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Evaluation of Groundwater Vulnerability to Pollution using GIS Based DRASTIC Method in Koradi, India - A Case Study

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ABSTRACT

Groundwater (GW) contamination due to urbanization, industrialization and agriculture is a major environmental problem in India. The present case study aims to estimate the vulnerability of the aquifer with the help of GIS based DRASTIC method. A micro watershed, characterized by Granites and Gondwana Formation in the vicinity of Koradi, 15 km from Nagpur in Central India has been considered. The DRASTIC method accounts for hydrogeological parameters like depth to water, net recharge, aquifer media, soil media, impact of vadose zone and hydraulic conductivity. The DRASTIC index (DI) for GW vulnerability to pollution is calculated as the sum of the product of ratings and weights assigned to each of the parameter on the scale of 1 to 10 and 1 to 5 respectively. A Groundwater vulnerability map has been prepared using the Arc GIS software (Version 10.1) and it delineates the total study area into two vulnerable zones with vulnerability score ranging from 107 to 142 and indicates that 33% and 67% of the area lies in low and moderate vulnerability zones respectively. The vulnerability score as obtained is also verified with field data.

INTRODUCTION

Groundwater is an indispensable resource to mankind and it accounts for nearly 97% of the available fresh water. It is an important source for drinking and agriculture and it constitutes approximately 85% of the drinking and agricultural requirements in the rural areas. It is necessary that utmost care is taken to maintain this resource with respect to quality and quantity. However, the increase in urbanization has led to significant generation of both liquid and solid waste. In the absence of proper disposal practices, the groundwater resources are vulnerable to pollution from the untreated waste as well as improperly disposed waste. In view of this, it is important to undertake vulnerability assessment in any region having considerable urbanization.

Preventing groundwater pollution is requisite for effective groundwater resource management. The National Research Council defines groundwater vulnerability to contamination as "The introduction of potential contaminants to a location on top of an aquifer at a specified position in an underground system" (Sniffer, 2004). The concept of groundwater vulnerability has been dealt by several authors (Aller et al. 1985; Sinan and Moumtaz, 2009; Polemio et al. 2009). They observed that the factors leading to variable vulnerability is the difference in hydrogeological settings. Vulnerability assessment processes are divided into three categories, namely; the process-based simulation methods, the statistical methods, and the overlay and index methods. Process based methods and statistical methods are more intricate to use on a regional scale. The process based simulation models have the inherent limitation when parameters required in modelling the flow and transport are not available in a representative manner for the regional setting. The statistical methods also have the limitation when large data base is not available to represent the regional setting. The overlay and index methods have emerged as effective tool to assess groundwater vulnerability. As geographic information systems (GIS) involves overlaying and aggregation of multiple maps, overlay and index methods are more suitable (EPA 2003). This has led to significant efforts both at the national and International level (Aller et al. 1985; Polemio et al. 2009; Foster, 1987; Richards, 1996; Zekster et al. 2004; Prasad and Shukla, 2014; Suryanarayana, 1965; Rubia and Jhariya, 2019; Singhal et al. 2016; Thirumalaivasan et al. 2003; Umar et al. 2009; Venkatesan et al. 2019).

In the present study, vulnerability assessment by DRASTIC approach which is an overlay and index method has been attempted in a watershed of the Kanhan river, near Nagpur, India. The assessment is necessary in view of the study area having significant agriculture and built up areas, absence of centralized sewerage and presence of ash dykes of coal based thermal power plants. This will also facilitate policy decisions for future growth of urbanization.

STUDY AREA

The study area (Fig.1) is situated in the Nagpur district, north-eastern part of Maharashtra, India. It is bounded by latitudes 21°09'59" N to 21°16'00"N and longitudes 79°05'00"E to 79°15'00" E. The study area covers approximately 66 sq. km. The area has an arid climate with the temperature varying in the range from 10° C to 46° C. The average rainfall is approximately 1,100 mm (CGWB, 2015) and it is received from the southwest monsoon during the period June to September. As the watershed has limited extent in area, there is no climatic variation in terms of rainfall, temperature and humidity.

