

# Hydro-environmental assessment of a regional ground water aquifer: Hirakud command area (India)

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**Abstract** A hydro-environmental assessment has been performed for Hirakud command area (India) in terms of quantity and physicochemical quality analysis of groundwater. Quantity analysis has been performed in terms of water level variation and groundwater potential zone identification. Groundwater table fluctuation analysis reveals that water level is declining rapidly due to insufficient recharge owing to frequent recession of monsoon and excessive pumping of groundwater. Inefficient distribution of canal water especially in the tail end of the Hirakud command is accentuating the high dependency on ground water. The groundwater potential zone index map is generated using analytic hierarchy process along with different influencing features, e.g., land use/cover, soil type, geology. Three zones have been identified for Hirakud command area (poor: 21.15 %, moderate: 46.32 %, and good: 32.53 %). Physical and chemical parameters of

groundwater, e.g., electrical conductivity, pH, total dissolved solids, total hardness, nitrate, iron, sodium, potassium, calcium, magnesium, chlorine, bicarbonate and fluoride are analyzed for the study area. Piper analysis is used to identify dominant hydrochemical facies. United States Salinity Laboratory and Wilcox Diagram are used to determine the irrigation water quality. Principal component analysis is utilized to find out key groundwater quality parameters. The chemical analysis shows that values of all parameters are within permissible limit. However, nitrate, iron and fluoride are found above permissible limit in some areas. The assessment reveals the state of the aquifer in terms of quantity and quality.

**Keywords** Groundwater · Potential zone · PCA · USSL · Wilcox diagram

## Introduction

Groundwater depletion is a common problem in most of the states in India (Rodell et al. 2009) due to excessive withdrawal for agricultural and industrial uses. Moreover, excessive use of fertilizers in agriculture, indiscriminate disposal of human and animal waste has aggravated the point/non-point pollution scenario. The western part of Odisha falling inside the Hirakud command area is facing drinking water crisis almost every year due to aberration of monsoon, large-scale deforestation, unplanned use of irrigation water, unscientific or poor water management strategy. An analysis has been performed for evaluating groundwater quantity and quality scenario of Hirakud command area, Odisha (India). The present study aims at assessing availability and suitability of water for drinking and agricultural purposes.

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Groundwater potential zone identification is a general technique for quantity assessment. As remote sensors cannot detect groundwater directly, the presence of groundwater is inferred from different surface features derived from satellite imagery, e.g., geology, soils, land use/land cover (Jha and Peiffer 2006). Rao et al. (2009) carried out hydrogeological mapping for evaluating groundwater potential in Madhurawada, India using GIS and remote sensing techniques. Only Shahid and Nath (2002), Madrucci et al. (2008), and Chowdhury et al. (2009) have used MCDA techniques (i.e., analytic hierarchy processes) for processing the weights assigned to different features and their sub-features. Several studies are available in the direction of groundwater potential zoning both in India and abroad (Jaiswal et al. 2003; Solomon and Quiel 2006). Other studies include Krishnamurthy and Srinivas (1995), Saraf and Choudhary (1998), Kumar (1999), Krishnamurthy et al. (2000), Murthy (2000), Srivastava and Bhattacharya (2000), Shahid et al. (2000), Khan and Moharana (2002), Sreedevi et al. (2005).

A large number of groundwater quality studies for different regions in India are available, e.g., Palar and Cheyyar river basins, South India (Rajmohan and Elango 2005); Chithar River Basin, Tamil Nadu (Rajmohan and Elango 2005); Sukinda Valley mining area of Odisha (Dhakate and Singh 2008); Tumkur Taluk, Karnataka (Sadashivaiah et al. 2008); Jaipur city, Rajasthan (Tatawat and Chandel 2008); Malda district of West Bengal (Pukrait and Mukharjee 2008); Industrial area of Mettur taluk, Salem district, Tamil Nadu (Srinivasamoorthy et al. 2008); Manimuktha River basin, Tamil Nadu (Kumar et al. 2009); Bhavanagar region, Gujarat (Mishra et al. 2009); Erode district, Tamilnadu (Karthikeyan et al. 2010); Parts of Nalgonda District, Andhra Pradesh (Brindha and Elango 2010); Tirupur Region, Tamil Nadu (Karuppapillai and Krishnan 2010); Chithar River basin, Tamil Nadu (Brindha and Elango 2010).

Chemical classification reveals the concentration of various predominant cations, anions and their interrelationship. The graphical representation yields better results considering the combined chemistry of all the ions rather than individual or paired ionic characters. Number of studies have utilized Piper trilinear Diagram for chemical characterization of groundwater, e.g., the Quaternary aquifer of Calcutta and Howrah twin city (Sikdar et al. 2001); alluvial aquifer of Gangetic plain, North India (Singh et al. 2005); Tumkur Taluk, Karnataka (Sadashivaiah et al. 2008); Jaipur city, Rajasthan (Tatawat and Chandel 2008).

Groundwater quality data can be interpreted easily from the graphical representation of Wilcox Diagram and USSL Diagram to identify the suitability of irrigation water for

irrigation and domestic use, e.g., Wilcox (1948), Tabios and Salas (1985), Jeevanandam et al. (2007), Sadashivaiah et al. (2008), Kumar et al. (2009), Subramani et al. (2010), Alexakis (2011), Monjerezi and Ngongondo (2012).

Identification of dominant parameters responsible for overall scenario is an important step. Principal component analysis (PCA) is a method through which dominant parameters (spatial and temporal variations) can be identified for water quality-related problems, e.g., Passaic aquifer located in the northern part of the State of New Jersey, USA (Bengraime and Marhaba 2003); LSJR basin is located in northeast Florida, USA (Ouyang 2005); Shizuishan City, China (Zhang et al. 2011); Quaternary aquifer of Calcutta and Howrah twin city, India (Sikdar et al. 2001); alluvial aquifer of Gangetic plain, India (Singh et al. 2005); Gomti River (Singh et al. 2004); Tamiraparani basin, India (Ravichandran et al. 1996); an industrial area from Patancheru, Medak District, Andhra Pradesh, India (Krishna et al. 2009).

