Natural Resources Research, Vol. 28, No. 2, April 2019 (© 2018)
https://doi.org/10.1007/s11053-018-9405-4

Original Paper

Groundwater Quality Assessment in a Hyper-arid Region of Rajasthan, India

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Received 10 March 2018; accepted 17 August 2018
Published online: 23 August 2018

Groundwater is an important source of livelihood in regions where rainfall is scanty, surface water sources are absent, and all domestic and agricultural needs are fulfilled with groundwater. This study deals with groundwater quality assessment in a hyper-arid region using multivariate statistical analysis. A total of 43 samples were collected and analyzed using principal component analysis and hierarchical cluster analysis to model the relationship and interdependence among the various physicochemical variables contributing to groundwater quality in the study area. The results of the statistical techniques showed that the variables are in strong correlation with each other. Cluster analysis proved to be a good tool to ascertain the spatial similarity between the contributing variables. The methodology adopted in the present study has been found to be effective and can be utilized to establish strong water quality monitoring network in similar areas.

KEY WORDS: Sustainable groundwater development, Water quality, Multivariate statistical methods, Geochemistry, Hyper-arid region.

INTRODUCTION

Groundwater is considered as a blue gold of vital social and economic importance. Its quality has significant effects on human health and agriculture. The sustainability of groundwater quality and quantity is essential for its domestic and agricultural uses, so that it can be utilized effectively for a long time in an optimal manner without damaging the environment (Singh 2010). As water is a good solvent, it is highly vulnerable to quality degrade action due to geological and anthropogenic sources of pollution and other developmental actions (Tiwari et al. 2017; Das et al. 2010). Therefore, hydrogeochemical processes that impact groundwater quality are a matter of growing interest. Vasanthavigar et al. (2010) considered hydrogeochemical parameters to ascertain groundwater suitability for human needs as well as for irrigation purposes. Li et al. (2016) reported that variations in regional hydrology and water resources are driven by human activities and natural environmental changes. When groundwater comes in contact with dissolved salts derived by weathering of mineral rocks, its salinity increases the concentrations of various cations and anions in it as well. The active management of agricultural landscapes affects the quality of groundwater in aquifers. The use of wide variety of fertilizers, manure, and excessive phosphorus and nitrogen substances during agricultural production causes degradation of groundwater quality (Getahun and Keefer 2016). Groundwater quality in arid to hyper-arid regions occurs due to over-exploitation of groundwater and

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exposure of groundwater to mineral deposits in aquifers.

Many researchers have carried out groundwater quality assessment in India (Kamra et al. 2002; Singh et al. 2002; Ravindra and Garg 2006; Gautam et al. 2015; Kumar et al. 2015). Certain studies have found that over-exploitation of groundwater results in degradation of its quality and gradual drop of groundwater table up to 30 m for many wells (Chintalapudi et al. 2017). These increase groundwater salinity, which increases the content of fluoride, nitrate, iron, and other heavy metals in the groundwater (Kamra et al. 2002; Singh et al. 2002; Gautam et al. 2015). Once contamination of groundwater occurs from agricultural residues, fertilizers, and over-exploitation, it can persist for decades because groundwater movement in aquifer is very slow. Earlier studies of groundwater quality reveal that its chemistry is governed by typical correlations and interactions among a wide range of physicochemical variables (Praveena et al. 2010; Singh and Mukherjee 2015). Singh and Mukherjee (2015) assessed groundwater geochemistry in the western part of India, whereas Praveena et al. (2010) assessed groundwater quality in unconfined aquifers using numerical and hydro-chemical approaches. Groundwater chemistry is a major criterion for its use for drinking and agricultural needs. Jasrotia et al. (2018) evaluated groundwater quality parameters using geochemical plots and various other hydro-chemical analytical methods in order to assess groundwater geochemistry.

Rajasthan is the largest state in India that stands at very critical juncture due to its alarming decrease in groundwater levels. Because of inadequate surface water potential and meager rainfall, there is an increased dependence on groundwater for meeting almost all types of water requirements. Contamination of groundwater in Rajasthan is prone to increase due to inefficient water pumps and irrigation systems. Excess infiltration of groundwater is due to its low prices and believed abundant availability in aquifers, which are not true for every location (Schmoll et al. 2006).

The present study deals with the Bikaner block of Rajasthan, which belongs to the category of hyper-arid zone because it receives 100–350 mm of precipitation every year. In recent years, the prevailing groundwater situation in the block has become alarming due to incessant falling of water levels in the wells. The number of pumping wells for drinking and irrigation purposes has increased drastically in the block in the last decade. The block is facing an acute shortage of groundwater resources with the stage of groundwater development reaching as high as $\sim 147\%$. Most of the block comprises alluvial aquifer system and is underlain by highly permeable and well-drained coarse sandy to sandy loam soils. The alluvial aquifers become vulnerable to contamination due to their high permeability and shallow characteristics (Singh et al. 2005a, b). Along with this, anthropogenic sources and hydrogeochemical processes may be accountable for contaminating the groundwater. The aquifer chemistry is severely affected by the anthropogenic and natural activities, and so attention is required to focus on these activities for sustainable management of the ground water (Subba Rao et al. 2006). Thus, there is a need to carry out extensive investigation on the issues to assess different processes involved in groundwater contamination in the block (Helena et al. 1999).

Multivariate methods, such as hierarchical cluster analysis (HCA) and principal component analysis (PCA), have been applied for understanding multifaceted data in order to derive a clearer understanding of water quality in an area under consideration (Srinivas et al. 2015). Probable factors that are liable for variations in groundwater quality can be determined effectively by applying the above-said methods. These methods are important tools for formulating suitable policies for real-time and sustainable management of groundwater assets (Singh and Ghosh 2003; Singh et al. 2005a, b; Singh 2008). Bhakar and Singh (2018) assessed environmental impacts of groundwater supply system in a hyper-arid region of India and found that life cycle assessment is also a possible tool for identifying major hot spots for sustainable groundwater management.

In the present study, groundwater samples have been collected during both pre- and post-monsoon periods in the year 2016. The samples were analyzed using charge balance error method, and statistical z-scores were computed. Finally, 14 out of 43 samples were found appropriate for further analysis. Different multivariate statistical techniques were applied to extract information about the similarities or dissimilarities between the sampling sites for the identification of (a) water quality variables responsible for spatial and temporal variations in groundwater quality, (b) hidden factors explaining the structure of the database, and (c) the influence of possible factors (natural and anthropogenic) on groundwater quality parameters.

The major issues addressed in this study are (1) evaluation of the suitability of groundwater in the Bikaner block of Rajasthan, (2) assessment of prevailing association among the contributing parameters and/or groundwater occurrence, and (3) determination of the utility of multivariate statistical methods in order to achieve sustainable groundwater quality management.

Figure 1 depicts the graphical representation of the research work discussed in this paper. It explains the major problem and need of the study, research methodology adopted, and findings of the present study. This study meticulously contributes to the limited number of groundwater quality studies in the Bikaner block, which faces water scarcity, and discusses its applicability to other similar regions. The current study presents a novel approach using multicriteria decision-making tools and hydrogeochemical plotting to understand the interrelationship among various groundwater quality parameters in a hyper-arid region of western Rajasthan in order to support decision-makers in devising a suitable policy for sustainable groundwater management. This study discusses critical issues of groundwater quality and identifies critical physicochemical parameters regulating the groundwater quality in the block, which will hopefully create mass awareness among the various stakeholders and policymakers as well. Hence, it is expected to yield direct benefits to society and to create awareness among people in a groundwater-dependent ecosystem.

