

Index-based groundwater vulnerability mapping using quantitative parameters

Satiprasad Sahoo¹ · Anirban Dhar² · Amlanjyoti Kar³ · Durjoy Chakraborty⁴

Received: 14 July 2015 / Accepted: 20 January 2016 / Published online: 18 March 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract To evolve a proper management scenario for groundwater utilization, identification of groundwater vulnerability zones is a critical step. In the present study, an attempt has been made to identify plausible groundwater vulnerability zones based on DRASTIC, Agricultural DRASTIC, AHP (Analytic Hierarchy Process) DRASTIC and Modified DRASTIC methods in the Hirakud command area. The main objective is to determine vulnerability zones for groundwater pollution based on quantitative parameters with the help of geographic information system (GIS) platform. DRASTIC model is an integrated GIS based tool used to evaluate the groundwater vulnerability mapping. DRASTIC models use seven hydrogeological parameters: depth to water table (D), recharge rate (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C). Modified DRASTIC model is used to assess the groundwater vulnerability considering land use/land cover (LULC). Finally, vulnerability map is validated using water quality parameters (EC , Cl^- , Mg^{2+} and SAR) over the study area. Moreover, DRASTIC vulnerability map indicate that the northern part of the study area is more vulnerable for groundwater pollution. Groundwater vulnerability is an

important environmental concern that needs to be assessed for proper groundwater management. This analysis demonstrates the potential applicability of the methodology for a general aquifer system.

Keywords Groundwater vulnerability · DRASTIC · Analytic hierarchy process (AHP) · GIS

Introduction

Groundwater vulnerability is a hypercritical issue of general aquifer system for groundwater framework. Efficient monitoring networks can provide initial state of the aquifer (Dhar 2013). However, detailed hydrogeological investigation is required for better understanding of the sustainable groundwater management. Geographic information system (GIS) technique can provide an estimate of the groundwater vulnerability mapping without much investment. An index-based methodology is applied for groundwater vulnerability mapping based on standard DRASTIC index and its variations.

A large number of studies are available for vulnerability assessment of groundwater aquifers. The Florida Aquifer Vulnerability Assessment (FAVA) based on weights of evidence (WofE) is a data driven, Bayesian-probabilistic model (Arthur et al. 2007). A groundwater vulnerability zone mapping using a new model of DRARCH has been attempted in Taiyuan basin, northern China (Guo et al. 2007). Dynamic visualization method has been used for assessment of groundwater vulnerability maps of two urban watersheds in Mexico (Bojorquez-Tapia et al. 2009). Estimation of the aquifer vulnerability mapping has been done using RISKE model in Banyas catchment, West Syria (Katta et al. 2010). A case study of groundwater

✉ Anirban Dhar
anirban.dhar@gmail.com; anirban@civil.iitkgp.ernet.in

¹ School of Water Resources, Indian Institute of Technology Kharagpur, Kharagpur, India

² Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India

³ Central Ground Water Board, Bhujal Bhawan, Faridabad, Haryana, India

⁴ Central Ground Water Board, Jamnagar House, New Delhi, India

vulnerability assessment in Tarim Basin, Northwest China has been reported using DRAV model (Zhou et al. 2010). Analytic of Hierarchy Process is used to evaluate the groundwater vulnerability mapping in Jiangyin city (Hailin et al. 2011). GIS-based fuzzy pattern recognition model has been applied to generate groundwater vulnerability index map (Pathak and Hiratsuka 2011). Assessment of groundwater vulnerability using combining model of DRASTIC and Dyna-Clue is reported from Argentine Pampas (Lima et al. 2011). Groundwater vulnerability is opined as a new geographic information system- based index (Beynen et al. 2012). Groundwater vulnerability assessment using optimization of DRASTIC method by supervised committee machine artificial intelligence has been applied for the Maragheh-Bonab plain aquifer, Iran (Fijani et al. 2013). A aquifer vulnerability maps has been generated using novel probability-based DRASTIC model in the Choushui River alluvial fan, Taiwan (Chen et al. 2013). Groundwater vulnerability assessment using logistic regression modeling has also been attempted in Hawaii, USA (Mair and El-Kadi 2013). To delineate the groundwater vulnerability zones based on pesticide, DRASTIC, modified DRASTIC, modified pesticide DRASTIC and susceptibility index methods are used by some workers (Brindha and Elango 2015). A comparison of groundwater vulnerability mapping using by Multi Criteria Analysis (MCA) and DRASTIC index values is available in the literature (Junior et al. 2015). Groundwater vulnerability maps generated by various models reported by some workers also could be seen (Kumar et al. 2015). Groundwater vulnerability assessment using GOD model has been worked out in arid environment (Ghazavi and Ebrahimi 2015). Groundwater vulnerability to pollution assessment based on fuzzy pattern recognition model has been reported from Ranchi district (Iqbal et al. 2015), India. Integrating indicator-based aquifer vulnerability mapping for groundwater protection zones (Jang and Chen 2015). Groundwater vulnerability mapping using barometric response functions in semi-confined aquifer has been done by some workers (Odling et al. 2015). Other relevant studies include Secunda et al. (1998), Foster et al. (2003), Dixon (2004), Jasrotia and Singh (2005), Babiker et al. (2005), Ettazarini (2006), Almasri (2008), Rahman (2008), Liggett and Talwar (2009), Mohammadi et al. (2009), Pathak et al. (2009), Ahmed (2009), Baalousha (2010), Yang and Wang (2010), Kazakis and Voudouris (2011), Prasad et al. (2011), Hallaq and Elaish (2012), Huan et al. (2012), Shirazi et al. (2012), Chandoul et al. (2014), Neshat et al. (2014), Shekhar et al. (2014), Pacheco et al. (2015), and Kazakis and Voudouris (2015).

DRASTIC is a standard method for groundwater vulnerability assessment. DRASTIC uses seven parameters e.g., depth to water table, recharge rate, aquifer media, soil media, topography, impact of vadose zone, hydraulic conductivity. A Modified DRASTIC model is used to assess the groundwater vulnerability considering land use/land cover. Four models: DRASTIC, Agricultural DRASTIC, AHP DRASTIC and Modified DRASTIC are used for the groundwater vulnerability mapping. Most of the studies have focused on single water quality parameter validation of the DRASTIC index. This may lead to biased evaluation of the vulnerability maps. In the present study models are validated by multiple water quality parameters (EC, Cl^- , Mg^{2+} and SAR). The proposed methodology is applied to Hirakud command area, INDIA.

Study area

Hirakud command area is situated in the western part of Odisha, India. The study area (Fig. 1) is bounded by North Latitudes $20^{\circ}53'$: $21^{\circ}36'$ and East Longitudes $83^{\circ}25'$: $84^{\circ}10'$ and falls in the survey of India Toposheets 64 O, 64 P, 73 C. The total area of 2260 km² consists of five blocks of Sambalpur District, Six blocks of Bargarh District, two blocks of Suvarnapur District and one block of Bolangir District (Dhar et al. 2015a). The study area receives rainfall during south-west monsoon from June to October (July and August being the rainiest months). The average annual rainfall of this area is 1184.87 mm. The temperature varies between 8 °C (in January) to 47.5 °C (in May). The average temperature is 28 °C. The relative humidity variation is in between 52 % (in May) and 94.27 % (in September) (Dhar et al. 2015a).