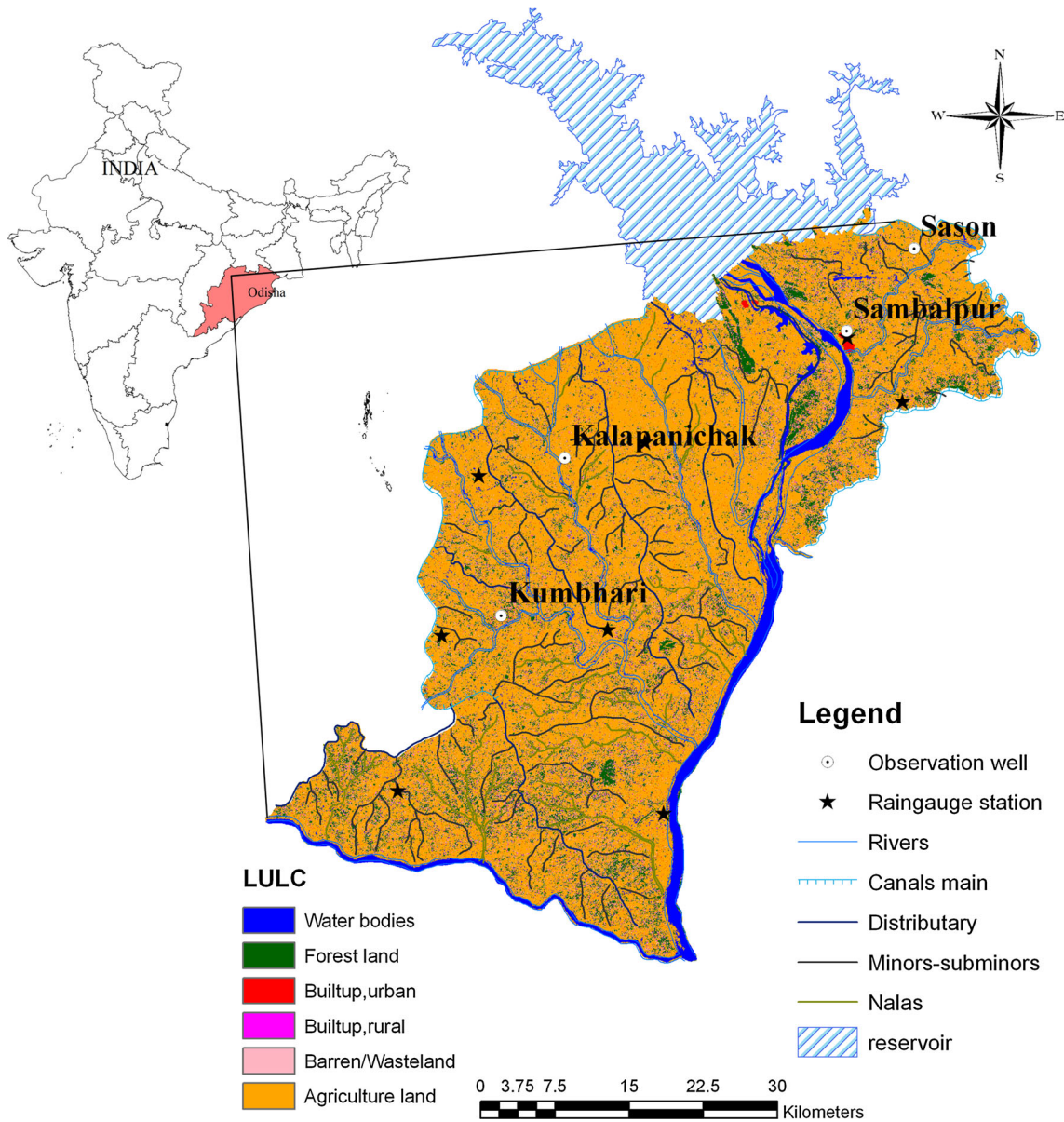
In the present study, hydro-environmental assessment of the aquifer has been performed considering both quantity and quality aspects. Quantity aspect is addressed by hydraulic head analysis and groundwater potential zone identification. The quality is analyzed using Piper trilinear Diagram, USSL method, Wilcox method, and PCA.

## Materials and methods

### Study area

Hirakud command area is situated in the western part of Odisha (North Latitudes 20°53': 21°36' and East Longitudes 83°25': 84°10'), INDIA. The study area (Fig. 1) includes five blocks (administrative units) of Sambalpur District, Six blocks of Bargarh District, two blocks of Suvarnapur District and one block of Bolangir District covering a total area of 2,260 km<sup>2</sup>. The general slope (average slope is varies from 0 to 6 %) of the area is towards the south–east direction. The eastern part is more undulating in nature compared to other parts of the study area. The study area is bounded by the Mahanadi River and Sason main canal (eastern boundary); Ong River (southern boundary); Bargarh main canal (western boundary); and Hirakud reservoir (north boundary). 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 1,184.87 mm. The temperature varies between 8 °C (in January) and 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).

A major portion of the geographical area of the command is underlain by granite, granite gneisses and



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

quartzite’s which lack primary porosity and possess secondary porosity in the form of fractures and fissures. Differential weathering in the rock formations could be seen in the area which is caused due to variation in mineral content and existence of fractures and fissures in them. In the shallow horizon, constituted by the weathered residuum, groundwater occurs under phreatic condition, while in the deeper locales groundwater occurs in the fractured basement rock where the ground water percolates through the fracture conduits. In deeper fractured horizon, groundwater remains under semi-confined to confined situation. Soils in the area are mostly derived from granite to granite gneisses. The chief constituent of the soils are gravels, quartz sand, ferruginous concretions. The soil of the high land

areas is loamy sand at the surface and sandy clay loam at the sub-surface level. The medium land soils are sandy clay loam at the surface and clay to clayey loam at the sub-surface. The soils of the low lands are fine loam. The common types of soil occurring in the area are Inceptisols (red and yellow soil) 66 %, Vertisols (Black soil) 15 %, and Alfisols (Lateritic soil) 19 % (Central Groundwater Board (CGWB) 1998).

**Origin of data**

Groundwater level and quality data are collected (from Central Ground Water Board) from 59 observation wells scattered over the study area for hydro-environmental

assessment. The quantitative database required for the groundwater study is the groundwater level data observed directly from the observation wells. Moreover, to identify the groundwater potential zones in the study area, 10 thematic maps (geology, soil, LULC, drainage density, recharge rate, rainfall, slope, relief (elevation), NDVI, groundwater depth) are prepared through satellite imagery and conventional data. Relief, slope and drainage density maps are prepared from the CARTOSAT 1 data. Land use/cover map and Normalized Difference Vegetation Index (NDVI) for the study area are generated from the Landsat 7 Enhanced Thematic Mapper Plus (LANDSAT 7 ETM+, ACQUISITION\_DATE: 2000-11-22). Soil and geology maps are prepared from NBSS & LUP and Geological Survey of India.

Groundwater quality analysis has been performed for nine measured chemical parameters namely: total hardness (TH), total dissolved solids (TDS), bicarbonate ( $\text{HCO}_3^-$ ), chloride ( $\text{Cl}^-$ ), nitrate ( $\text{NO}_3^-$ ), fluoride ( $\text{F}^-$ ), calcium ( $\text{Ca}^{2+}$ ), sodium ( $\text{Na}^+$ ), and magnesium ( $\text{Mg}^{2+}$ ) in the pre-monsoon month (April) for the years 1993, 1994, 1997, 2000, and 2003.

#### Groundwater quantity analysis

Groundwater variation can be quantified by the spatio-temporal fluctuation of hydraulic head. Generally, groundwater head data are noted as depth to water level from ground surface or below ground level (bgl).

