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GIS-based assessment and characterization of groundwater quality in a hard-rock hilly terrain of Western India

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Abstract The growing population, pollution, and misuse of freshwater worldwide necessitate developing innovative methods and efficient strategies to protect vital groundwater resources. This need becomes more critical for arid/semi-arid regions of the world. The present study focuses on a GIS-based assessment and characterization of groundwater quality in a semi-arid hard-rock terrain of Rajasthan, western India using long-term and multi-site post-monsoon groundwater quality data. Spatio-temporal variations of water quality parameters in the study area were analyzed by GIS techniques. Groundwater quality was evaluated based on a GIS-based Groundwater Quality Index (GWQI). A Potential GWQI map was also generated for the study area following the Optimum Index Factor concept. The most-influential water quality parameters were identified by performing a map removal sensitivity analysis among the groundwater quality parameters. Mean annual concentration maps revealed that hardness is the only parameter that exceeds its maximum permissible limit for drinking water. GIS analysis revealed that sulfate and nitrate ions exhibit the highest (CV $> 30\%$) temporal variation, but groundwater pH is stable. Hardness, EC, TDS, and magnesium govern the spatial pattern of the GWQI map. The groundwater quality of the study area is generally suitable for drinking and irrigation (median GWQI > 74). The GWQI map indicated that relatively high-quality groundwater exists in northwest and southeast portions of the study area. The groundwater quality parameter group of Ca, Cl, and pH were found to have the maximum value (6.44) of Optimum Index factor. It is concluded that Ca, Cl, and pH are three prominent parameters for cost-effective and long-term water quality monitoring in the study area. Hardness, Na, and SO_4, being the most-sensitive water quality parameters, need to be monitored regularly and more precisely.

Keywords Groundwater quality · Spatial and temporal variability · Groundwater Quality Index · GIS · Hard-rock aquifer · Semi-arid region

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Introduction

Groundwater is one of the most valuable natural resources, which supports human health, socio-economic development, and functioning of ecosystems (e.g., Zektser 2000; Humphreys 2009; Steube et al. 2009). Of the 37 Mkm^3 of freshwater estimated to be present on the earth, about 22% exists as groundwater, which constitutes about 97% of all liquid freshwater potentially available for human use (Foster 1998). However, the worldwide groundwater overdraft, declining well yields, drying up of springs, streamflow depletion, and land subsidence due to overexploitation of groundwater as well as the growing degradation of groundwater quality by natural and/or anthropogenic pollutants, are threatening our ecosystems and even the lives of our future generations (e.g., Bouwer 2000; Shah et al. 2000; Zektser 2000; Evans and Sadler 2008). The quality of groundwater is critical in the regions that are characterized by a semi-arid/arid climate and dominated by agricultural activities; the water quality is generally affected by diffuse contamination originating from intensive irrigated agriculture (Saidi et al. 2009).

India has been facing increasingly severe water scarcity in several parts of the country, especially in arid and semi-arid regions. The overdependence on groundwater to meet ever-increasing demands of domestic, agriculture, and industry sectors has resulted in overexploitation of groundwater resources in several states of India such as Gujarat, Rajasthan, Punjab, Haryana, Uttar Pradesh, Tamil Nadu, among others (CGWB 2006; Garg and Hassan 2007; Rodell et al. 2009). In addition, groundwater contamination by point and non-point sources of pollution, as well as by seawater intrusion in coastal freshwater aquifers is also posing a serious threat to the sustainability of groundwater resources in different parts of India. The study area (Udaipur district), situated in the hard-rock hilly terrains of Aravalli Range in Rajasthan (the largest and driest state of India), is no exception and suffers from frequent droughts due to weak and delayed monsoon activity, low rainfall, abnormally high summer temperatures, and inadequate water resources (Bhuiyan et al. 2006). Droughts have a profound effect on the quantity and quality of groundwater in arid/semi-arid regions in general and hilly Aravalli terrain in particular. Groundwater quality has also deteriorated due to overexploitation of groundwater resources, intensive agriculture, and industrial activities in many districts of Rajasthan, including Udaipur. Thus, there is an urgent need to critically assess groundwater quality in most parts of India (including the study area) in order to ensure sustainable utilization of vital groundwater resources.

Assessment of groundwater quality necessitates establishment of comprehensive groundwater quality monitoring networks and the use of improved communication tools/techniques for water quality interpretation. Where such monitoring networks exist, there is often a knowledge gap between the scientists and the beneficiaries. Also, traditional reports on water quality tend to be too technical and detailed for a lay person and present data on individual parameters without providing a whole and interpreted picture of water quality. One way of bridging this gap could be the use of water quality indices, which can serve as useful aggregation and communication tools, particularly when considering the possibility of incorporating drinking water standards frequently used in water pollution policies (Mitchell and Stapp 1996; Cude 2001; Liou et al. 2004; Said et al. 2004; Stigter et al. 2006). As identifying high-quality groundwater resources in arid and semi-arid regions with increasing population and agricultural development is an expensive task, a Water Quality Index (WQI) can serve as a useful tool for evaluating the quality of groundwater and surface water (Abassi 1999; Adak et al. 2001; Pradhan et al. 2001), especially in developing countries where cost is a major issue for water resources management and the beneficiaries are poorly educated. A WQI should be specific to a water use or a set of goals (Schultz 2001). Despite the fact that a correct assessment of water quality is essential for sustainable water resources management, a globally accepted, cost-effective, and easy-to-construct Groundwater Quality Index is presently lacking (Hueting 1991). Also, water quality is sometimes difficult to evaluate from a large number of sampling points (Chapman 1992; Pesce and Wunderlin 2000). Although there exist no hard and fast rules for constructing a Water Quality Index, two steps are generally required. First, it is necessary to select a set of water quality parameters that measure important physical, chemical, and microbiological water characteristics. Of course, the selection of these parameters will be dependent upon the intended use of the water. Once this selection is made and the scientific characteristics of this set of parameters are known, a rule is needed to summarize all of the information into a unique number, i.e., the quality index. Provencher and Lamontagne (1977) proposed one pioneering Water Quality Index. It is based on several parameters scored using the same transformations, generally but not always linear, and a final global score is reached. In the past, a variety of water quality indices have been proposed by researchers (Table 1).

Geographic information system (GIS) has emerged as a powerful tool for storing, analyzing, and displaying spatial data and using these data for decision making in several areas including engineering and environmental fields (e.g., Stafford 1991; Goodchild 1993; Burrough and McDonnell 1998; Lo and Yeung 2003). It allows for swift organization, quantification, and interpretation of a large volume of spatial data, providing an efficient environment. The main intent of the present study was to evaluate groundwater quality and characterize its spatial and temporal variations in a semi-arid and hilly hard-rock terrain of Rajasthan (i.e., Udaipur district), western India by using long-term and multi-site post-monsoon groundwater quality data and GIS technique. The present study is first of its kind in western India in general and Rajasthan in particular.

Overview of the study area

Location and land use

In the present study, Udaipur district was selected as the study area, which is situated in southern part of the largest and driest state (Rajasthan) of India (Fig. 1). It lies between 23°45′ and 25°10′ north latitude and 73°0′ and 74°35′ east longitude encompassing a geographical area of about 12,698 km^2. It consists of 11 blocks (viz., Badgaon, Bhinder, Dhariawad, Girwa, Gogunda, Jhadol, Kherwara, Kotra, Mavli, Salumber, and Sarada). A state (province) in India is divided into districts, districts into blocks, and blocks into *Gram Panchayats*; each *Gram Panchayat* consists of several villages. The land use/land cover of the study area comprises cultivable land, forest, pasture, waste land, water bodies, and built-up land.

