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ORIGINAL PAPER

Quality criteria for groundwater use from a rural part of Wanaparthy District, Telangana State, India, through ionic spatial distribution (ISD), entropy water quality index (EWQI) and principal component analysis (PCA)

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Abstract The present study region comprises granite and granite gneisses aquifer system constituted by Precambrian rocks. Groundwater is the primary source for drinking and other domestic purposes. Many developing regions in the world suffer from lack of safe drinking water. A rural part of Wanaparthy District in Telangana State, India, is one of them. For this reason, the groundwater samples collected from the study region were analyzed for pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- and F^- and evaluated groundwater quality criteria, using ionic spatial distribution (ISD), entropy water quality index (EWQI) and principal component analysis (PCA). The ISD maps show that some locations are not suitable for drinking purpose due to exceeding concentrations of TDS, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, $NO_3^-$and F^-, compared to those with national drinking water quality standards. According to the EWQI, about 3%, 47%, 43% and 7% of the total area come under the excellent, good, medium and extremely poor water quality types for drinking purpose, respectively. Chadha's diagram classified the area as carbonate hardness (63%), non-carbonate alkali (17%), carbonates alkali (13%) and non-carbonate hardness (7%) zones. The binary diagrams ($Na^+ + K^+$ vs TC, Na^+ vs Ca^{2+} and HCO_3^- vs TC) indicate that the quality of groundwater is controlled by influences of water–rock interactions, mineral weathering and dissolution, ion exchange and evaporation as well as the impact of anthropogenic sources. The PCA transferred the chemical variables into three principal components accounts for about 81% of the total variance. The high positive loadings of PC1 (Cl^-, TDS, SO_4^{2-}, Na^+, NO_3^-, Mg^{2+} and HCO_3^-) stand for processes of silicate weathering and dissolution, ion exchange and evaporation, and the influence of domestic waste waters, irrigation return flows and chemical fertilizers on the groundwater system, the PC2 (F^- and pH) signifies the alkaline nature of groundwater, which causes fluorosis, and the PC3 (K^+) is a result of potassium fertilizers. The study helps to take remediate measures at a specific site and hence suggests the treatment of water before its drinking and also the recharge of the aquifer artificially to improve the groundwater quality.

Keywords Groundwater quality · Ionic spatial distribution · Entropy water quality index ·

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Hydrogeochemical processes · Principal component analysis

Introduction

Especially in hard rock terrain aquifers, ions from the soil and weathered rocks are dispersed into the groundwater during soil–water–rock interactions (Subba Rao et al. 2017a). Hence, it is an imperative to study the processes controlling the chemistry of groundwater (Perrin et al. 2011; Ehya and Saeedi 2018; Subba Rao et al. 2018; Barakat et al. 2019). On the other hand, the availability of groundwater for drinking in many parts of the world is a problem due to not only over-exploitation of groundwater, but also contamination of groundwater (Subba Rao 2012; Bouderbala et al. 2016; Al-Abadi 2017; Adimalla et al. 2018a; Adimalla 2019a, b; Subba Rao and Chaudhary 2019; Subba Rao et al. 2019).

About 90% of the rural India's drinking water comes from the groundwater resources (Adimalla et al. 2018a; Verma et al. 2018). Human interferences can contaminate the groundwater body (Subba Rao et al. 2017a, 2019). Consuming safe drinking water is a basic human right. However, the continuous usage of poor chemical quality of water for drinking leads to various health hazards (Mgbenu and Egbueri 2019; Wang et al. 2019). That's why, the public awareness on quality of water is being increased everywhere due to its direct affect the human health. Geographic Information System (GIS) and Surfer software's are being used to generate the spatial distribution maps for understanding and identifying the groundwater vulnerable zones (Ramachandran et al. 2012; Duraisamy et al. 2019; Verma et al. 2018). Entropy water quality index (EWQI) method was applied in various studies to assess the groundwater quality for various purposes (Adimalla et al. 2018a; Hamlat and Guidoum 2018).

The researchers in recent years are mainly concentrated to identify the groundwater suitability and its contamination sources all over the world. For instance, Singh et al. (2017) studied the groundwater quality investigations in New Delhi, India, and observed that the hydrogeochemical process (water–rock interactions, weathering, ion exchange and evaporation) and anthropogenic activities (domestic wastes) deteriorate the groundwater quality. A survey on quality of groundwater was carried out by Subba Rao et al. (2017a) for assessing the geochemical characteristics and controlling factors of chemical composition of groundwater in a part of Guntur district, Andhra Pradesh, India, using graphical and binary diagrams, principal component analysis and geochemical modeling, and stated that the composition of groundwater is mainly controlled by geogenic processes (rock weathering, mineral dissolution, ion exchange and evaporation) and anthropogenic sources (irrigation return flows, wastewaters, agrochemicals and constructional activities). Abboud (2018) assessed the geochemistry and quality of groundwater of the Yarmouk basin aquifer, north Jordan, and found that the mineral dissolution mechanism under the alkaline conditions releases ions into the groundwater for enrichment and anthropogenic sources are also the main reasons for contamination of groundwater. Further, the study shows that the some groundwater samples are unsuitable for drinking and irrigation purposes. Aminiyan (2018) evaluated the multiple water quality indices for drinking and irrigation purposes for the Karoon River, Iran, and observed that the most dominant water type belongs to sodium and chloride type and the water quality indices demonstrate a decline in water quality. An and Lu (2018) examined the hydrogeochemical processes and the causes of groundwater pollution in the northern Ordos Cretaceous Basin, China, and the results show that the leaching, evaporation and condensation, mixing and anthropogenic activities are the dominant factors to control the groundwater chemistry and the landfill leachate, domestic sewage and other organic pollutants, excessive use of pesticides and fertilizers are the secondary sources of groundwater pollution. Duraisamy et al. (2019) evaluated the hydrogeochemical characteristics of groundwater and its suitability for drinking water supply in Kangayam Taluk, Tirupur District, Tamil Nadu, India, and demarcated the groundwater quality zones for drinking purpose. Khound and Bhattacharyya (2019) studied the groundwater quality, using multivariate statistical techniques, for identification of pollution sources and also for assessment of spatial variations in water quality in the north Brahmaputra plain, India. Rezaei and Hassani (2018) studied the chemistry and quality of groundwater in the north of Isfahan, Iran, and assessed that the chemical weathering of rock-forming minerals is the main factor controlling the water chemistry, using correlation matrix and principal component analysis, and the quality of water is suitable for drinking and irrigation purposes. Adimalla (2019b) studied the controlling factors and mechanism of groundwater quality variation in semiarid region of South India and found that the weathering of rocks and dissolution of fluoride-bearing minerals and anthropogenic sources are the major reasons for deterioration of groundwater quality and also observed the hazard risk. Chitsazan et al. (2019) assessed the hydrochemical processes, quality change and groundwater pollution in the suburban area of Urmia City, Iran, and found that the mineral weathering, ion exchange and anthropogenic activity (domestic wastes and chemical fertilizers) lead to groundwater contamination. Khanoranga and Khalid (2019) studied the groundwater quality in an arid region of Balochistan Province, Pakistan, using multivariate statistical approaches, and the results show the contribution of both natural and anthropogenic activities in altering the hydrochemistry of the groundwater. In a study, Sajil Kumar and James (2019) applied the geostatistical and geochemical models to distinguish the groundwater quality flow pattern and also to identify the vulnerable spatial variations in the Coimbatore District, South India. Subba Rao and Chaudhary (2019) studied the groundwater quality from an area of Visakhapatnam, Andhra Pradesh, India, and evaluated the controlling processes of groundwater chemistry spatially, depending upon the geogenic processes and the anthropogenic activities, which lead to groundwater contamination.

From the literature, it is concluded that the evaluation of groundwater quality is essential, as it is directly related to human health and also provides baseline information for establishment of long-term groundwater monitoring programs for sustainable development of any area. Since the quality of groundwater in rural parts of Wanaparthy District, Telangana State, India (Fig. 1) is not potable in general, a part of the district is chosen for this purpose. Therefore, the objectivities of the present study are (1) to delineate the spatial distribution of various chemical variables on the basis of national drinking water quality standards, (2) to classify the area into groundwater quality types on the basis of entropy water quality index (EWQI) for drinking purpose and (3) to assess the hydrogeochemical processes controlling the groundwater quality, using Chadha's and binary diagrams, and principal component analysis. The outcome of the present study helps the local residents and also the decision makers for taking the protection and management of groundwater resources at a specific site.

Study region

The study region located in Wanaparthy District, Telangana State, India (Fig. 1) experiences a semiarid climate. The average annual temperature varies from 16.9 °C in winter to 41.5 °C in summer. The average annual rainfall is 605 mm. Southwest monsoon contributes 61% of the total rainfall. The River Sarala vagu draining through the region shows sub-dendritic type (Fig. 2).

Sandy soils, black cotton soils and sandy loamy soils are the important soil types. Calcium carbonate concretions occur in the soil zone. The study area is underlain by Precambrian rocks (Fig. 3). The rocks include granite and granite gneiss with dykes, pegmatites and quartzite veins, which are medium to coarse grained and equigranular in texture. They are composed of quartz, plagioclase and potash feldspars, apatite, biotite and hornblende. The rocks show N–S or E–W direction, with a deviation toward the E–W, NW–SE and NE–SW with a dip of 55°–70° southeast. The soils and alluvium occur over the basement rocks.

Groundwater is extracted through dug wells and bore wells. Groundwater occurs under unconfined conditions in the weathered rocks and under semi-confined conditions in the fractured rock portions. The depth to groundwater level varies from 5.1 to 19.5 m bgl (Table 1). Comparatively, the shallow depth to groundwater level is observed at low-lying areas and the deep depth to groundwater level at topographic highs. The yields of the wells range between 250 and 350 cubic meter per day (m^3/day; CGWB 2013).