The study area is made up of weathered and fractured zones. In W–E direction the thickness of weathered zone varies from 11.70 m at Attabira (W18) to 31.50 m at Godbhaga (W17). Four to six water bearing fracture zones occur within the depth of 172 m (Conjunctive Use Project, CGWB 1998). The groundwater level (sufficiently below canal bed) is locally parallel to topography slope. However, small effluent streams are formed at Danta and Jira (Fig. 2a). Figure 2b shows that in order direction thickness of weathered zone varies from 7.5 m at Kumbhari (W29) to 31.5 m at Goshala (W11). Two to six water bearing fracture zones occur within the depth of 200 m. Number of weathered zones encountered are shown in Fig. 2b. Figure 2c shows that weathered zone varies in thickness from 31.5 m at Goshala (W11) to 13.20 m at Gondtutum (W37). Regional study

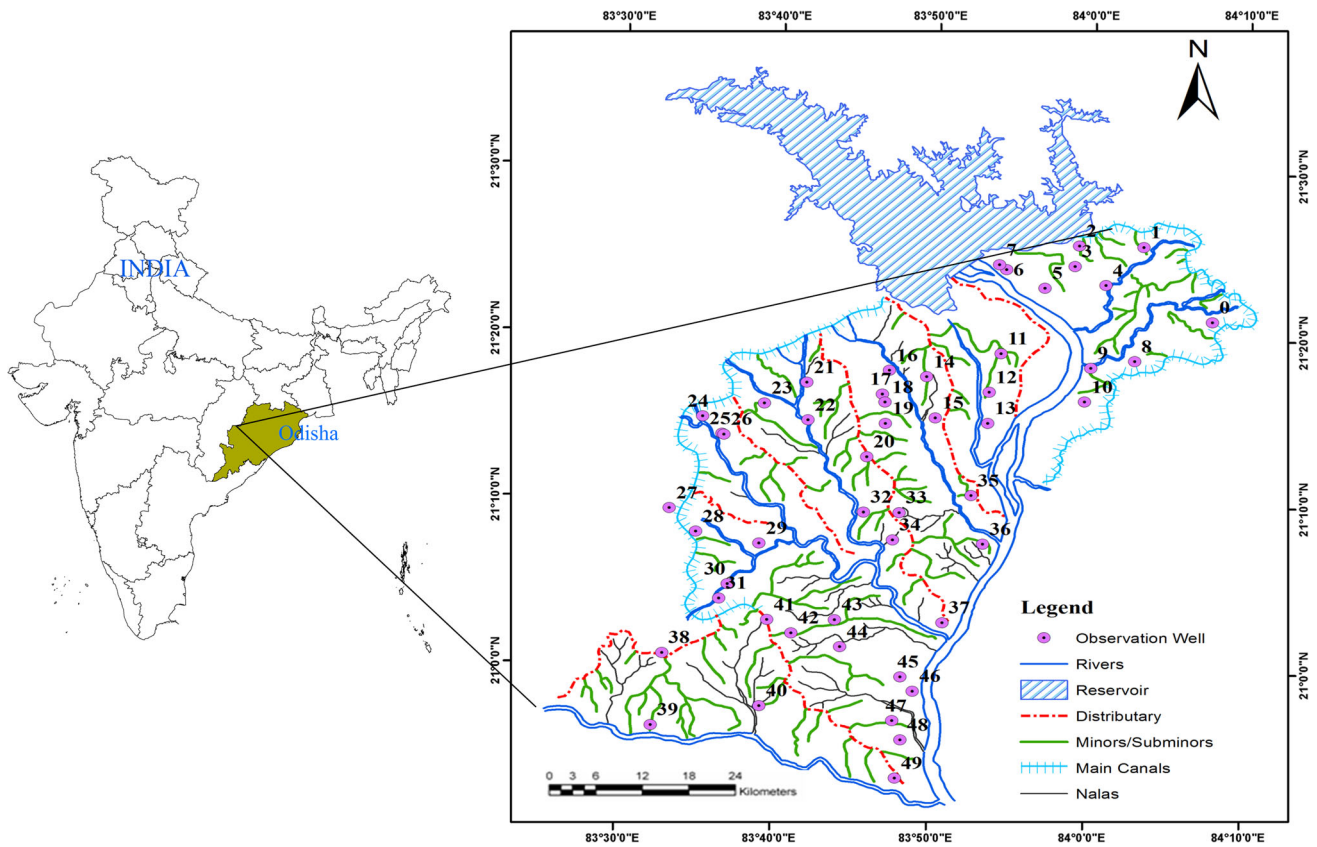


Fig. 1 Location map of the study area (Hirakud Canal Command)

(drilling data and pumping test) reveals the existence of shallow and deep aquifers (Conjunctive Use Project, CGWB, Central Groundwater Board (CGWB) 1998).

Materials and methods

Data used

Depth to water table (1995–2014) is collected from Central Ground Water Board (CGWB). Recharge rate data (2009) is collected from Central Ground Water Board. Impact of vadose zone and hydraulic conductivity data of the study area are used from CGWB (1998). Topography map (<http://bhuvan-noeda.nrsc.gov.in>) is prepared using the CARTOSAT-1 PAN (2.5 m) Stereo data (C1_DEM_16b_2006-2008_V1_85E20N_F45T). Aquifer media and soil media maps are prepared from Geological Survey of India, 2010 and NBSS & LUP (National Bureau of Soil Survey and Land Use planning, 1999) maps respectively. Land use/land cover map (source: <http://glcf.umd.edu>) for the study area is generated from the Landsat 7 Enhanced Thematic Mapper Plus (LANDSAT 7 ETM+, ACQUISITION_DATE:

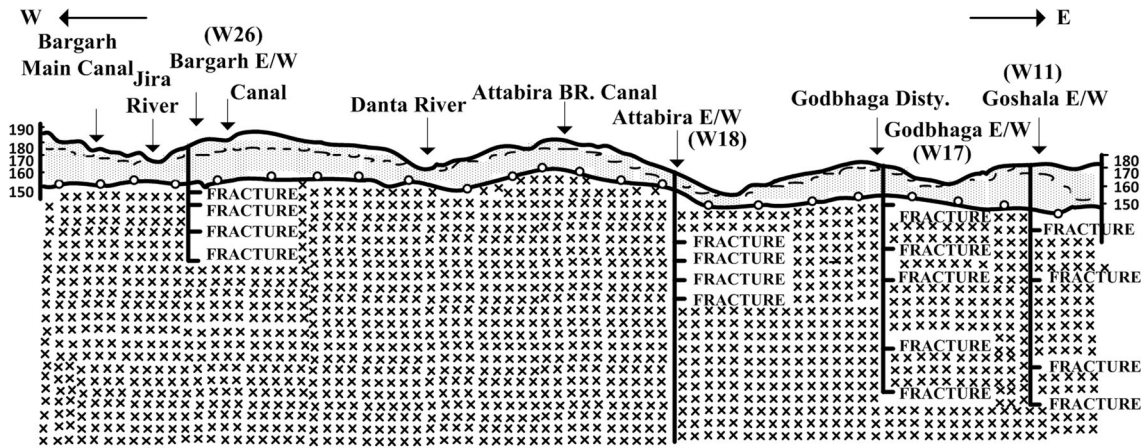
2000-11-22) image. Water quality data is collected from Central Ground Water Board for 2010.