Hydrometeorology and surface water resources

The climate of Udaipur is tropical, semi-arid with temperatures ranging from a maximum of 42.3°C and a minimum of 28.8°C during summers. Winters are cold with the maximum temperature rising to 28.8°C and the minimum dipping to 2.5°C. January is the coldest month and May is the hottest month. The mean annual evapotranspiration in the study area is 1,380 mm. The mean annual rainfall is 625 mm, with more than 80% of precipitation occurring from June through September. The rainy season (i.e., wet season) usually starts in mid-June and lasts until the end of October. November to May is characterized as the dry period. Som, Jhakham, Wakal, Sei, Sabarmati, and Berach are the main rivers in the study area (Fig. 1), which have intermittent flow. The western portion of the district is drained by the Sabarmati River, which originates in the Aravalli Range of Udaipur district and flows towards Gujarat state in south. The northern portion of the district is drained by tributaries of the Banas River, including the Ahar River which flows through the City of Udaipur. The southern and central portions of the district are drained by tributaries of the Mahi River, including the Som River and the Gomati River. Besides the rivers, there are several surface reservoirs and lakes in the district. The surface reservoirs and lakes mainly supply water for drinking, irrigation, and industrial purposes in the study area. Surface irrigation is mainly confined to canal commands located in southern and southeast portions of the study area.

Geologic settings

Six types of geology (phyllite–schist, schist, gneiss, granite, and quartzite) including hillocks are available in the study area (Fig. 2). Phyllite–schist geologic formations are dominant and cover western half of the study area. A localized pocket occupied

Table 1 Overview of water quality indices used in the earlier studies

Sl. no.	Name of water quality index	Location of study	Water quality parameters used	Source
1	Groundwater Contamination Index	Finland	F, NO_3, UO_2, As, B, Ba, Cd, Cr, Ni, Pb, Rn, Se, pH, $KMnO_4$ consumption, SO_4, Cl, Ag, Al, Cu, Fe, Mn, Na, and Zn	Backman et al. (1998)
		Slovakia	TDS, SO_4, Cl, F, NO_3, NH_4, Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, Sb, Se, and Zn	
2	Groundwater Quality Index	Israel	Cl and NO_3	Melloul and Collin (1998)
3	Groundwater Quality Index	Egypt	NO_3, PO_3, Cl, TDS, BOD, Cd, Cr, Ni, and Pb	Soltan (1999)
4	Surface Water and Groundwater Quality Index	Croatia	Temperature, mineralization, corrosion coefficient, DO, BOD, total N, protein N, total P, and total coliform	Štambuk-Giljanović (1999)
5	Groundwater Quality Index and Groundwater Composition Index	Portugal	NO_3, SO_4, Cl, and Ca	Stigter et al. (2006)
6	Surface Water Quality Index	Argentina	Temperature, hardness, DO, pH, EC, alkalinity, turbidity, NO_3, NO_2, NH_3, Cl, and SO_4	Vignolo et al. (2006)
7	Malaysian Department of Environment—Surface Water Quality Index	Malaysia	DO, COD, BOD, TSS, NH_3-N, and pH	Shuhaimi-Othman et al. (2007)
8	Groundwater Quality Index	Japan	Cl, Ca, Na, Mg, SO_4, TDS, and NO_3	Babiker et al. (2007)
9	Surface Water Quality Index	Spain	pH, EC, TSS, NH_3, NO_2, NO_3, COD, BOD, DO, temperature, and total P	Sánchez et al. (2007)
10	Fuzzy Surface Water Quality Index	Brazil	Temperature, pH, DO, BOD, Coliforms, dissolved inorganic N, total P, total solids, and turbidity	Lermontov et al. (2009)
11	Groundwater Quality Index	India	pH, EC, Na, Cl, SO_4, total alkalinity, total hardness, Ca, Mg, Fe, F, NO_3, NO_2, Mn, Zn, Cd, Cr, Pb, Cu, Ni, total coliform, salmonella	Ramesh et al. (2010)

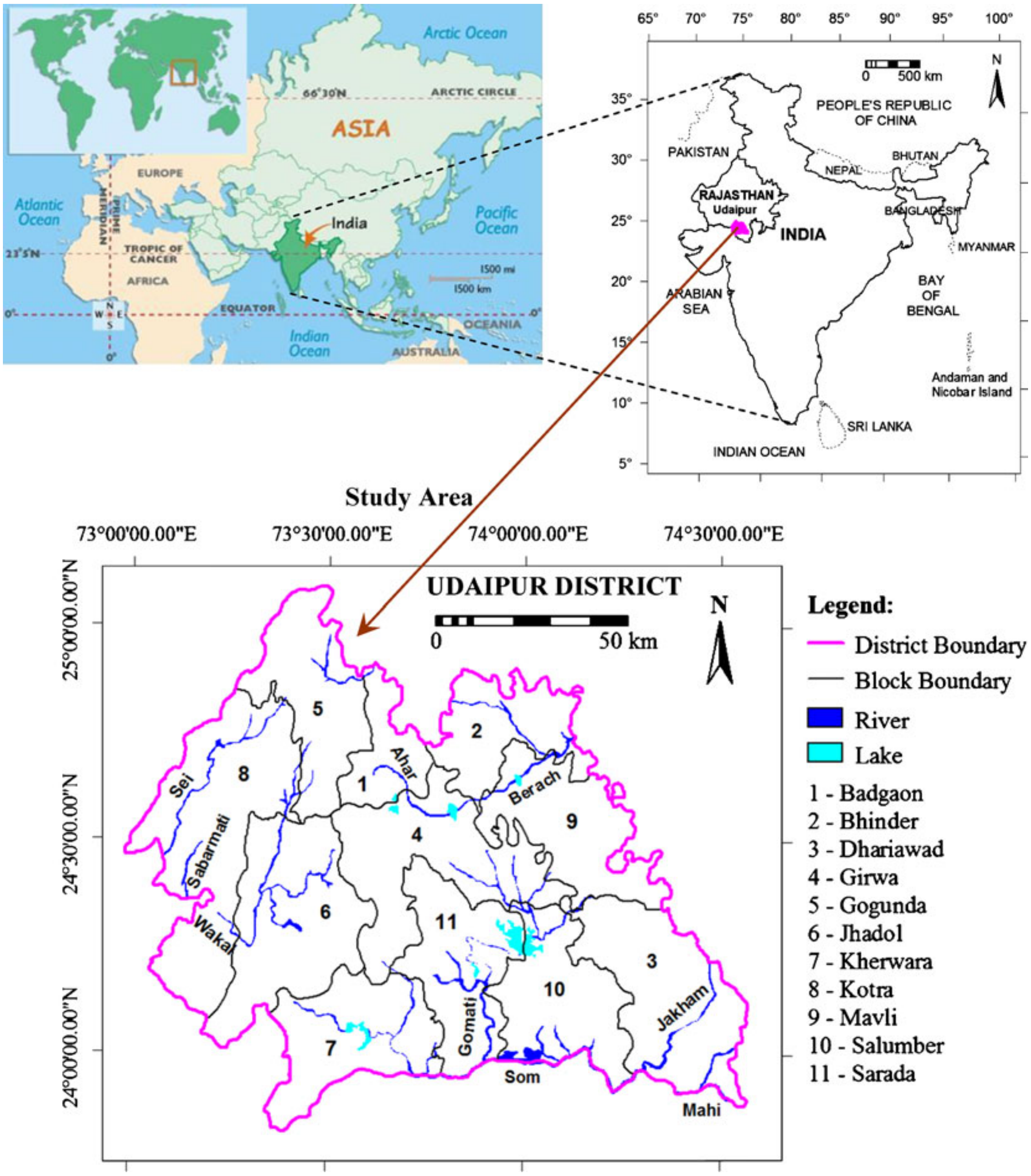
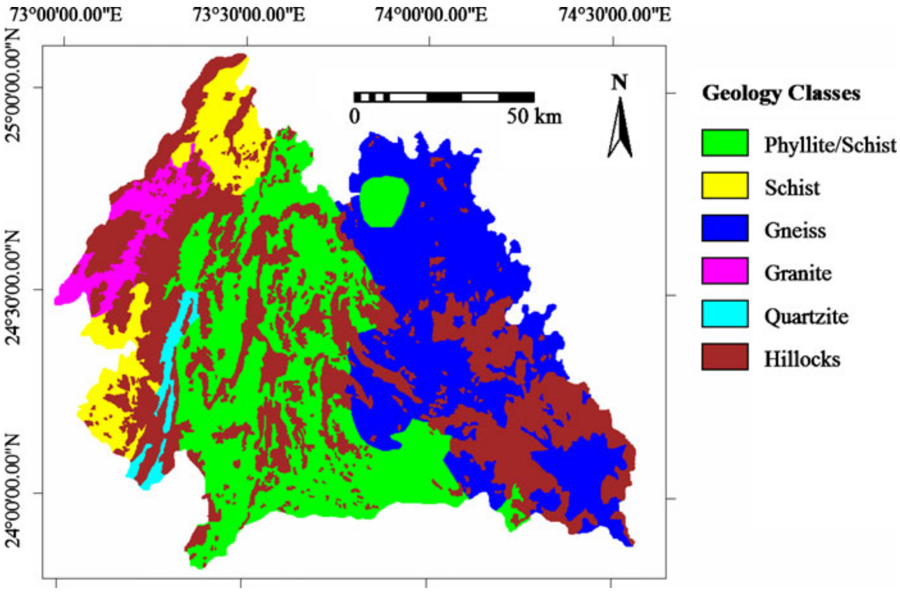