About 49% of the study region is occupied by agricultural land, 44% by waste land, 4% by built-up land and 3% by water bodies. Agriculture is the main occupation of the people. Irrigation practice is intensive and time-consuming. Agrochemicals are used for improvement in soil permeability and also for higher crop yields. The important crops grown are cotton, chilly, paddy, pulses and millets. Dumping of wastes

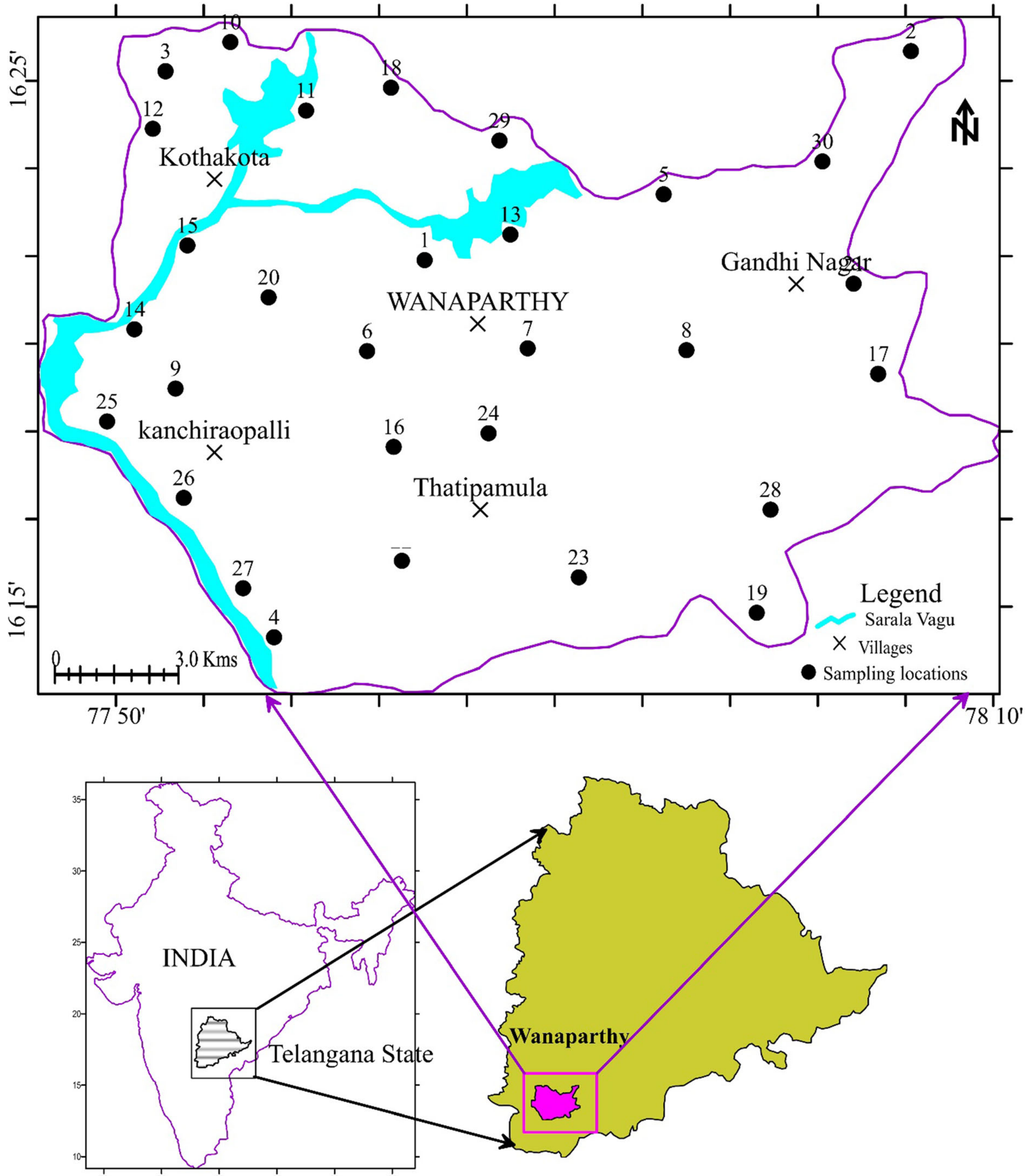


Fig. 1 Location of the study region in Wanaparthy District, Telangana State, India

on empty places, leakage of drainage channels and septic tanks are very common.

Methodology

Groundwater samples were collected from 30 locations during summer (May) 2015 (Fig. 1), following

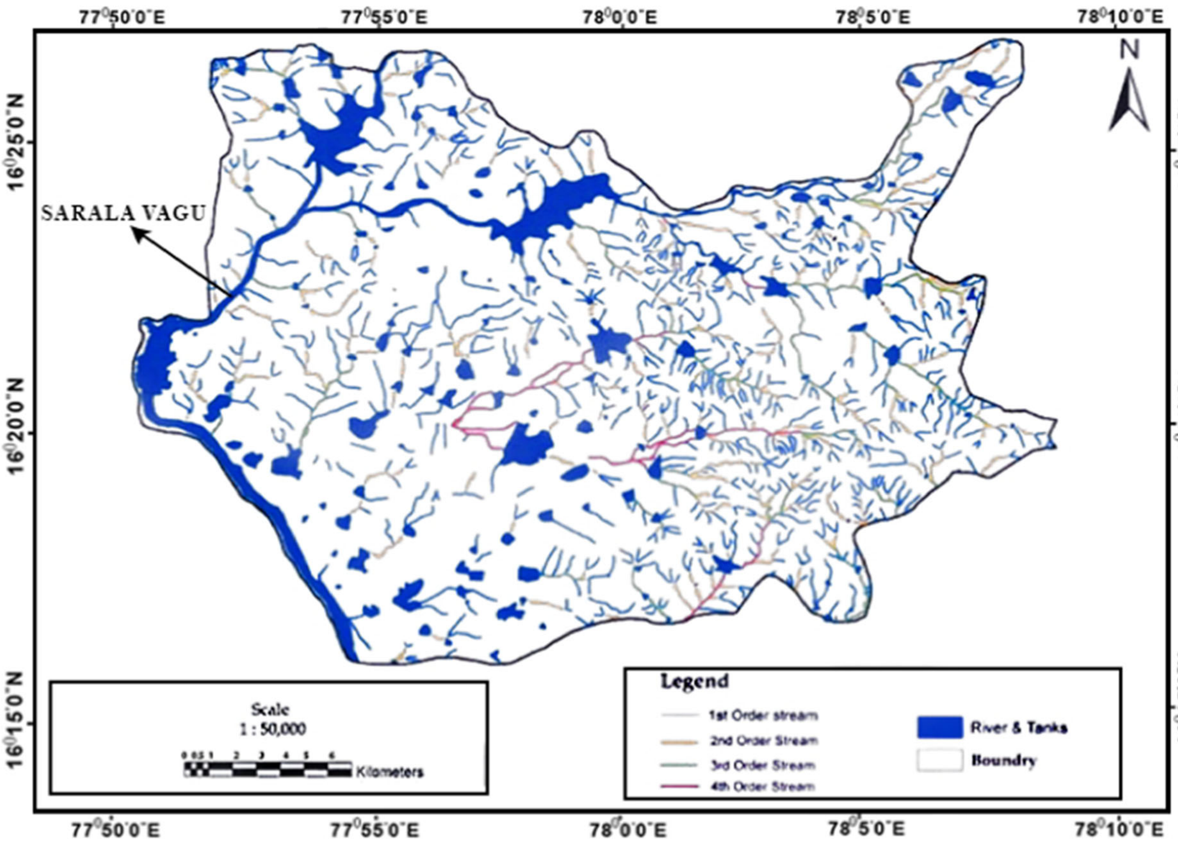


Fig. 2 Drainage map of the study region

Fig. 3 Geology of the study region (after CGWB 2013)