Lithologically, the area comprises rocks of Sausar group (quartzites, marbles, schists and gneisses), sedimentary formations (sandstone, shale and clay) equivalent of Kamthi stage of Gondwana supergroup (Suryanarayana, 1965, 1968). The area is predominantly covered by archeans except small patch of Gondwanas in the south and north (Fig.2). Hydrogeologically, the study area is characterized by unconfined to semi confined aquifers. It is observed that the ground-water level varied from 6 feet to 59 feet in pre-monsoon and 3 feet to 52 feet to post-monsoon season.

The land use and land cover classification (Fig.3) of the remote sensing data (LISS-IV) based on Supervised classification (Maximum likelihood) indicates that vegetation (41.9 %) and built up (24.2 %) area constitute the predominant land use. The water body, ash dyke and waste land constitute 3.01 %, 10.6 % and 20.13 % respectively.

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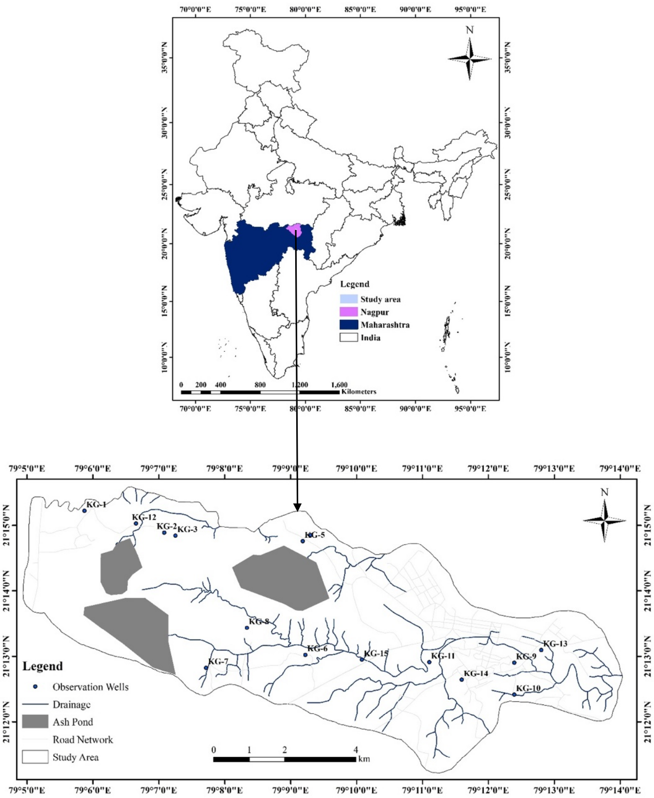