Fig. 1 Location of the study area

by the phyllite–schist is located near Mavli block. The gneiss formation occupies the eastern part of the study area in Bhinder, Dhariawad, Girwa, Mavli, Salumber, and Sarada blocks. The schist formation covers small areas in parts of Gogunda and Kotra blocks. The granite geologic setting is present in the western peripheral portion within the boundary of Kotra block, while the quartzite geologic setting occupies southwest portion of the study area and is confined to Jhadol block. The hillocks present in the study area are small hills, which have negligible groundwater potential. However, foothills of the hillocks form important geomorphologic features namely valley fills and buried pediment, which are effective in recharging underlying shallow and deep bedrock aquifers.

Fig. 2 Geology map of the study area

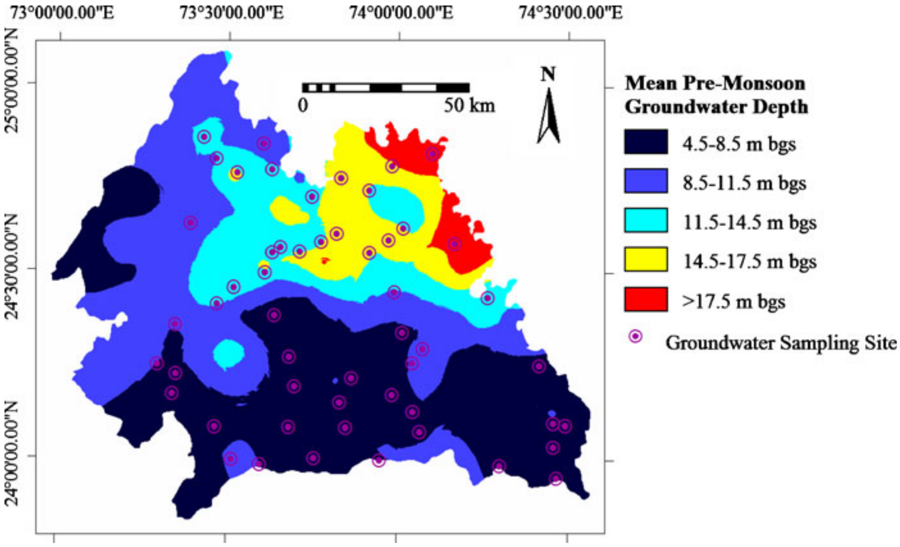


Hydrogeology and groundwater scenario

The major hydrogeological formations in Udaipur are phyllite–schist, and gneiss of 'Aravalli' Supergroup. These rocks have very little primary porosity. The movement of groundwater through these rocks is mainly through secondary porosity such as joints and fractures, which are limited. Such hydrogeologic formations are typically termed "hard-rock formations" (CGWB 1997). The geomorphic controls play an important role in the occurrence of groundwater in the study area. As mentioned earlier, the foothills generally form the recharge zone. The shallow aquifers present in the study area are mainly unconfined in nature and constitute the major source of groundwater. Deep aquifers are reported to exist at greater than 100-m depth, but little is known about these aquifers (GWD 2004).

The mean pre-monsoon groundwater level in the study area generally varies from 4.8 to 23 m below ground surface (m bgs), with a major por-

Fig. 3 Mean pre-monsoon groundwater level map of the study area and groundwater sampling sites



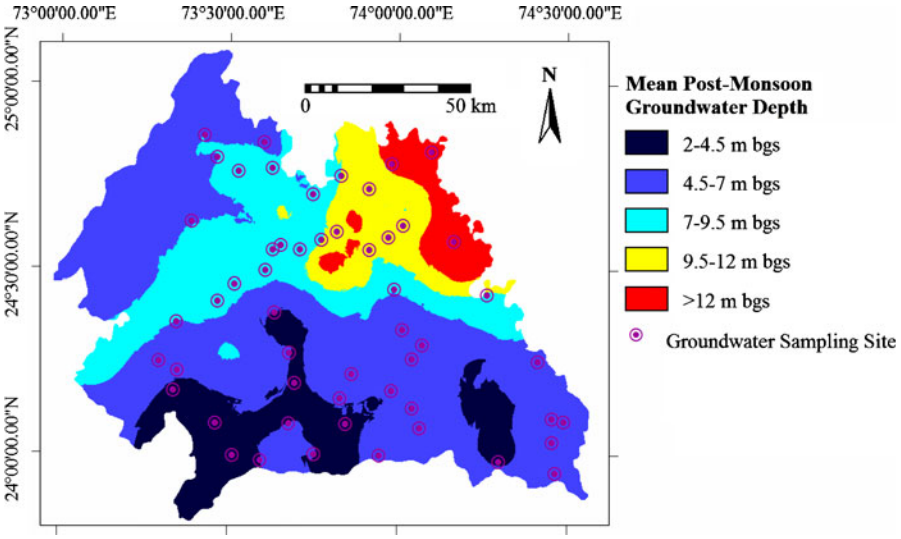


Fig. 4 Mean post-monsoon groundwater level map of the study area and groundwater sampling sites

tion of the area having 4.5 to 11.5 m bgs depth as shown in Fig. 3 (Machiwal 2009). In the north-east portion of the area, the mean pre-monsoon groundwater depth varies from 14.5 to 17.5 m. In contrast, in the western and central portions and at some scattered places in the south, the mean pre-monsoon groundwater depth ranges from 8.5 to 11.5 m. On the other hand, the mean post-monsoon groundwater depth varies from 2.3 to 18 m, with a majority of the study area having a mean post-monsoon groundwater depth of 2 to 7 m (Fig. 4). Currently, groundwater is a major source of irrigation contributing 69% of the total irrigated area, whereas surface water contributes only 31% of the total irrigated area. In Udaipur district, 51,147 dug wells and 2,117 shallow and deep tubewells are in use, of which 34,217 wells are fitted with ordinary centrifugal pumps or hand pumps and the remaining 16,930 wells are operated by traditional water lifting devices such as Bullock Mote and Persian Wheel (GWD 2007). The dug wells and tubewells are also used for domestic water supply purposes both in rural and urban areas. In addition, about 120 shallow and deep tubewells are used for industrial water supply in the study area. There is an increasing dependence on groundwater supply for meeting water demands in various sectors, including the domestic sector because of uncertainty in surface water supply and growing pollution of surface water resource.