Methodology

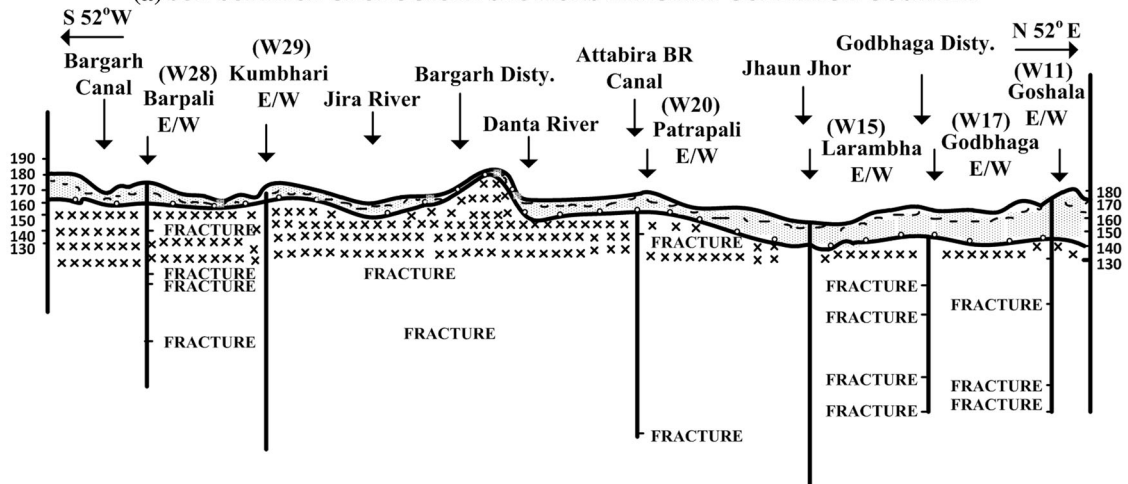
Vulnerability index (VI)

Vulnerability assessment is an important yardstick for resources management and land use planning. One of the most popular aquifer vulnerability models is DRASTIC model (Aller et al. 1985).

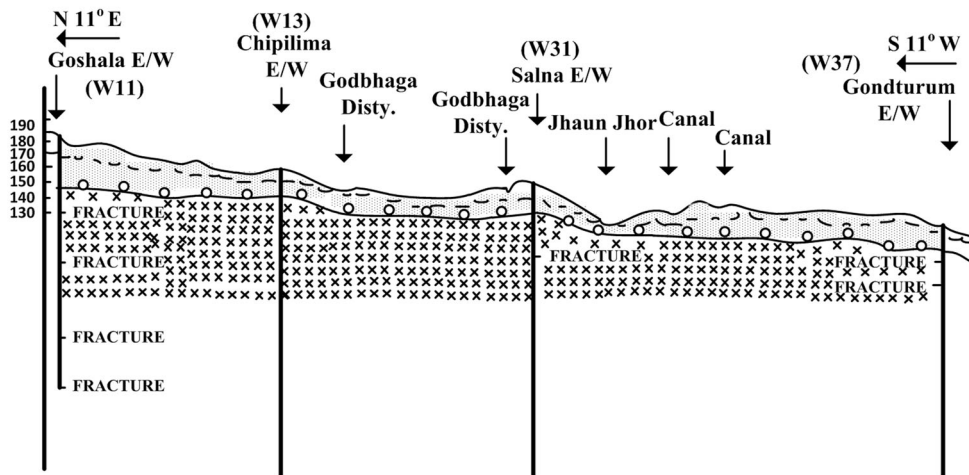
Groundwater vulnerability is generally performed based on standard index approach. All influencing feature layers (e.g., depth to water table, recharge rate) are converted into raster format. In the first stage, individual feature layers are reclassified into sub-features and accordingly ranks are assigned. During final stage, all feature maps are combined using a weighted approach in the GIS platform to generate vulnerability index map. The integrated layer is reclassified into different groundwater vulnerability zone based on vulnerability index values. Groundwater vulnerability index (GWVI) can be calculated as



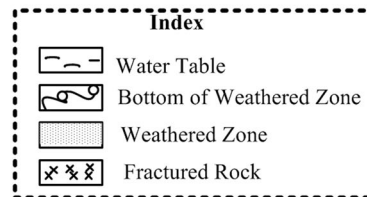
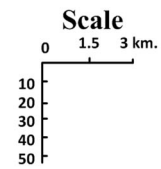
(a) SUB-SURFACE GEOLOGICAL SECTIONS BARGARH-GODBHAGA-GOSHALA



(b) SUB-SURFACE GEOLOGICAL SECTIONS BARPALI-PATRAPALI-GOSHALA



(c) SUB-SURFACE GEOLOGICAL SECTIONS GOSHALA-KHUTLIPALI-GONDTURUM



◀ **Fig. 2** Sub-surface geological sections for different directions including well locations (well number are indicated within *bracket*) [Adopted from CGWB 1998]

$$GWVI_{vx,vy} = \sum_{i=1}^{N_F} W_i \left(\sum_{k=1}^{N_{SF}^i} R_k^i \chi_{A_k^i} \left(C_{vx,vy}^p \Big|_i \right) \right) \tag{1}$$

where, indices (*i*, *k*) denote feature and sub-feature respectively; N_F is the total number of features; N_{SF}^i is the number of sub-features for *i*th feature; W_i is the weight of *i*th feature; R_k^i is the rating of *k*th sub-feature for *i*th feature; $C_{vx,vy}^p \Big|_i$ denotes the class value of the cell (*vx*, *vy*) for *i*th feature; A_k^i denotes the sub-feature interval; $\chi_{A_k^i}$ denotes the indicator function for *k*th sub-feature of *i*th feature and defined as

$$\chi_{A_k^i} \left(C_{vx,vy}^p \right) = \begin{cases} 1 & \text{if } C_{vx,vy}^p \Big|_i \in A_k^i, \\ 0 & \text{if } C_{vx,vy}^p \Big|_i \notin A_k^i. \end{cases} \tag{2}$$

DRASTIC Index The standard relative ranking scheme used in DRASTIC is a combination of weights and ratings to produce DRASTIC Index value. DTASTIC index is calculated as linear combination following Eqs. (1) and (2).

Agricultural DRASTIC index Agricultural DRASTIC is an exceptional case of the DRASTIC index with same set of parameters. Standard weights are assigned to reflect the agricultural usage of herbicides and pesticides. Agricultural DTASTIC index is calculated as linear combination following Eqs. (1) and (2).

AHP DRASTIC index Groundwater vulnerability is analyzed by DRASTIC index based on Analytic Hierarchy Process (AHP). AHP can be applied for estimation of W_i (Eq. 1). In AHP (Saaty 1980; Dhar et al. 2015b), 1–9 scale (i.e., extremely unimportant, strongly unimportant, unimportant, moderately unimportant, equally important, moderately important, more important, strongly important, extremely important) is adopted for constructing judgment matrices. The following steps are adopted for calculation of weights and consistency ratio (C.R.):

Development of judgment matrices (**A**) by pair wise comparison.

Calculation of relative weight W_k :

$$W_i = GM_i / \sum_{m \in F} GM_m \tag{3}$$

Where, the geometric mean of the *k*th row of judgment matrix is calculated as $GM_i = \sqrt[N_F]{a_{i1} a_{i2} \dots a_{iN_F}}$, N_F is the total number of features.

Step 1. Strength assessment of judgment matrix based consistency ratio (CR)

$$C.R. = C.I./R.C.I. \tag{4}$$

Consistency index (CI) is evaluated as

$$C.I. = \frac{\lambda_{max} - N_F}{N_F - 1} \tag{5}$$

where the latent root of judgment matrix is calculated as

$$\lambda_{max} = \sum_{m \in F} \frac{(\mathbf{AW})_m}{N_F W_m} \tag{6}$$

where **W** is the weight vector (column). Random consistency index (R.C.I.) can be obtained from standard tables (Alonso and Lamata 2006). C.R. value less than 0.1 is acceptable for a specific judgment matrix. However, revision in judgment matrix is needed for C.R. ≥ 0.1 .

Finally, index maps can be generated from the above-mentioned procedure.

Modified DRASTIC index A Modified DRASTIC model can be used to assess the groundwater vulnerability considering land use/land cover. The model is formulated by rebuilding the index system with depth to water table, recharge rate, aquifer media, soil media, topography, impact of vadose zone, hydraulic conductivity and land use/land cover. Generally, modifications are based on simple statistical procedures (Antonakos and Lambrakis 2007) involving (1) revision of the rating scale of each parameter (2) revision of the factor weights and (3) addition and subtraction of parameters based on their correlation to water quality parameters. In this study, addition of parameter (LULC) rule is implemented in modified DRASTIC model. Modified DTASTIC index is calculated as linear combination (Eqs. 1, 2).