LITERATURE REVIEW

Table 1 depicts the major research work carried out within the knowledge field in which thus study falls in terms of contribution, location, parameters, methodology, and regional aspects. It is observed from the contemporary literature that a groundwater quality assessment in terms of hydrogeochemical parameters is a common approach to understand the hydrology and status of groundwater. The studies reviewed by this study are found close to our research aim, which is toward assessment of groundwater quality in an arid to hyper-arid region. The studies reviewed aim to promote research in groundwater quality, which is rapidly deteriorating due to intensified human activities and fresh water needs (Li et al. 2016). A study by Li et al. (2017) discussed contemporary research on groundwater quality level and its deterioration due to fast economic and anthropogenic activities in an arid region in Western China.

Important observations made from the literature review are the following:

- Most of the existing studies found that groundwater quality is deteriorating due to fast economic and anthropogenic growth.
- In many of the studied regions, groundwater is not drinkable, especially in arid and semi-arid regions.
- The existing studies assessed the major factors of groundwater quality deterioration.
- The research community believes that both anthropogenic and natural processes affect groundwater quality.
- The research community argues that groundwater recharge and groundwater contamination are two major problems.

STUDY AREA

Location and Extent

The Bikaner block is located in the northwestern part of the state of Rajasthan, and it has an international border with Pakistan (Fig. 2). It occupies 30,381.75 sq. km and lies between 27°11′ and 29°03′ north latitudes and 71°54′ and 74°12′ east longitudes.

Climate and Rainfall

The climate of the Bikaner block ranges from arid in the east to extremely arid/hyper-arid in the west and is characterized by extreme high temperature, erratic rainfall, and high evaporation. Being situated on the western side of the Aravalli hill ranges, the area is characterized as a typical rain shadow region resulting in low precipitation. The normal annual average rainfall of the block is 262.11 mm during the last 108 years (1901–2008). The temperature in winter season is fairly low, and there is a probability of frost occurrence once in three years. Wind speeds during winter season are low with an average of 4.5 km/h, the main direction of wind being NE. High temperatures in the block start from April onwards, whereas May and June are the hottest months of the year.

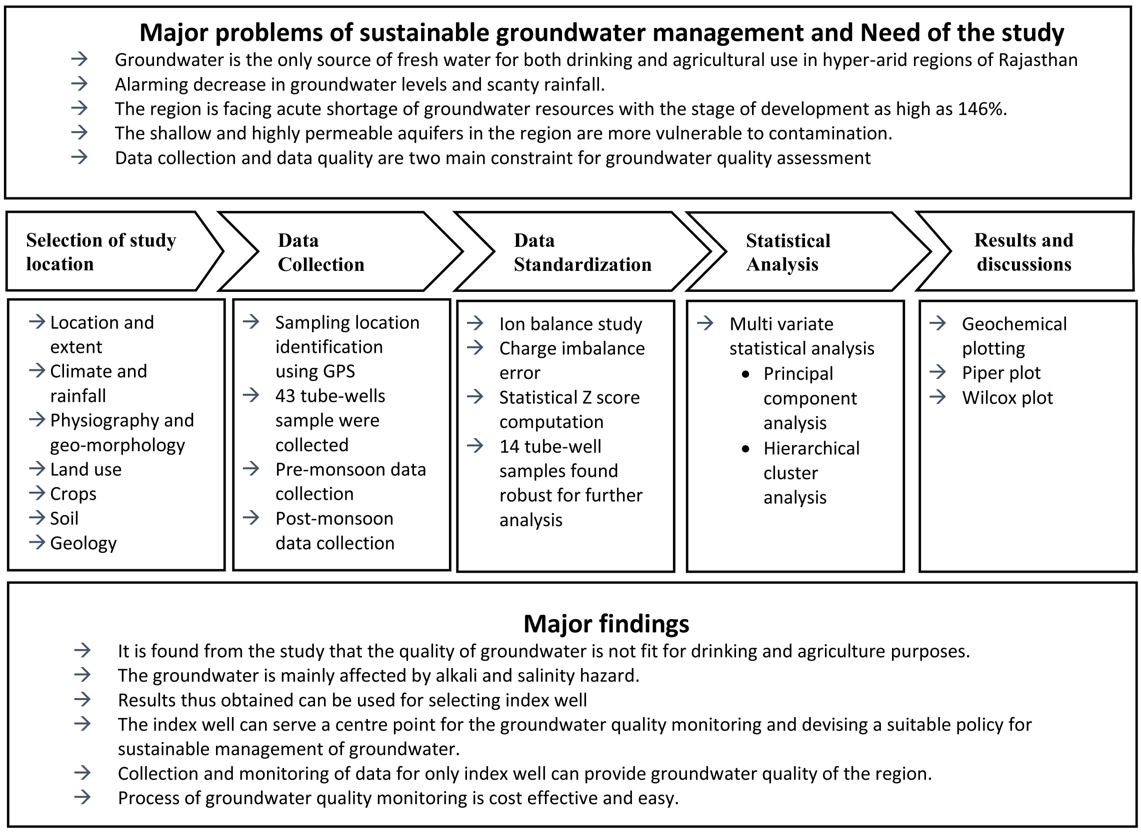

Figure 1. Summary of graphical representation of the present study.

Physiography and Geomorphology

The general regional slope of the block is from SSE to NNW, and regional elevation above MSL is about 152 m in the western part and about 275 m in the eastern part. The block has no major river. Alluvium, Tertiary, and Paleozoic sandstone are the main water-bearing formations in the block. The depth to water in the block ranges between 5 and 136 m below ground level. Based on historical evolution, slope, erosion and depositional characteristics, size and nature of sediments, drainage system and salinity hazards, the existing landforms of the block can be described as flat and gravelly aggraded older alluvial plains.

Land Use

About 35 percent of the total area of the block is cultivated. However, the area sown varies up to 45 percent depending upon rainfall occurrence in a particular season of the year. The percentage of uncultivable land is about 55 percent depending on annual rainfall characteristics, nature of geomorphology, and non-availability of water sources. The forest and pasture lands account for 2.59 percent and 1.77 percent of the total area of the block, respectively.

Geology

The rock formations in the block are mainly concealed beneath a thick cover of dune sand. However, a very few isolated rocks are exposed to the surface. Based on the available literature and lithology of existing dug wells and tube wells in the region, the rock units in the block exist from Paleozoic to Quaternary periods. A generalized geologic succession of the rock formations occurring in the block along with their lithological characters is given in Table 2.