Methodology

Data acquisition

The monitoring of groundwater quality in the study area is usually done during post-monsoon seasons (from October to December) at 53 randomly selected sites over the study area; the locations of the sampling sites are shown in Figs. 3 and 4. The groundwater quality parameters analyzed at each site are: calcium (Ca), magnesium (Mg), sodium (Na), sulfate (SO_4), chloride (Cl), bicarbonate (HCO_3), nitrate (NO_3), pH, electrical conductivity (EC), total dissolved solids (TDS), and hardness. The post-monsoon groundwater quality data were collected for an 11-year period (1992–2002) from the Central Ground Water Board, Jaipur, Rajasthan. These 11 water quality parameters are listed in the drinking water standards provided by the World Health Organization (WHO), Geneva. These data were used for the analysis of spatio-temporal variations of groundwater quality as well as for the development of Groundwater Quality Index.

Analysis of spatio-temporal variations of groundwater quality

The availability of multi-year and multi-site groundwater quality parameters provided an opportunity for exploring spatial and temporal variations of groundwater quality in the study area. The coefficient of variation is a measure of variability in time and space, which was used in this study. In order to compute the coefficient of variation, annual concentration maps of individual water quality parameters were used to create mean ($\overline{\mathrm{C}}$) and standard deviation (SD) maps using following equations:

$$\overline{C}_i = \frac{\sum_{n=1}^{N} C_{\mathrm{in}}}{N} \tag{1}$$

and

$$\mathrm{SD}_i = \sqrt{\frac{\sum_{n=1}^{N} (C_{\mathrm{in}} - \overline{C})}{N-1}} \tag{2}$$

Where $\overline{\mathrm{C}}_{\mathrm{i}}$ = mean annual concentration map of the ith water quality parameter, C_{in} = annual concentration map of the ith parameter in nth year, N = total number of years of availability of the parameters, and SD_i = standard deviation map for the ith parameter.

Thereafter, the coefficient of variation maps for individual parameters were developed using the following equation:

$$CV_i = \frac{\mathrm{SD}_i}{\overline{C}_i} \tag{3}$$

Where CV_i = coefficient of variation for the ith groundwater quality parameter.

Development of Groundwater Quality Index

The development of Groundwater Quality Index (GWQI) involved the following steps, which are described below.

Step 1: Generation of normalized difference maps

The mean annual concentration maps ($\overline{\mathrm{C}}$) representing concentrations of the groundwater quality parameters were constructed for each parameter from the point data with moving average inverse distance weighting interpolation technique using ILWIS software (ILWIS 2001). Thereafter, observed mean annual concentrations (C_{obs}) of the water quality parameters were related to their maximum desirable limits (C_{mdl}) prescribed by the WHO (2006) on a pixel basis using a GIS-based normalized difference index (NDI), which is given as (Babiker et al. 2007):

$$\mathrm{NDI} = (C_{\mathrm{obs}} - C_{\mathrm{mdl}})/(C_{\mathrm{obs}} + C_{\mathrm{mdl}}) \tag{4}$$

The resultant 'normalized difference map' thus displays for each pixel NDI values ranging between −1 and 1. This is similar to the contamination index (CI) approach, which is calculated as the ratio of measured contaminant concentration to the prescribed maximum permissible contaminant limit (Melloul and Collin 1998; Praharaj et al. 2002). However, the NDI provides fixed upper and lower limits for the contamination level.

Step 2: Generation of rank maps

The normalized difference maps were rated between 1 and 10 to generate a 'rank map'. Rank 1 indicates minimum impact on groundwater quality, while rank 10 indicates maximum impact. The minimum NDI value (−1) was set equal to 1, the median value (0) was set equal to 5 and the maximum value (1) was set equal to 10. The following polynomial equation was used to rank the contamination level (or NDI) of every pixel between 1 and 10:

$$r = 0.5 \times (\mathrm{NDI})^2 + 4.5(\mathrm{NDI}) + 5 \tag{5}$$

Where r = rank value of each pixel corresponding to its NDI value.

Step 3: Preparation of Groundwater Quality Index map

Finally, the Groundwater Quality Index was calculated as follows (Babiker et al. 2007):

$$\mathrm{GWQI} = 100 - [(r_1 w_1 + r_2 w_2 + \ldots + r_n w_n)/N] \tag{6}$$

Where r = rate of the rank map (1–10), w = relative weight of the parameter which corresponds to the 'mean' rating value (r) of each rank map (1–10), and N = total number of parameters used in the suitability analysis.

The expression of GWQI [i.e., Eq. 6] looks similar to the weighted linear combination method. The weight (w) assigned to each parameter indicates its relative importance to groundwater quality and corresponds to the mean rating value of its 'rank map'. Parameters that have a higher impact on groundwater quality (high mean rate) are assumed to be more important in evaluating overall groundwater quality. The total number of parameters (N) used in the expression for GWQI averages and limits the index values between 1 and 100. In this way, the impact of individual parameters is greatly reduced and the index computation is never limited to a certain number of chemical parameters. The constant '100' in the first part of the formula was incorporated to directly project the GWQI value such that high index values close to 100 reflect 'high water quality' and the index values far below 100 (close to 1) indicate 'low water quality'. The entire process of developing a Groundwater Quality Index map is shown in Fig. 5. All the GIS analyses in this study were performed by using ILWIS software (ILWIS 2001).

The index scores of the developed GWQI map were classified based on the scheme introduced by Chung and Fabbri (2001). According to their classification scheme, the groundwater quality indices are classified based on a fixed interval of area percentage in the study area. The index values were first sorted in an ascending form and then the indices corresponding to each 10% of the total area were taken as thresholds for the classification. Because this representation demonstrates the results without imposing arbitrary thresholds, it is considered free of subjectivity and useful in comparing results from different areas. Colors were then assigned to the ranges of the subsequent percentages of pixels. The cool colors (shades of blue) indicate "Maximum" water quality, the shades of green indicate "Medium" water quality, and the warm colors (shades of red) indicate "Minimum" water quality.

Development of Potential Groundwater Quality Index map

The GWQI discussed above involves integration of many groundwater quality parameters. There may be two critical concerns originating from the spatial distribution and association of different groundwater quality parameters. First, many of the groundwater quality parameters are spatially invariable which imply that they contribute little to the variation of overall GWQI in an area. Second, most of the major chemical constituents in groundwater are spatially correlated with each other, which involve duplication in calculation. These redundant parameters increase computation time and probability of misjudgement in the computation of GWQI. Since the abovementioned data properties might affect the reliability

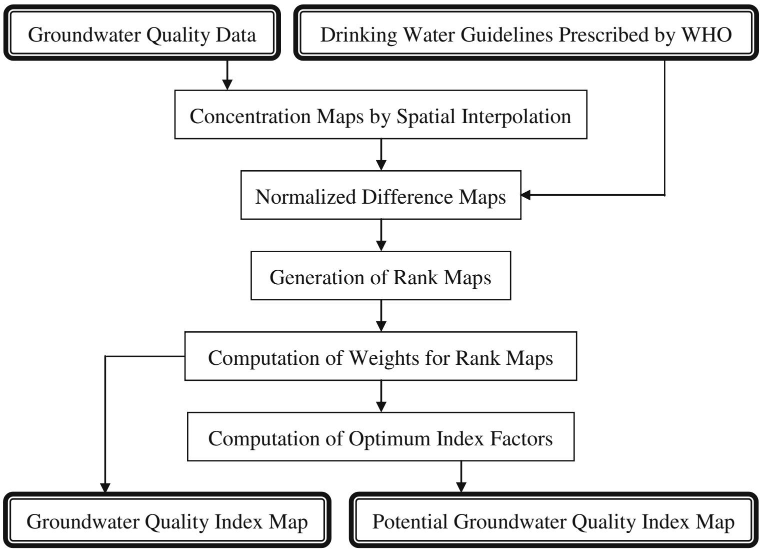


Fig. 5 Flowchart for developing Groundwater Quality Index and Potential Groundwater Quality Index maps

of a computed index, an objective method is preferred to select the best combination of groundwater quality parameters to generate a GWQI that could best display the real situation of groundwater quality in an area. The Optimum Index Factor (OIF) was used to select the optimum combination of three rank maps with the highest amount of information (highest sum of standard deviations) and the least amount of duplication (lowest correlation among map pairs). OIF is mathematically expressed as (ILWIS 2001):

$$\mathrm{OIF} = (\mathrm{SD}_i + \mathrm{SD}_j + \mathrm{SD}_k) / (|\mathrm{Corr}_{i,j}| + |\mathrm{Corr}_{j,k}| + |\mathrm{Corr}_{k,i}|) \tag{7}$$

Where SD = standard deviation; Corr = correlation; and i, j, and k = best combination parameters with the highest value of OIF.

