameter maps. Later, these maps were converted into rating maps followed by index map by multiplying weights into the ratings to get DRASTIC parameter index units. Finally, all the seven parameter index map layers were combined using combine tool of Arc GIS to obtain a final GW vulnerability map.

The DRASTIC model is based on seven parameters, corresponding to seven layers to be used as input parameters for modelling, whose required information was obtained from various government organizations and reports at a desired scale (Table 4).

The hydraulic conductivity, vadose zone and aquifer media directly control GW movement in the saturated zone, thereby controlling the degree and fate of the contaminants. The geological description of the study area indicated the existence of fractured basalt which is the parent material of soils. Therefore, just one class on range and rating was used for the hydraulic conductivity, vadose zone and aquifer media.

Results and discussion

Depth to water table

The depth to water is important, primarily because, it determines the depth of material through which a contaminant must travel before reaching the aquifer, and it may help to determine the amount of time during which contact with the surrounding media is maintained. The depth to water table (DTWT) was measured from tube wells. Maps of depth to water table range, rating and index have been prepared, which are shown in Figure 4 and details are given in Table 5.

Net recharge

The primary source of GW is precipitation, which infiltrates through the ground and reaches the water table. Net recharge indicates the amount of water per unit area of land, which penetrates the ground surface and reaches the water table. This

Table 3. Soil permeability class (ref. 25).

Texture class	Texture	Permeability rate	Permeability class
Coarse	Gravel, coarse sand	> 20 inches/h	Very rapid
	Sand, loamy sand	6–20 inches/h	Rapid
Moderately coarse	Coarse sandy loam, sandy loam, fine sandy loam	2–6 inches/h	Moderately rapid
Medium	Very fine sandy loam, loam, silt loam, silt	0.60–2 inches/h	Moderate
Moderately fine	Clay loam, sandy clay loam, silty clay loam	0.20–0.60 inches/h	Moderately slow
Fine	Sandy clay, silty clay, clay (<60%)	0.06–0.20 inches/h	Slow
Very fine	Clay (>60%), clay pan	< 0.06 inches/h	Very slow

Table 4. Hydrogeological parameters and their sources used for DRASTIC model

Parameters	Sources	Format
Depth to water	Primary data (through well inventory)	Table
Net Recharge	Secondary data (rainfall data collected from Collector office, Mandla, M.P.)	Table
Aquifer media	Secondary data (District Resource Map, published by GSI, 2003)	Map
Soil media	Secondary data (National Bureau of Soil Survey and Land use Planning) (NBSS&LUP, ICAR)	Map
Topography	Secondary data (Topo sheet 64B-9, 10 published by SOI)	Map
Impact of the vadose zone	Secondary data (District Resource Map, published by GSI, 2003)	Map
Hydraulic conductivity	Secondary data (D. G. Limaye[18])	Table