#### Groundwater potential zoning

The assessment involves groundwater potential zone (GWPZ) identification. GWPZ identification is generally performed by standard index approach. All feature layers (e.g., soil type, geology) are converted into raster format. Then, individual feature layers are reclassified into sub-features and ranks are assigned accordingly. Finally, feature maps are integrated using a weighted linear combination approach in the GIS platform to generate potential index map. Potential index can be calculated as

$$\text{GWPI}_{i,j} = \sum_{k \in F} W_k \left( \sum_{l \in S_k} w_l^k \chi_{A_l^k} \left( C_{i,j}^v \Big|_k \right) \right) \quad (1)$$

where index  $(i, j)$  denotes row column location of a pixel;  $F$  denotes the set of all features,  $k$  denotes element of feature set;  $S_k$  denotes set of sub-features for  $k$ th feature;  $l$  denotes element of sub-feature set;  $W_k$  normalized weight of  $k$ th feature;  $w_l^k$  normalized weight of  $l$ th sub-feature for  $k$ th feature;  $C_{i,j}^v \Big|_k$  denotes the class value of the cell  $(i, j)$  for  $k$ th feature;  $A_l^k$  denotes the sub-feature interval;  $\chi_{A_l^k}$  denotes the indicator function for  $l$ th sub-feature of  $k$ th feature and defined as

$$\chi_{A_l^k} \left( C_{i,j}^v \Big|_k \right) = \begin{cases} 1 & \text{if } C_{i,j}^v \Big|_k \in A_l^k, \\ 0 & \text{if } C_{i,j}^v \Big|_k \notin A_l^k. \end{cases} \quad (2)$$

Analytic hierarchy process (AHP) can be applied for estimation of  $W_k$  and  $w_l^k$ . In AHP (Saaty 1980), 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.):

Step I Development of judgment matrices (**A**) by pairwise comparison

Step II Calculation of relative weight  $W_k$ :

$$W_k = GM_k \Big/ \sum_{m \in F} GM_m \quad (3)$$

where the geometric mean of the  $k$ th row of judgment matrix is calculated as  $GM_k = \sqrt[N_F]{a_{k1} a_{k2} \dots a_{kN_F}}$ ,  $N_F$  is the total number of features.

Step III Strength assessment of judgment matrix based consistency ratio (C.R.)

$$\text{C.R.} = \text{C.I.} / \text{R.C.I.} \quad (4)$$

Consistency index (C.I.) is evaluated as

$$\text{C.I.} = \frac{\lambda_{\max} - N_F}{N_F - 1} \quad (5)$$

where the latent root of judgment matrix is calculated as

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

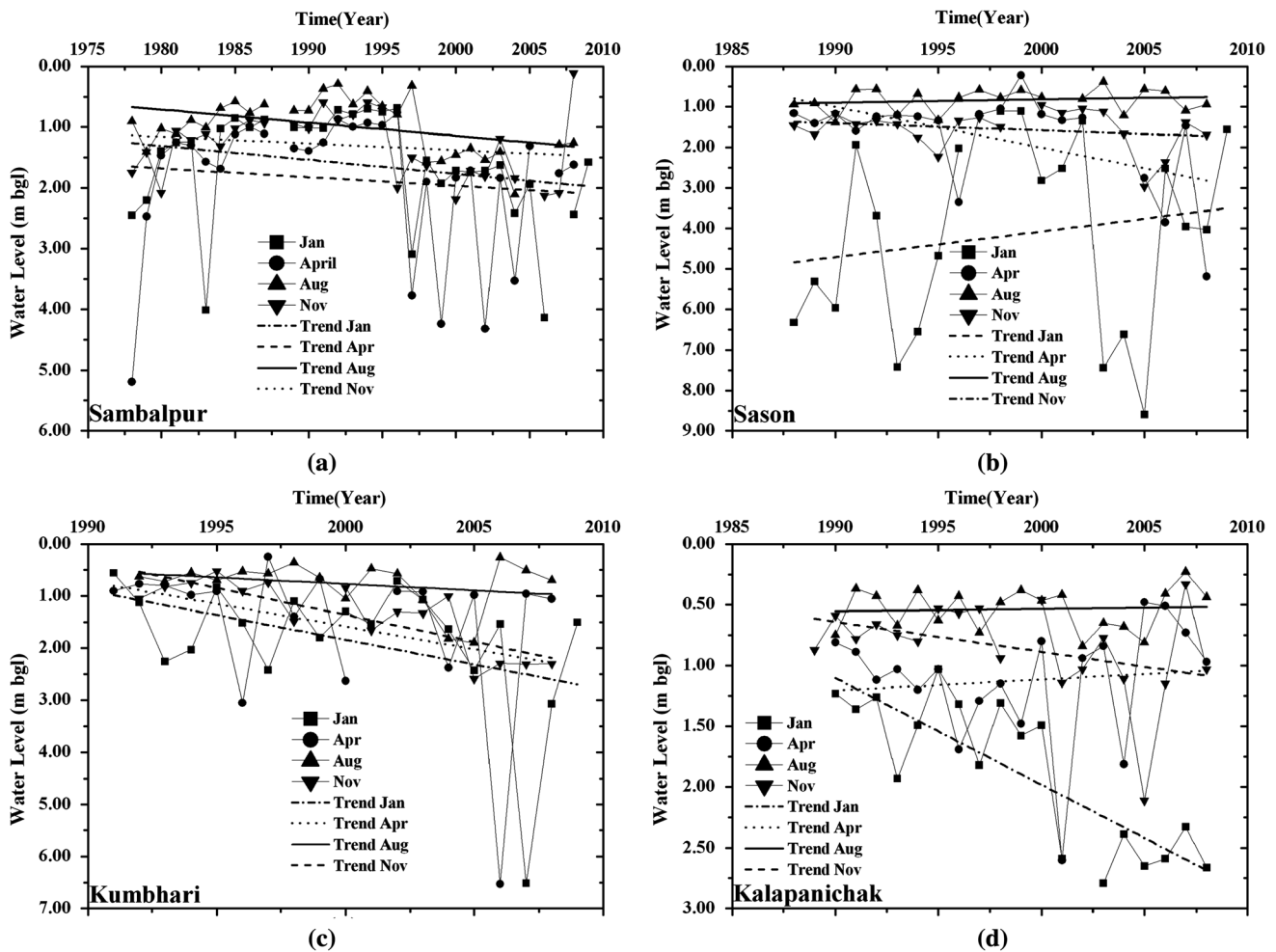
where  $\mathbf{W}$  is the weight vector (column). Random consistency index (R.C.I.) can be obtained from standard tables. C.R. value  $< 0.1$  is acceptable for a specific judgment matrix. However, revision in judgment matrix is needed for  $\text{C.R.} \geq 0.1$ .

Same procedure should be followed for  $w_l^k$  calculation. Finally, potential zone map can be generated from the abovementioned procedure.

#### Groundwater quality analysis

Groundwater quality analysis (from irrigation water point of view) can be performed in terms of graphical (Piper trilinear Diagram, USSL method, and Wilcox Diagram)





**Fig. 2** a Groundwater level variation at Sambalpur (1978–2009), b groundwater level variation at Sason (1988–2009), c groundwater level variation at Kumbhari (1991–2009), d groundwater level variation at Kalapanichak (1989–2008)

and multivariate analysis (Principal Component Analysis).

Piper trilinear diagram

Presentation of chemical analysis in graphical form makes understanding of complex groundwater system simpler and quicker. In the present study, Piper trilinear diagram is utilized for identifying the water quality. The piper diagram has two simple triangular plots on the right and left side of a 4-sided center field. In the triangular plots, the axes should run from 0 to 100 on each of the three sides. In the right triangle, the axes increase in a counterclockwise direction and restart from zero at each apex; in the left triangle, the axes increase in a clockwise direction, restarting at zero at each apex.