The OIF was developed to select an optimum combination of three bands in a satellite image in order to create a color composite. The OIF for all possible combinations of three groundwater quality parameters was computed by using ILWIS GIS software and then combination with the highest value of OIF was selected. The Potential Groundwater Quality Index was then computed by using rank maps of three parameters obtained from the best OIF combination. That is,

$$\text{Potential GWQI} = 100 - \{(r_1 w_1 + r_2 w_2 + r_3 w_3)/3\} \tag{8}$$

The procedure for the development of 'Potential Groundwater Quality Index' map is illustrated in Fig. 5.

Sensitivity analysis

Geographical "sensitivity analysis" is defined as the study of the effects of imposed perturbations (variations) on the inputs of a geographical analysis on the output of that analysis (Lodwick et al. 1990). Unlike geographical 'error analysis', the 'sensitivity analysis' does not require a priori knowledge of the error but perturbations are imposed on the inputs or underlying assumptions of the geographical analysis to gain knowledge about the behavior of the analysis in question. A geographical sensitivity analysis of such type of overlay-based suitability analysis can indicate which map(s) is (are) the most/least critical in determining the values of the output map. These critical maps denote where most/least care must/may be taken while preparing the input data in order to draw reliable conclusions from the output (Lodwick et al. 1990). In this study, map removal sensitivity measure (Lodwick et al. 1990) was used to examine the impacts of removing any of the 11 parameters used for the computation of GWQI. The map removal sensitivity tests the sensitivity of the output GWQI to the removal of one or more of the rank maps from the analyses and is expressed in terms of a variation index as given below:

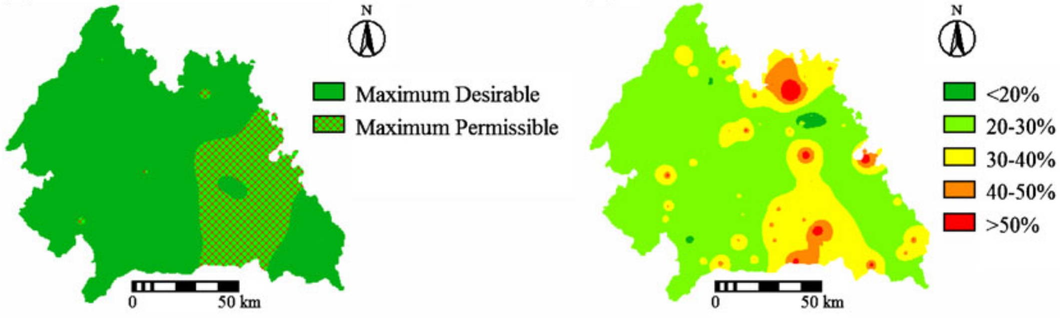
$$V_{\mathrm{wi}} = (|\mathrm{GWQI} - \mathrm{GWQI}_{\mathrm{wi}}|/\mathrm{GWQI}) \times 100 \tag{9}$$

Where V_{wi} = variation index (%) without ith rank map, GWQI = Groundwater Quality Index with all the 11 rank maps, and $\mathrm{GWQI}_{\mathrm{wi}}$ = Groundwater Quality Index without ith rank map.

Results and discussion

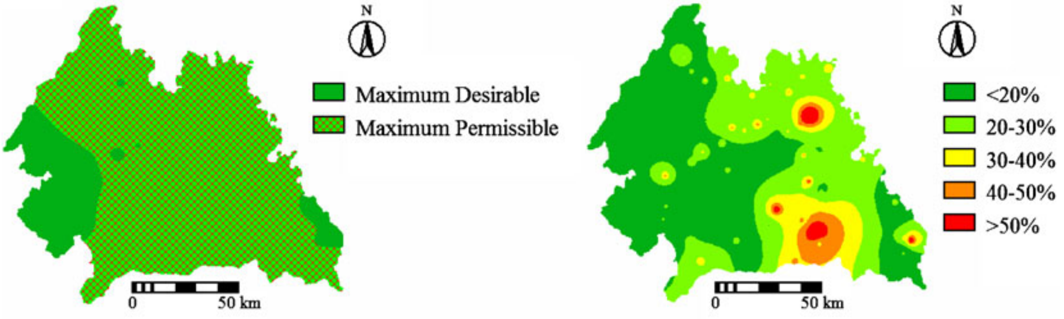
Spatial and temporal variations of groundwater quality parameters

Eleven groundwater quality parameters, viz., Ca, Mg, Na, HCO_3, SO_4, Cl, NO_3, TDS, EC, pH, and hardness, for which WHO has prescribed maximum desirable limits for drinking purpose were analyzed by GIS techniques for determining their spatial and temporal variations. The mean annual concentration and coefficient of variation maps for individual water quality parameters are shown in Figs. 6a–v. It is apparent from Fig. 6a that the mean concentration of calcium remains below the maximum desirable limit (<75 mg/L) of WHO (2006) in 79% of the study area and within the maximum permissible limit (75–200 mg/L) in 21% of the area. On the other hand, the CV map [Fig. 6b] indicates that the temporal variability of calcium remains within 20–30% in major part of the area. The temporal variability seems to be the highest in scattered locations in the northeast, southern, and southeast portions of the study area. A major portion of the study area (83%) contains magnesium within its maximum permissible limit