Fig.1. Location of Study area

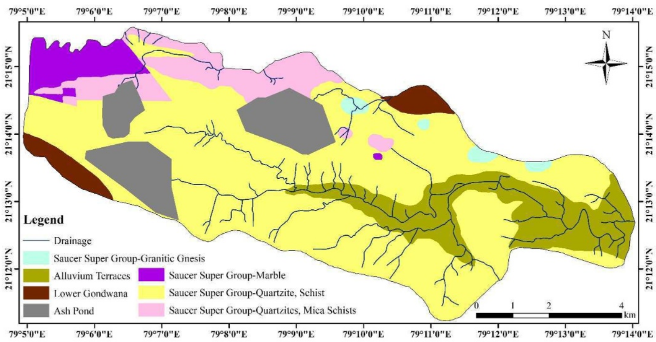

Fig.2. Geology of the study area

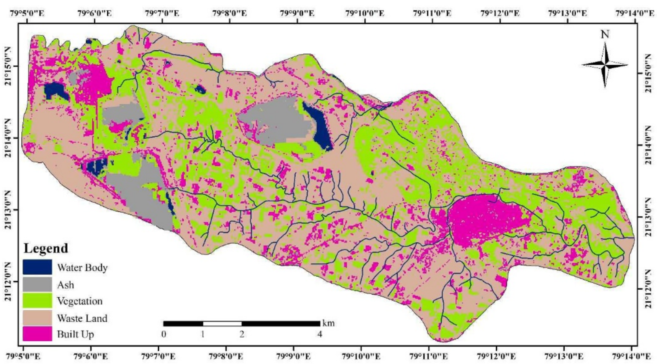

Fig.3. Landuse and Land cover of the study area

METHODOLOGY

Description of DRASTIC

The DRASTIC method was developed in the United States under mutual agreement between the National Water Well Association (NWWA) (Aller et al. 1985) and the US Environmental Protection Agency (EPA). The key assumptions made by DRASTIC method are: (1) the contamination occurs at the ground surface; (2) the contaminant enters the water table when rain falls on the surface and percolates into the saturated zone; (3) the contaminant travels with water, at the same rate as water; (4) The area evaluated is 100 acres or larger.

The method (Fig. 4) produces a numerical index that is derived from ratings and weights assigned to the seven hydrogeological parameters. The weights correspond to the relative importance of parameters and the ratings correspond to the relative importance of categories within each parameter are assigned accordingly. More the DRASTIC Index, more will be the area susceptible to groundwater pollution and vice versa. The final vulnerability map is based on the DRASTIC Index (DI) which is computed as the weighted sum overlay of the seven layers using the following equation.

$$\text{"}DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw\text{"} \quad (1)$$

Where, D, R, A, S, T, I, and C represents the seven parameters, r is the rating value, and w the weight assigned to each parameter.

Where;

Dr = Ratings to the depth to water table
Dw = Weights assigned to the depth to water table
Rr = Ratings for ranges of aquifer recharge
Rw = Weights for the aquifer recharge
Ar = Ratings assigned to aquifer media
Aw = Weights assigned to aquifer media
Sr = Ratings for the soil media
Sw = Weights for soil media
Tr = Ratings for topography (slope)
Tw = Weights assigned to topography
Ir = Ratings assigned to vadose zone
Iw = Weights assigned to vadose zone
Cr = Ratings for rates of hydraulic conductivity
Cw = Weights given to hydraulic conductivity

The standard weights assigned for seven hydrogeological DRASTIC parameters (Aller et al. 1985) are given in Table 1 and the degree of vulnerability is based on the Drastic index (Table 2).

Depth to Water

Depth to water determines the depth of material through which a contaminant must travel (Thirumalaivasan et al. 2003) before reaching

Table 1. Standard Assigned Weights for DRASTIC Parameters (Aller et al. 1985).

Parameters	DRASTIC Weight
D-Depth to water	5
R-Net Recharge	4
A-Aquifer media	3
S-Soil media	2
T-Topography	1
I-Impact of Vadose Zone	5
C-Hydraulic Conductivity	3

Table 2. Standard criteria to evaluate vulnerability classes for DRASTIC method (Aller et al. 1985).

Degree of Vulnerability	DRASTIC Index
Low	26 - 120
Moderate	121 - 160
High	161 - 200
Very high	200 - 226