Table 1. Summary of the existing literature on groundwater/surface water quality analysis

S. no.	Author	Contribution	Location	Parameters	Methodology	Region
1	Li et al. (2016)	To provide a clear picture of status and extent of groundwater pollution for the purpose of policy and decision-makers the groundwater quality was assessed	Hua County, China	SAR and RSC	Wilcox and USSL (Statistical and hydrogeochemical plotting)	Arid
2	Maroufpoor et al. (2017)	To predict the spatial distribution of groundwater EC. The study utilized geo-statistic-based Kriging and co-Kriging methods and compared with data-driven ANN and ANFIS models for predicting spatial distribution of groundwater EC	Kerman Province, Iran	EC	ANN and ANFIS	Arid
3	Yang et al. (2016)	To evaluate the hydrogeochemical processes that probably affect the groundwater quality	Ordos basin, China	Cations and anions	Piper trilinear diagram plotting	Arid
4	Hosseinifard and Aminiyan (2015)	To evaluate the factors regulating groundwater quality	Rafsanjan plain, Iran	Major ions, pH, SAR, EC, TDS	Hydrochemistry diagrams	Arid
5	Patel et al. (2016)	To evaluate hydrogeochemical parameters	Andhra Pradesh, India	Major ions, TDS	Piper trilinear diagram plotting, PCA	Arid
6	Marghade et al. (2015)	To assess the spatial controlling processes of groundwater contamination using PCA. The PCA helps as a tool to assess the controlling processes of the groundwater quality	Nagpur, India	Major ions, pH, EC, TDS, TH	PCA	Arid/semi-arid
7	Bhuiyan and Ray (2017)	To identify and demarcate zones and levels of pollution. The study has revealed that groundwater in many parts of the region is unsuitable either for drinking or for irrigation by using a comparison of the obtained values with BIS and WHO	Rajasthan, India	Major ions, pH, EC	GIS	Arid
8	Ma et al. (2014)	To understand the controlling factors of groundwater quality. This work can help to identify the main controlling factor of groundwater quality in North China plain, to make better and more informed decisions for achieving sustainable groundwater development	North China	Major ions, heavy metals	DA and factor analysis	Arid/semi-arid
9	Nazzal et al. (2015)	To map groundwater quality. It is observed that both natural and anthropogenic processes contribute to the groundwater quality, but anthropogenic impacts are more important and result in further deterioration of groundwater quality	Central Saudi Arabia	Major ions, pH, EC	PCA	Arid
10	Bencer et al. (2016)	To highlight the hydro-chemical processes of groundwater	Eastern Algeria	Major ions	CA and PCA	Arid
11	Singh et al. (2017)	To study major hydrogeochemical processes and to decipher the impact of anthropogenic activities using multivariate statistical techniques and conventional graphical plots	Delhi, India	Major ions, EC	PCA, HCA, and DA	Arid/semi-arid
12	Jalali (2012)	To assess the controlling factors of groundwater chemistry	Western Iran	Major ions	PCA, graphical plots, chemical analysis	Arid/semi-arid
13	Brandsegg et al. (2010)	To investigate the structure of variations within highly heterogeneous data	Mid-Norway	Wireline well log data	Structured PCA	–

Table 1. continued

S. no.	Author	Contribution	Location	Parameters	Methodology	Region
14	Praveena et al. (2010)	To evaluate the groundwater quality of unconfined aquifer	East Malaysia	Major ions	Hydro-chemical analysis	–
15	Voudouris et al. (2000)	Assessment of groundwater hydro-chemistry, especially in situations where numerous samples are available	Peloponnese, Greece	Major ions, pH, EC, TDS, TH	Simple and multiple regression, factor, and trend-surface analyses	Semiarid
16	Sheikh et al. (2017)	To infer hydrogeochemical processes	Haryana, India	Major ions	Stable isotopes, GIS, Piper plots	Arid
17	Sharma et al. (2015)	To identify useful pollution indicators of groundwater	Rajasthan, India	Major ions	Factor analysis	Arid
18	Mondal et al. (2016)	To identify major impacting physico-chemical parameters of groundwater quality	Rajasthan, India	Major ions, pH, EC, TDS, TH	Standard hydro-chemical analysis	Semiarid
19	Ahada and Suthar (2017)	To discuss the hydrochemistry of the groundwater	Rajasthan, India	Major ions, pH, EC, TDS, TH	Hydro-chemical analysis, Piper plot	Arid
20	Tiwari et al. (2017)	To provide an overview of the spatial variation of groundwater quality parameters	Rajasthan, India	Major ions, pH, EC, TDS, TH	Hydro-chemical analysis, Piper plot, GIS	Arid
21	Lapworth et al. (2017)	To explore the hydrochemistry of the top 160-m aquifer systems	Northwest India	Major ions, trace elements	Hydro-chemical analysis	Arid
22	Chintalapudi et al. (2017)	To assess the groundwater quality contamination threat around industrial cluster at Rajasthan State Industrial Development and Investment Corporation (RIICO) in Jaipur	Jaipur, Rajasthan, India	Major ions, pH, EC, TDS, TH, SAR	Hydro-chemical analysis, Piper plots, Gibbs plots	Arid
23	Kumar et al. (2016)	To understand the effect of canal recharge on groundwater and subsurface movement of recharge pathways	Bikaner, Rajasthan, India	Major ions, pH, EC	Hydro-chemical analysis	Hyper-arid
24	Singh et al. (2017)	To evaluate the geochemical mechanism of fluoride enrichment in groundwater of western India	Western India	Major ions	Hydro-chemical analysis, X-ray diffraction, geochemical plots	Arid region
25	Vasanthavigar et al. (2010)	To develop a water quality index by understanding hydrogeochemical parameters for Thirumanimuttar sub-basin of Tamilnadu, India	South India	Cations and anions Na, Mg, Ca, K Cl, HCO_3, SO_4	Hydro-chemical analysis, geochemical plots	Tropical Savanna/ semiarid
26	Tirkey et al. (2017)	To identify the groundwater quality status in peri-urban agglomeration of Ranchi City	Northeast India	Cations and anions; heavy metals	Hydro-chemical analysis, water quality index (WQI)	Tropical Savanna
27	Jain and Vaid (2018)	Analyzed water quality parameters to observe the suitability for drinking and irrigation purposes in Nalbari District of Assam	Eastern India	Cations and anions	Hydro-chemical analysis, SAR, USSL diagram, Gibb's scatter diagram	Subtropical humid (dry winter)
28	Vijay et al. (2011)	Assessed and evaluated the deterioration of groundwater quality due to anthropogenic activities in the Puri City, India	Eastern India	Physicochemical and bacteriological	Hydro-chemical analysis, bacteriological analysis, water level fluctuations	Tropical Savanna