DRASTIC features are assigned according to each hydrogeological setting. Maps are reclassified based on the classification available in Aller et al. (1985, 1987). Rating values can be chosen based on site specific conditions or based on standard values available in literature (Aller et al. 1985, 1987; Neshat et al. 2014; Brindha and Elango 2015). Agricultural DRASTIC is designed for vulnerability assessment due to application of application of pesticides. Same ratings are used for AHP DRASTIC and DRASTIC methods. However, weight calculation in AHP-DRASTIC is performed based on AHP. Modified DRASTIC model utilizes land use/land cover feature in addition to the seven standard DRATIC parameters.

Validation of vulnerability is performed using multiple water quality parameters (EC, Cl^- , Mg^{2+} and SAR). Finally, correlation values (between water quality parameter and vulnerability index value) are used to assess the

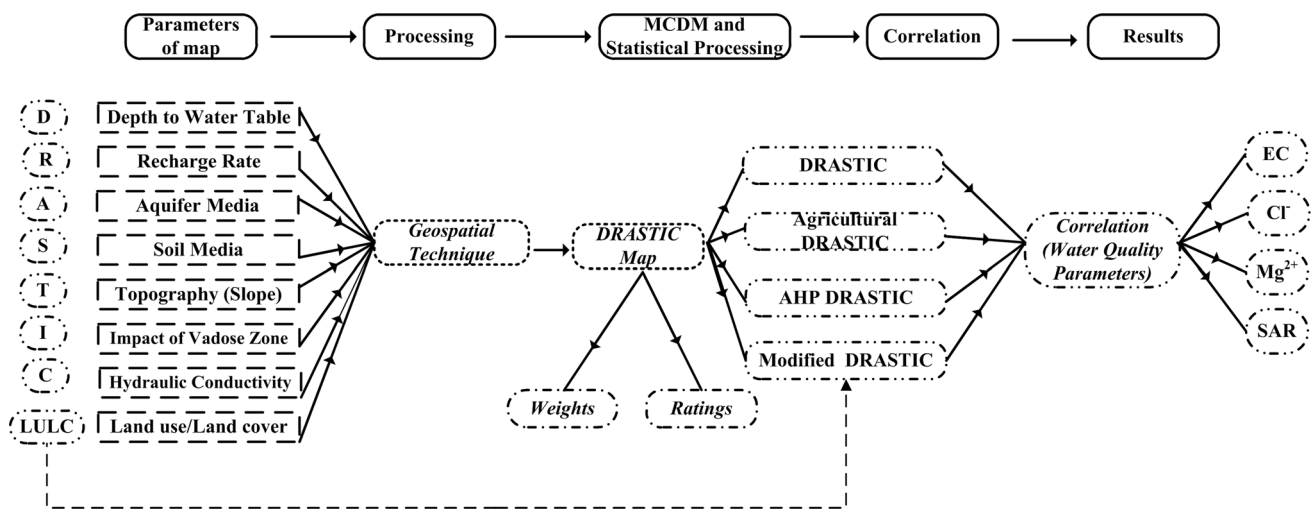


Fig. 3 Overall methodology for GWVI

validity of the vulnerability maps. Overall methodology is given in Fig. 3.

Results and discussion

The DRASTIC index, Agricultural DRASTIC index, AHP DRASTIC index and Modified DRASTIC index are applied for Hirakud canal command area system. Groundwater vulnerability zones in Hirakud command area are determined based on eight features layer of Depth to water table (*D*), Recharge rate (*R*), Aquifer media (*A*), Soil media (*S*), Topography (*T*), Impact of vadose zone (*I*), Hydraulic conductivity (*C*) and Land use/land cover (*LULC*). Individual features are described in the following sub-sections.

Depth to water table (*D*)

Water level fluctuation generally occurs due to hydrological or anthropogenic forcing (Dhar et al. 2015a). Average depths to groundwater table values are utilized for determination of groundwater vulnerability zones. Maximum water level fluctuation is observed in west to east direction. The study area (Fig. 4a) is divided into two classes: (a) 2.33–3.04 m bgl (99.52 %), and (b) 3.04–6.25 m bgl (0.47 %). Low depth to water represents high vulnerability zones.

Recharge rate (*R*)

Groundwater is recharged naturally by rain and to a smaller extent through surface water (Dhar et al. 2014). Recharge is the prime factor of pollutant transport to aquifer. It controls the dispersion of the pollutants to vadose zone. Normal

recharge due to monsoon-rainfall is commonly computed by the water level fluctuation method. The study area can be divided into three recharge classes: (a) 3034.43–4678.89 ha-m (70.47 %), (b) 4678.89–6423.61 ha-m (9.73 %) (c) 6423.61–8168.61 ha-m (19.80 %) as shown in Fig. 4b.

Aquifer media (*A*)

The study area is underlain by rocks belonging to Archaean (no life) and Proterozoic (early life) age. The Archean crystallines are normally very hard and compact and occasionally jointed and fractured. In the study area four major types of geologic assemblage, namely (a) Conglomerate, shale and sandstone (2.48 %) (b) Granite gneiss, migmatite, augen-gneiss (89.98 %) (c) Quartz-garnet—Sillimanite schist and gneiss with graphite, calc silicate, leptynite, metabasic rocks (6.92 %) (d) Gabbro, norite and anorthosite (0.70 %) are found (Fig. 4c). High permeability permits movement of more water through the weathered and fractured aquifer, while the tract with high permeability also represents high vulnerable zones.

Soil media (*S*)

Soil map of the study area, prepared by NBSS & LUP, is scanned, rectified and geometrically corrected. Different soil polygons representing different types of soil texture are digitized. Different attributes of soil are assigned to these polygons. The feature layer of soil map for the study area consist of six soil classes, namely (a) fine (67.02 %) (b) fine loamy (9.83 %) (c) fine, loamy skeletal (0.20 %) (d) fine, montmorillonitic (14.61 %) (e) loamy skeletal (1.62 %) (f) and river (6.72 %) is shown in Fig. 4d. Fine loamy soil is ranked excellent as it has very good