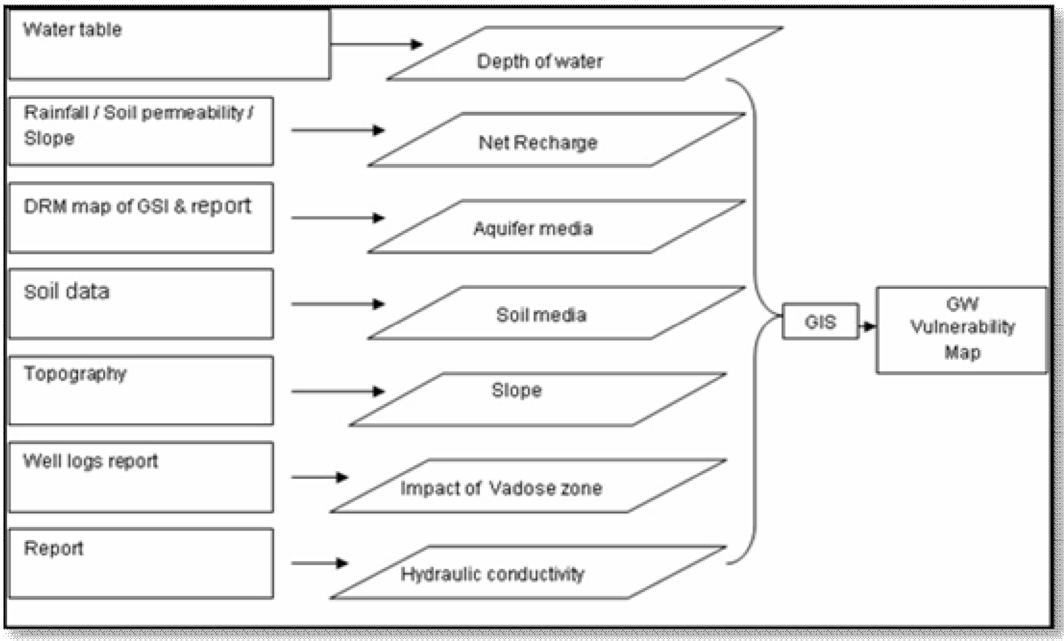

Figure 3. Methodology for groundwater vulnerability analysis.

recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. More the water that leaks through, the greater the potential for the recharge to carry pollutants into the aquifer. Recharge is enhanced by practices such as irrigation or artificial recharge.

Net recharge data were not available for the study area. Therefore, it is calculated through a combination of slope, soil permeability and rainfall following the method of Piscopo[24]. Recharge was calculated using the formula

Recharge value = Slope (%) + Rainfall + Soil permeability.

Recharge value for the study area was measured using data given in Table 6 A, 6 B (modified from Piscopo[24]), (soil permeability is based on USDA[25]). Net recharge range and rating are shown in Figure 5.

Ratings have been assigned to each slope class in the slope map in GIS environment.

Aquifer media

Aquifer media refers to the consolidated or unconsolidated medium which serves as aquifer. The aquifer media is defined by geology. The Basalt is a basic rock formation in the study area. The range, rating and index of aquifer media are given in Table 7 and aquifer media map is given in Figure 6.

Soil media

Soil media refers to that uppermost portion of the vadose zone characterized by significant biological activity. Soil is commonly considered as the upper weathered zone of the earth which averages 6 feet or less in the area. Soil has a significant impact on the amount of recharge which can infiltrate the ground and hence on the ability of a contaminant to move vertically into the vadose zone. A soil map was prepared from the District Soil Map of National Bureau of Soil Survey and Land Use Planning[26]. Assigned range, rating and index of soil media of the study area are given in Table 8. The range, rating and index of soil media are shown in Figure 7.

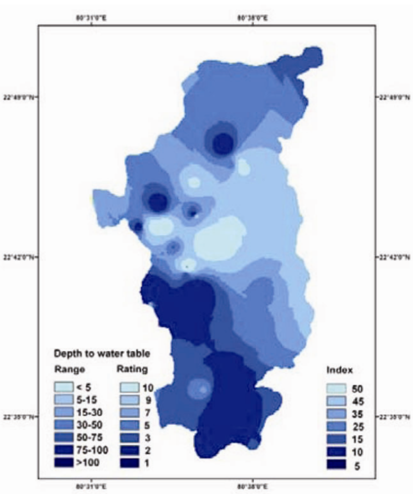

Figure 4. Depth to ground water range, rating and index map.

Table 5. Range, rating and index for depth to groundwater (weight 5)

Range (feet)	Rating	Index (*DrDw*)
<5	10	50
5–15	9	45
15–30	7	35
30–50	5	25
50–75	3	15
75–100	2	10
>100	1	5

Topography

Topography refers to the slope and slope variability of the land surface. Topography controls the likelihood of a pollutant disposed as runoff or retaining it in the area remains long enough to infiltrate. Topography is also significant from the standpoint that the gradient and direction of flow often can be inferred for water table condition from the general slope of the land. Typically, steeper slopes signify higher ground water velocity. Slope classes with their range, rating and index of the study area are given in Table 9 and shown in Figure 8.

Impact of vadose zone

The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table.

Impact of vadose zone range, rating and index on the study area is given in Figure 9 and numerical values are shown in Table 10.