Table 1. continued

S. no.	Author	Contribution	Location	Parameters	Methodology	Region
29	Singh and Singh (2018)	Analyzed the groundwater samples for arsenic contamination and also plotted the observation using Piper diagrams for groundwater samples	Northeast India	Major ions, arsenic contamination	Multivariate statistical analysis, geochemical plotting	Subtropical humid (dry winter)
30	Ahamad et al. (2018)	Analyzed the geochemistry of groundwater samples from Varanasi using various geochemical plots such as Gibb's plot and Piper plots	Northern India	Cations and anions	Water quality index, Gibb's plot, and Piper plot	Subtropical humid (dry winter)
31	Srivastava and Ramanathan (2008)	To assess the impacts of landfills on groundwater quality using various hydrogeochemical methods and multivariate statistical tools	Northern India	Major ions and heavy metals	Hydrogeochemical plots, multivariate statistical techniques	Subtropical humid (dry winter)
32	Jasrotia et al. (2018)	To evaluate the groundwater quality parameters to assess the geochemistry of the groundwater in the Western Doon Valley region	Northern India	Cations and anions	Piper's diagram, Expanded Durov diagram, Kelley's ratio index, and permeability index	Subtropical humid (dry winter)
33	Chabukdhara et al. (2017)	Assessed the groundwater quality and health risk associated with it using hydrogeochemical methods and multivariate techniques	Northern India	Heavy metals and major ions	Fuzzy comprehensive assessment (FCA) and PCA	Subtropical humid (dry winter)
34	Arumugam and Elangovan (2009)	To assess the groundwater contamination due to anthropogenic activities using various geochemical plots and various hydrogeochemical methods for Tirupur Region of Coimbatore District, Tamil Nadu, India	South India	Major ions	PCA analysis	Tropical Savanna/ semiarid
35	Avtar et al. (2013)	Conducted a hydro-chemical study in order to establish the suitability of groundwater for drinking, agricultural and industrial purposes	Central India	Major ions	PCA analysis, Piper diagram , and geochemical plotting	Subtropical humid (dry winter)
36	Raju (2007)	Estimated SAR, RSC, permeability index (PI) using Chadha rectangular diagram for geochemical classification and hydro-chemical processes	South India	Major ions	Chadha rectangular diagram, and geochemical plotting	Tropical Savana
37	Singh et al. (2011)	To ascertain the presence of heavy metals in groundwater samples and used Piper and other graphical methods to represent the groundwater geochemistry	Northern India	Major ions	PCA, Piper diagram, and geochemical plotting	Subtropical humid (dry winter)
38	Singh (2010)	The study explains the feasibility of conjunctive use of surface water and groundwater for sustainable irrigation for agricultural crop production	Northwest India	Soil moisture and salinity	Model-based simulation of conjunctive water use, management of saline water	N/A
39	Singh (2014)	Presented an overview of major issues and methods for the conjunctive use of both groundwater and surface water resources for sustainably irrigated agriculture	Widespread	Conjunctive use of water	Review paper	N/A

SAR sodium absorption ratio, *RSC* residual sodium carbonate, *PCA* principal component analysis, *DA* discriminant analysis, *ANFIS* adaptive neuro-fuzzy inference system, *EC* electrical conductivity, *ANN* artificial neural network

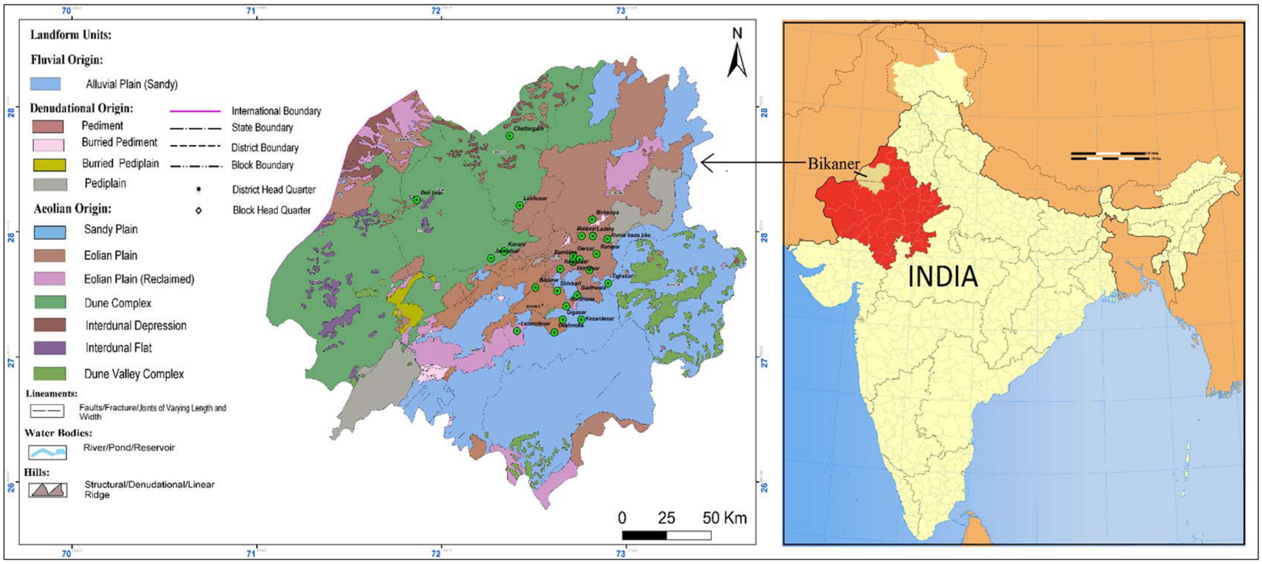

Figure 2. Location of the study area.

Table 2. Geological succession in the Bikaner block

Group	Series	Geological unit	Lithological characteristics	Water-bearing properties
Quaternary	Recent	Windblown sand	Very fine to fine, buff to gray sand, well-rounded to sorted by wind action	Generally lies above the zone of saturation
	Pleistocene	Alluvium	Unconsolidated to loosely consolidated sand, fine to medium, silty clays and Kanker with occasional horizons of gravel sand and coarse sand. Sodium salt and gypsum occur at places. Thickness varies from 4 to 70 m	Yield low to moderate supplies of water. Quality varies from potable to brackish
Tertiary	Eocene	Sandstone	Coarse and gritty sandstone usually semi-unconsolidated, porous with intercalated clays and gravel. Fuller's earth, bentonite, and lignite also occur in this sequence. Its thickness varies from 50 to more than 276 m	Supplies moderate to fair quantity of water to wells. Quality varies from fresh to saline
Paleozoic	Marwar Super Group	Nagaur Sandstone	Hard, compactly consolidated, reddish sandstone. Thickness varies from 140 to 250 m. Interbedded with red shales	Yields low to moderate discharge. Quality of groundwater is fresh to saline
		Bilara Limestone	Limestone, hard, massive. Gray to blackish in color with occasional cavities. Thickness varies from 115 to 225 m	Yields low to moderate discharge. Quality is fresh to saline

MATERIALS AND METHODS

Data Collection and Standardization

Groundwater samples were collected from 43 tube wells located in various villages in the Bikaner block during the pre- and post-monsoon periods in the year 2016. Sampling locations were identified using a global positioning system (GPS) as given in Table 3.

Groundwater samples were collected in polyethylene bottles. The samples were filtered through 0.45-μm membrane filter and split into two portions: one acidified with concentrated HNO_3^- for dissolved cation estimation and the other for rest of the estimations. Electrical conductivity, pH, and total

Table 3. GPS coordinates (longitude, latitude) and average mean sea level of villages

S. no.	Village	GPS location		Mean sea level (m)	S. no.	Village	GPS location		Mean sea level (m)
		Longitude	Latitude				Longitude	Latitude	
1	Bambloo	73.496	28.033	214	2	Shivbari	73.383	27.887	214
3	Bikaner	73.272	27.903	229	4	Surdhana	73.428	27.816	235
5	Chattargarh	73.143	28.610	266	6	Deli Talai	72.673	28.311	181
7	Deshnoke	73.368	27.694	266	8	Gadwala	73.483	27.867	228
9	Gersar	73.463	28.050	210	10	Gigasar	73.410	27.754	265
11	Himtasar	73.462	28.021	206	12	Kavani	73.115	28.071	180
13	Jaimalsar	73.048	28.039	184	14	Kesardesar	73.504	27.754	269
15	Malasar	73.506	28.143	202	16	Ladera	73.562	28.142	203
17	Molaniya	73.559	28.219	201	18	Lakhusar	73.193	28.285	205
19	Nuarangdesar	73.545	27.984	227	20	Lalamdesar	73.179	27.701	273
21	Ranisar	73.581	28.059	215	22	Naggasar	73.398	27.989	208
23	Runiabada bas	73.635	28.129	212	24	Tejrasar	73.640	27.922	172

dissolved solids were measured in the field using portable meters. The samples were stored at 4 °C in the laboratory, and alkalinity, chloride, phosphate, nitrate, and sulfate were estimated as per the standard methods (Clesceri et al. 1998).