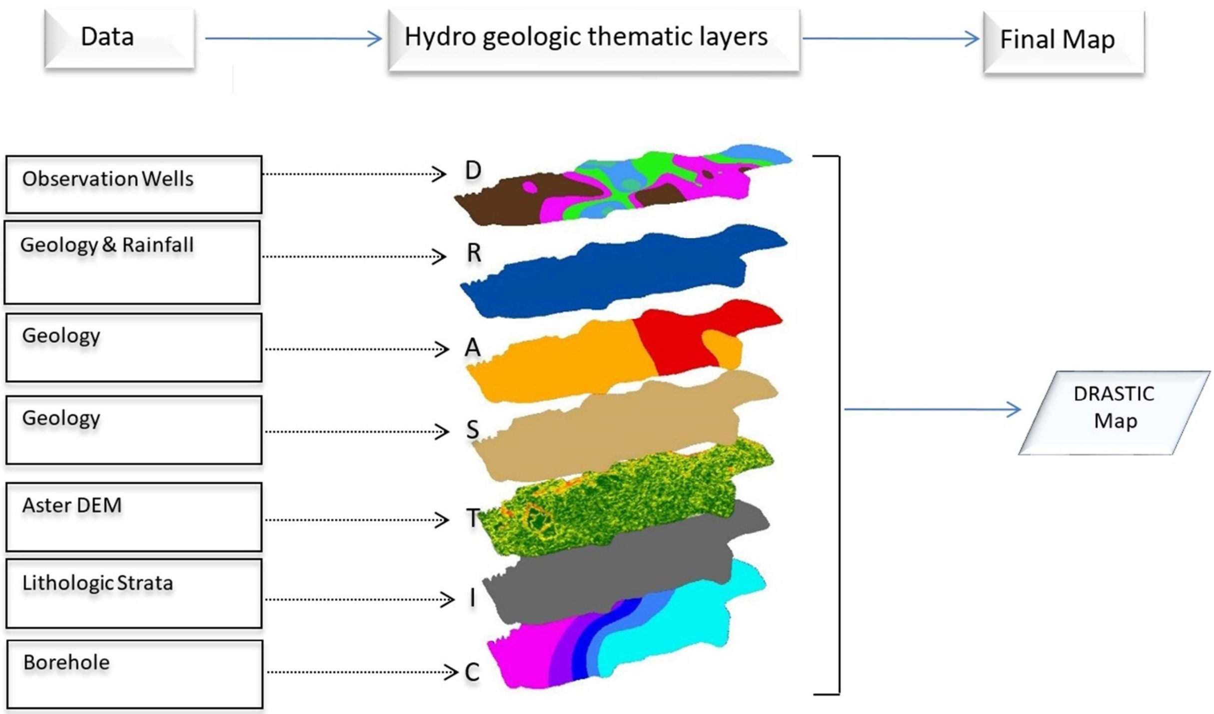

Fig.4. Flowchart of the methodology

the water table in the aquifer. The depth to water is crucial as it provides maximum opportunity to oxidation by atmospheric oxygen (Herlinger and Viero, 2007). Hence, the greater the depth to the water table, the lesser the chance of pollutants arriving at the water table. Data from observation wells (15 nos) in the study area were used to prepare depth to water table map. The observation wells were open wells and Mark II hand pumps. Map of depth to water table range, rating and index was prepared (Fig.5a) by using spatial interpolation technique of Arc GIS. The depth to water table in the study area is classified into 3 categories ranging from 3 to 16 feet, 17 to 29 feet and 30 to 52 feet and ratings (Table 3) of 9, 7 and 5 were assigned respectively to depth to water table thematic layer with the weight 5.

Net Recharge

Net recharge represents the amount of water per unit area of land which penetrates the ground surface and reaches the water table. This recharge water thus transport a contaminant vertically to the water table and horizontally within the aquifer. In addition, the quantity of water available for dispersion and dilution of the contaminant in the vadose zone and in the saturated zone is controlled by this parameter. Net recharge map (Table 3, Fig.5b) is prepared on the basis of infiltration factor based on GEC (2015). The net recharge ranges of six classifications are 7 to 10 inches, 4 to 7 inches, 0 to 2 inches, 2 to 4 inches, 4 to 7 inches and 4 to 7 inches and ratings 8, 6, 1, 3, 6 and 6 with weight 4 were assigned respectively.

Aquifer Media

The flow system within the aquifer is affected by the aquifer medium (Rahman, 2008). In general, larger the grain size, the higher the permeability and lower the attenuation capacity of the aquifer media (Aller et al. 1985). Aquifer media parameter is obtained using data from bore holes drilled in the study area. Drilling was carried out at six locations in the study area and based on the lithological data, it is indicated that the aquifer was weathered metamorphic rock in part of the study area and massive limestone at other places. Hence, ratings 4 and 6 with weight 3 were given to the aquifer media and the aquifer map was prepared (Table 3, Fig.5c).

Soil Media

Soil has a significant impact on the amount of recharge that can infiltrate into the ground (Aller et al. 1985). In general, the less the clay shrinks and swells and smaller the grain size of the soil, the less likely contaminants will reach the water table. The soil type in the study area is predominantly clay and uniform rating of 7 and weight 2 was assigned to the whole study area and is shown in Fig.5d.