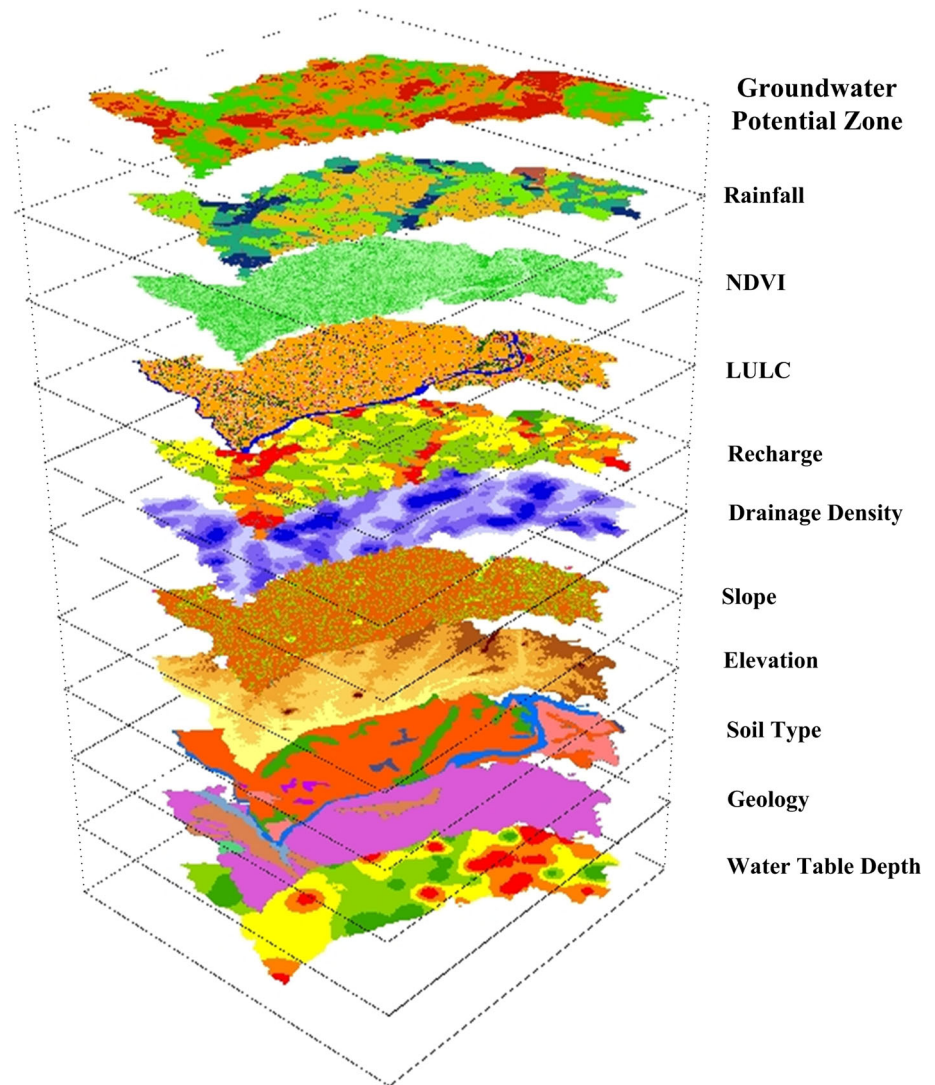
The major ions present in groundwater are  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{NO}_3^-$ ,  $\text{F}^-$  and  $\text{SO}_4^{2-}$ . By grouping  $\text{Na}^+$  and  $\text{K}^+$  together in one side of a triangle

the other major cations,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , are displayed on other two sides of the trilinear diagram. Similarly,  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$  are grouped together on one side of another triangle, the other anions  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  are displayed on the other two sides of the trilinear diagram.

Wilcox diagram and USSL diagram

High concentrations soluble salts make groundwater unsuitable for irrigation. Sometimes low salt concentration with continuous irrigation causes deposition of salts in the root zone. Appropriate evaluation of water quality is necessary in planning, design, and operation of irrigation systems for ensuring non-occurrence of deleterious salts or compounds in the irrigation water (Sangodoyin and Ogedengbe 1991). Wilcox Diagram is used to classify groundwater for irrigation purposes based on exchangeable sodium percentage (ESP) and electrical conductivity (EC) at 25 °C. ESP determines the ratio of sodium in total

**Fig. 3** Raster layer of different features considered for GWPI calculation



cations including sodium, potassium, calcium and magnesium expressed in equivalents per million. ESP is calculated as follows:

$$\text{ESP (Na\%)} = \frac{\text{Na}^+}{(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})} \times 100 \quad (7)$$

The US Salinity Laboratory (USSL) (1954) has presented an irrigation water classification diagram on the basis of specific conductance and sodium adsorption ratio (SAR). The USSL Diagram is a simple scatter plot of sodium hazard (SAR) on the Y-axis versus salinity hazard (EC) on the X-axis. The EC is plotted in a log scale. Water can be grouped into 16 classes. Class limits are selected considering the relationship between the electrical conductivity of irrigation waters and the electrical conductivity of saturation extracts of soil. The sodium adsorption ratio (SAR), which is calculated for the water samples based on

the formula provided by the US Salinity Laboratory (1954) is as follows:

$$\text{SAR} = \frac{(\text{Na}^+)}{\sqrt{\frac{[(\text{Mg}^{2+})+(\text{Ca}^{2+})]}{2}]}} \quad (8)$$

Principal component analysis (PCA)

Principal component analysis (PCA) helps in establishing the relationship between a set of variables by reducing their number through orthogonal transformation keeping the information of the original variables intact. The new set of variables is known as principal components (PC) and they may be equal to or less than the number of original variables. The values of the original data defined by the loadings of the PCs are called scores. The first PC is the normalized linear combination of the variables with maximum variance. The PCs are accompanied by a variance

**Table 1** Assigned and normalized weights for the individual features of the ten attributes for groundwater potential zoning