The accuracy of estimations was verified by analyzing standard reference materials. The data thus obtained were first of all tested for charge imbalance error, and only 14 samples were found suitable for further analysis. As far as PCA is concerned, Bartlett's sphericity test and Kaiser–Meyer–Olkin (KMO) test were conducted to justify the groundwater sample data and their adequacy. The Bartlett's sphericity test carried out on the correlation matrix shows a calculated χ^2 value of 452.7, which is greater than the critical value as specified in the literature, χ^2 = 146.6 (with Pearson's coefficient (r) = 0.05% and degrees of freedom 91°). Thus, PCA can be applied to the data to achieve significant reduction in the dimensionality of the original dataset.

The initial step to carry out PCA and HCA is to standardize the dataset of all physicochemical water quality parameters, of all water samples. The hydrochemical data were analyzed in the following steps. If $x_i,\ldots,x_p$ denotes the P variables, with N number of observations, the jth observation of the ith variable is X_{ij}, where $i = 1, \ldots, P$ and $j = 1, \ldots, N$. If S and X_m denote the standard deviation and mean, respectively, estimated from N observations of the ith variable, then the jth observation of the ith variable is expressed in the standardized forms as:

$$Z_{ij} = \frac{X_{ij} - X_m}{S_i}, \quad (1)$$

where Z_{ij} is the jth value of the standardized variable Z_i. The value of Z_i is called as z-score (Liu et al. 2003). For PCA and HCA in this study, the data were first standardized by computing z-scores from the non-normal condition and ascertaining the normal distribution of the data. The mean and variance of z-score were found to be 'zero' and 'one,' respectively, for all variables. Standardization of data enhances the impact of variables having small variance and decreases the impact of variables with large variance. Further, standardization of data nullifies the impact of units of measurement and makes the data dimensionless.

Principal Component Analysis

In this study, PCA was applied to extract significant principal components (PCs) and the values thus obtained were subjected to varimax rotation analysis for generating varifactors (VFs). Principal components are linear combinations of original variables. The aim of PCA is to dimensionally reduce the contribution of the variable of less importance as compared to another variable in the water quality dataset. The variance of data obtained in the analysis helps to identify the most contributing variable in the dataset (Shrestha and Kazama 2007). The PCs so obtained lie along the directions of maximum variance. Three principal components were retained, following the criteria which suggest using all the PCs up to and including the first one after the break, with eigenvalues more than unity and describing percent of the variance in the original dataset (Cattell and Jaspers 1967). If the eigenvalue of a PC is more than unity, then it provides more useful information about the underlying facts and impact of contribution, thus ensuring the reduction in dimensionality (Cattell and Jaspers 1967). Along with obtaining PCs, PCA provides a correlation matrix that describes the relationship of each parameter with one another.

Hierarchical Cluster Analysis

In the present study, HCA was applied to identify the relatively homogenous groups of cases or variables based on their intrinsic properties. In HCA, clusters are generated successively starting with the most alike pairs of variables and generating greater clusters progressively. Cluster analysis is the task of combining a set of variables in a way that the variables in the group known as cluster show much more similarity with one another than those variables in other clusters. The outcomes of HCA help in understanding the data and designating the patterns (Singh et al. 2005a, b). The HCA was applied to the standardized dataset by deploying Ward's method using Euclidean distance as a degree of resemblance.

RESULTS

Principal Component Analysis

The PCA was carried out to assess water quality by evaluating the chemical associations as described by principal component loadings and using a dataset consisting 14 groundwater samples from Bikaner block. The first three PCs were selected by adopting the correlation criteria as described in Table 4, to represent the prevailing hydrogeochemical phenomenon described in Figure 3, which helped in the formation of the present groundwater chemistry without losing the information of interest. The output of PCA reveals that the eigenvalues of the first three PCs together account for over 87% of the total variability of the combined population for pre-monsoon and over 85% for post-monsoon (Tables 5 and 6, respectively).

Table 4. Correlation criteria

Eigen values	Correlation
0–0.29	Negligible
0.3–0.49	Low
0.5–0.69	Moderate
0.7–0.89	High
0.9–1.00	Very high

For the pre-monsoon data, the first principal component (PC1) after varimax rotation accounts for more than 63% of the total variance (Table 7a) and has very high loadings on TDS, Na^+, K^+, and NO_3^- and significant/high loadings on EC, Mg^{++}, F^-, SO_4^-, and TH. For the post-monsoon data, the PC1 has very high loadings on EC, TDS, Na^+, Mg^{++}, Cl^-, and TH and significant/high loadings on Ca^{++} and SO_4^- (Table 7b). For the pre-monsoon data, the second principal component (PC2) after varimax rotation, which accounts for more than 16% of the total variance, has very high loading on pH and significant/high loading on Ca^{++}. For the post-monsoon data, PC2 has significant/high loadings on K. For the pre-monsoon data, the third principal component (PC3) after varimax rotation, which accounts for more than 7% of the total variance, has significant/high loadings on HCO_3^-, whereas for the post-monsoon data, the PC3 has very high loading on CO_3^- and significant/high loading on HCO_3^-.

The major contributor of Ca^{++} seems to be gypsum, dolomite, and limestone, which occur in the sedimentary basin of the area. Water in contact with gypsum can attain higher calcium contents, and solubility of gypsum increases in saline waters. Principal sources of Na^+ could be the precipitate of sodium salts impregnating the soil in shallow water tracts, particularly in arid and semiarid regions. Certain clay minerals and zeolites may contribute to the sodium content in groundwater (Karanth 1987). The primary source of carbonate and bicarbonates in the present samples could be due to higher pH values of the samples ranging in between 4.5 and 8.2 and above 8.2. The presence of bicarbonate is indicated when pH is between 4.5 and 8.2 and carbonate if pH above 8.2 (Karanth 1987). The important contributor of sulfate in present samples seems to be gypsum and anhydrite found in the sedimentary rocks of the reason. Local abnormal concentrations of sulfate may be due to traversing of groundwater through lignite, coal, and gypsiferous beds. In sedimentary rocks, dolomite and limestone contain magnesium carbonates that seem to be the major contributor of magnesium in the water samples (Karanth 1987). A solution of halite and other evaporite deposits in the aquifer material are the primary sources of chloride in the present case along