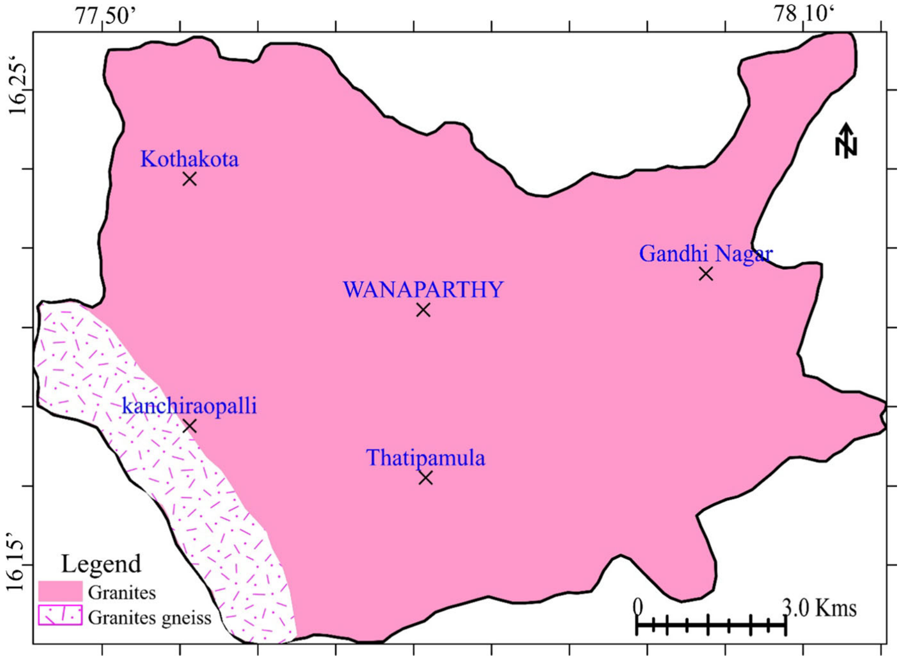


Table 1 Chemical composition of groundwater

Sample numbers	pH units	TDS mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	Na^{+} mg/L	K^{+} mg/L	HCO_3^- mg/L	Cl^- mg/L	SO_4^{2-} mg/L	NO_3^- mg/L	F^- mg/L	DGWL (m bgl)
WGW-1	8.6	354	34	34	65	6	200	22	28	12.00	2.20	15.6
WGW-2	8.5	400	18	44	60	6	88	50	36	6.00	2.30	17.3
WGW-3	7.2	350	28	39	55	1	130	30	27	0.10	0.63	11.9
WGW-4	7.8	570	28	34	130	18	210	60	32	2.00	1.00	10.4
WGW-5	8.0	950	18	44	258	1	143	310	60	2.15	1.20	11.5
WGW-6	7.2	701	40	87	58	1	202	68	34	0.30	0.81	10.6
WGW-7	7.3	420	58	25	81	1	13	30	38	10.90	0.81	19.5
WGW-8	7.1	2106	50	119	434	4	142	680	200	59.00	0.45	11.1
WGW-9	7.3	950	65	49	238	2	215	350	88	9.10	0.40	8.3
WGW-10	7.2	200	18	20	38	2	52	40	18	2.54	0.26	13.5
WGW-11	7.7	340	48	19	78	2	66	90	94	1.00	0.66	9.8
WGW-12	7.8	440	40	26	69	5	58	20	20	3.00	1.90	9.7
WGW-13	7.3	400	40	26	56	2	100	20	24	2.66	0.98	5.8
WGW-14	7.2	345	60	20	59	6	120	80	30	1.10	0.38	8.9
WGW-15	7.3	300	38	34	33	2	38	30	22	3.00	0.76	5.3
WGW-16	8.5	334	32	28	63	4	158	28	26	14.12	2.30	7.2
WGW-17	8.4	460	19	47	62	5	94	54	42	6.84	2.20	5.4
WGW-18	7.6	370	31	36	58	2	141	42	29	0.24	0.58	6.2
WGW-19	7.7	550	33	36	124	14	215	64	34	2.42	1.20	10.1
WGW-20	7.9	970	19	42	249	2	75	278	64	2.46	1.12	6.5
WGW-21	7.4	745	43	84	57	5	195	72	38	0.50	0.64	5.1
WGW-22	7.2	456	56	28	84	4	75	28	42	10.60	0.87	5.9
WGW-23	7.1	1606	48	109	428	4	453	540	184	48.24	0.85	5.7
WGW-24	7.3	850	67	51	247	2	400	284	98	9.25	0.42	6.1
WGW-25	7.2	250	18	21	41	4	48	48	14	3.46	0.26	5.2
WGW-26	7.1	345	50	28	176	2	64	94	104	2.00	0.66	5.1
WGW-27	8.3	485	44	29	72	4	128	22	26	3.04	1.84	5.9
WGW-28	7.3	472	42	24	61	2	145	24	28	2.68	0.84	5.7
WGW-29	7.5	365	58	32	64	6	64	84	38	1.10	0.48	5.5
WGW-30	7.3	424	36	34	38	4	104	36	28	3.24	0.84	5.7
Average	7.56	583.60	39.30	41.63	117.87	4.10	137.87	119.27	51.53	7.50	0.99	15.6
SD	0.48	409.46	14.80	25.34	108.69	3.67	97.51	163.02	45.31	13.19	0.63	17.3
CV	6.35	70.16	37.66	60.87	92.21	89.51	70.72	136.68	87.93	175.87	63.64	11.9

SD standard deviation, *CV* coefficient of variance (%), *DGWL* depth to groundwater level

the procedures of American Public Health Association (APHA 2012). The groundwater samples were analyzed for hydrogen ion concentration (pH), electrical conductivity (EC), total dissolved solids (TDS), total hardness ((as $CaCO_3$), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) and fluoride (F^-), following the standard methods of APHA (2012). The pH and EC were measured, using their portable meters. The TDS was computed, using EC × 0.65 (Hem 1991). The TH and Ca^{2+} were estimated by EDTA titration method. The Mg^{2+} was computed, taking the difference between TH and Ca^{2+}. A flame photometer was used for estimation of Na^+ and K^+ ions. The HCO_3^- was measured by HCl volumetric method. The Cl^- was analyzed by $AgNO_3$ titration method. The SO_4^{2-} was determined, using turbidimetric procedure, the NO_3^-, using colorimetric method, and the F^-, using specific ion analyzer. The units of chemical variables (except pH) are expressed in milligrams per liter (mg/L).

The ionic balance error (IBE) was computed between the cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) and anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- and F^-) to verify the accuracy of a complete chemical analysis of each groundwater sample. The IBE was observed to be within the standard limit of ± 5% (Domenico and Schwartz 1990).

Entropy water quality index (EWQI)

Entropy water quality index (EWQI) is a comprehensive tool, which is widely used for quantification of water quality for drinking purpose (Zhou et al. 2016; Wu et al. 2017; Alizadeh et al. 2018; Su et al. 2018). The steps of entropy, entropy weight and EWQI are as follows:

The eigenvalue matrix, X, (Eq. 1) associated with groundwater quality data for "m" samples and "n" parameter is as shown as follows (Su et al. 2018):

$$X = \begin{vmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{vmatrix} \tag{1}$$

Then, using Eq. (2), the eigenvalue matrix X is converted into a standard-grade matrix Y in Eq. (3):

$$y_{ij} = \frac{x_{ij} - (x_{ij})\mathrm{min}}{(x_{ij})_{\max} - (x_{ij})_{\min}} \tag{2}$$

$$Y = \begin{vmatrix} y_{11} & y_{12} & \ldots & y_{1n} \\ y_{21} & y_{22} & \ldots & y_{2n} \\ y_{m1} & y_{m2} & \ldots & y_{mn} \end{vmatrix} \tag{3}$$

The information entropy (e_j) is calculated by the following equations (Su et al. 2018):

$$e_j = -\frac{1}{\mathrm{Inm}} \sum_{i=1}^{m} P_{ij} \mathrm{In} P_{ij} \tag{4}$$

$$P_{ij} = \frac{(1 + y_{ij})}{\sum_{i=1}^{m} (1 + y_{ij})} \tag{5}$$

The entropy weight (w_j) and quality rating scale (q_i) are computed, using the following equations, respectively:

$$w_j = \frac{(1 - e_j)}{\sum_{i=1}^{m} (1 - e_j)} \tag{6}$$

$$q_j = \frac{C_j}{S_j} \times 100 \tag{7}$$

where C_j is the concentration of chemical parameters j (mg/L) and S_j is the permissible limits of World Health Organizations (WHO) and Bureau of Indian standards (BIS) of parameter j (mg/L). However, the final EWQI is computed using Eq. (8):

$$\mathrm{EWQI} = \sum_{j=1}^{m} w_j q_j \tag{8}$$

Principal component analysis

Principal component analysis (PCA) is a powerful tool to explain a variance of interrelated variables for reducing the dimensionality of the data set (Subba Rao et al. 2007; Subba Rao 2014; Wu et al. 2014). The chemical variables, such as pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- and F^-, measured from the present study area were used for PCA, using STATISTICA (version 6). The varimax rotation procedure was applied to principal components (PCs) with Kaiser's criterion, which was used with eigenvalue greater than one (Kaiser 1958). PC1 gives the largest eigenvalue and explains the greatest amount of variance in the data set. PC2 (orthogonal and uncorrelated with the PC1) represents the low eigenvalue and explains the greatest of the remaining variance and so forth. The PC loadings, which are the uncorrelated variables obtained by multiplying the original correlated variables, are used to explain the relative contribution of chemical species over the quality of groundwater.

Results and discussion

General chemistry and spatial distribution of groundwater

Detailed analyzed chemical variables of 30 groundwater samples of the present study region and their drinking water quality standards are listed in Tables 1 and 2, respectively. The values of pH vary from 7.1 to

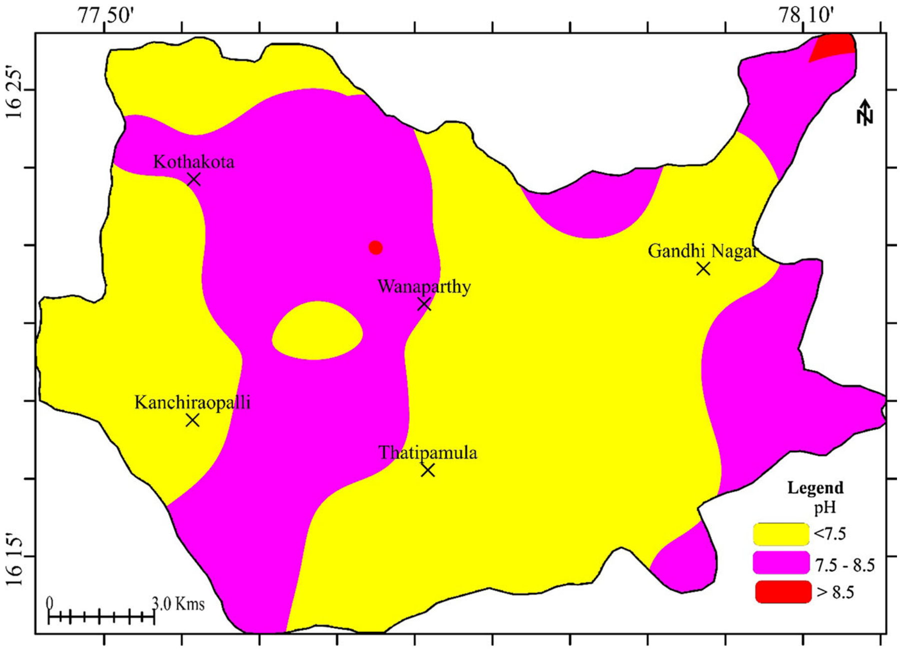
Table 2 Compliance of groundwater quality to drinking water standards

Chemical parameter	WHO (2011)	BIS (2012)	Rate of concentration exceeding safe limit	Percent of samples
pH (units)	6.5–8.5	7.0–8.5	–	–
TDS (mg/L)	500	500	0.40–4.21	33.33
Ca^{2+} (mg/L)	75	75	–	–
Mg^{2+} (mg/L)	30	30	1.07–3.96	60
Na^{+} (mg/L)	200	200	1.19–2.17	20
K^{+} (mg/L)	12	–	1.16–1.50	6.67
HCO_3^{-} (mg/L)	–	300	1.33–1.51	6.67
Cl^{-} (mg/L)	200	250	1.13–2.72	20
SO_4^{2-} (mg/L)	250	200	–	–
NO_3^{-} (mg/L)	45	45	1.07–1.31	6.67
F^{-} (mg/L)	1.5	1.5	1.22–1.53	20

8.6 with an average of 7.56, indicating an alkaline water quality, which is within its safe limit of 6.5–8.5 prescribed for drinking water (BIS 2012). The eastern and western parts of the study region show alkaline groundwater with pH more than 7.5 (Fig. 4).