Hydraulic conductivity of the aquifer

Hydraulic conductivity controls the rate at which ground water will flow under a given hydraulic gradient. It is controlled by the amount and interconnection of void spaces and intergranular porosity, fracturing, etc. Hydraulic conductivity values for the weathered basalt aquifer system vary from 0.01 to 1.5 m/day (0.245–36.75 gpd/ft^2)[27]. The numerical range and rating for hydraulic conductivity of the study area is given in Table 10 and the map is shown in Figure 10.

Compiling the database for the DRASTIC index

A range of secondary data were required in order to provide quantitative information for the GW vulnerability assessment, including the distribution of soil types, depth to GW and the spatial rainfall distribution, etc. These data were derived from a variety of sources and were obtained in a range of formats. Information concerning the type, source and characteristics of individual data sets is given in Table 4.

Development of the DRASTIC vulnerability index

The DRASTIC index was calculated using eq. (1) in the Arc View GIS environment to map the GW vulnerability of the study area. However, net recharge data were not available for the study area. Therefore, net recharge is calculated by a combination of ratings for slope, soil permeability and rainfall following the method given by Piscopo[24]. The details are given in Table 6. The GIS

Table 6. A, Data used for measurement of net recharge in the study area

Slope (%)		Rainfall (mm) (2006–2007 data)		Permeability of soil	
Range	Rating	Range	Rating	Range	Rating
0–2	10	956.8	4	Very slow Moderate	1 3
2–6	9				
6–12	5				
12–18	3				
>18	1				

B, Net recharge ratings for study area[24]

Net recharge value (weight 2)		
Range	Rating	Index (*RrRw*)
6–8	1	2
8–10	3	6
10–12	5	10
12–15	8	16
15–17	10	20

coverage (Figures 4–10) was in raster format and values for each overlay were summed up in Arc View GIS according to the pixel value of each area that resulted from multiplying the ratings with appropriate DRASTIC weight. DRASTIC index was calculated using the formula given below

$$\text{DRASTIC Index} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw.$$

Since the minimum DRASTIC index value using these parameters is 92 and the maximum is 164, this range has been divided into three equal classes. These classes are: (i) 92–123 (low vulnerable), (ii) 123–142 (moderate vulnerable) and (iii) 142–164 (high vulnerable) which are shown in the GW vulnerability zone map in Figure 11.

Table 7. Range, rating and weight for aquifer media (weight 3)

Range	Rating	Index (*ArAw*)
Basalt	9	27

Table 8. Range, rating and weight for soil media (weight 2)

Range	Rating	Index (*SrSw*)
Sandy loam	6	12
Loam	5	10
Clay Loam	3	6

Table 9. Range, rating and weight for topography (weight 1)

Slope Range	Rating	Index (*TrTw*)
0–2	10	10
2–6	9	9
6–12	5	5
12–18	3	3
>18	1	1

Table 10. Range, rating and weight for Impact of vadose zone (weight 5)

Range	Rating	Index (*IrIw*)
Weathered Basalt	9	45

Table 11. Range, rating and Index for hydraulic conductivity (GPD/ft^2) (weight 3)

Ranges	Rating	Index (*CrCw*)
0.245–36.75	1	3

Validation of DRASTIC model

For validation of the vulnerability assessment, 28 GW samples were collected from different vulnerability zones of the study area for estimation of concentration of fluoride and nitrate. It has been found that 16 samples (57.14%) are contaminated by fluoride and the remaining 12 samples (42.86%) are within permissible limit (1.5 ppm). Location of high fluoride concentration is superimposed on vulnerability zones, which shows that 62.5%, 25.0% and 12.5% samples were

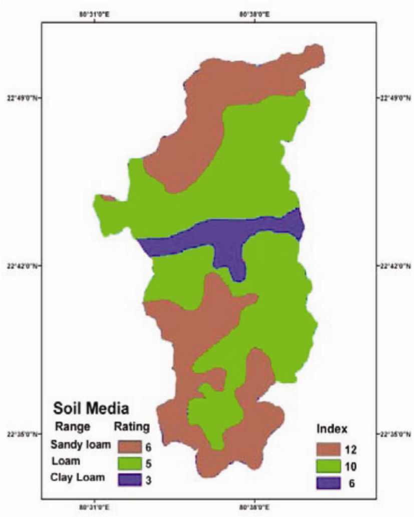

Figure 7. Soil media range, rating and index map.