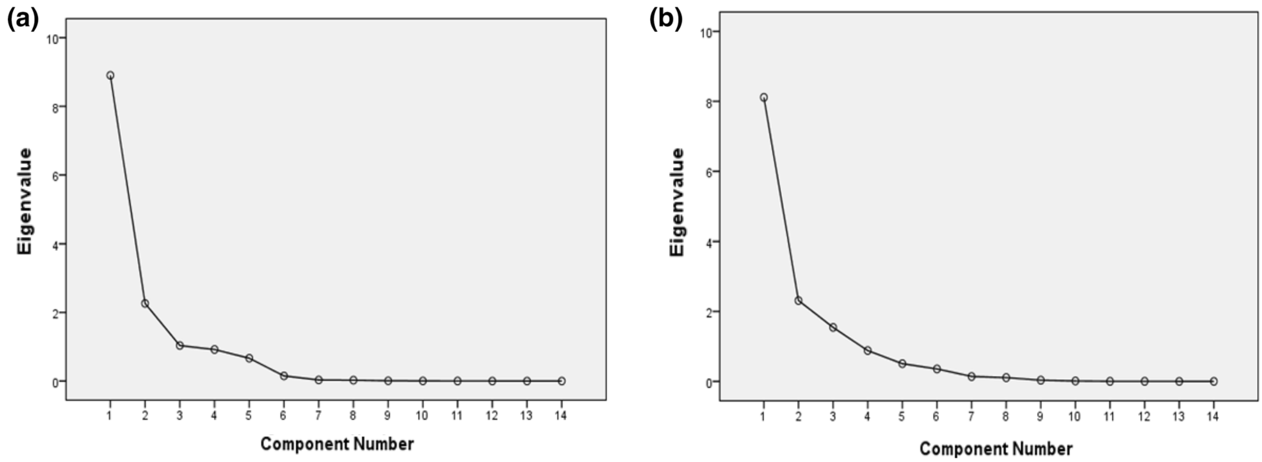

Figure 3. Scree plots for (**a**) pre-monsoon data and (**b**) post-monsoon data.

Table 5. Total variance explained by the pre-monsoon data

Total variance explained pre-monsoon									
Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
PC 1	8.904	63.596	63.596	8.904	63.596	63.596	7.514	53.673	53.673
PC 2	2.262	16.158	79.755	2.262	16.158	79.755	2.720	19.427	73.100
PC 3	1.035	7.394	87.149	1.035	7.394	87.149	1.967	14.049	87.149

Table 6. Total variance explained by the post-monsoon data

Total variance explained post-monsoon									
Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
PC 1	8.115	57.961	57.961	8.115	57.961	57.961	7.588	54.199	54.199
PC 2	2.311	16.509	74.470	2.311	16.509	74.470	2.367	16.907	71.106
PC 3	1.544	11.026	85.497	1.544	11.026	85.497	2.015	14.391	85.497

with atmospheric sources. Fluoride in the water samples seems to be derived from certain amphiboles, mica, and complex fluoride-bearing silicates (Karanth 1987). By far the greatest contribution of nitrate in groundwater may be from the excessive use of fertilizers and dung of field grazing cattle such as cow, sheep, and goat in the study area. As the area is a hyper-arid zone, mineralization and concentration of ions by evaporation (Jalali 2012; Marghade et al. 2015; Yang et al. 2016; Singh et al. 2017) may result in higher values of TDS in the samples.

Hierarchical Cluster Analysis

On the basis of similar hydrogeochemical features and sources of natural background, HCA effectively reproduced three clusters in pre-monsoon water samples and four clusters in post-mon-

Table 7. Rotated components for (a) pre-monsoon data and (b) post-monsoon data

Variable	PC 1	PC 2	PC 3	Variable	PC 1	PC 2	PC 3
(a) Rotated component pre-monsoon				*(b) Rotated component post-monsoon*			
NO3	.945	− .115	− .264	TDS	.980	.154	− .003
TDS	.942	.236	.186	EC	.978	.125	.047
K	.941	− .004	− .217	Mg	.950	.058	− .018
Na	.927	.131	.203	Na	.945	.053	− .029
EC	.889	.256	.302	Cl	.927	.054	− .137
SO4	.875	.391	.122	TH	.911	.323	− .093
F	.794	.178	− .114	SO4	.894	.354	− .116
Mg	.792	.483	.353	Ca	.818	.377	− .019
TH	.700	.592	.381	NO3	.688	− .081	.371
Cl	.622	.397	.577	K	− .055	.865	.350
pH	− .120	− .917	.172	F	.247	.802	.042
Ca	.529	.717	.399	pH	− .371	− .580	.481
CO3	.068	− .535	− .480	CO3	− .104	.029	.947
HCO3	.047	.031	− .795	HCO3	.175	.459	.761

Table 8. Distribution of groundwater sample sites in different cluster

Pre-monsoon		Post-monsoon	
Cluster	Sites	Cluster	Sites
1	Bikaner, Malasar, Molaniya, Shivbari, Gersar, Ranisar, Runia Bas, Surdhana, Bambloo, Deshnoke, Naurangdesar	1	Chattargarh, Kavani
2	Chattargarh	2	Tejrasar, Gigasar, Gadwala, Kesar Desar Jatan, Bambloo, Molaniya, Deshnoke, Ladera, Deli Talai, Lalamdesar
3	Himtasar, Jaimalsar	3	Jaimalsar
		4	Lakhusar, Naggasar

soon water samples. The details of the produced clusters are given in Table 8. The nearby locations of the water sample sites primarily fall in the same cluster due to the orderly and appropriate involvement of sampling sites in the development of cluster. The clustering of water samples in both pre- and post-monsoon shows that groundwater quality varies smoothly with a few gradual changes over the entire block. This variation may be due to the equally prevailing hydrogeological environment in the area. The dendrograms for both pre- and post-monsoon (Figs. 4 and 5, respectively) show a clear picture of the spatial similarity occurring among the water samples in the area under consideration.

The branching-type nature of the dendrograms allows to trace backward or forward to any individual case or cluster at any level. In our case, if we examine the dendrogram for pre-monsoon, it is very clear that samples from Bikaner, Malasar, Molaniya, Shivbari, Gersar, Ranisar, Runia Bas, Surdhana, Bambloo, Deshnoke, and Naurangdesar villages are very similar, whereas in another cluster, samples from Himtasar and Jaimalsar villages are very similar. Further, we can extract sub-clusters from the picture shown in Figure 4. From the dendrogram for post-monsoon, it is very clear that samples from Chattargarh and Kavani villages are very similar, whereas in another cluster samples from Tejrasar, Gigasar, Gadwala, Kesardesar Jatan, Bambloo, Molaniya, Deshnoke, Ladera, Deli Talai, and Lalamdesar villages are very similar. Further, we can extract sub-clusters from the picture shown in Figure 5. To develop an effective groundwater quality monitoring system in the block, HCA offers a reliable classification of groundwater by selecting representative wells within a cluster that will help in formulating well-suited policy to spatially monitor groundwater quality. This will also help to signifi-

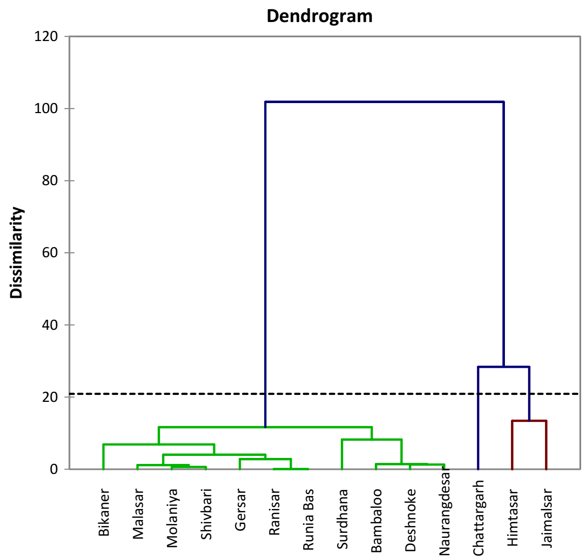

Figure 4. Dendrogram using Ward's method for pre-monsoon data.