The TDS ranges from 200 to 2106 mg/L, and its average is 583.60 mg/L (Table 1), which shows the differences in the degree of water quality due to gradual increase in foreign matter into the aquifer system (Subba Rao 2018). The TDS (701–2106 mg/L) is 0.40–4.21 times higher than its recommended limit of 500 mg/L in about 33% of the total groundwater samples (Table 2). The higher TDS decreases palatability and causes gastrointestinal irritation on human beings (BIS 2012). Generally, the lower TDS indicates a rock–water interactions, while the higher TDS is a result of the influence of domestic wastewaters, irrigation return flows and chemical fertilizers (Subba Rao et al. 2017a, 2019; Duraisamy et al. 2019; Subba Rao 2018; Adimalla 2019b). Further, the spatial distribution map of TDS shows that more than 50% of the study region has TDS less than 500 mg/L

Fig. 4 Spatial distribution map of pH



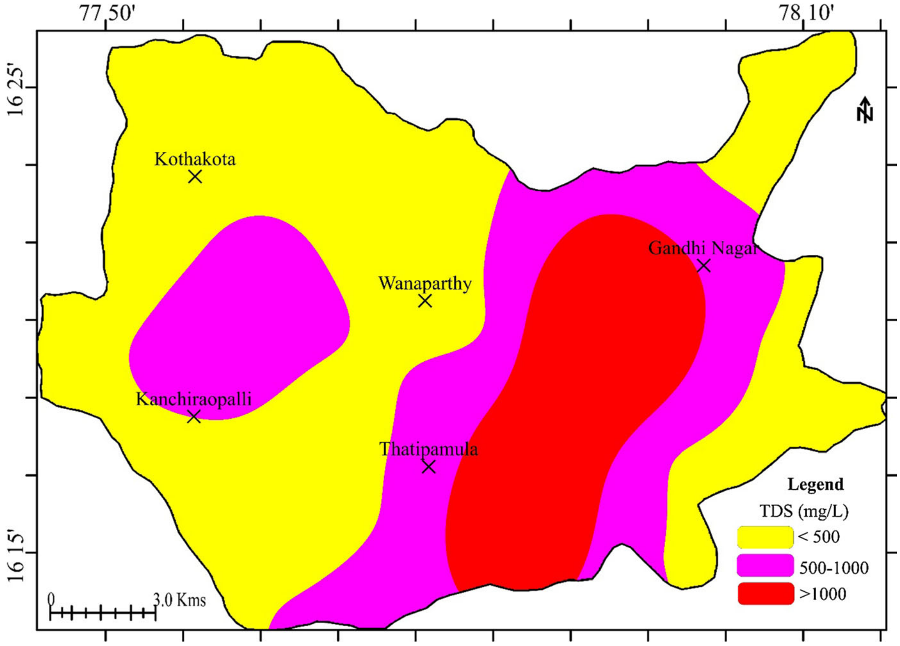


Fig. 5 Spatial distribution map of TDS

(Fig. 5), indicating that the groundwater source from this part is suitable for drinking purpose. The safe drinking water range of TDS (500–1000 mg/L) is observed from the western and eastern parts. The TDS more than 1000 mg/L is called brackish water type, which is observed from the eastern part of the study region. The gradual increasing of TDS from freshwater to brackish water could be due to influence of anthropogenic source on the groundwater system.

Ferromagnesium minerals, ion exchange (between Na$^+$ and Ca^{2+}) and precipitation of CaCO$_3$ are the main causes for the concentration of Mg^{2+} (19 and 119 mg/L with an average of 39.30 mg/L) than that of Ca^{2+} (18–67 mg/L with an average of 41.63 mg/L) in the groundwater (Table 1). The Mg^{2+} (31–60 gm/L) is 1.07–3.96 times higher than its standard safe limit of 30 mg/L allowed for drinking water in 60% of the total groundwater samples (Table 2). The concentration of Ca^{2+} in all groundwater samples is below its desirable limit of 75 mg/L (BIS 2012). Both Ca^{2+} and Mg^{2+} ions develop scale formation on well structures. Spatial distribution map of Ca^{2+} (Fig. 6) shows that the entire study region comes under the potable zone (acceptable limit) for drinking purpose. About 40% of the study region (western and eastern parts) shows Mg^{2+} below its desirable limits for drinking use (Fig. 7). About forty percent of the region with Mg^{2+} between 30 and 60 mg/L is observed from the western and eastern parts, while the rest of the area (20%) shows Mg^{2+} more than 60 mg/L, which is spread in the eastern part of the study region.

The concentration of Na$^+$ is from 33 to 434 mg/L, being an average of 117.87 mg/L (Table 1). Moreover, Na$^+$ is the dominant ion among the other cations (Ca^{2+}, Mg^{2+} and K$^+$), which indicates the silicate rock weathering and/or dissolution of soil salts caused by evaporation and anthropogenic activities on the aquifer system (Stallard and Edmond 1983; Subba Rao et al. 2012, 2017a, 2019). The higher Na$^+$ (average: 117.87 mg/L) than the Ca^{2+} (average: 41.63 mg/L) is expected due to a result of ion exchange and precipitation of CaCO$_3$ (Saxena and Ahmed 2003; Chitsazan et al. 2019; Sajil Kumar and James 2019). The Na$^+$ (238–434 mg/L) is 1.19–2.17 times higher than its threshold limit of 200 mg/L in 20% of the total groundwater samples (Table 2). It causes hypertension (Qasemi et al. 2018). Spatial distribution of Na$^+$ is shown in Fig. 8. About eighty percent of the study region shows Na$^+$ content is below the safe limit (< 200 mg/L) and the rest of the study region (20%) is above its safe limit (> 200 mg/L) mainly in the eastern part. The lower concentration of K$^+$ (1–18 mg/L with an average of 4.10 mg/L; Table 1) compared to other cations is a result of potassium feldspars, which are more resistant to chemical weathering and its fixation on clay products