(a) Mean Concentration of Calcium

(b) Coefficient of Variation for Calcium

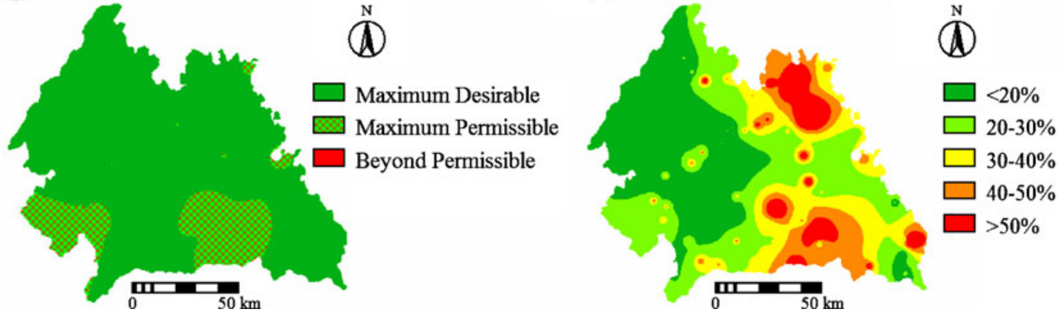


(c) Mean Concentration of Magnesium

(d) Coefficient of Variation for Magnesium

(e) Mean Concentration of Sodium

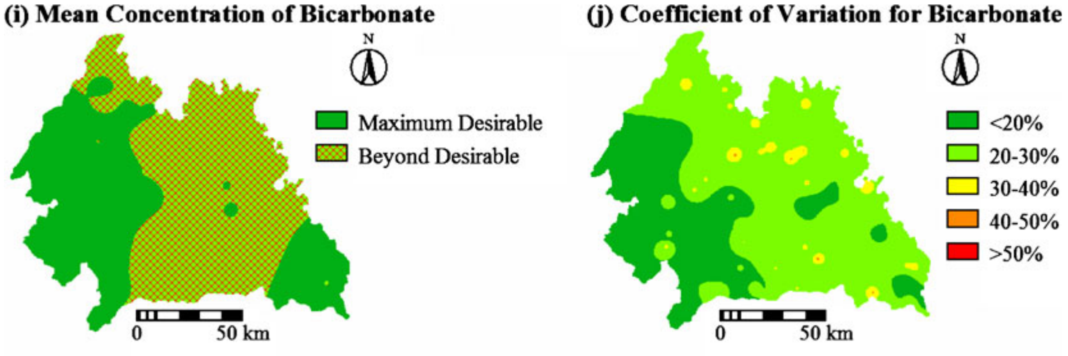
(f) Coefficient of Variation for Sodium



(g) Mean Concentration of Chloride

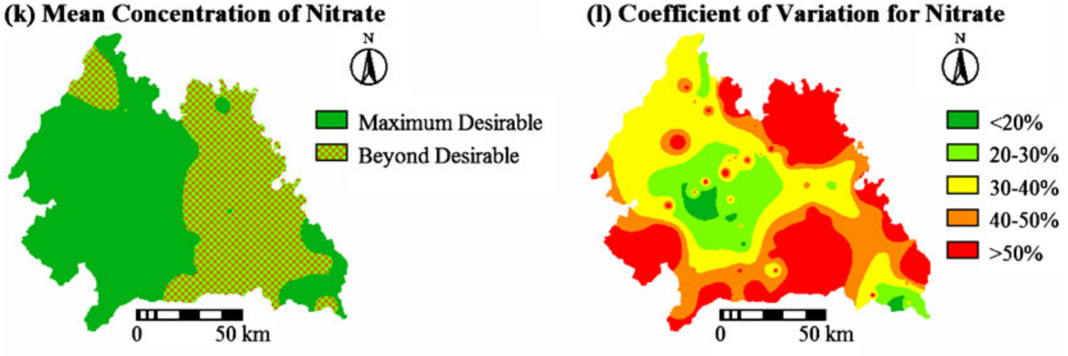
(h) Coefficient of Variation for Chloride

Fig. 6 **a–v** Spatial variation and status of groundwater quality based on the WHO standards for drinking water along with the temporal variation of groundwater quality



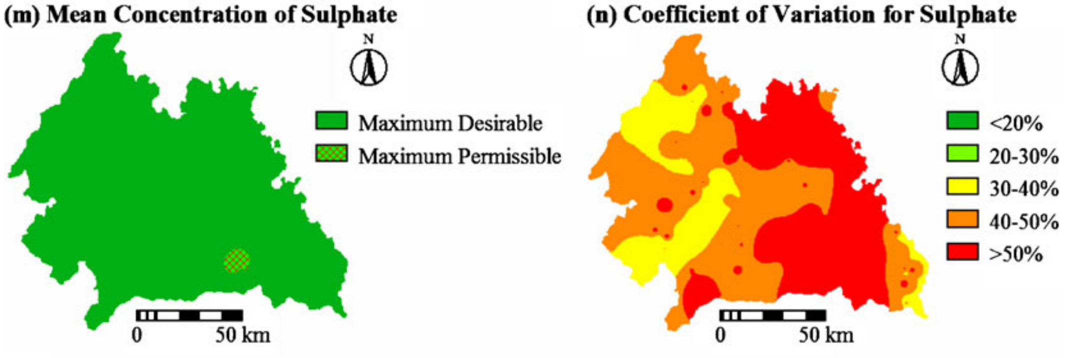
(i) Mean Concentration of Bicarbonate

(j) Coefficient of Variation for Bicarbonate



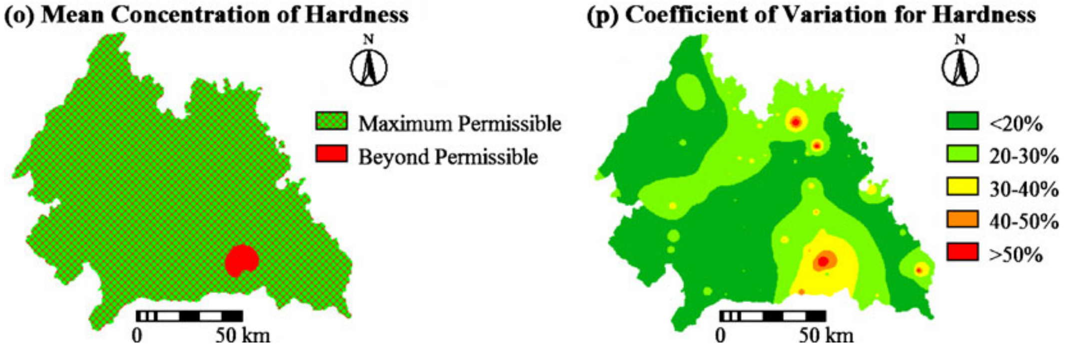
(k) Mean Concentration of Nitrate

(l) Coefficient of Variation for Nitrate



(m) Mean Concentration of Sulphate

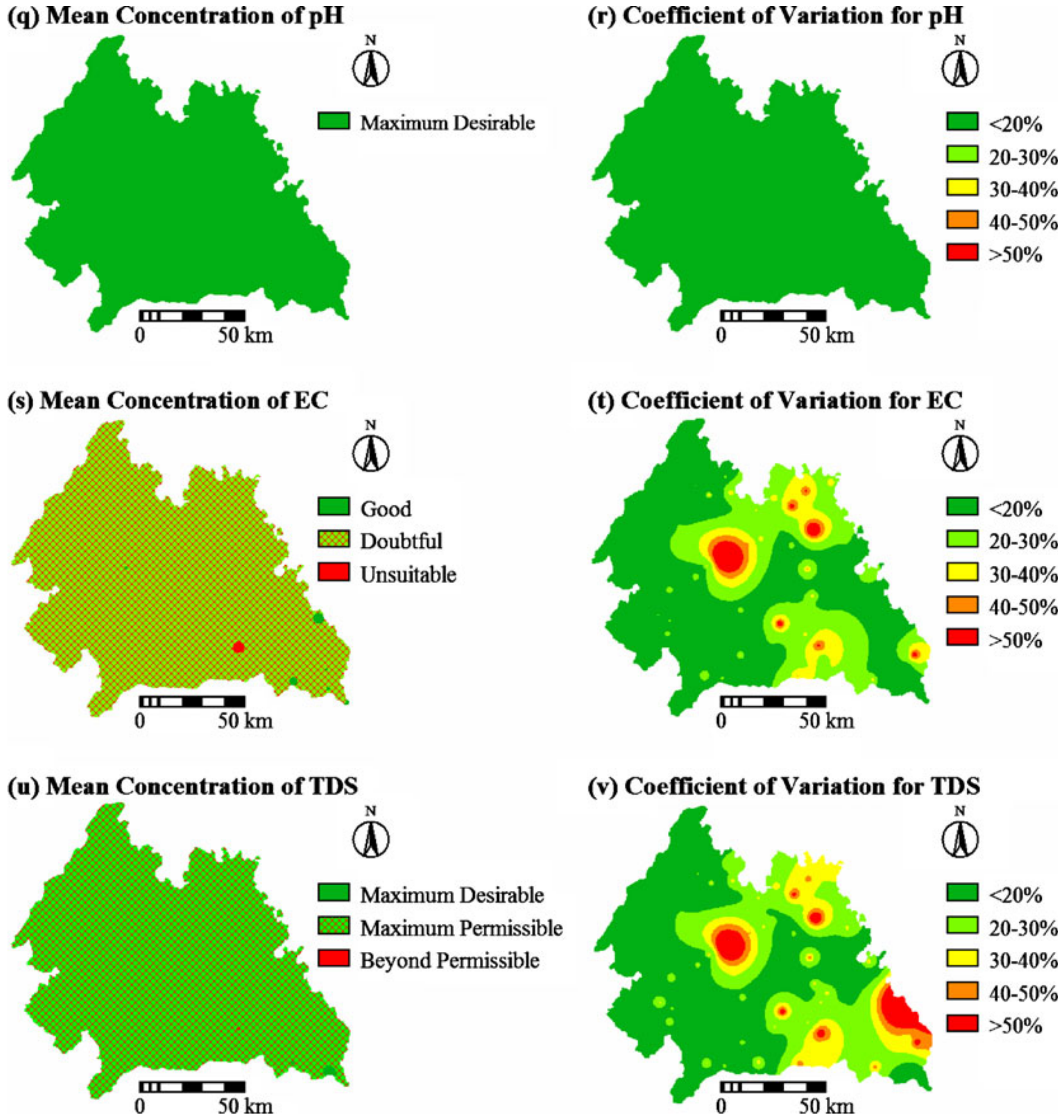
(n) Coefficient of Variation for Sulphate