SL no.	Theme	Weight	Class	Area in %	Groundwater prospect	Weight assigned	Normalized weight
1	LULC	3	Water bodies	5.41	Very good	7	0.2593
			Forest land	10.06	Good	5	0.1852
			Agriculture land	74.82	Very good	8	0.2963
			Barren land/wastelands	6.48	Poor	2	0.0741
			Built-up, urban	0.65	Very poor	1	0.0370
			Built-up, rural	2.59	Moderate	4	0.1481
2	Soil	8	Fine	67.02	Very good	8	0.1905
			Fine loamy	9.83	Excellent	9	0.2143
			Fine, loamy skeletal	0.20	Good	6	0.1429
			Fine, montmorillonitic	14.61	Good	5	0.1190
			Loamy skeletal	1.62	Very good	7	0.1667
			River	6.72	Very good	7	0.1667
3	Geology	9	Conglomerate, shale and sandstone	2.48	Very good	7	0.4118
			Granite gneiss, migmatite, augen gneiss	89.89	Moderate	5	0.2941
			Quartz garnet sillimanite schist and gneiss	6.92	Poor	3	0.1765
			graphite, calc silicate, leptynite, meta basic rocks				
4	Recharge rate	7	Gabbro, norite and anorthosite	0.70	Very poor	2	0.1176
			0–24.70 cm year <sup>-1</sup>	3.53	Poor	2	0.0714
			24.70–40.20 cm year <sup>-1</sup>	31.24	Moderate	4	0.1429
			40.20–47.20 cm year <sup>-1</sup>	32.29	Good	6	0.2143
			47.20–55.30 cm year <sup>-1</sup>	22.90	Very good	7	0.2500
			55.30–70.30 cm year <sup>-1</sup>	10.04	Excellent	9	0.3214
5	Drainage density	5	0–0.70 km/km <sup>2</sup>	26.90	Very Good	7	0.3684
			0.70–1.36 km/km <sup>2</sup>	28.15	Good	5	0.2632
			1.36–2.09 km/km <sup>2</sup>	25.14	Moderate	4	0.2105
			2.09–2.99 km/km <sup>2</sup>	12.91	Poor	2	0.1053
			2.99–4.65 km/km <sup>2</sup>	6.89	Very poor	1	0.0526
6	Rainfall	4	0–267 mm	3.53	Very poor	1	0.0500
			267–432 mm	32.59	Poor	2	0.1000
			432–506 mm	33.36	Moderate	4	0.2000
			506–589 mm	20.82	Good	6	0.3000
			589–752 mm	9.70	Very good	7	0.3500
7	Slope (degree)	4	0–2.63	90.52	Very good	7	0.3182
			2.63–7.64	5.59	Good	6	0.2727
			7.64–22.12	2.12	Moderate	5	0.2273
			22.12–47.13	0.77	Poor	3	0.1364
			47.13–72.26	1.00	Very poor	1	0.0455
8	Elevation (m)	3	0–75 m	12.13	Very good	7	0.3043
			75–93 m	30.65	Good	6	0.2609
			93–109 m	35.10	Moderate	5	0.2174
			109–156 m	21.62	Poor	3	0.1304
			156–304 m	0.50	Very poor	2	0.0870
9	NDVI	2	–0.66 to –0.05	2.67	Very poor	1	0.0476
			–0.05 to 0.07	27.86	Poor	2	0.0952
			0.07–0.15	36.93	Moderate	5	0.2381
			0.15–0.24	23.67	Good	6	0.2857
			0.24–0.58	8.86	Very good	7	0.3333

**Table 1** continued

SL no.	Theme	Weight	Class	Area in %	Groundwater prospect	Weight assigned	Normalized weight
10	Ground water depth	6	0.58–1.60 m bgl	12.69	Excellent	9	0.3103
			1.60–2.07 m bgl	32.11	Very good	7	0.2414
			2.07–2.54 m bgl	33.06	Good	6	0.2069
			2.54–3.06 m bgl	15.72	Moderate	4	0.1379
			3.06–4.93 m bgl	6.41	Poor	3	0.1034

**Table 2** Pairwise comparison matrix (ten attribute layers) developed for AHP-based groundwater potential zoning

Features	LULC	Soil	Geology	Recharge rate	Drainage density	Rainfall	Slope	Elevation	NDVI	Groundwater depth	Normalized weight
LULC	3/3	3/8	3/9	3/7	3/5	3/4	3/4	3/3	3/2	3/6	0.0593
Soil	8/3	8/8	8/9	8/7	8/5	8/4	8/4	8/3	8/2	8/6	0.1581
Geology	9/3	9/8	9/9	9/7	9/5	9/4	9/4	9/3	9/2	9/6	0.1779
Recharge rate	7/3	7/8	7/9	7/7	7/5	7/4	7/4	7/3	7/2	7/6	0.1383
Drainage density	5/3	5/8	5/9	5/7	5/5	5/4	5/4	5/3	5/2	5/6	0.0988
Rainfall	4/3	4/8	4/9	4/7	4/5	4/4	4/4	4/3	4/2	4/6	0.0791
Slope	4/3	4/8	4/9	4/7	4/5	4/4	4/4	4/3	4/2	4/6	0.0791
Elevation	3/3	3/8	3/9	3/7	3/5	3/4	3/4	3/3	3/2	3/6	0.0593
NDVI	2/3	2/8	2/9	2/7	2/5	2/4	2/4	2/3	2/2	2/6	0.0395
Groundwater depth	6/3	6/8	6/9	6/7	6/5	6/4	6/4	6/3	6/2	3/6	0.1106

which characterizes its statistical properties. In PCA, the reduction of variables takes place by ignoring the linear combinations with smaller variances and considering the ones with large variances.

## Results and discussions

### Groundwater quantity

Water level variations have been analyzed for different observation points scattered. To show the overall variation of hydraulic head four representative observation well locations are selected within the study area (Fig. 1), namely: Sambalpur, Sason, Kumbhari, Kalapanichak, scattered over the study area. Quarterly observed data (January, April, August, and November) shows (Fig. 2a–d) the variation of water level. Inter-annual plot of hydraulic head (for the years 1978–2009) for Sambalpur (Fig. 2a) shows a slightly decreasing trend for all the 4 months. Much variability in head is present for last few years (1996–2009), i.e., abruptly decline in water level. However, variability in water level is much larger for the months of January and April. Overall variation in Kumbhari (for the

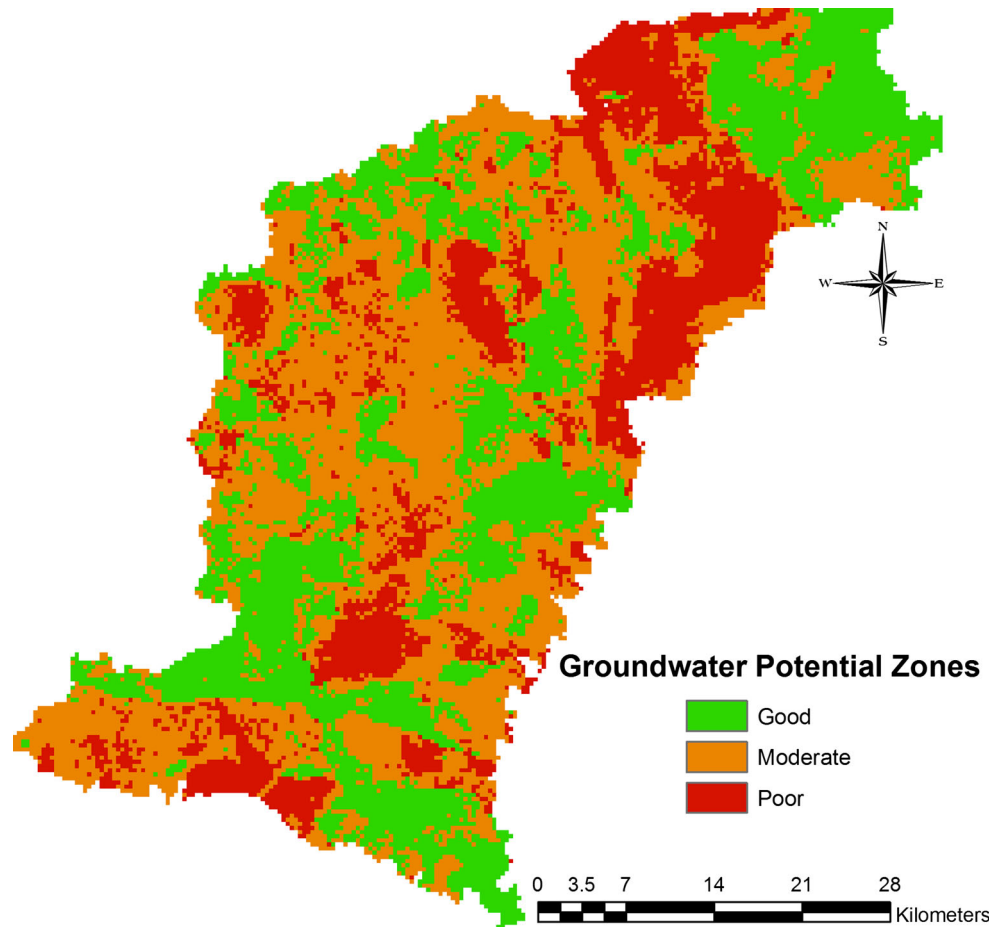
years 1991–2009) shows (Fig. 2c) similar trends as of Sambalpur. Variability in water level is much larger for the months of January (0.5–6.50 m) and April (0.25–6.50 m). Maximum and minimum groundwater table has been observed at January, 2006 and April, 1997. However, water level variation analysis for Sason (for the years 1988–2009) indicates (Fig. 2b) decreasing trend only for the month of April. Variability for the month of January is much larger (1.25 m for 1999–8.75 m for 2005) and variation shows increasing trend in water table. There is not much change in the water level variation trends for August and November. Water logging condition is observed in Sason for the month of August. In contrast to the other locations, variation in Kalapanichak (for the years 1989–2008) shows (Fig. 2d) a declining trend for the months January and November. There is depletion in the water level in the month of January. Interestingly, in the month of April there is a slightly increasing trend in water table.