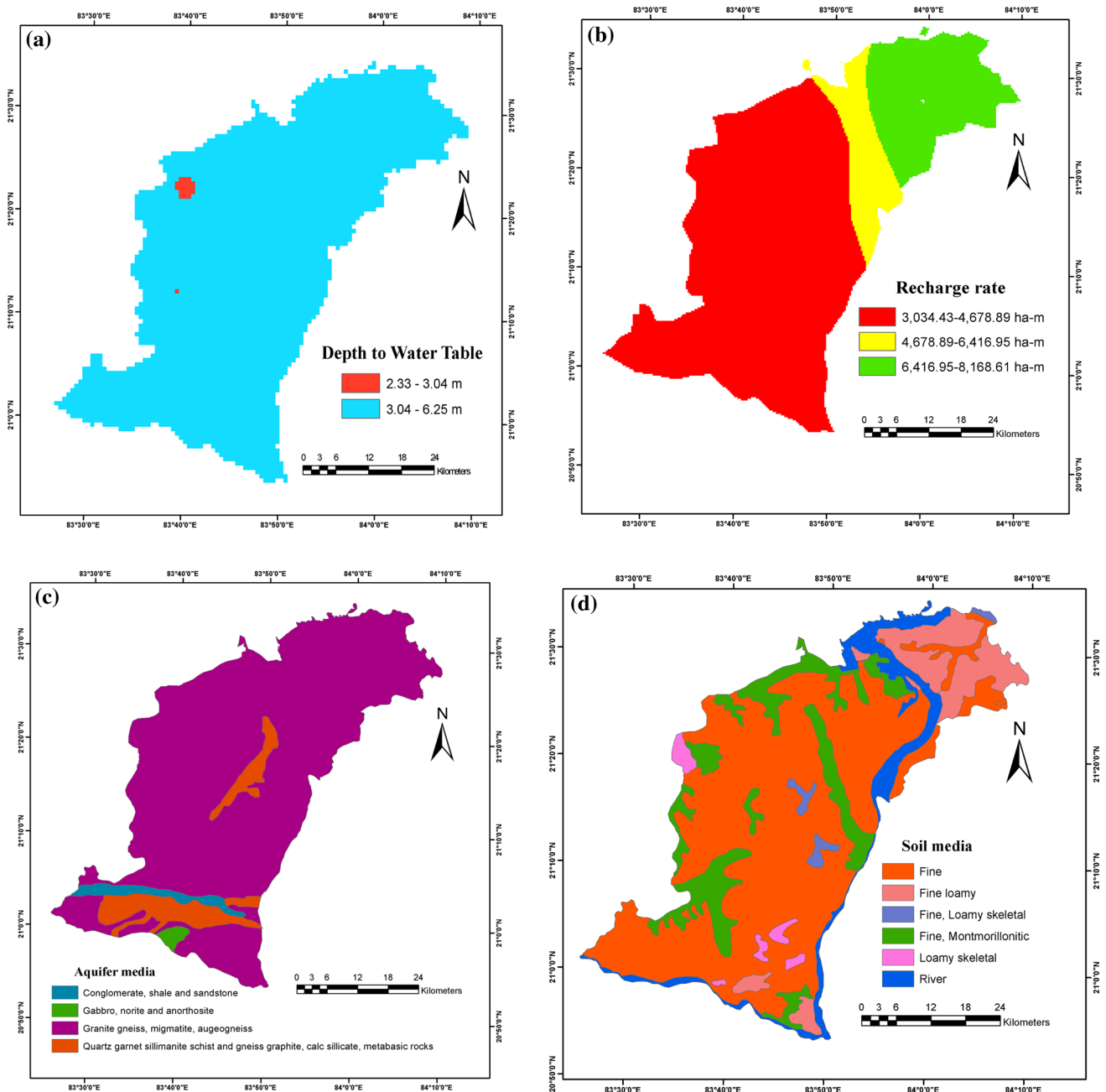


Fig. 4 a Depth to water table; b Recharge rate; c aquifer media; and d soil media map of the study area

infiltration capacity. The majority of the study area is dominated by fine soil.

Topography (T)

Topography refers to slope. It affects the type of soil at the surface of the land. The slope map of the study area is shown in Fig. 5a. Slope controls infiltration of groundwater into the subsurface. Gentle slope gives more residence time for rainwater to percolate. Thus, it is an indicator for the

suitability for groundwater prospect. The study area is divided into five classes: (a) 0°–1.15° (90.52 %) (b) 1.15°–3.43° (5.59 %) and (c) 3.43°–6.84° (2.12 %) (d) 6.84°–10.20° (0.77 %) and (e) >10.20° (1 %).

Impact of vadose zone (I)

Impact of vadose zone is the unsaturated zone of subsurface above the water table. It controls different physio-chemical processes. It is a complex factor, influences on aquifer

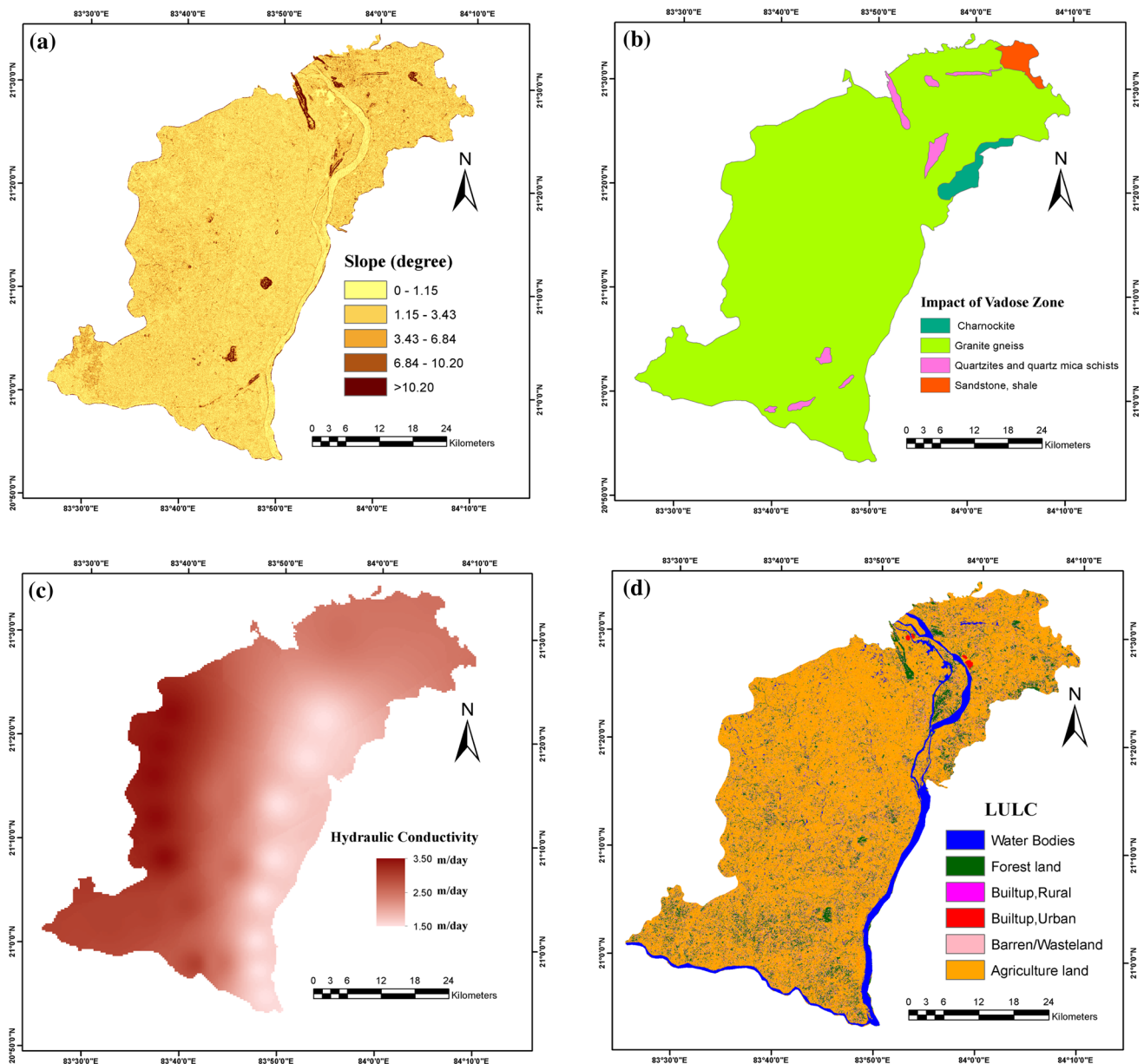


Fig. 5 a Slope; b impact of vadose zone; c hydraulic conductivity; and d LULC map of the study area

pollution potential. It is measured based on the thickness, porosity and permeability of soil and weathered horizon. The study area (Fig. 5b) is divided into four classes: (a) Charnockite (1.44 %) (b) Granite gneiss (95.58 %) (c) Quartzites and quartz mica schist (1.77 %) (d) Sandstone, shale (1.21 %).

Hydraulic conductivity (C)

Hydraulic conductivity indicates the aquifer capacity to transmit water. It depends on the permeability, saturation, density and viscosity. High values (C) also represent high contamination potential. The feature layer of hydraulic

conductivity for the study area reveals single class (Fig. 5c).