Topography

Topography controls the likelihood of a pollutant disposed as runoff or retaining it in the area long enough to infiltrate. Slope map (Fig.5e) was generated from ASTER DEM (30m resolution) by using slope tool in spatial analyst toolbar. The slope layer was classified (Table 3) into four categories ranging from 0 to 2 %, 3 to 6 %, 6 to 12 % and 18+ % and and ratings 10, 9, 5 and 1 with weight 1 were assigned respectively.

Impact of Vadose Zone

The vadose zone media controls the path length and routing, thus affecting the time available for attenuation and the quality of material encountered (Timmons and Dylla, 1981; Richards et al. 1996). Raster layers with two classifications were prepared and impact of vadose zone map (Fig.5f) was generated from it. The vadose zone takes into account the capillary fringe. Most of the study area (Fig.2) is covered by metamorphic rocks (quartzite, schist and mica schist) and remaining part is covered by limestone (marble). Hence, the rating of 6 to the zone covered by metamorphic rock and rating 4 to the zone covered by limestone with weight 5 is assigned.

Hydraulic Conductivity

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which groundwater will flow under a given hydraulic gradient. The rate at which the groundwater flows also controls the rate at which a contaminant will be moved away from the point at which it enters the aquifer (Aller et al. 1985). Hydraulic conductivity is controlled by the amount and interconnection of void spaces within the aquifer which may occur as