### Groundwater potential zone identification

The objective of the work is to assess the shallow aquifer of Hirakud command area. The quantity aspect is represented by groundwater potential zone index (GWPZI). The



**Fig. 4** Groundwater potential zones map of the study area



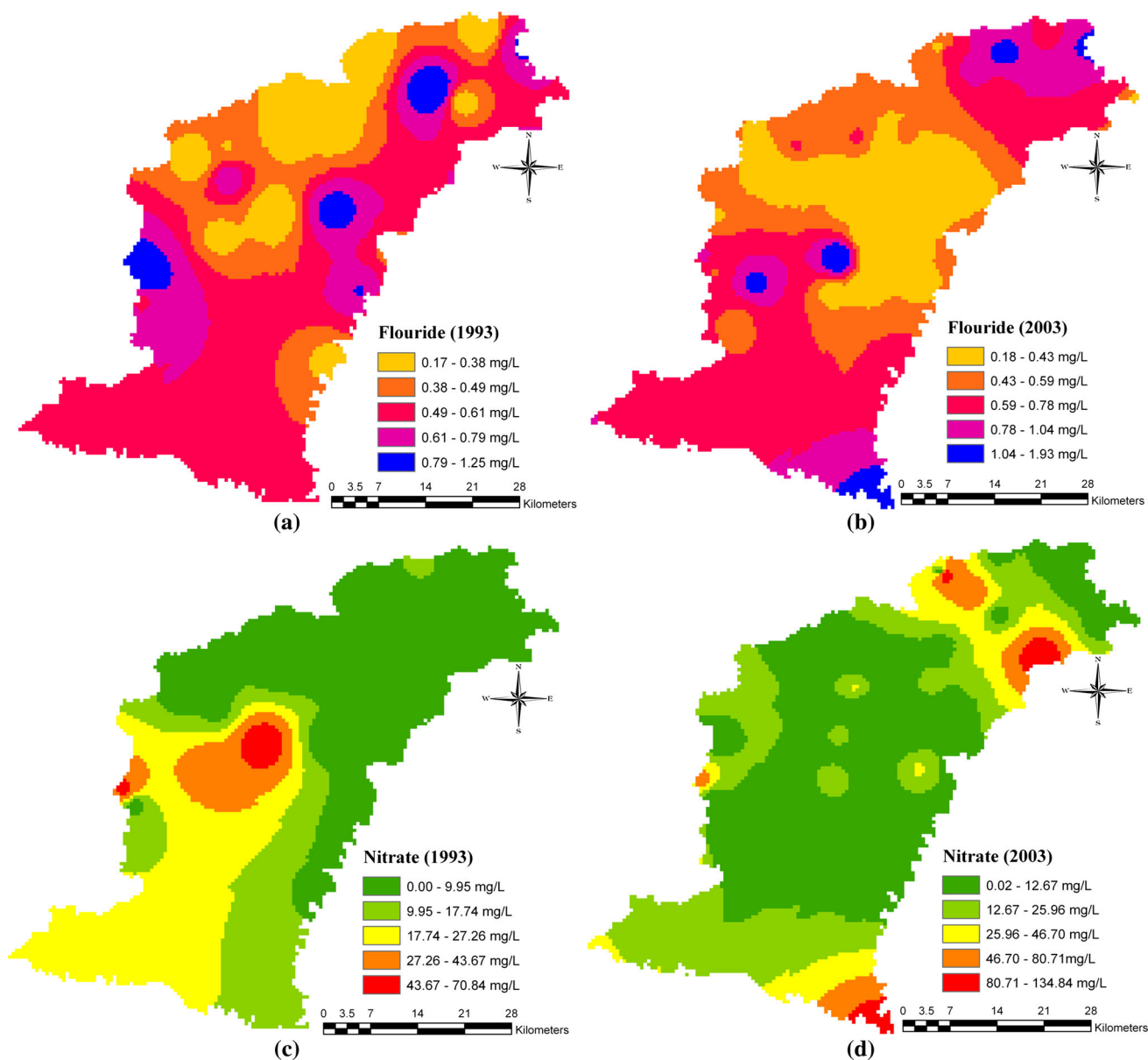
GWPZI considers land use/cover (LULC), soil type (ST), geology (GG), recharge rate (RR), drainage density (DD), rainfall (RF), slope (SL), elevation (EL), normalized difference vegetation index (NDVI), groundwater depth or depth to groundwater table (GD) as influencing features. All feature layers are converted into raster format (Fig. 3). Then, individual feature layers are reclassified into sub-features and ranks are assigned accordingly.

Suitable weights are assigned (Table 1) to the ten features and their individual sub-features after assessing their hydrogeological importance in causing groundwater occurrence in the study area. Normalized weights for individual attributes are obtained (Table 2) from Saaty’s analytical hierarchy process (AHP). Similar approach is applied to obtain normalized weight for individual sub-features. After obtaining normalized weights for individual features and sub-features expression (1) is utilized to calculate the GWPI for the study area. Final integration of attributes yields a GWPI map (Fig. 4). The resulting map has been classified into three groundwater potential zones namely: poor, moderate and good covering 21.15, 46.32, and 32.53 %, area, respectively. The GWPI reveals the overall groundwater quantity scenario in the study area.

**Groundwater quality**

Water quality parameters (pH, TDS, Ca, Mg, Na, HCO<sub>3</sub>, CO<sub>3</sub>, NO<sub>3</sub>, Cl, F) are analyzed for different observation stations (measured by Central Groundwater Board, INDIA) scattered over the study area. The permissible range of pH for drinking and agricultural purposes is 6.5–8.5 (IS: 10500-1991). The pH values of groundwater samples for Sambalpur district varies from 7.3 to 8.5 and for Bargarh district varies from 7.32 to 9.66. As the pH values are found above 8 in most of the cases, the regional groundwater quality can be inferred as alkaline. This variation of the pH in groundwater may be due to natural and anthropogenic causes.

