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Groundwater Quality Assessment in Korba Coalfield Region, India: An Integrated Approach of GIS and Heavy Metal Pollution Index (HPI) Model

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GIS
Correlation matrix
Cluster analysis
KCF region

ABSTRACT

The goal of this study was to examine the water quality for drinking and domestic purposes in the Korba coalfield region of Chhattisgarh, India. The Korba Coalfield region has seen the collection of fifteen groundwater samples from different places. The content of eight metals was determined using ICP-MS instruments: aluminum (Al), barium (Ba), cadmium (Cd), iron (Fe), magnesium (Mn), lead (Pb), nickel (Ni), and zinc (Zn). Spatial distribution maps were produced using GIS software to make it simple to understand the groundwater's quality. The groundwater samples were collected during the pre-monsoon season and the amount of Al, Ba, Cd, Fe, Mn, Pb, Ni, and Zn exceeded the ideal drinking water standards in a few sites. The elevated metal concentrations in the study region's groundwater could be hazardous to the quality of water. The HPI value based on mean concentration was calculated to be 21.64, which is significantly lower than the reference pollutant index score of 100. The HPI calculation revealed that 73.33% of groundwater samples had low HPI values, 6.67% had medium HPI values, and the remaining 20% had high HPI values. The correlation between heavy metals and HPI was calculated; HPI is positively correlated with Fe ($r > 0.9471$), Pb ($r > 0.9666$), and Zn ($r > 0.9634$), indicating that these elements contribute significantly more to heavy metal concentration in the various samples examined than the other selected elements. The box plot seems to be a graphical representation of the outcomes of the different parameter concentrations which show the mean, maximum, and minimum metal values. The cluster analysis was performed and it was classified into two clusters. Cluster-1 comprises 14 members (93.33%) of the water samples examined and is distinguished by relatively low Ba (<700 $\mu g.L^{-1}$), pH, TDS, Al, Fe, Cd, Mn, Pb, and Zn concentrations. Cluster-II is made up of 1 member (6.67%), which is primarily made up of groundwater samples (GW-10) taken in the KCF region, India. High values of HPI are found in the eastern portion of Chhattisgarh's KCF region, reflecting the spatial distribution of metals. Heavy metal leaching from open-pit mining and transit routes was observed to have contaminated groundwater in the eastern section of the research region.

INTRODUCTION

Water is very essential for all living things for sustaining on earth, therefore, its quality and quantity examination are important at a certain time interval. Sharp changes have been found in demands for potable water due to surface water scarcity and the vast increase in population in many regions around the world. Two vital methods HPI and GIS were used to map the distribution of metals in groundwater in the KCF Region. People in India mostly use groundwater for household and drinking uses, therefore water contamination from mining is a big problem in this area (Tiwari et al. 2017). Chemical contamination in the surrounding area is only increasing as a result of the mining process, disposal of overburdens, and coal washing, which also impacts the quality and quantity of surface and groundwater (Singh et al. 2008, Ahmed et al. 2022)

The quality of groundwater is degraded due to untreated waste discharge and groundwater resource overexploitation. In India, approx 21% of communicable diseases in humans are occurring only because of contaminated water (Brandon & Hommann 1995, Dheeraj et al. 2022). The HPI assesses the total impact of individual pollutants on water quality (Giri & Singh 2014). Many of the researchers have done their studies on topics related to mining and its impacts on surface and groundwater with reference to heavy metals for different coal mines (Singh 1988; Tiwary & Dhar 1994; Prasad & Bose 2001; Giri et al. 2010; Tiwari et al. 2017). However, only a few studies are available on mines, especially on surface and groundwater regarding heavy metals in India (Senapaty & Behera 2012, Mahato et al. 2014, Tiwari et al. 2017, Singh et al. 2017).