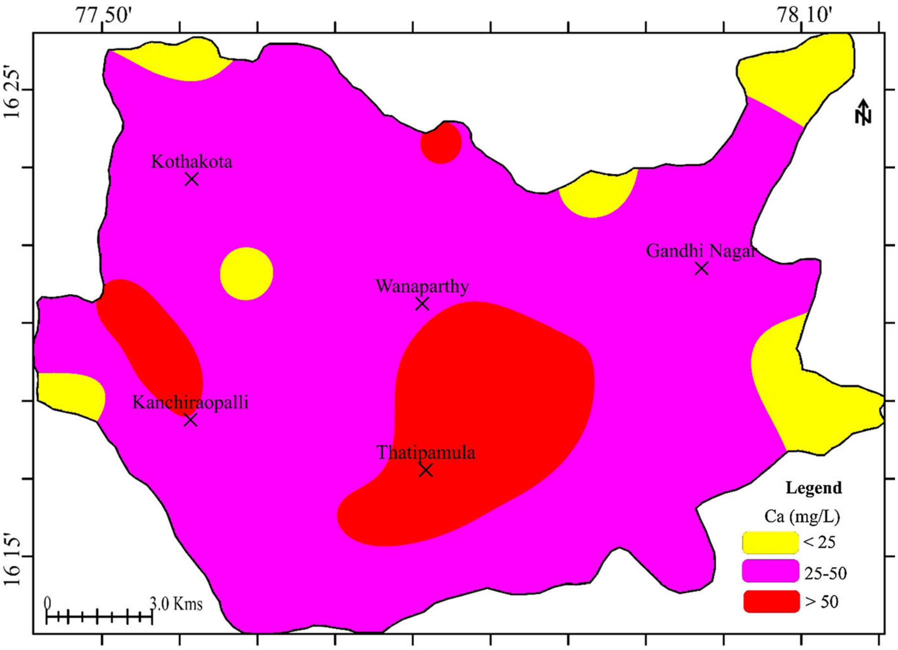


Fig. 6 Spatial distribution map of Ca^{2+}

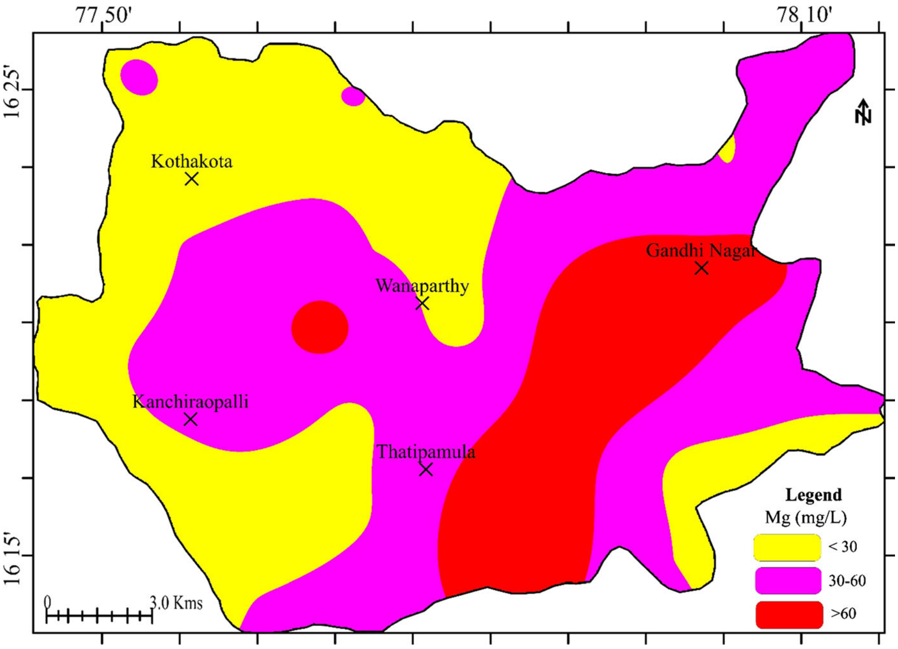


Fig. 7 Spatial distribution map of Mg^{2+}

(Chitsazan et al. 2019). The K^+ (14–18 mg/L) is 1.16–1.50 times higher than its normal limit of 12 mg/L in the groundwater in about 7% of the total groundwater samples (Table 2), spreading in the southern part as isolated zones (Fig. 9).

Among the anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- and F^-), the HCO_3^- varies from 13 to 453 mg/L and its average of 137.87 mg/L (Table 1). The soil CO_2 is the main source of HCO_3^- in the groundwater system (Subba Rao et al. 2012). The HCO_3^- should not exceed 300 mg/L in potable water (BIS 2012). In 6.67% of the total groundwater samples, the concentration of HCO_3^- (400–453 mg/L) is 1.33–1.51 times higher than its safe limit (Table 2). The spatial

Fig. 8 Spatial distribution map of Na^+

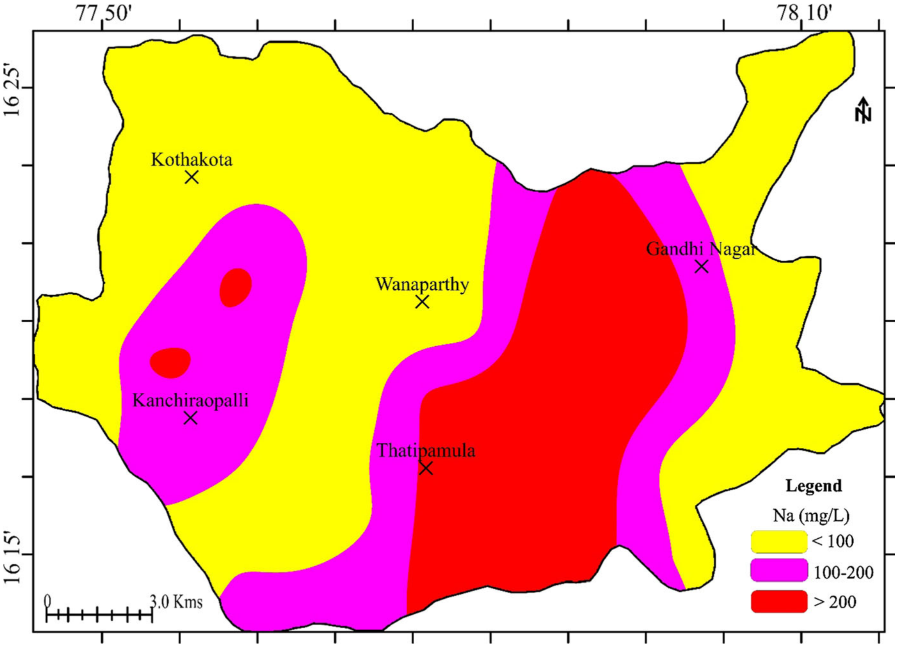
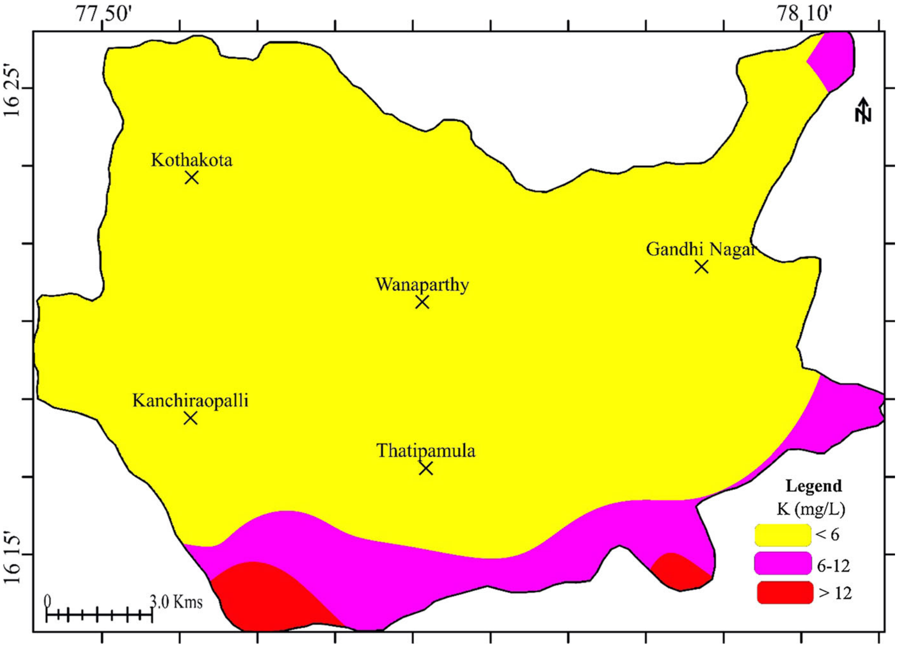


Fig. 9 Spatial distribution map of K^+



distribution of HCO_3^- shows (Fig. 10) that about 93% of the study region has HCO_3^- below the drinking water quality standard limit of 300 mg/L. The rest of the study region (7%) shows HCO_3^- above its safe limit in the southern part.

The clay products, irrigation return flows and domestic waste waters are the prime source of Cl^- content (20–680 mg/L with an average of 119.27 mg/L) in the groundwater (Table 1). The desirable limit of Cl^- is 250 mg/L for drinking purpose (BIS 2012). The Cl^- content (278–680 mg/L) is 1.13–2.72 times greater than its recommended limit in 20% of the total groundwater samples (Table 2). Figure 11 illustrates the spatial distribution of Cl^- content. Like Na^+,

Fig. 10 Spatial distribution map of HCO_3^-

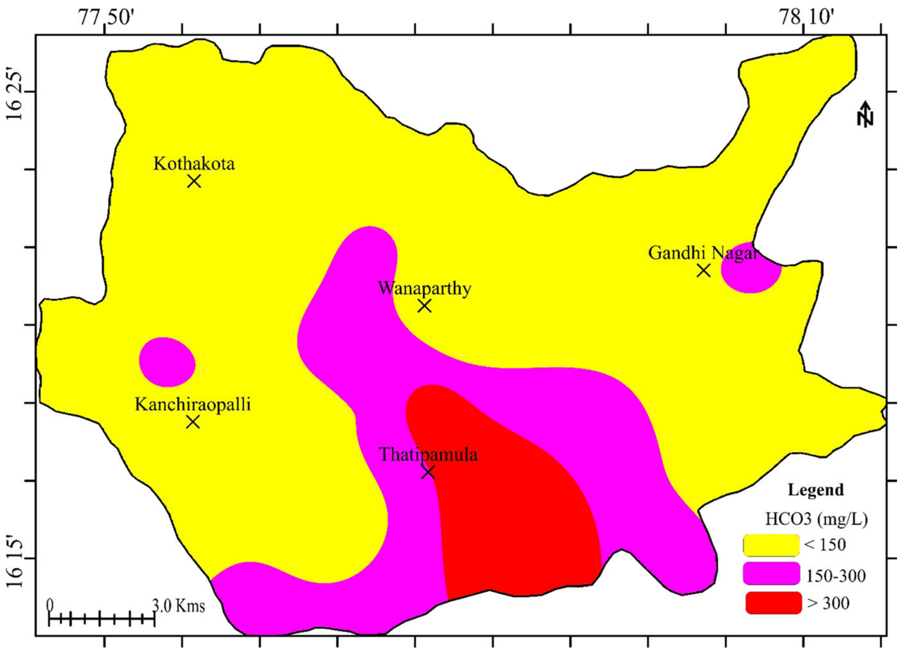
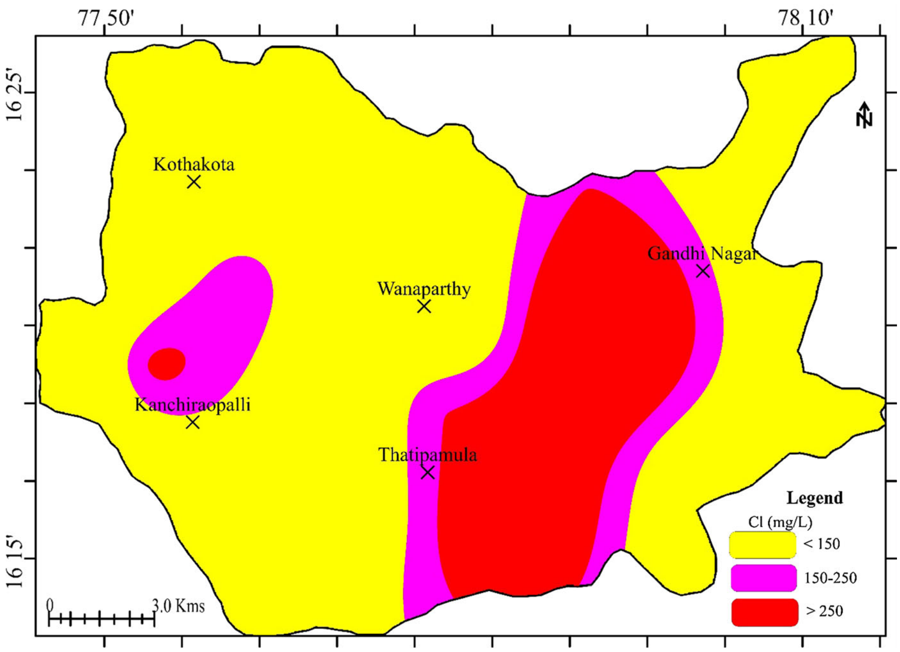