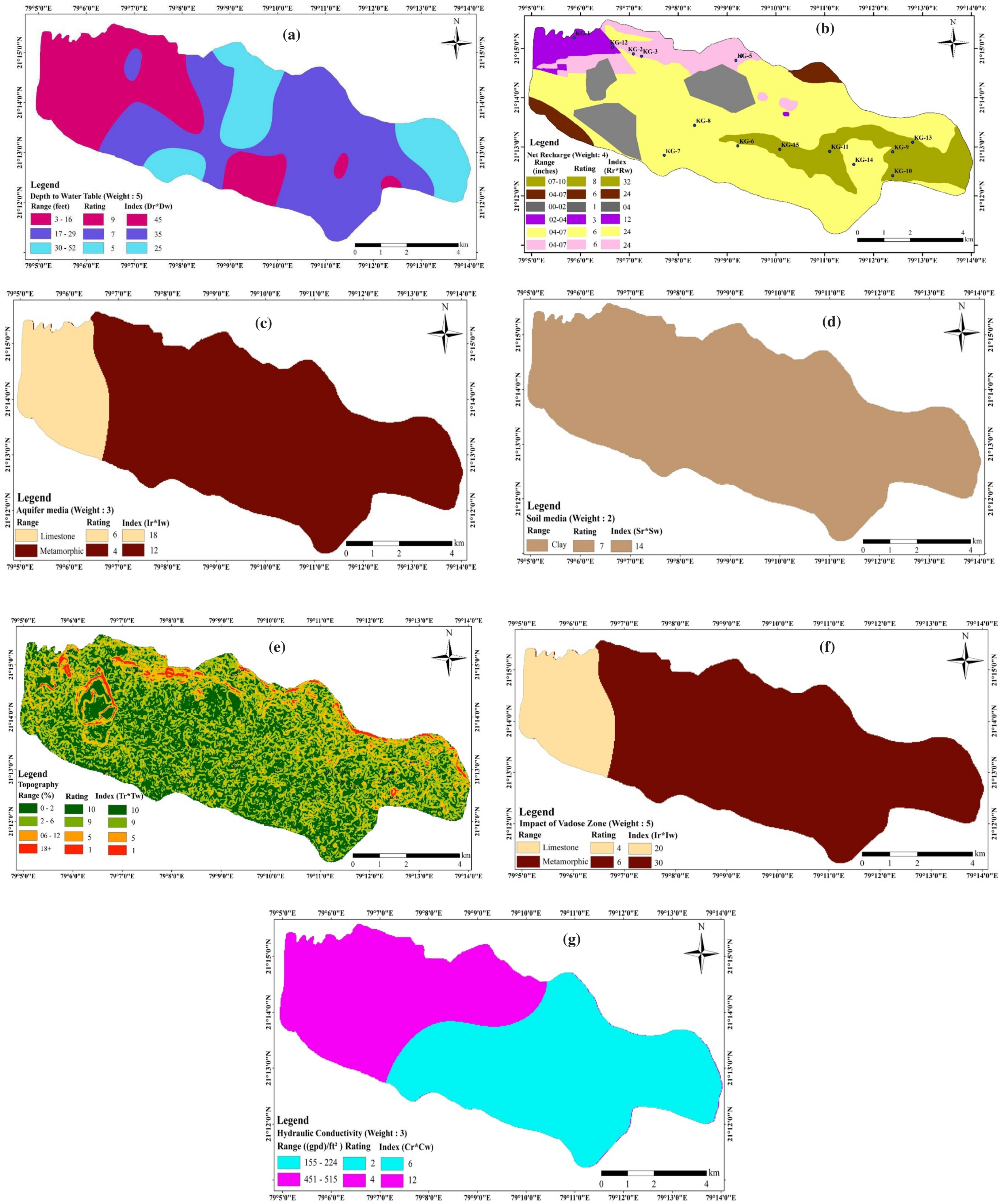

Fig.5. Map showing **(a)** Depth to Water Table, **(b)** Net Recharge, **(c)** Aquifer media, **(d)** Soil media, **(e)** Map showing Topography, **(f)** Impact of Vadose Zone, **(g)** Hydraulic Conductivity at Koradi.

Table 3. Criteria to evaluate DRASTIC parameters (Aller et al. 1985).

Depth to Water (D)		Net Recharge (R)		Aquifer media (A)	
Range (feet)	Rating	Range (inches)	Rating	Parameter	Rating
0-5	10	0-2	1	Massive Shale	2
5-15	9	2-4	3	Metamorphic/Igneous	3
15-30	7	4-7	6	Weathered Metamorphic/Igneous	4
30-50	5	7-10	8	Thin Bedded Sandstone, Limestone Shale Sequences	6
50-75	3	10+	9	Massive Sandstone	6
75-100	2			Massive Limestone	6
100+	1			Sand and Gravel	8

Soil media (S)		Topography (T)		Impact of Vadose Zone (I)		Hydraulic Conductivity (C)	
Parameter	Rating	Range (percent slope)	Rating	Parameter	Rating	Range (GPD/FT2)	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	18+	1	Bedded Limestone, Sandstone, Shale	6	700 - 1000	6
Shrinking and Aggregated Clay	7			Sand and Gravel with significant Silt and Clay	6	1000 - 2000	8
Sandy Loam	6			Metamorphic/Igneous	4	2000+	10
Loam	5			Sand and Gravel	8		
Silty Loam	4			Basalt	9		
Clay Loam	3			Karst Limestone	10		
Muck	2						
Non shrinking Non-aggregated Clay	1						

a consequence of factors such as intergranular porosity, fracturing and bedding planes. The whole study area was delineated into two hydraulic conductivity zones (Fig.5g) on the basis of hydraulic conductivity estimated from the pumping tests conducted in the study area. It is classified into two categories ranging from 155 to 224 and 451 to 515 and ratings 2 and 4 with weight 3 were assigned respectively.

RESULTS AND DISCUSSION

To assess groundwater vulnerability to contamination, DRASTIC method with hydrogeological thematic layers and spatial analyst tools of GIS environment were used. Extensive primary data collected have been used in the study. Depth to water table, net recharge, hydraulic conductivity are crucial parameters in DRASTIC method. The depth of the water table is calculated from observation wells (15 nos) by using water level indicator. Net recharge is calculated from infiltration factor. The hydraulic conductivity estimated from pump tests has been used. The DRASTIC index (Table 4) is calculated for the study area and it ranged from 107 to 142. The final map (Fig.6) obtained from seven thematic layers delineates the study area into two vulnerable zones i.e., low and moderate on the basis of the Drastic score (Table 2). The DRASTIC index indicates that 33% of the study area is having low vulnerability and 67% is moderately vulnerable to groundwater pollution. It indicates that so far the study area does not have any high vulnerable zones.