(o) Mean Concentration of Hardness

(p) Coefficient of Variation for Hardness

Fig. 6 (continued)


(q) Mean Concentration of pH

(r) Coefficient of Variation for pH

(s) Mean Concentration of EC

(t) Coefficient of Variation for EC

(u) Mean Concentration of TDS

(v) Coefficient of Variation for TDS

Fig. 6 (continued)

(30–150 mg/L) and about 17% of the area contains magnesium within its maximum desirable limit (<30 mg/L) [Fig. 6c]. Figure 6d shows that the majority of the area has less temporal variability of magnesium with a CV of less than 30%. The highest temporal variability of magnesium is discernible in small patches in the northeast, south, and southeast portions of the study area.

Mean concentration of sodium [Fig. 6e] in almost the entire study area is within its maximum desirable limit (<200 mg/L), with a coefficient of variation of less than 30% in a major portion of the area [Fig. 6f]. Similar to calcium and magnesium, the temporal variability of sodium is the highest in small patches in the northeast, south, and southeast portions of the area. It is apparent from Fig. 6g that the majority of the area (84%) has chloride concentration within its maximum desirable limit (<200 mg/L), whereas 16% of the area in south and southwest portions has chloride concentration within its maximum permissible limit (200–600 mg/L). Furthermore, the chloride concentration has the highest temporal variability (coefficient of variation >40%)

in northeast and southeast portions of the area [Fig. 6h].

The mean concentration map of bicarbonate [Fig. 6i] reveals that 54% of the area contains high concentrations of HCO_3 exceeding its maximum desirable limit (>300 mg/L). Figure 6j shows that the temporal variability of bicarbonate concentration is low (coefficient of variation <30%) in almost the entire study area. Similarly, the mean concentration of nitrate is within its maximum desirable limit (<45 mg/L) in 59% of the area [Fig. 6k]. The coefficient of variation for nitrate is the highest (>40%) in 51% of the area (northeast, east, south, and southwest portions) as shown in Fig. 6l. Figure 6m reveals that the mean concentration of sulfate is within its maximum desirable limit (200 mg/L) in 99% of the area, with the highest temporal variability (coefficient of variation >40%) in 80% of the area except for two patches in the western portion [Fig. 6n]. In contrast, Fig. 6o reveals that the mean concentration of hardness is within its maximum permissible limit (500 mg/L) in almost the entire study area except for a small patch encompassing an area of 1.4% in the south portion, where concentration exceeds its maximum permissible limit. The coefficient of variation for hardness is below 40% in major portions (92%) of the study area [Fig. 6p].

Figure 6q, r depict that pH in the entire study area remains within the desirable limit (7–8.5) and its temporal variability is low (CV below 20%). The mean concentration map of electrical conductivity reveals that groundwater of the entire study area is doubtful to be used for drinking because its EC is more than 750 μS/cm [Fig. 6s]. The temporal variability of EC is less than 40% in 95% of the area [Fig. 6t]. Finally, Fig. 6u shows that mean concentration of total dissolved solids remains within its maximum permissible limit (500–1,500 mg/L) in entire study area, with the same pattern of coefficient of variation [Fig. 6v] as that for EC.

Groundwater Quality Index map for the study area

The mean Groundwater Quality Index (GWQI) map of Udaipur district (Fig. 7) reveals that the groundwater quality of Udaipur district is generally good (median GWQI >74, maximum GWQI = 100). Ten groundwater quality classes are identified in the study area at a 10% interval. The lowest three classes (0–30%) are grouped as ‘low quality’, next four classes (30–70%) as ‘moderate quality’, and the last three classes (70–100%) as ‘high quality’. Statistics of the 11 mean rank maps (parameters) used to compute GWQI are shown in Table 2. It is obvious from Table 2 that the parameters of hardness, EC, TDS, and Mg dictate the spatial pattern of groundwater quality shown in Fig. 7, which is due to their high mean rank values. Figure 7 reveals that high-quality groundwater exists in northwest and southeast portions of the study area, while the quality of

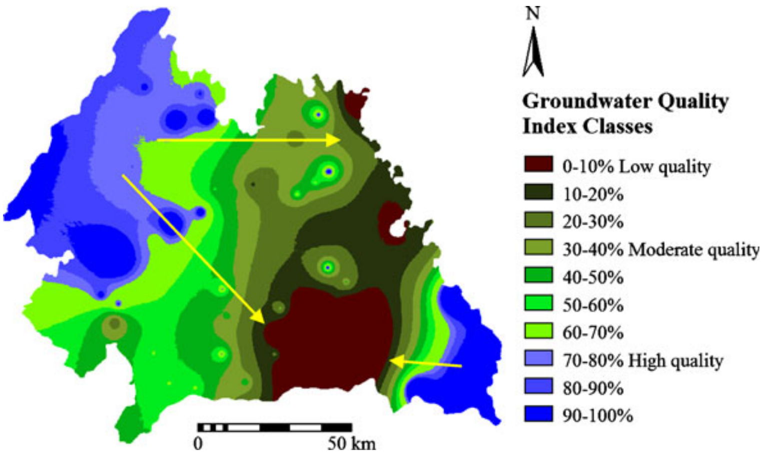


Fig. 7 Groundwater Quality Index map of the study area

Table 2 Statistics of the 11 mean rank maps used to generate Groundwater Quality Index

Parameter	Minimum	Maximum	Mean	Standard deviation
Ca	3.34	6.28	4.72	0.31
Mg	3.78	7.33	5.42	0.42
Na	1.99	5.79	3.77	0.56
Cl	2.09	6.80	4.31	0.67
HCO_3	3.88	5.93	4.99	0.23
NO_3	2.00	6.64	4.58	0.85
SO_4	1.66	5.76	3.07	0.48
Hardness	6.04	8.61	7.45	0.27
pH	4.81	4.94	4.87	0.01
EC	4.34	7.68	5.89	0.40
TDS	4.59	7.00	5.82	0.35

groundwater decreases in the northeast, eastern, and southern portions of the area.

Moreover, three gradients of groundwater quality can be seen in the study area (Fig. 7). First, there is a decrease in groundwater quality from northwest to south following the general groundwater flow direction. This decline in quality is attributed mainly to the shallow groundwater table (<8.5 m) in south and the increase of pollutant input from chemical fertilizers applied to agricultural fields. Higher pollutant concentration in the south suggests a higher rate of percolation, and hence low capacity of the vadose zone to attenuate the contaminant.

The second gradient is a decrease of groundwater quality from northwest towards northeast. This gradient of groundwater quality also follows the general groundwater flow direction. The Ahar and Berach Rivers of the area, which drain the densely populated area in the north, act as a potential source of recharge to the underlying groundwater and may transport urban pollutants to the aquifer system. Near the Berach River (northeast border), the low groundwater quality might be attributed to the relatively high population density in this region.