Fig. 11 Spatial distribution map of Cl^-



about 80% of the study region comes under the safe limit zone of 250 mg/L with respect to Cl^- content. The rest of the region (20%) shows a higher concentration of Cl^- (> 250 mg/L) mainly in the north to south parts due to influences of geogenic (clays) and anthropogenic sources (agricultural activities and waste waters) on the aquifer system.

The application of gypsum and nitrogen fertilizers appears as the main source of SO_4^{2-} (14–200 mg/L with an average of 51.53 mg/L) and NO_3^- (0.1–59 mg/L with an average of 7.50 mg/L) in the groundwater (Table 1). The desirable limits of SO_4^{2-} and NO_3^- are 200 and 45 mg/L, respectively, for drinking purpose (BIS 2012). The concentration of

SO_4^{2-} is below its safe limit in all groundwater samples, while that of NO_3^- (48.24–59 mg/L) is 1.07–1.31 times higher than its standard limit in 6.67% of the total groundwater samples (Table 2), which causes blue baby syndrome (Stuart et al. 2011; Menció et al. 2016; Adimalla 2019b). As shown in Figs. 12 and 13, the entire study region comes under the permissible limit of SO_4^{2-} (200 mg/L), while one isolated zone in the eastern part shows the concentration of NO_3^- more than its desirable limit of 45 mg/L prescribed for drinking purposes.

The geogenic (apatite, biotite, hornblende and clays) and anthropogenic (chemical fertilizers) origins, in addition to the higher rate of evaporation and longer contact of water with the aquifer system, are the prime sources for the concentration of F^- content (0.26–2.30 mg/L with an average of 0.99 mg/L; Table 1) under alkaline environment in the groundwater (Subba Rao and John Devadas 2003; Narsimha and Sudarshan 2017a, b; Subba Rao 2017; Adimalla 2019b). The F^- content (1.84–2.30 mg/L) is 1.22–1.53 times higher than the allowable limit of 1.5 mg/L (BIS 212) in 20% of the total groundwater samples (Table 2), which causes fluorosis. The lower fluoride content (< 0.6 mg/L) is observed from the eastern, western and central parts as isolated zones (Fig. 14), causing dental caries. The safe range of F^- (0.6–1.5 mg/L) for drinking is spread in 80% of the study region. A few isolated zones show the F^- content more than 1.5 mg/L in the entire study region, indicating that the groundwater is not suitable for drinking from these parts.

EWQI and its distribution

The computed data of EWQI and its classification are presented in Tables 3 and 4. The values of EWQI range from 22.70 to 170.69 with an average of 59.33. As per the classification of EWQI, the groundwater quality can be categorized into five types, which are excellent (rank 1), good (rank 2), medium (rank 3), poor (rank 4) and extremely poor (rank 5) water quality types. When the values of EWQI are more than 100, the groundwater is not suitable for drinking purpose (Zhou et al. 2016; Wu et al. 2017; Alizadeh et al. 2018; Su et al. 2018).

According to the EWQI, 3.33%, 46.67%, 43.33% and 6.67% of the total groundwater samples come under the excellent, good, medium and extremely poor water quality types for drinking purpose, respectively. Excellent and good water quality types are fit for drinking purpose. Medium water quality type is fit only for the domestic purpose. The poor and extremely poor water quality types are totally unsuitable for drinking purpose.

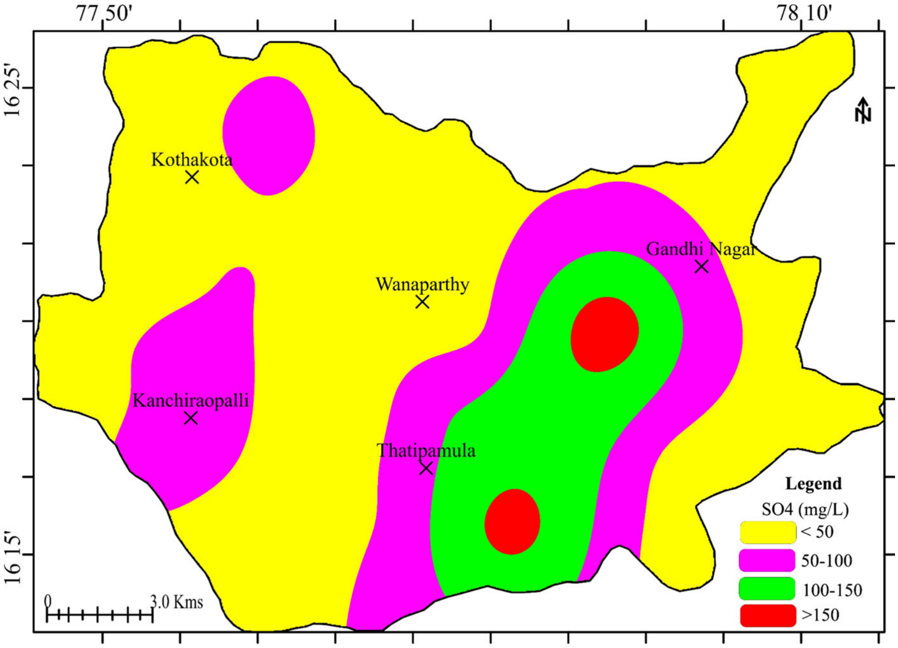


Fig. 12 Spatial distribution map of SO_4^{2-}

Fig. 13 Spatial distribution map of NO_3^-

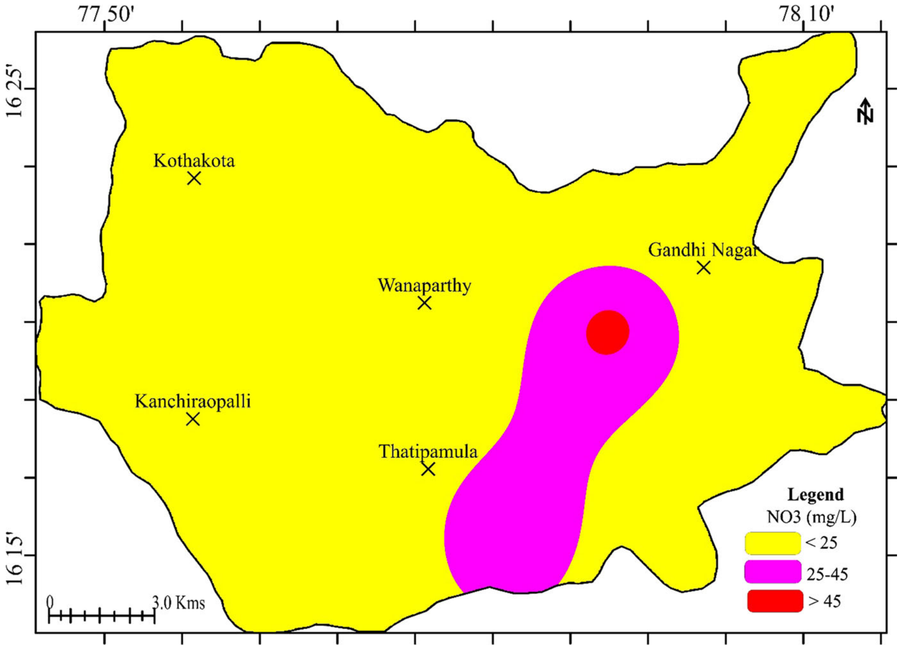
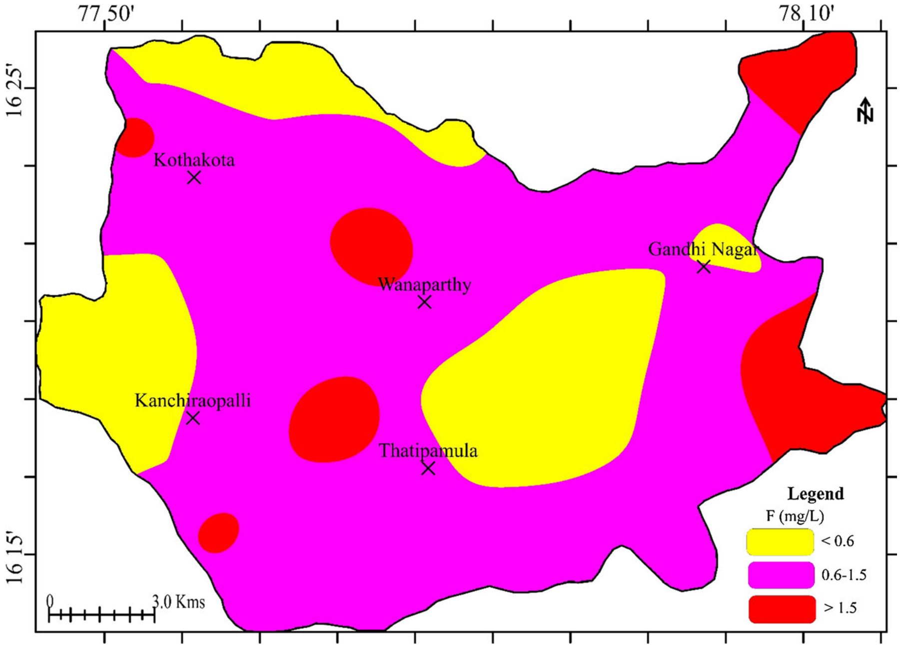


Fig. 14 Spatial distribution map of F^-



Spatial distribution of EWQI is shown in Fig. 15. Excellent water quality type is observed from the extreme northwestern and western parts, good water quality type from the center to eastern, western and northern parts, medium water quality type from eastern, central, western, northern and southern parts, and extremely poor water quality type from the eastern part as an isolated zone. The increase in water quality from excellent to extremely poor types could be due to influences of anthropogenic sources, which increase the concentrations of TDS, Mg^{2+}, Na^+ and Cl^- compared to other chemical parameters (Subba Rao et al. 2017a; Subba Rao and Chaudhary 2019).