Validation of DRASTIC Method

The validation of DRASTIC method is attempted by considering the nitrate concentration in the drinking water wells (15 nos.) in the study area.

The nitrate concentration map was prepared by the interpolation

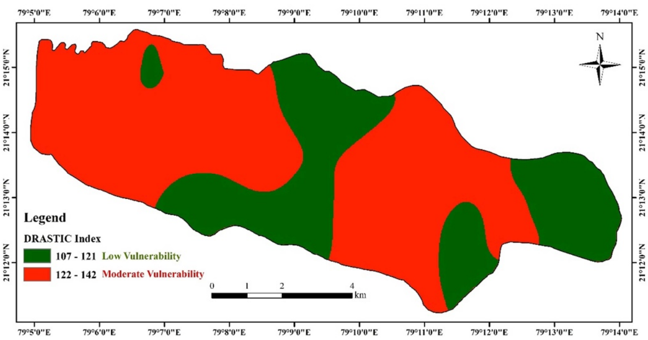

Fig.6. Map of groundwater vulnerability to pollution (DRASTIC index)

Table 4. Vulnerability classes for DRASTIC method in the study area

Degree of Vulnerability	DRASTIC Index
Low	107-121
Moderate	122-142

method of ArcGIS. A careful analysis of the DRASTIC index (Fig.6) and the nitrate map (Fig.7) indicates that high nitrate concentration (>45 mg/L i.e. the desirable limit of WHO) broadly overlap with moderate DRASTIC index though there is a slight deviation at some places. Samples namely KG-5, KG-6, KG-7, KG-8, KG-9, KG-10, KG-12, KG-13 and KG-14 are in the low vulnerability zone. The samples collected from moderate vulnerability zones obtained from DRASTIC method have high nitrate concentration and samples KG-1, KG-2, KG-3, KG-11 and KG-15 collected from low vulnerability

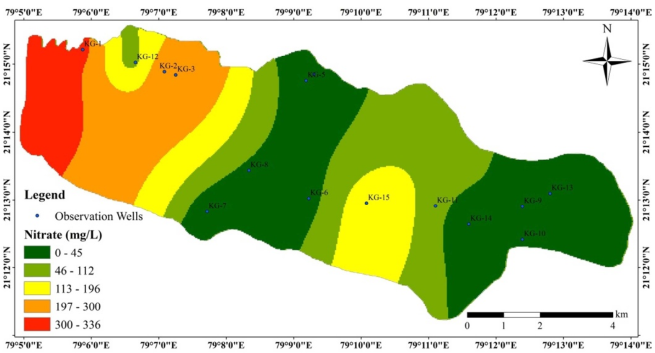

Fig.7. Spatial distribution of nitrate concentration in the study area.

zones have low nitrate concentration. This indicates that the there is broad agreement between the field data and the vulnerability assessment by DRASTIC.

CONCLUSION AND RECOMMENDATIONS

In this study, the DRASTIC map prepared in the Arc GIS platform was used to determine the vulnerability of groundwater to pollution in Koradi area. The low and moderately vulnerable zones constitute 33% and 67% of the study area respectively. It is noteworthy that the study area does not have high vulnerable areas which may be attributed to the presence of clay soil.

The applicability of DRASTIC tool in vulnerability assessment is validated as the spatial distribution of nitrate concentration in the study area shows that high nitrate concentration overlaps with moderate DRASTIC index. Hence, it is necessary that measures are taken for mitigation of nitrate concentration like proper sewerage may be installed. However, regular monitoring in the region is recommended.

The study indicates that DRASTIC method is a very quick and effective tool for semi-quantitative vulnerability assessment in any geoenvironmental studies. The study suggests also that the DRASTIC method can be used for prioritization of vulnerable areas in order to prevent further pollution and take policy decisions on land use planning. It can be further used as a tool for facilitating decisions on siting of industries or growth of existing industrial clusters.

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