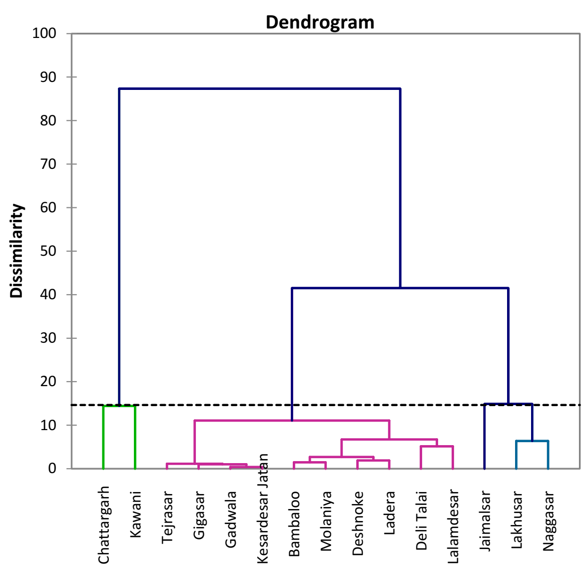

Figure 5. Dendrogram using Ward's method for post-monsoon data.

cantly reduce number of sampling sites as well as monitoring cost.

Hydrogeochemical Plotting of Water Samples

The Bikaner block's groundwater is the only source of water for domestic and agricultural purposes; groundwater quality of the block has also been evaluated by the use of geochemical plots, such as Piper diagram (Piper 1944) and Wilcox plot (Wilcox 1955). These graphical representations of groundwater quality data help to visualize the status of the prevailing groundwater quality in the block. A Piper diagram basically helps to make several conclusions about water type, precipitation or solution, mixing, and ion exchange. This diagram developed by Piper (1944) is a combination of anion and cation triangles with an intervening diamond. In the lower left triangle, values of three cations (Ca^{++}, Mg^{++}, Na^{+}) are plotted, whereas in the lower right triangle three anions (HCO_3^-, SO_4^-, Cl^-) are plotted, and the central diamond is used to show the overall chemical character of water. On the basis of placement of samples near the four corners of the diamond, water can be classified into four basic categories. Water samples that plot near the top of the diamond are high in $Ca^{++} + Mg^{++}$ and $Cl^- + SO_4^-$ and are characterized by permanent hardness. Water samples that plot near the left corner are rich in $Ca^{++} + Mg^{++}$ and HCO_3^- and are characterized by temporary hardness. In the lower corner, water samples are basically comprised of alkali carbonates ($Na^+ + K^+$ and $HCO_3^- + CO_3^-$), whereas in the right side of the diamond, water samples are categorized as saline water types ($Na^+ + K^+$ and $Cl^- + SO_4^-$).

The prime use of Wilcox plots is to categorize water samples for irrigational use and to classify water quality, so that the seasonal effects on water quality could be visualized. The Wilcox diagram is plotted with EC as abscissa and sodium absorption ratio (SAR) as ordinate. The Wilcox diagram explicitly depicts the two important aspects of water quality named as salinity hazard and sodium (alkali) hazard. The diagram in terms of salinity deduces the water samples as low-salinity (C1), medium-salinity (C2), high-salinity (C3), and very-high-salinity water (C4). In terms of alkali hazard, the water samples can be deduced as low-sodium (S1), medium-sodium (S2), high-sodium (S3), and very-high-sodium water (S4).

According to Wilcox (1955), water sample with SAR value up to 10 and EC up to 250 can be considered as S1 water. If the SAR value lies between 10 and 18 and EC value lies between 250 and 750, then it is considered as S2 water. Further, a SAR value up to 26 and EC value up to 2250 defines S3 water. Water with more than 26 SAR and more than 2600 EC can be defined as an S4 type. The various

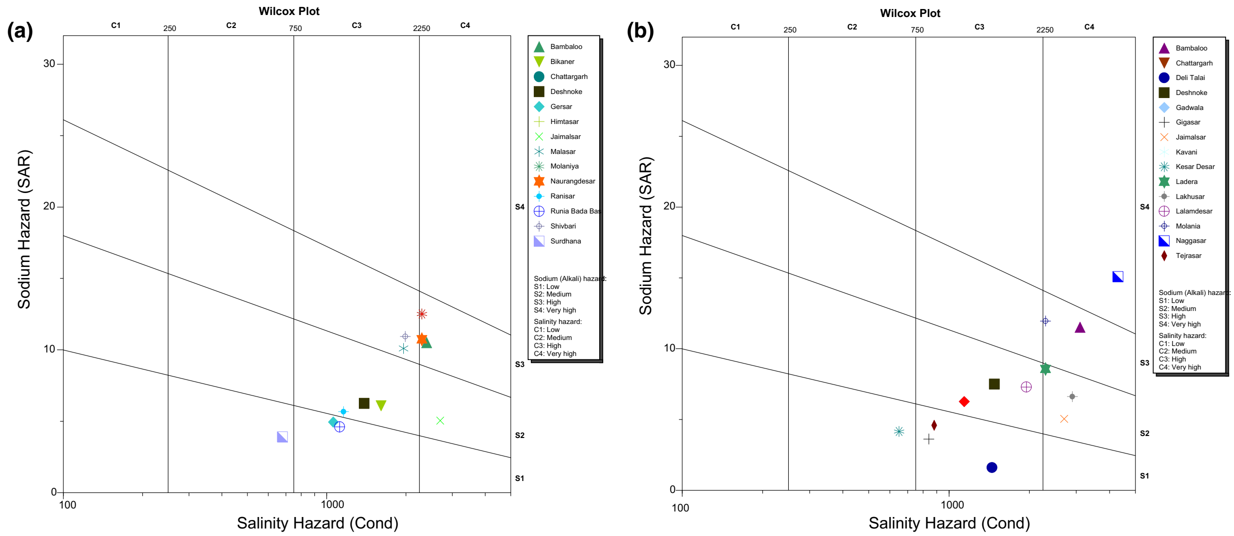

Figure 6. Wilcox plots for (**a**) pre-monsoon data and (**b**) post-monsoon data water samples.