Table 3 Assessment results of the EWQI values for the classified data in the study region

Sample numbers	EWQI	Rank	Water quality	Sample numbers	EWQI	Rank	Water quality
WGW-1	56.14	3	Medium	WGW-16	52.40	3	Medium
WGW-2	56.62	3	Medium	WGW-17	58.17	3	Medium
WGW-3	37.02	2	Good	WGW-18	38.33	2	Good
WGW-4	63.12	3	Medium	WGW-19	62.65	3	Medium
WGW-5	78.48	3	Medium	WGW-20	75.44	3	Medium
WGW-6	66.33	3	Medium	WGW-21	68.72	3	Medium
WGW-7	41.34	2	Good	WGW-22	46.88	2	Good
WGW-8	170.69	5	Extremely poor	WGW-23	156.73	5	Extremely poor
WGW-9	86.83	3	Medium	WGW-24	87.33	3	Medium
WGW-10	22.70	1	Excellent	WGW-25	26.05	2	Good
WGW-11	39.87	2	Good	WGW-26	48.90	2	Good
WGW-12	48.13	2	Good	WGW-27	51.18	3	Medium
WGW-13	38.33	2	Good	WGW-28	39.76	2	Good
WGW-14	40.29	2	Good	WGW-29	44.73	2	Good
WGW-15	35.22	2	Good	WGW-30	41.56	2	Good

Table 4 Classification of groundwater quality based on EWQI

EWQI	< 25	25–50	50–100	100–150	> 150
Rank	1	2	3	4	5
Percentage of samples	3.33	46.67	43.33	–	6.67
Water quality	Excellent	Good	Medium	Poor	Extremely poor

Spatial distribution of EWQI gives baseline information on the occurrence of vulnerable zones at a specific site. Accordingly, it can be possible to take the protection and management measures at specific site for sustainable development of groundwater resources.

Hydrogeochemical types

Basically, Piper (1944) introduced the concept of hydrogeochemical types, which provide significant information on compositional classes that are presented dominant ions in the groundwater system. Later on, Chadha (1999) simplified the concept of hydrogeochemical types in a different perspective (Fig. 16).

As shown in Fig. 16, alkaline earths (Ca^{2+} and Mg^{2+}) and weak acids (HCO_3^- and CO_3) exceed the alkalies (Na^+ and K^+) and strong acids (Cl^- and SO_4^{2-}) in 63.33% of the total groundwater samples collected from the present investigated region, which fall in zone 5, indicating the carbonate or temporary hardness or freshwater type (Ca^{2+}–Mg^{2+}–HCO_3^- type). The temporary hardness can be easily removed by boiling of water. Further, 16.67% of the groundwater samples are observed from zone 7 (non-carbonate alkali or saline water type; Na^+–Cl^- type), which shows more alkalies (Na^+ and K^+) and strong acids (Cl^- and SO_4^{2-}) than alkaline earths and weak acids. This type develops salinity problems in drinking water. Some groundwater samples (13.33%) fall in zone 8, which is characterized by more alkalies and weak acids than alkaline earths and strong acids. This type is called carbonate alkali water type (Na^+–HCO_3^- type), which causes foaming problems in domestic water. A few groundwater samples (6.67%) are observed from zone 6, which shows non-carbonate or permanent hardness water type (Ca^{2+}–Mg^{2+}–Cl^- and SO_4^{2-} type) that is characterized by more alkaline earths and strong acids than alkalies and weak acids. The permanent hardness cannot be easily removed by boiling of water.

Fig. 15 Spatial distribution map of entropy water quality index (EWQI)

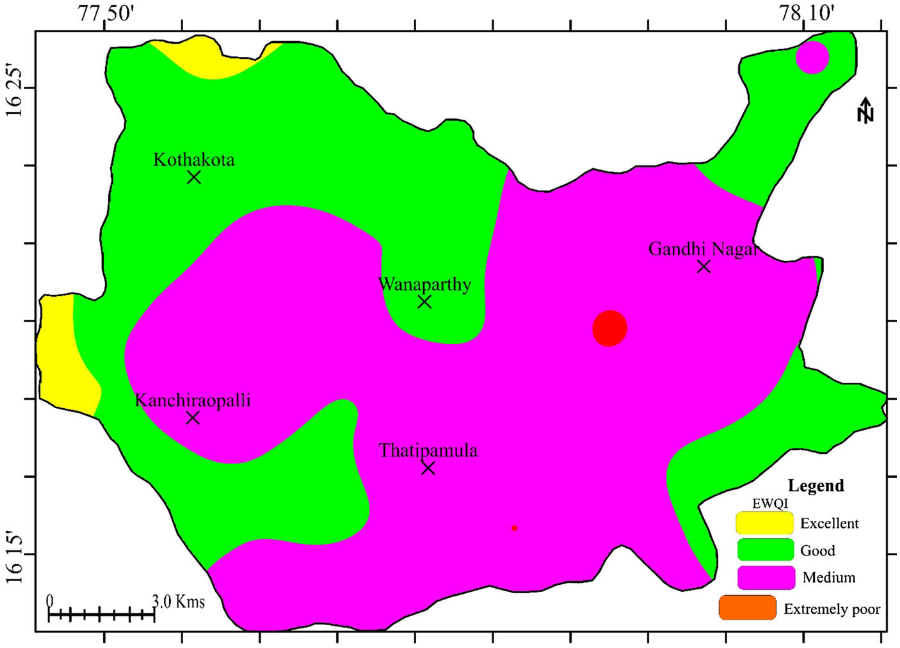
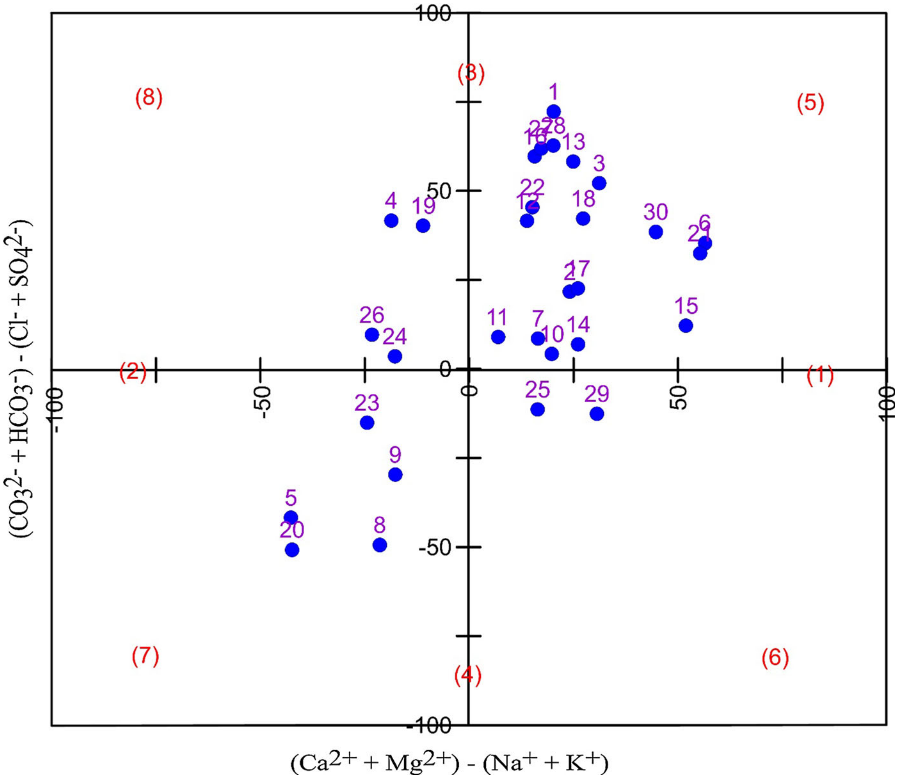


Fig. 16 Chadha's diagram showing the hydrochemical facies of groundwater in the study region. (1) Alkaline earths (Ca^{2+} and Mg^{2+}) exceed alkalies (Na^{+} and K^{+}), (2) alkalies exceed alkaline earths, (3) weak acids (CO_3^{2-} and HCO_3^{-}) exceed strong acids (Cl^{-} and SO_4^{2-}), (4) strong acids exceed weak acids, (5) HCO_3^{-}–Ca^{2+}–Mg^{2+}, HCO_3^{-}–Ca^{2+} or HCO_3^{-}–Mg^{2+} types, (6) $Cl^{-}SO_4^{2-}$–Ca^{2+}–Mg^{2+}, Cl^{-}–Ca^{2+}–Mg^{2+} or SO_4^{2-}–Ca^{2+}–Mg^{2+} types (7) SO_4^{2-}–Cl^{-}–Na^{+} or SO_4^{2-}–Na^{+} types and (8) HCO_3^{-}–Na^{+} type



Hydrogeochemical proceseses controlling the groundwater quality

Stallard and Edmond (1983), Subba Rao (2002) and Subba Rao et al. (2017a) suggested a diagram, $Na^+ + K^+$ versus TC, to explain the contribution of silicate weathering and/or soil salts stored by evaporation as a supply of cations to the groundwater system. All groundwater sampling points fall below the theoretical line of $Na^+ + K^+$ versus TC (Fig. 17a). It indicates that the rock weathering and/or soil salts contribute to the groundwater system.