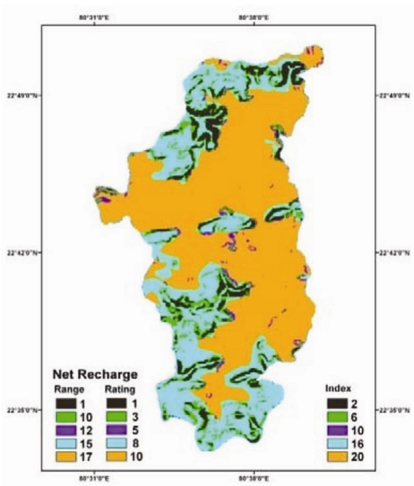

Figure 5. Net recharge range, rating and index map.

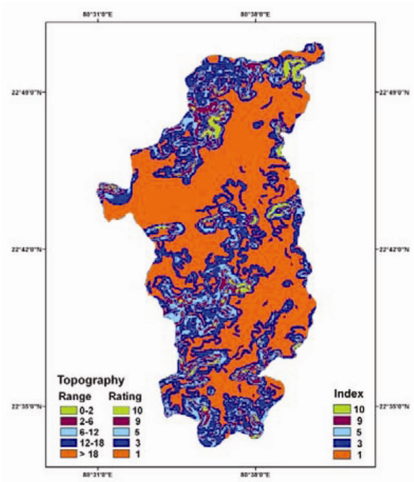

Figure 8. Slope range, rating and index map.

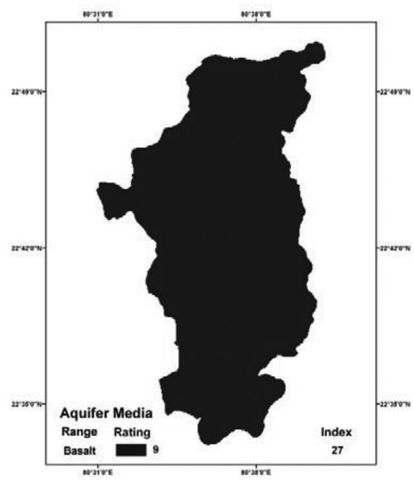

Figure 6. Aquifer media range, rating and index map.

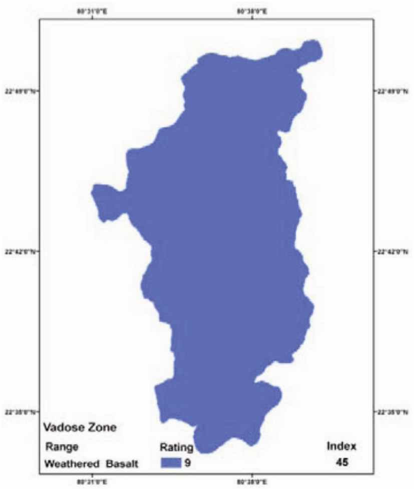

Figure 9. Vadose zone range, rating and index map.

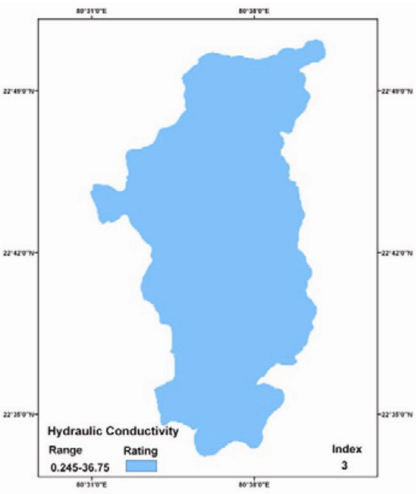

Figure 10. Hydraulic conductivity range, rating and index map.