Total dissolved solids (TDS), chloride, calcium and bicarbonate values are found to be within the permissible limits (IS: 10500-1991) for all the places during the study period. Total hardness (TH) values are within permissible limit for the years 1993 and 1994. However, for the year 1997, TH values exceeded the limit (600 mg/l) at Sambalpur (1,260 mg/l), Gorupali (730 mg/l), and Mahulpali (770 mg/l). Similarly, fluoride concentration for the years 1993 (Fig. 5a) and 1994 is within permissible limit. For the

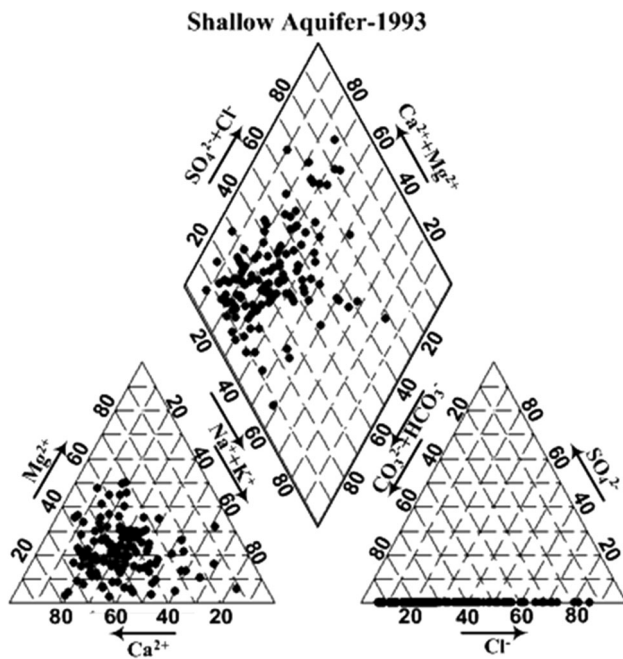


**Fig. 5** Decadal variation of flouride (a–b) and nitrate (c–d) over the study area

years 1997, 2000, and 2003 (Fig. 5b), it exceeded the limit (1.5 mg/l) at some places namely Jugipali (1.7 mg/l), Diptipur (1.75 mg/l), Thuapali (1.54 mg/l) and Burda (1.96 mg/l). Nitrate concentration exceeds the permissible limit (45 mg/l) at large number of places, e.g., in Remerha (190 mg/l), Mundher (236 mg/l), Gorupali (156 mg/l), Jagdalpur (114 mg/l), Sargibahal (216 mg/l), Gorbhaga (133 mg/l), Christianpara (118 mg/l), Maneswar (135 mg/l). Figure 5c, d shows the decadal change of nitrate concentration over space. Chemical analysis of pre-monsoon data of 2003 showed that Iron concentration is above the permissible limit (1 mg/l) at different palace of Bargrah district, e.g., Kalapanichak (1.25 mg/l), Rengalpal

(1.3 mg/l), Deobahal (1.37 mg/l), Berangpali (3.49 mg/l), Satlama (2.41 mg/l), Burda (1.57 mg/l). Similar trend is observed for Dhama (1.92 mg/l) and Rengali (2.45 mg/l) of Sambalpur district.

Chemical characteristics of groundwater are identified using Hill–Piper trilinear Diagram for various parts of the study area. Figure 6 shows the water quality types of the whole study area. From Fig. 6, it is evident that the most predominating types of water are Ca–HCO<sub>3</sub>, Ca–Mg–HCO<sub>3</sub> and mixed types. Ca–Mg–Na–HCO<sub>3</sub> and CaCl<sub>2</sub> types of water also occur as a result of ion exchange reactions taking place during the movement of water through aquifers.

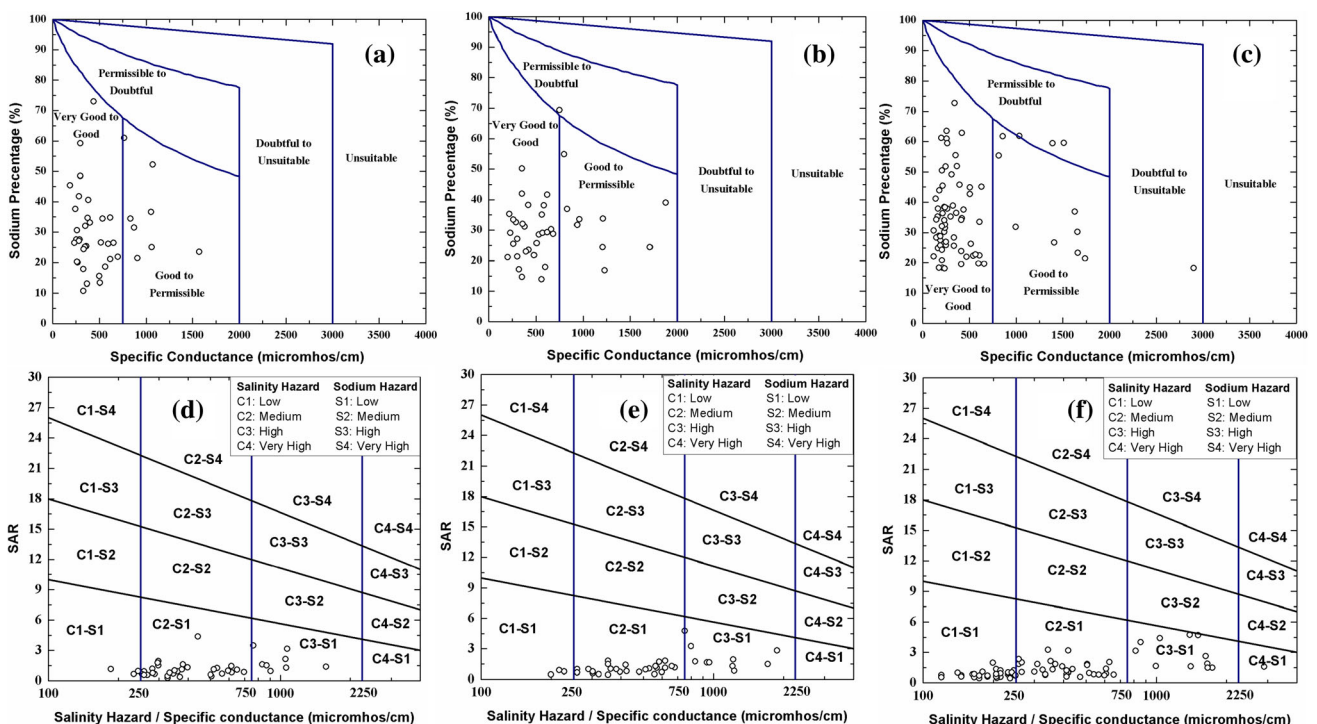


**Fig. 6** Piper trilinear diagram showing the groundwater quality of shallow aquifer for the year 1993

Soluble salt content and exchangeable sodium percentage (ESP) are the two parameters which govern the soil chemical characteristic. High ESP (exceeding 10–20 % of the exchange capacity) and high pH (above