Land use/land cover (LULC)

LULC plays an important role in the development of groundwater resources. LULC plays a significant role in the groundwater vulnerability assessment in the Hirakud command area. 74.82 % area of the command is covered by agricultural land. Land use and land cover are interpreted from Enhanced Thematic Mapper Plus (ETM+) satellite image. LULC analysis has been performed by unsupervised classification technique. Six LULC patterns

(Fig. 5d) have been identified for the entire study area namely (a) water bodies (5.41 %), (b) forest land (10.06 %), (c) agriculture land (74.82 %), (d) Barren land/Wastelands (6.48 %), (e) built-up-urban (0.65 %) and (f) built-up-rural (2.59 %).

The groundwater vulnerability zone maps are computed using DRASTIC models in a GIS platform (Table 1). Figure 6a–d shows groundwater vulnerability index map based on DRASTIC, Agricultural DRASTIC, AHP DRASTIC and Modified DRASTIC models. The DRASTIC resulting map has been classified into three

groundwater vulnerability zones namely: ‘low’, ‘moderate’ and ‘high’ covering 18.22, 52.28, and 29.50 % area respectively. AHP DRASTIC results has been classified into three vulnerability zones respectively, ‘low’ (22.58 %), ‘moderate (47.89 %)’ and ‘high’ (29.52 %). DRASTIC and AHP DRASTIC result shows similar trend. Agricultural DRASTIC map categorized groundwater vulnerability zones into three classes: ‘low’ (60.94 %), ‘moderate’ (28.94 %) and ‘high’ (10.12 %). Agricultural DRASTIC result shows ‘low’ vulnerability zone covered by maximum in the study area. Four models result

Table 1 Rating and weighting value used in the DRASTIC, Agricultural DRASTIC, AHP DRASTIC and Modified DRASTIC

Parameters			DRASTIC		Agricultural DRASTIC		AHP DRASTIC		Modified DRASTIC	
Feature	Sub feature	Area in %	Rating	Weight	Rating	Weight	Rating	Weight	Rating	Weight
Depth to water table (m)	2.33–3.04 m bgl	99.52	9	5	9	5	9	0.2174	9	5
	3.04–6.25 m bgl	0.47	7		7		7		7	
Recharge rate (ha-m)	3034.43–4678.89 ha-m	70.47	1	4	1	4	1	0.1739	1	4
	4678.89–6423.61 ha-m	9.73	8		8		8		8	
	6423.61–8168.61 ha-m	19.80	9		9		9		9	
Aquifer media	Conglomerate, shale and sandstone	2.48	6	3	6	3	6	0.1304	6	3
	Granite gneiss, migmatite, augeogneiss	89.89	3		3		3		3	
	Quartz garnet sillimanite schist and gneiss graphite, calc silicate, leptynite, metabasic rocks	6.92	3		3		3		3	
Soil media	Gabbro, norite and anorthosite	0.70	4		4		4		4	
	Fine	67.02	3	2	3	5	3	0.0870	3	2
	Fine loamy	9.83	4		4		4		4	
	Fine, loamy skeletal	0.20	4		4		4		4	
	Fine, Montmorillonitic	14.61	7		7		7		7	
	Loamy skeletal	1.62	3		3		3		3	
Topography (slope°)	River	6.72	6		6		6		6	
	0°–1.15°	90.52	10	1	10	3	10	0.0435	10	1
	1.15°–3.43°	5.59	9		9		9		9	
	3.43°–6.84°	2.12	5		5		5		5	
	6.84°–10.20°	0.77	3		3		3		3	
>10.20°	1.00	1		1		1		1		
Impact of vadose zone	Charnockite	1.44	4	5	4	4	4	0.2174	4	5
	Granite neiss	95.58	3		3		3		3	
	Quartzites and quartz mica schists	1.77	4		4		4		4	
	Sandstone, shale	1.21	6		6		6		6	
Hydraulic conductivity	1.5–3.5 m/day	100	1	3	1	2	1	0.1304	1	3
LULC	Water bodies	5.41	–	–	–	–	–	–	5	5
	Forest land	10.06	–		–		–		2	
	Agriculture land	74.82	–		–		–		6	
	Barren land/wastelands	6.48	–		–		–		1	
	Builtup, Urban	0.65	–		–		–		9	
	Builtup, Rural	2.59	–		–		–		7	

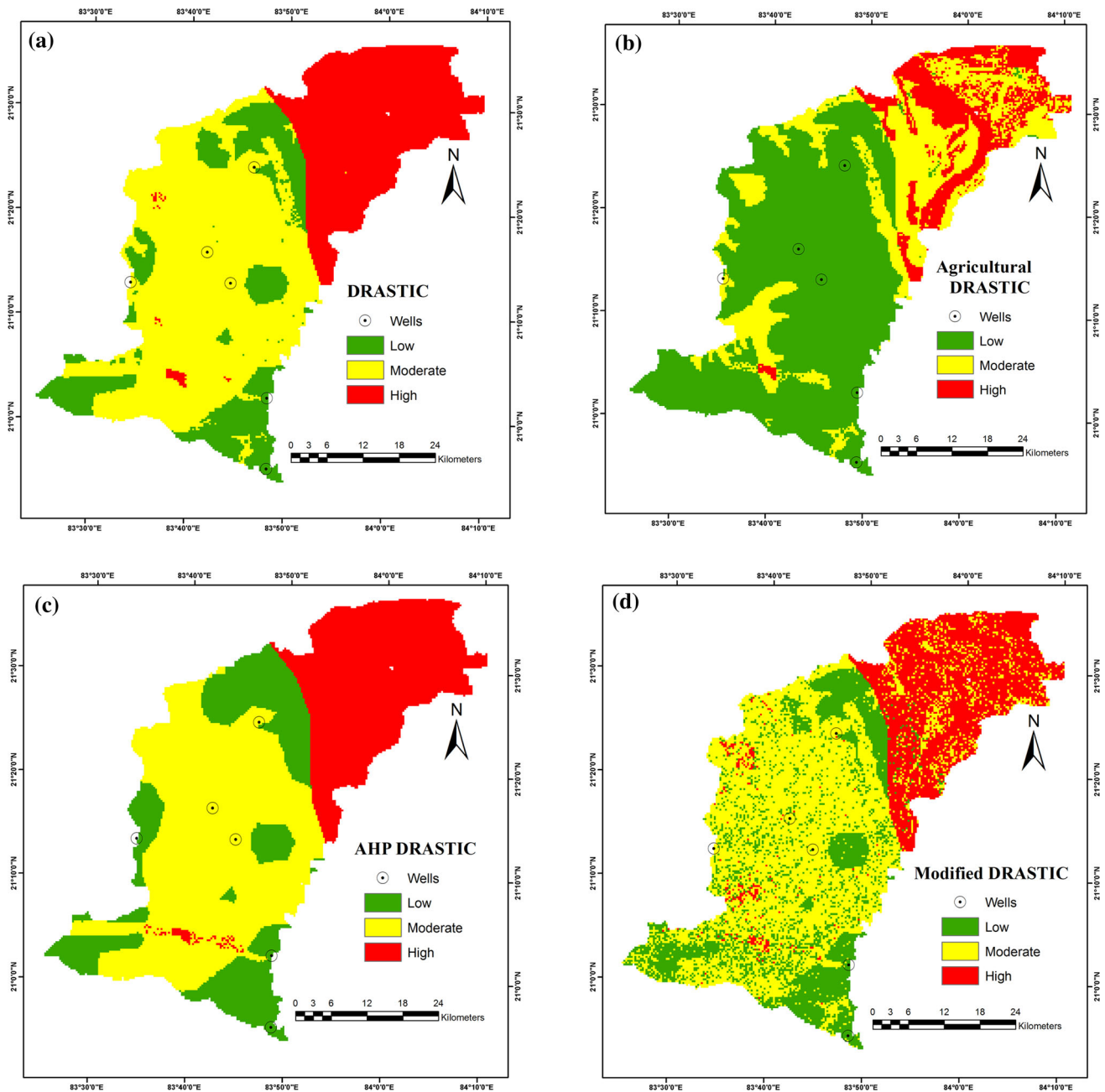


Fig. 6 a DRASTIC; b Agricultural DRASTIC; c AHP DRASTIC; and d modified DRASTIC map

indicates relatively higher pollution in the northern part of the study area. Modified DRASTIC vulnerable map shows that about 51.60 % of the study area is under the threat of moderate risk of pollution. Low and high indices in the maps derived from the models indicate the pollution status in the groundwater zones in the study area with lower and higher tunes.