Heavy metal concentration is induced in groundwater through many sources that may be natural or anthropogenic

(Adaikpoh et al. 2006, Vishwakarma et al. 2020). In most native habitats, the metal content is extremely low which is almost generated from weathering of geological formations and minerals (Karbassi et al. 2008). The solid waste generated from municipal can share some amounts of metals into groundwater through medicines and household pesticides, body care products, plastics, and paints and inks (Bardos 2004). According to (Lee et al. 2007, Adams et al. 2008, Lohani et al. 2008), non-biodegradable metal contamination is extremely important due to its potential toxicity for both humans and human body systems, such as the nervous system and internal organs, which can be damaged rapidly. In this study, the main aim was to evaluate the groundwater suitability for drinking uses around the mining area of KCF through the HPI model.

STUDY REGION

The Korba Coalfield region is situated in the Korba district of Chhattisgarh which lies between 22° 15' N 22° 30' N latitude and longitude of 82° 15' to 82° 55' E as given in Fig. 1. This selected region of KCF is extended around 226.57 km^2 in Chhattisgarh state and lies in the Toposheet number F44K11 as per Survey of India (SOI). The non-coking coal is produced by these KCF coal mines.

These coal mines are located in the basin of the Hasdev River, a tributary of the Mahanandi River. The three mega-operated opencast mines such as Gevra OC, Dipka OC, and Kushmunda OC come under the Korba mine. KCF region is characterized by tropical climates having very hot about 45°C in May- June month and low about 2-4°C from December to January month. The average annual rainfall is around 1287 mm in the monsoon season (June - September) accounting for more than 85% of the total.

Geology and Hydrogeology

The geology of the research region is defined by the Gondwana Super Group's Barakar Formation, which lies directly above the Precambrian schist (Raja Rao 1983). The formations in this area have an overall dip of 5° to 8° to the south and are trending E-W. Many transverse faults that run NE-SW, NW-SE, and EW and have different throw magnitudes further distinguish the area differently. Among these, the E-W trending fault with a southerly throw in the northern half of the study region is significant because it is in juxtaposition with the Upper and Lower Barakar formations. This fault divides the Upper Barakar Formation from the Lower Barakar and it likely disappears or has a negligible throw near the Hasdeo River (CMPDIL 2014). The majority