The third gradient of the groundwater quality is from southeast direction towards south direction. The Jakham River (southeast border) drains the southeast portion of the area and recharges shallow groundwater in the south. The southern portion of the study area has a canal network for irrigating crops. Thus, relatively poor groundwater quality in the southern portion of the study area is most likely due to deep percolation of irrigation water including chemical fertilizers to shallow groundwater. According to the Groundwater Quality Index map, the northwest and southeast regions have the best quality of groundwater for drinking, irrigation, and other domestic purposes. High groundwater quality is attributed to the greater capacity of the vadose zone to attenuate contaminant percolation in northwest and southeast parts of the area. The GWQI developed in this study is based on 11 years groundwater quality data, and hence it can be used for long-term planning and management of groundwater resources in the study area. It is worth mentioning that the developed GWQI is not a biological, aesthetic, or radioactive indicator of the water quality as it did not take into account biological (total coliform or faecal coliform), aesthetic (odors, taints, color, and floating matter), and radioactive indicators (alpha, beta, and gamma radiations) due to the lack of such data in the study area. Thus, the developed GWQI represents physicochemical groundwater quality of the study area.

Potential Groundwater Quality Index map of the study area

The values of Optimum Index Factors for different groups of water quality parameters are summarized in Table 3. Calcium, chloride, and pH constitute the highest ranking group with an Optimum Index Factor of 6.44. However, this value is only 0.12 units greater than that of the second group consisting of chloride, nitrate, and pH.

Table 3 Optimum Index Factors for the six groups of three parameters

S. no.	Group of three parameters			Optimum Index Factor
1	Ca	Cl	pH	6.44
2	Cl	NO_3	pH	6.32
3	Ca	Na	pH	4.67
4	Na	NO_3	pH	3.60
5	Cl	Hardness	pH	2.21
6	Cl	Mg	pH	1.98

The Potential GWQI map of the study area (Fig. 8) developed by using mean concentration maps of the Optimum Index Factors (Ca, Cl, and pH) has a very similar pattern of spatial distribution of groundwater quality in the study area to that depicted by the GWQI map (Fig. 8) except that quality is high in the northeast portion and low in the southwest portion compared to the GWQI map. The absolute mean value of the Potential GWQI (78.54) is slightly higher than that of the GWQI (74) suggesting higher groundwater quality. Also, the Potential GWQI reveals less spatial variability than the GWQI (standard deviation = 1.58 and 1.24, respectively). Thus, it can be inferred that Ca, Cl, and pH are three representative parameters for cost-effective and long-term water quality monitoring in the study area.

Sensitivity of groundwater quality parameters

Results of the map removal sensitivity analysis for the 11 parameters are presented in Table 4. It is apparent from Table 4 that the highest mean, minimum, and maximum values of the variation index (mean = 3.98%) is for hardness. The mean variation indices of sulfate (2.26%) and sodium (1.62%) are relatively high compared to other parameters. Thus, the individual removal of hardness, sulfate, and sodium from computation of GWQI appears to cause the highest variation in the attribute of the unperturbed index. The GWQI was rather insensitive to the removal of any of the input parameter maps probably because the index was generated by averaging. This ensures the stability of the index and the comparability of the results from different locations using different datasets. Hardness reflects lowest groundwater quality (highest mean rank value) and also it is a sensitive parameter. This finding is in agreement with that reported by Babiker et al. (2007). Generally, the parameters that reflect relatively lower water quality (i.e., high mean rank value) and significant spatial variability (large standard deviation of concentration) have a large impact on the GWQI (Babiker et al. 2007). However, hardness concentration does not exhibit a significant spatial variation (standard deviation = 0.27; Table 2). The standard deviations of sulfate

Fig. 8 Potential Groundwater Quality Index map of the study area

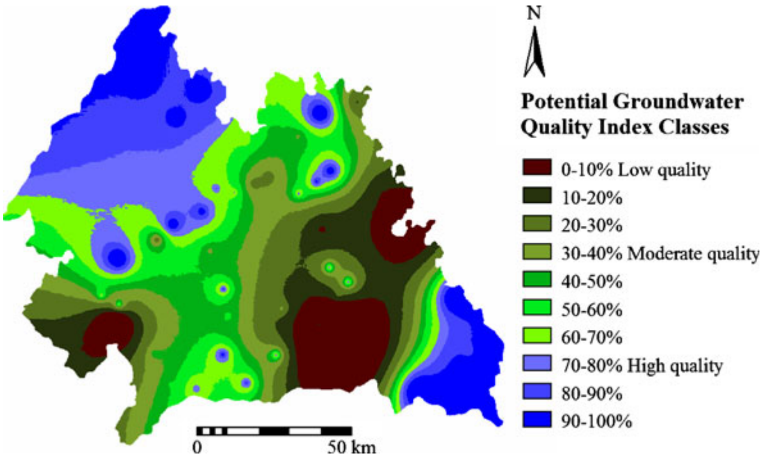


Table 4 Results of the map removal sensitivity analysis

Parameter removed	Variation index (%)			
	Minimum	Maximum	Mean	Standard deviation
Ca	0.09	1.30	0.53	0.15
Mg	0	1.23	0.44	0.16
Na	0.80	2.20	1.62	0.21
Cl	0	1.70	1.02	0.27
HCO_3	0	1.20	0.19	0.16
NO_3	0	2.06	0.7	0.39
SO_4	1.72	2.79	2.26	0.11
Hardness	2.97	4.63	3.98	0.16
pH	0	1.45	0.34	0.22
EC	0.56	1.89	1.16	0.16
TDS	0.56	1.66	1.05	0.13

and sodium are high (0.48 and 0.56, respectively), but those of chloride and nitrate are higher than sulfate and sodium (Table 2). Thus, it can be concluded that hardness, sulfate, and sodium should be monitored with a higher accuracy in the study area.

Conclusions

The present study was carried out in a semi-arid and hilly hard-rock terrain of Rajasthan, western India in order to evaluate and characterize groundwater quality using 11-year (1992–2002) post-monsoon groundwater quality data of 53 sites. The spatial and temporal variations of water quality parameters in the study area were analyzed using GIS techniques. Groundwater quality was evaluated based on a GIS-based Groundwater Quality Index. A Potential GWQI map was also generated for the study area following the Optimum Index Factor concept. The most-influential water quality parameters were identified by performing a map removal sensitivity analysis of groundwater quality parameters.

The mean annual concentration maps of 11 groundwater quality parameters indicated that except for hardness, all other water quality parameters are within the maximum permissible limits prescribed for drinking water. Coefficient of variation maps for all 11 water quality parameters revealed a large temporal variation (coefficient of variation >30%) of sulfate and nitrate concentrations in a major portion of the study area, but pH was found to be stable. Hardness, EC, TDS, and magnesium govern the spatial pattern of the GWQI map. The developed GWQI and Potential GWQI maps indicated that relatively good quality groundwater exists in northwest and southeast parts of the area. However, relatively poor quality groundwater exists in the northeast, eastern, and southern portions of the study area based on the maximum desirable limit for drinking and irrigation water. However, the groundwater quality is generally suitable for domestic and irrigation purposes. Three gradients of groundwater quality are discernible in the study area, which are attributed to shallow water table (low capacity of the vadose zone to attenuate the contaminants and greater percolation rate), industrial activities (various urban pollutants), and agricultural practices (mostly chemical fertilizers). The group of Ca, Cl, and pH was found to have the maximum value (6.44) of Optimum Index Factor, which suggests that they are the most important parameters for cost-effective and long-term water quality monitoring in the study area. Furthermore, hardness, sodium, and sulfate are the most sensitive water quality parameters, and hence they need to be monitored regularly with higher accuracy.

The GWQI map developed in this study is easy to understand, interpret, and communicate information on water quality to the beneficiaries, water resources managers, policy makers, and environmentalists. The methodology adopted in this study can easily be applied to other regions of

India and abroad, and the developed GWQI maps can be compared among themselves because the classification scheme used in this study reduces subjectivity in identifying 'low', 'moderate', and 'high' water quality classes. It is recommended that concerned decision-makers should formulate efficient groundwater utilization and management strategies for the study area based on the findings of this study in order to ensure improved health and sanitation of the inhabitants as well as to avoid environmental degradation.

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