To determine validity of vulnerability zones from the four methods correlation analysis is performed with EC, Cl^- , Mg^{2+} and SAR concentration values for the wells.

Validation of GWVI

Groundwater vulnerability map is validated using water quality parameters (EC, Cl^- , Mg^{2+} and SAR) obtained from the results of chemical analysis of water samples collected from the wells scattered over the study area (Table 2). DRASTIC index map shows ‘good’ co-relation between Cl^- ($R^2 = 0.7036$) parameter. EC, Mg^{2+} and SAR parameter are showing ‘moderate’ co-relation with the DRASTIC index values. Agricultural DRASTIC map

Table 2 Co-relation between water quality parameters and DRASTIC index values

Water quality parameters	DRASTIC (R^2)	Agricultural DRASTIC (R^2)	AHP DRASTIC (R^2)	Modified DRASTIC (R^2)
EC	0.6595	0.7423	0.5409	0.5629
Cl ⁻	0.7036	0.8623	0.7432	0.6389
Mg ²⁺	0.5710	0.8081	0.4689	0.4469
SAR	0.6604	0.3078	0.5502	0.7863

Bold italic values indicate better results

shows ‘good’ co-relation between the EC ($R^2 = 0.7423$), Cl⁻ ($R^2 = 0.8623$) and Mg²⁺ ($R^2 = 0.8081$) parameters. Sodium adsorption ration (SAR) is the most reliable index of the sodium hazard of irrigation water. SAR parameter is having ‘poor’ co-relation with the Agricultural DRASTIC index values. AHP DRASTIC map shows ‘good’ co-relation between the Cl⁻ ($R^2 = 0.7432$) values. Modified DRASTIC index map shows ‘good’ co-relation between the SAR ($R^2 = 0.7863$) values inside the Hirakud command area. Moreover, the highest vulnerability values are observed in the north eastern part of the command area.

Conclusions

DRASTIC modeling is a challenging issue of the groundwater management. This study is mainly focused on the sustainable groundwater management perspective and carried out to develop index based vulnerability mapping using DRASTIC, Agricultural DRASTIC, AHP DRASTIC and Modified DRASTIC models within the Hirakud command area. Groundwater vulnerability assessment is based on DRASTIC methods using geographic information system (GIS) environment. DRASTIC models use seven hydrogeological parameters (e.g., depth to water table, recharge rate, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity). Modified DRASTIC model uses seven hydrogeological parameters excluding land use/land cover. Finally, DRASTIC vulnerability map indicate that the northern part of the study area is more vulnerable and central part represents low vulnerable zone. Vulnerability map is validated using EC, Cl⁻, Mg²⁺ and SAR. It is evident that agricultural DRASTIC method provides a very high correction with water quality parameters. Modified DRASTIC method shows high correlation with SAR values. DRASTIC and AHP DRASTIC models provide poor estimate of the groundwater vulnerability in the study area. Agricultural DRASTIC and Modified DRASTIC results conforms the nature of the study area (agricultural command area). These maps can be applied for regional level irrigation planning or for environmental vulnerability assessment (Sahoo et al. 2016) of the study area. The methodologies presented in the

paper are generic in nature. It can be applied to other regions without/with suitable modification(s).

Acknowledgments Authors are thankful to the Regional Director, Central Ground Water Board (CGWB) South Eastern Region (SER) for providing necessary data for this research work. The author (AK& DC) are thankful to the Chairman, CGWB for his encouragement and permission to publish the paper. The Authors would like to thank the anonymous reviewers for providing valuable comments and suggestions to improve the quality of the paper.

References

Ahmed A (2009) Using Generic and Pesticide DRASTIC GIS-based models for vulnerability assessment of the Quaternary aquifer at Sohag. Egypt Hydrogeol J 17:1203–1217

Aller L, Bennett T, Lehr JH, Petty RJ (1985) DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeological settings. In: Robert SK (ed) Environmental Research Laboratory office of Research and Development. U.S Environmental Protection Agency, Ada, Oklahoma. EPA/600/2-85/018

Aller L, Bennett T, Lehr JH, Petty RJ, Hackett G (1987) DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeological settings. In: Robert SK (ed) Environmental Research Laboratory office of Research and Development. U.S Environmental Protection Agency, Ada, Oklahoma. EPA/600/2-87/035

Almasri M (2008) Assessment of intrinsic vulnerability to contamination for Gaza coastal aquifer, Palestine. J Environ Manag 88:577–593

Alonso J, Lamata T (2006) Consistency in the analytic hierarchy process: a new approach. Int J Uncertain Fuzziness Knowl Based Syst 14(4):445–459

Antonakos AK, Lambrakis NJ (2007) Development and testing of three hybrid methods for the assessment of aquifer vulnerability to nitrates, based on the drastic model, an example from NE Korinthia, Greece. J Hydrol 333:288–304

Arthur JD, Wood HA, Baker AE, Cichon JR Raines GL (2007) Development and implementation of a bayesian-based aquifer vulnerability assessment in Florida Nat Resour Res 16(2), DOI: 10.1007/s11053-007-9038-5

Baalousha H (2010) Assessment of a groundwater quality monitoring network using vulnerability mapping and geostatistics: a case study from Heretaunga Plains, New Zealand. Agric Water Manag 97(2):240–246

Babiker IS, Mohamed MAA, Hiyama T, Kato K (2005) A GISbased DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, Central Japan. Sci Total Environ 345(1–3):127–140