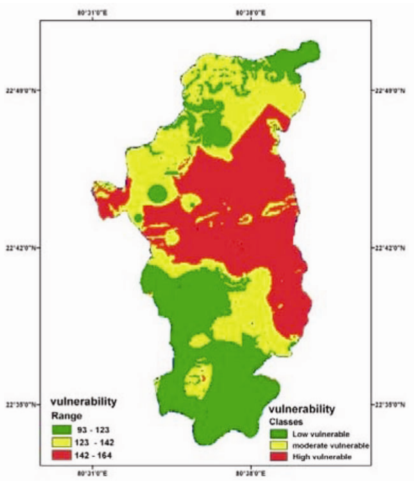

Figure 11. Groundwater vulnerability zone map.

situated in high, moderate and low vulnerable zones respectively (Figure 12). Distribution of nitrate is below permissible limit in the study area, but value varies from place to place. In the high vulnerable zone, concentration of nitrate varies between 0.221 and 0.396 ppm; in the low vulnerable zone, it varies between 0.109 and 0.200 ppm and in the moderate vulnerable zone, it varies between 0.118 and 0.198 ppm. Twelve samples lie in high vulnerable zone and 11 in low vulnerable zone and 5 samples in moderate vulnerable zone (Figure 13).

Recommendation

Farmers should avoid using fertilizers and pesticides when the DRASTIC index is present in high vulnerable zone.

Recharging the aquifer through rainwater harvesting at appropriate locations in the high vulnerable zone to improve the quality of existing GW through dilution is recommended by guidelines of Central Ground Water Board, New Delhi, May 2000 for artificial GW recharge.

Conclusion

A GIS model was employed to determine the vulnerability of GW to contamination in the study area. This was accomplished using the DRASTIC model. The output map was obtained to determine the vulnerability of GW pollution in basaltic aquifers. The vulnerable zones were classified into three, i.e. low, medium and high zones. About 34.87% of the study area lies in low vulnerable zone, 30.28% in moderate vulnerable zone and 34.85% in high vulnerable zone.

From the results of the study, it is clear that GW vulnerability zones are directly controlled by 'DRASTIC' parameters and GIS is a valuable tool for the managers, because it gives a comprehensive picture of GW contamination vulnerability. Fluoride contamination is reaching GW through recharge GW that is in contact with fluoride-bearing minerals[28–30] such as apatite, uranyl fluoride and carbonate fluorapatite in the basaltic terrain.

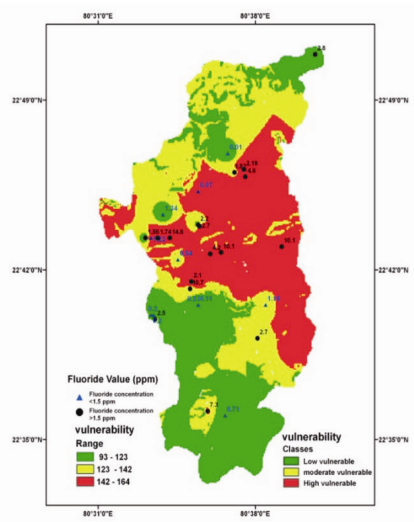

Figure 12. Fluoride value in different vulnerability zones.

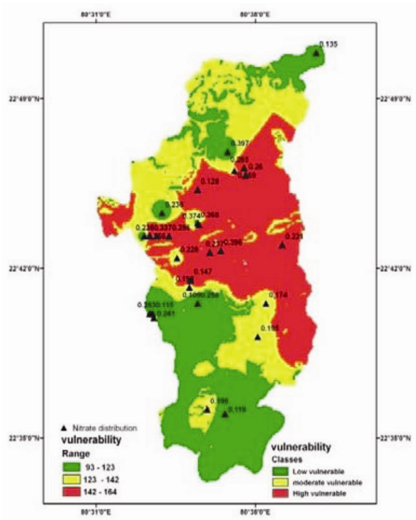

Figure 13. Nitrate value in different vulnerability zones.

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