8.5) make soil infertile and hampers plant growth. Wilcox Diagrams (Fig. 7a–c) for the year 1993, 1994, and 1997 show that the water conditions are well within permissible limit for irrigation purposes. In Kusanpur (for the year 1994), Gorbhaga (for the year 1994), and Gondtarum (for the year 1997), the application of water for irrigation is doubtful. The water quality of Jugipali (for the year 1997) is unsuitable for irrigation. The USSL diagrams for the years 1993 (Fig. 7d) and 1994 (Fig. 7e) shows that major parts of the study area have medium salinity and low sodium type water. Large number of places show low salinity–low sodium water and medium salinity–low sodium water for the year 1997 (Fig. 7f). Some places have high salinity and low sodium water. In those areas, the water can be used for irrigation for salt-tolerant crops with adequate drainage facilities. Only in Kusanpur (for the year 1997) the water is having very high salinity and low sodium. The water is not suitable for irrigation under ordinary conditions.

Principal component analysis (PCA) is performed to characterize the chemical properties of water statistically. Moreover, it aims at identifying the dominant parameters governing the water quality. Table 3 briefly lists the minimum, maximum, and means value of the nine hydrochemical variables of the samples for the years 1993, 1994, and 1997. Three components for the 3 years 1993, 1994, and 1997 are extracted (Table 4) from PCA method. The



**Fig. 7** Classification of irrigation water **(a)** Wilcox diagram for the year 1993, **(b)** Wilcox diagram for the year 1994, **(c)** Wilcox diagram for the year 1997, **(d)** USSL diagram for the year 1993, **(e)** USSL diagram for the year 1994, and **(f)** USSL diagram for the year 1997

**Table 3** Statistical description of different samples

Year	Category	TH	TDS	HCO <sub>3</sub>	Cl	NO <sub>3</sub>	F	Ca	Na	Mg
1993	Minimum	45.000	112.000	49.000	7.100	0.000	0.170	14.000	6.900	1.200
	Maximum	510.000	943.000	403.000	328.000	80.000	1.260	172.000	105.000	36.000
	Mean	170.357	302.833	158.810	69.362	15.579	0.453	48.000	35.045	12.217
1994	Minimum	70.000	120.000	73.000	11.000	0.000	0.140	18.000	9.200	1.200
	Maximum	525.000	1126.000	281.000	390.000	95.000	1.300	156.000	143.000	49.000
	Mean	193.333	368.000	146.615	86.769	20.756	0.570	47.846	41.095	17.972
1997	Minimum	33.000	72.000	0.000	5.300	0.000	0.150	8.000	7.600	1.200
	Maximum	1260.000	1741.000	409.000	922.000	236.000	1.700	174.000	285.000	242.000
	Mean	174.978	337.462	109.707	99.431	23.852	0.589	41.462	43.508	17.407
2000	Minimum	–	–	–	8.863	0.000	0.000	–	–	–
	Maximum	–	–	–	446.670	133.580	1.750	–	–	–
	Mean	–	–	–	88.405	20.336	0.456	–	–	–
2003	Minimum	–	–	–	–	0.000	0.180	–	–	–
	Maximum	–	–	–	–	134.960	1.960	–	–	–
	Mean	–	–	–	–	17.448	0.542	–	–	–

**Table 4** Loadings of chemical parameters on 3 principal components

Parameters	Principal components								
	1993			1994			1997		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
TH	0.424	−0.037	0.252	0.417	0.052	0.213	−0.410	0.131	−0.011
TDS	0.431	−0.056	−0.196	0.431	−0.016	0.055	−0.426	0.071	0.023
HCO <sub>3</sub>	0.203	0.606	0.286	0.074	−0.656	0.424	−0.239	−0.492	0.148
Cl	0.373	−0.297	−0.357	0.410	0.118	0.046	−0.404	0.273	0.140
NO <sub>3</sub>	0.276	−0.157	0.334	0.277	0.285	−0.525	−0.220	−0.222	−0.828
F	0.067	0.701	−0.215	0.058	−0.628	−0.529	−0.134	−0.723	0.331
Ca	0.401	−0.08	0.203	0.382	0.044	0.368	−0.353	−0.110	−0.283
Na	0.311	0.119	−0.643	0.340	−0.271	−0.257	−0.334	0.030	0.218
Mg	0.341	0.056	0.274	0.352	0.052	−0.113	−0.357	0.275	0.189
% Variance	56.011	16.168	9.248	58.821	15.982	10.902	59.593	12.764	9.280
% Cumulative variance	56.011	72.179	81.427	58.821	74.803	85.705	59.593	72.357	81.637

cumulative variances explained by the three components are 81.427, 85.705 and 81.637 %, respectively.

The first component measures the overall composition of the groundwater. The second component reveals high loadings for fluoride and bicarbonate which indicates the interaction of water with the underlying rocks. The main reason behind excessive fluoride concentrations in some places may be due to the local hydrogeological formation. Presence of fluoride-bearing minerals like apatite and fluorite in the host rocks and their interaction with water and its weathering, role of topography and interconnection of fracture zones can be considered as the main causes of occurrence of fluoride in groundwater. The third component for the years 1994 and 1997 shows high loadings for

nitrate, which confirms the inclusion of organic and inorganic fertilizers washed away from the agricultural fields.

## Conclusions

Groundwater quantity and quality analysis needs large data set to understand the behavior of the complex hydrogeological systems. Groundwater table fluctuation analysis suggests that the region is facing threat due to decline in groundwater table. Groundwater level is declining rapidly due to excessive pumping of groundwater. Groundwater quantity assessment is performed on the basis of GWPZI map. The GWPZI map is generated using AHP method

along with different features, e.g., LULC, ST, GG, RR, DD, RF, SL, EL, NDVI, GD. Three zones have been identified for Hirakud command area.

The quality analysis is based on data of nine chemical parameters for the years 1993, 1994, 1997, 2000, 2003. However, in recent years (in 2003) only two parameters (fluoride and nitrate) are measured. The groundwater quality analysis shows that there is an increase in the concentration (above permissible limit) of nitrate, fluoride, and iron in Bargarh district. The nitrate and fluoride concentration are above permissible limit in Sambalpur district. The increase in the concentration of nitrate is due to anthropogenic and agricultural activities. However, increasing trends of fluoride and iron are due to the geogenic effect.

The groundwater of study area is mostly alkaline in nature with average pH of 8.5. The parameter values of TDS, TH, Ca, Na, Cl, and Mg are below permissible limit. The analysis performed for the year 2000 and 2003 show that the concentrations are above permissible limit for NO<sub>3</sub>, F and Iron. PCA analysis also showed NO<sub>3</sub>, F as important parameters. The classification of cation and anion facies in triangular fields of Piper diagram shows that the majority of groundwater samples fall into nondominant and calcium type in cations. Moreover, majority of groundwater samples are of bicarbonate type and chloride type in anions. The predominant types of groundwater are Ca–Mg–HCO<sub>3</sub> type and mixed types.

The overall hydro-environmental assessment methodology of the present work is generic in nature. It can be suitably applied to any other area with or without slight modification.

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