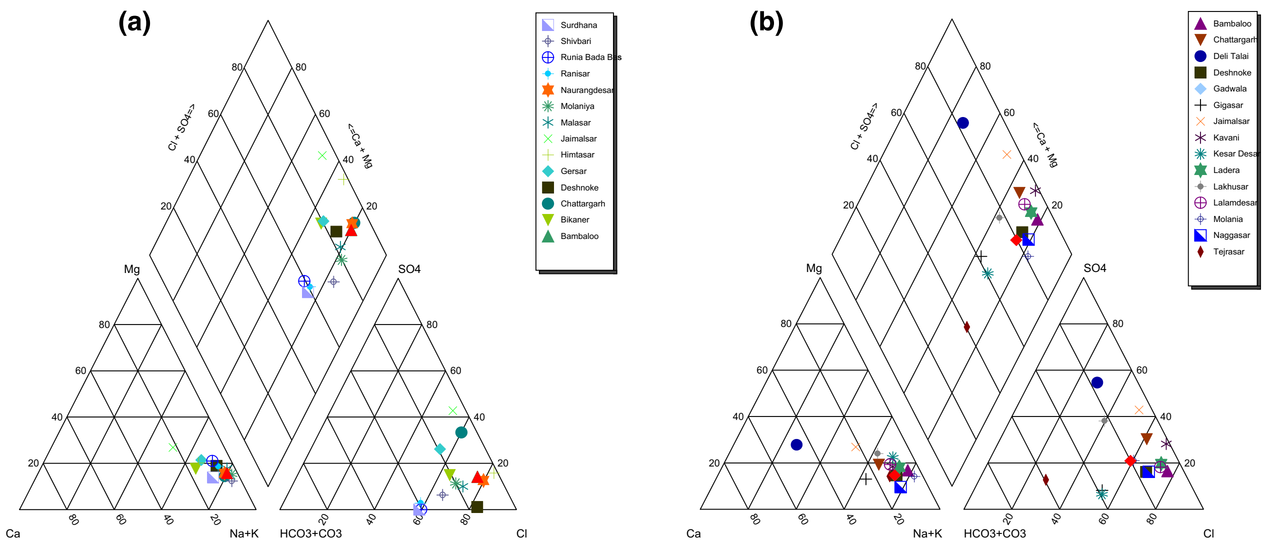

Figure 7. Piper plots for (**a**) pre-monsoon data and (**b**) post-monsoon data water samples.

physicochemical parameters analyzed in this study were plotted in a Wilcox (Fig. 6) and Piper (Fig. 7) diagrams, and the results are tabulated in Table 9. The Wilcox plot clearly shows high salinity hazard in the block and medium-to-high alkali hazard in the majority of the block. Approximately 42% of the samples are under very high salinity hazard, 46% high salinity hazard, and rest moderate salinity hazard. In the same manner, 33% of the samples are under high alkali hazard, 38% medium alkali hazard, and the rest low alkali hazard.

Considering the Piper diagram, Na^{+} and Mg^{++} are the dominant cations, whereas Cl^{-} and SO_4^{-} are the dominant anions in the respective left and right triangles of the diagram. This indicates that majority of the water samples falls under the category of saline water. Majority (37.5%) of groundwater samples are Na^{+}–Cl^{-} water type and $\sim$ 33% of the

Table 9. Water quality status of the study area

S. no.	Village	Hazard		Water type	S. no.	Village	Hazard		Water type
		Salinity	Alkali				Salinity	Alkali	
1	Bambloo	Very high	High	Na–Cl	13	Shivbari	High	High	Na–Cl
2	Bikaner	High	Medium	Na–Cl	14	Surdhana	Medium	Low	Na–Cl–CO_3
3	Chattargarh	Very high	High	Na–Cl–NO_3–SO_4	15	Deli Talai	High	Low	Ca–Mg–Na–SO_4–Cl
4	Deshnoke	High	Medium	Na–Cl	16	Gadwala	High	Medium	Na–Cl
5	Gersar	High	Low	Na–Mg–Cl–SO_4	17	Gigasar	High	Low	Na–Ca–Cl–HCO_3
6	Himtasar	Very high	High	Na–Mg–Cl	18	Kavani	Very high	Medium	Na–Cl–SO_4
7	Jaimalsar	Very high	Medium	Na–Mg–Ca–Cl–SO_4	19	Kesardesar	Medium	Low	Na–Mg–Cl–HCO_3
8	Malasar	High	High	Na–Cl	20	Ladera	Very high	Medium	Na–Cl
9	Molaniya	Very high	High	Na–Cl–NO_3	21	Lakhusar	Very high	Medium	Na–Mg–Cl–SO_4
10	Nuarangdesar	Very high	High	Na–Cl	22	Lalamdesar	High	Medium	Na–Mg–Cl
11	Ranisar	High	Medium	Na–Cl–HCO_3	23	Naggasar	Very high	Very high	Na–Cl
12	Runiabada bas	Low	High	Na–Cl–HCO_3	24	Tejrasar	High	Low	Na–Cl–HCO_3

samples represent alkali carbonates and remaining 29% are a mixed type (Table 9) for both pre- and post-monsoon samples.

DISCUSSION

The methodology described in this study can assist the research community to include the hydrogeochemical information from the analysis of semiarid and arid region aquifer systems. The methodology used in this study allows the successful outcomes of each method accommodating all information to generate a robust interpretation by incorporating the strength of various geochemical, statistical, and spatial grouping tools. Therefore, optimal groundwater extraction, integrated groundwater management, and checked use of fertilizer and pesticides for crops are desired to ensure acceptable groundwater quality in the study area. The race toward livelihood resilience can explain why groundwater is overexploited by end users. In the last few decades, several problems have arisen from the evolution of groundwater for irrigation purposes in developing nations of Asia and Africa (Shah 2005). The contamination of groundwater and its quality degradation affect the farmers in terms of crop choice and availability of potable drinking water (Ranjan 2012). This calls for identification of alternate solutions for drinking water in problem areas. In addition, the filtration system commonly used in households of India is not efficient. They discard 75% of water supplied for purification and only 25% is used for drinking purpose (Bhakar et al. 2016). This makes fewer choices available to the end users for satisfying their daily needs of livelihood. Singh (2014) claimed that the conjunctive use of surface water and groundwater can be a better option for sustainable irrigation system. When it comes to hyper-arid regions where groundwater availability is much lower, groundwater quality assessment of aquifer systems can support decision-making for developing sustainable groundwater policies. The use of remote sensing in combination with multivariate statistical tools or artificial intelligence techniques can provide better possibilities to assess and monitor the quality of large samples of water. Such methodology can also work to remove uncertainties in the analysis of data (Swain and Sahoo 2017).

CONCLUSIONS

The various physicochemical parameters in the hydro-chemical datasets from the study area were analyzed using multivariate statistical methods to identify contributing variables and spatial similarity between the groundwater samples. By PCA, three significant principal components were extracted explaining 87% of the total variability of the combined population for pre-monsoon data and 85% for post-monsoon data. The major variations in the datasets are due to the solubility of gypsum, a precipitate of sodium salts impregnating the soil, higher pH values, excessive use of fertilizers, dung of field grazing cattle, concentration of ions by evaporation, and weathering of the rocks. On the other hand, HCA played a key role in identifying the spatial similarity between the groundwater samples from the study area. The clusters generated can be utilized in order to select a representative well from spatially similar clusters to achieve effective groundwater quality monitoring in the area under consideration. It can be concluded from the graphical plots of groundwater quality data that groundwater sources in the Bikaner block are affected by alkali hazards and salinity, and therefore are not suitable for drinking and irrigation purposes. The outcomes of the present study can be used by practitioners and policymakers for development and implementation of strict groundwater management policies for sustainable management of this natural resource. The study is limited to a small area for groundwater quality assessment; however, the tools used for the assessment have capabilities to assess large regions/areas as well. In future, time series analysis of data can be carried out to have a wider picture of groundwater quality. Along with multivariate statistical tools, remote sensing technique can also play a vital role in managing groundwater resources. Using remote sensing for assessment of groundwater quality can be a future scope of this study in the Bikaner block.

ACKNOWLEDGMENTS

The authors express their gratitude to the State Ground Water Board, Government of Rajasthan, for providing valuable inputs and support to carry out the study. Authors are extremely thankful to the Editor-in-Chief, anonymous reviewers, and production team, for excellent support from receipt of manuscript till final publication. We are greatly thankful to the reviewers for providing valuable and timely input, which helped us to improve the quality of paper significantly.

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