Since the clay occurs in the present study region, it causes ion exchange between Na^+ and Ca^{2+}, leading to higher concentration of Na^+ in the groundwater system. This phenomenon is verified by plotting of Na^+ against Ca^{2+} (Fig. 17b). The concentration of Ca^{2+} varies from 1 to 4 meq/L, while that of Na^+ is from 2 to 20 meq/L. This supports the ion exchange process taking place in the present study region.

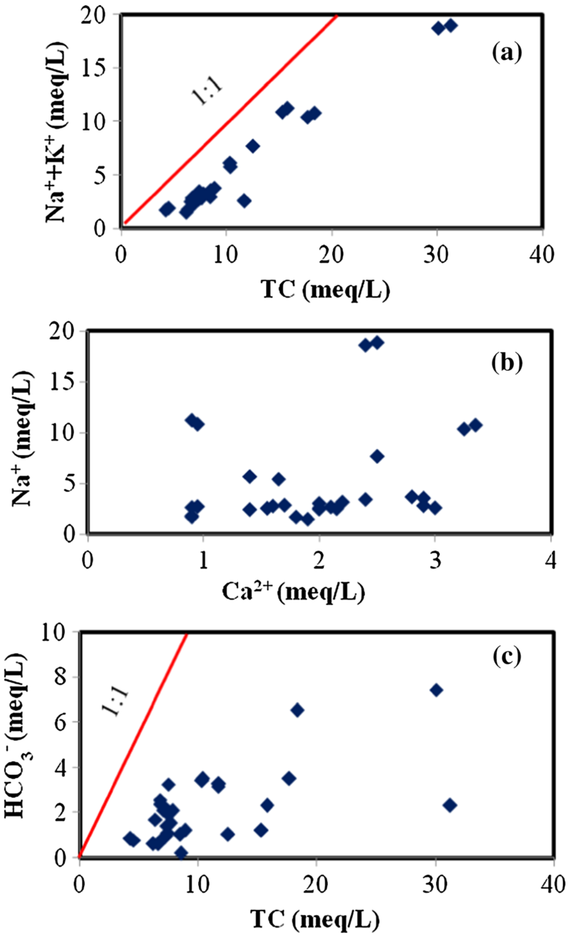


Fig. 17 Relationships **a** $Na^+ + K^+$ versus TC, **b** Na^+ versus Ca^{2+} and **c** HCO_3^- versus TC

The HCO_3^- is plotted against TC (Fig. 17c) to further explain not only the role of water–rock interactions, but also the influence of anthropogenic sources on the groundwater system (Subba Rao et al. 2017a). According to Kim (2003), the sampling points should be close to the equiline of HCO_3^-: TC, if there is dissolution of minerals as a dominant source over the controlling process of chemical quality of groundwater. In the present study region, all groundwater sampling points fall below the uniline of HCO_3^- versus TC, indicating the deviation from the groundwater quality formed by geogenic origin. Thus, it could be due to a result of influence of anthropogenic sources (domestic wastewaters, irrigation return flows and chemical fertilizers) on the aquifer system.

From these observations, it can be said that the water–rock interactions, mineral weathering and dissolution, ion exchange and evaporation are the primary processes and the anthropogenic activities are the secondary sources controlling the groundwater quality.

Principal component loadings

The computed data of principal components analysis are presented in Table 5. The chemical parameters

Table 5 Principal component loadings to be changed Principal component loadings (bold values denote high loadings)

Chemical variables	Principal component loadings		
	PC1	PC2	PC3
pH	– 0.363	**0.859**	– 0.110
TDS	**0.952**	0.165	– 0.073
Ca^{2+}	0.375	– 0.519	0.342
Mg^{2+}	**0.835**	0.176	– 0.028
Na^+	**0.934**	0.136	– 0.048
K^+	– 0.096	0.449	**0.766**
HCO_3^-	**0.613**	0.217	0.489
Cl^-	**0.956**	0.071	– 0.129
SO_4^{2-}	**0.937**	0.006	– 0.085
NO_3^-	**0.853**	0.207	– 0.113
F^-	– 0.307	**0.860**	– 0.141
Eigenvalues	5.748	2.120	1.020
% of variance	52.252	19.273	9.270
Cumulative %	52.252	71.525	80.796

(pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- and F^-) have yielded three principal components (PCs), depending upon the eigenvalues, which are more than 1 (Fig. 18).

The PC1 accounts for 52.252% of the total variance, which exhibits significant positive loadings of Cl^- (0.956), TDS (0.952), SO_4^{2-} (0.937), Na^+ (0.934), NO_3^- (0.853), Mg^{2+} (0.835) and HCO_3^- (0.613). The Na^+, Mg^{2+} and HCO_3^- stand for processes of rock–water interactions, silicate weathering and dissolution, ion exchange and evaporation, while those of Cl^-, SO_4^{2-}, Na^+ and NO_3^-represent the influence of domestic wastewaters, irrigation return flows and chemical fertilizers on the groundwater system. The results of this study are in accordance with Subba Rao et al. (2007, 2019), Adimalla and Venkatayogi (2018) and Subba Rao and Chaudhary (2019). The second component PC2 is much concerned with F^-(0.860) and pH (0.859), and its total variance is 19.273%, which signifies the alkaline nature of groundwater. The negative loading of Ca^{2+} (− 0.519) in PC2 is characteristically triggering the concentration of F^- in the groundwater (Adimalla and Venkatayogi 2017: Subba Rao 2017; Subba Rao et al. 2017a, b; Adimalla 2018; 2019b). The rocks of granites containing the fluoride-rich minerals (apatite, biotite and hornblende) are the main sources of fluoride content in the groundwater (Subba Rao et al. 2017a, b; Adimalla and Li 2018; Adimalla et al. 2018b). The PC3 accounts for 9.270% with a high positive loading of K^+ (0.766), which is mainly caused by the impact of potassium fertilizers on the groundwater system (Subba Rao et al. 2017a).

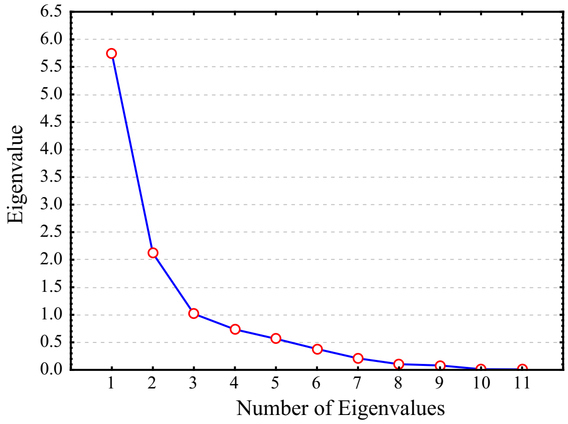


Fig. 18 Scree plot

Conclusions

The following conclusions were from the present study carried out from a rural part of Wanaparthy District, Telangana State, India:

- Groundwater quality is of the alkaline condition, with a dominance of carbonate hardness water type (Ca^{2+}–Mg^{2+}–HCO_3^- type) in about 63% of the total study region. The spatial distributions of various chemical parameters show that some locations are not suitable for drinking purpose, where the TDS, Mg^{2+}, Na^+, HCO_3^-, Cl^-, NO_3^- and F^- exceed their safe limits for drinking purpose. As per the classification of EWQI, about 3%, 47%, 43% and 7% of the total area come under the excellent, good, medium and extremely poor water quality types for drinking purpose, respectively.
- The binary diagrams ($Na^+ + K^+$ vs TC, Na^+ vs Ca^{2+} and HCO_3^- vs TC) indicate the influences of water–rock interactions, mineral weathering and dissolution, ion exchange and evaporation as the primary source and the impact of anthropogenic activity as the secondary source controlling the groundwater quality.
- The PCA was transferred the chemical variables (pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^- and F^-) into three principal components (PCs), which show eigenvalues more than 1. They account for about 81% of the total variance. The PC1 shows the high positive loadings of Cl^-, TDS, SO_4^{2-}, Na^+, NO_3^-, Mg^{2+}, and HCO_3^- representing the influences of geogenic origin (rock–water interactions, silicate weathering and dissolution, ion exchange and evaporation) and anthropogenic sources (wastewaters, irrigation return flows and chemical fertilizers) on the groundwater system. The high positive loadings of F^- and pH in PC2 stand for alkaline condition of groundwater, which causes a higher concentration of F^- content in the groundwater. The high positive loading of PC3 associated with K^+ is caused by the influence of potassium fertilizers.
- Since the groundwater is the prime source for drinking purpose in the present study region, the continuous usage of inferior water quality will lead to various health disorders. Therefore, the present study helps the civic authorities for taking the

protection and management of groundwater resources at a specific site. In view of this, artificial recharging of aquifers is imperative for sustainable development of the rural area, which improves the groundwater conditions, including groundwater quality. Meanwhile, it is also essential to treat the poor groundwater quality before its drinking.

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