- Beynen PE, Niedzielski MA, Jelinska B, Alsharif K, Matusick J (2012) Comparative study of specific groundwater vulnerability of a karst aquifer in central Florida. *Appl Geogr* 32:868–877
- Bojorquez-Tapia LA, Cruz-Bello GM, Luna-Gonzalez L, Juarez L, Ortiz-Perez MA (2009) V-DRASTIC: using visualization to engage policymakers in groundwater vulnerability assessment. *J Hydrol* 373:242–255
- Brindha K, Elango L (2015) Cross comparison of five popular groundwater pollution vulnerability index approaches. *J Hydrol* 524:597–613
- Central Groundwater Board (CGWB) (1998). Studies on conjunctive use of surface and groundwater resources in Hirakud irrigation project Odisha Ministry of Water Resources, Government of India
- Chandoul IR, Bouaziz S, Dhia HB (2014) Groundwater vulnerability assessment using GIS-based DRASTIC models in shallow aquifer of Gabes North (South East Tunisia). *Arab J Geosci*. doi:10.1007/s12517-014-1702-6
- Chen SK, Jang CS, Peng YH (2013) Developing a probability-based model of aquifer vulnerability in a agricultural region. *J Hydrol* 486:494–504
- Dhar A (2013) Geostatistics-based design of regional groundwater monitoring framework. *ISH J Hydraul Eng* 19(2):80–87
- Dhar A, Sahoo S, Dey S, Sahoo M (2014) Evaluation of recharge and groundwater dynamics of a shallow alluvial aquifer in central ganga basin, Kanpur (India). *Nat Resour Res* 23(4):409–422
- Dhar A, Sahoo S, Mandal U, Dey S, Bishi N, Kar A (2015a) Hydro-environmental assessment of a regional ground water aquifer: Hirakud command area (India). *Environ Earth Sci* 73:4165–4178
- Dhar A, Sahoo S, Sahoo M (2015b) Identification of groundwater potential zones considering water quality aspect. *Environ Earth Sci* 74:5663–5675 doi:10.1007/s12665-015-4580-7
- Dixon B (2004) Prediction of groundwater vulnerability using integrated GIS-based neuro-fuzzy techniques. *J Spat Hydrol* 4(2):1–38
- Ettazarini S (2006) Groundwater pollution risk mapping for the Eocene aquifer of the Oum Er-Rabia basin, Morocco. *Environ Geol* 51:341–347
- Fijani E, Nadiri A, Moghaddam AA, Tsai FTC, Dixon B (2013) Optimization of DRASTIC method by supervised committee machine artificial intelligence to assess groundwater vulnerability for Maragheh-Bonab plain aquifer, Iran. *J Hydrol* 503:89–100
- Foster S, Garduno H, Kemper K, Tuinhof A, Nanni M, Dumars C (2003) World Bank sustainable groundwater management: Concepts and tools, groundwater quality protection defining strategy and setting priorities. *GW-MATE Briefing Note Series*, World Bank, Washington, DC
- Ghazavi R, Ebrahimi Z (2015) Assessing groundwater vulnerability to contamination in an arid environment using DRASTIC and GOD models. *Int J Environ Sci Technol*. doi:10.1007/s13762-015-0813-2
- Guo Q, Wang Y, Gao X, Ma T (2007) A new model (DRARCH) for assessing groundwater vulnerability to arsenic contamination at basin scale: a case study in Taiyuan basin, northern China. *Environ Geol* 52:923–932
- Hailin Y, Ligang X, Change Y, Jiaying X (2011) Evaluation of groundwater vulnerability with improved DRASTIC method. *Proc Environ Sci* 10:2690–2695
- Hallaq A, Elaish B (2012) Assessment of aquifer vulnerability to contamination in Khanyounis Governorate, Gaza Strip—Palestine, using the DRASTIC model within GIS environment. *Arab J Geosci* 5:833–847
- Huan H, Jinsheng W, Yanguo T (2012) Assessment and validation of 10 groundwater vulnerability to nitrate based on a modified DRASTIC model: a case study in Jilin City of northeast China. *Sci Total Environ* 440:14–23
- Iqbal J, Gorai AK, Katpatal YB, Pathak G (2015) Development of GIS-based fuzzy pattern recognition model (modified DRASTIC model) for groundwater vulnerability to pollution assessment. *Int J Environ Sci Technol*. doi:10.1007/s13762-014-0693-x
- Jang CS, Chen SK (2015) Integrating indicator-based geostatistical estimation and aquifer vulnerability of nitrate–N for establishing groundwater protection zones. *J Hydrol* 523:441–451
- Jasrotia AS, Singh R (2005) Groundwater pollution vulnerability using the DRASTIC model in a GIS environment, Devak-Rui watershed, India. *J Environ Hydrol* 13:11
- Junior RF, Varandas SGP, Fernandes LFS (2015) Multi Criteria Analysis for the monitoring of aquifer vulnerability: a scientific tool in environmental policy. *Environ Sci Policy* 48:250–264
- Katta B, Fares W, Charideh AR (2010) Groundwater vulnerability assessment for the Banyas Catchment of the Syrian coastal area using GIS and the RISKE method. *J Environ Manage* 91:1103–1110
- Kazakis N, Voudouris, K (2011) Comparison of three applied methods of groundwater vulnerability mapping: a case study from the Florina basin, Northern Greece. In: Lambrakis N, Stournaras G, Katsanou K (eds) *Advances in the research of aquatic environment*. Environment Earth Sciences, pp 359–367
- Kazakis N, Voudouris K (2015) Groundwater vulnerability and pollution risk assessment of porous aquifers to nitrate: modifying the DRASTIC method using quantitative parameters. *J Hydrol* 525:13–25
- Kumar P, Bansod BKS, Debnath SK, Thakur PK, Ghansyam C (2015) Index-based groundwater vulnerability mapping models using hydrogeological settings: a critical evaluation. *Environ Impact Assess Rev* 51:38–49
- Liggett LE, Talwar S (2009) Groundwater vulnerability assessments and integrated water resource management. *Watershed Manag Bull* 13(1):18–29
- Lima ML, Zelaya K, Massone H (2011) Groundwater vulnerability assessment combining the drastic and Dyna-Clue model in the argentine pampas. *Environ Manage* 47:828–839
- Mair A, El-Kadi AI (2013) Logistic regression modeling to assess groundwater vulnerability to contamination in Hawaii, USA. *J Contam Hydrol* 153:1–23
- Mohammadi K, Niknam R, Majd V (2009) Aquifer vulnerability assessment using GIS and fuzzy system: a case study in TehranKaraj aquifer. *Iran Environ Geol* 58:437–446
- Neshat A, Pradhan B, Dadras M (2014) Groundwater vulnerability assessment using an improved DRASTIC method in GIS. *Resour Conserv Recycl* 86:74–86
- Odling NE, Serrano RP, Hussein MEA, Riva M, Guadagnini A (2015) Detecting the vulnerability of groundwater in semi-confined aquifers using barometric response functions. *J Hydrol* 520:143–156
- Pacheco FAL, Pires LMGR, Santos RMB, Sanches Fernandes LF (2015) Factor weighting in DRASTIC modeling. *Sci Total Environ* 505:474–486
- Pathak DR, Hiratsuka A (2011) An integrated GIS based fuzzy pattern recognition model to compute groundwater vulnerability index for decision making. *J Hydroenviron Res* 5:63–77
- Pathak D, Hiratsuka A, Awata I, Chen L (2009) Groundwater vulnerability assessment in shallow aquifer of Kathmandu Valley using GIS-based DRASTIC model. *Environ Geol* 57:1569–1578
- Prasad R, Singh VS, Krishnamacharyulu SKG, Banerjee P (2011) Application of drastic model and GIS: for assessing vulnerability in hard rock granitic aquifer. *Environ Monit Assess* 176:143–155
- Rahman A (2008) A GIS Based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. *Appl Geogr* 28(1):32–53
- Saaty TL (1980) *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill, New York

- Sahoo S, Dhar A, Kar A (2016) Environmental vulnerability assessment using Grey Analytic Hierarchy Process based model. *Environ Impact Assess Rev* 56:145–154
- Secunda S, Collin M, Melloul A (1998) Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel's Sharon region. *J Environ Manag* 54:39–57
- Shekhar S, Pandey AC, Tirkey AS (2014) A GIS-based DRASTIC model for assessing groundwater vulnerability in hard rock granitic aquifer. *Arab J Geosci*. doi:[10.1007/s12517-014-1285-2](https://doi.org/10.1007/s12517-014-1285-2)
- Shirazi SM, Imran HM, Akib S (2012) GIS-based DRASTIC method for groundwater vulnerability assessment: a review. *J Risk Res* 15(8):991–1011
- Yang YS, Wang L (2010) Catchment-scale vulnerability assessment of groundwater pollution from diffuse sources using the DRASTIC method: a case study. *Hydrol Sci J* 55:1206–1216
- Zhou J, Li G, Liu F, Wang Y, Guo X (2010) DRAV model and its application in assessing groundwater vulnerability in arid area: a case study of pore phreatic water in Tarim Basin, Xinjiang, Northwest China. *Environ Earth Sci* 60:1055–1063