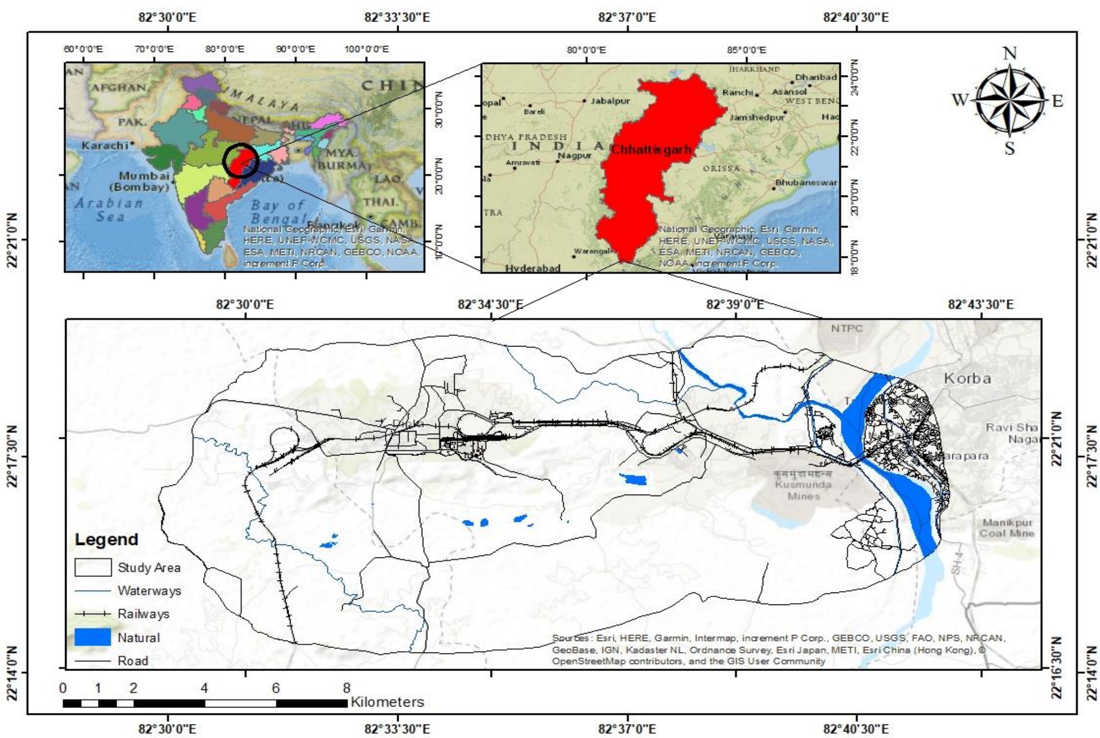


Fig. 1: Study area map.

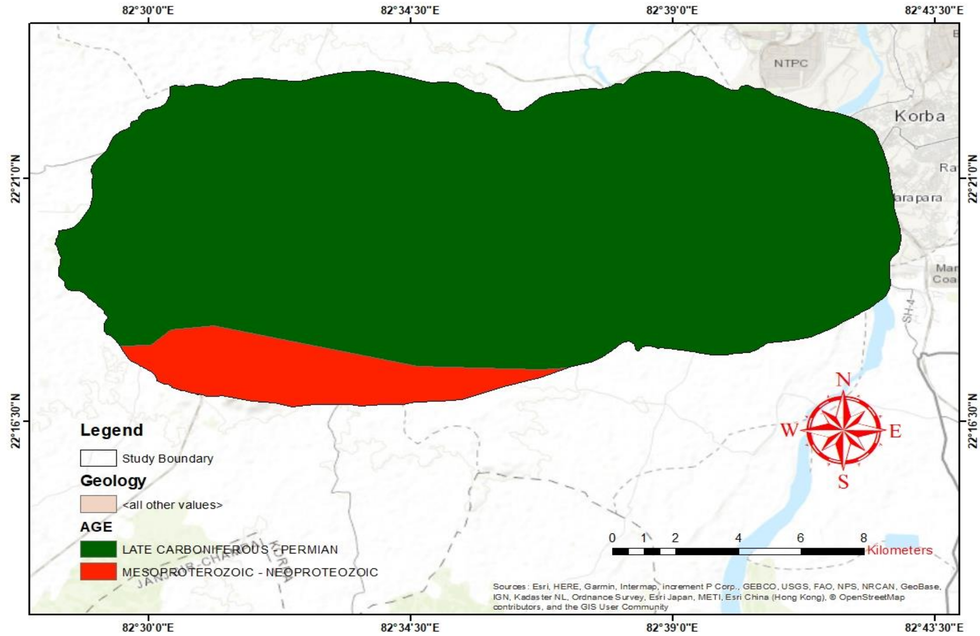


Fig. 2: Geology of the study area.

of the examined region is covered hydrogeological by the Upper Barakar Formation, which is composed of arkosic sandstone with a range of grain sizes, carbonaceous shale beds, and thick coal seams. The superficial deposit, which is composed mostly of alluvium & sandstone and is located above the active coal seams, acts as an unconfined aquifer. The lower formations, on the other hand, are semi-confined or confined aquifers because they are made mainly of compact sandstone with secondary porosity (CGWB 2012). Apart from it, the geology and geomorphology of this area are shown in Fig. 2 & 3 (GSI 2019).

MATERIAL AND METHODS

Sampling and Water Assessment

During the pre-monsoon season (March 2022), a total of (n=15) groundwater samples from the KCF region were collected in narrow-mouth polyethylene bottles with a capacity of 100 mL for this investigation. The pH concentration of groundwater samples was determined which ranged from 6.3 to 7.8 with the multiparameter instrument. This instrument was calibrated with pH 4.0 & 7.0 buffer solution. It was found that the water samples were near neutral to alkaline in nature in pre-monsoon season. Before experiments, all samples got filtered through a 0.22 m syringe filter by changing the pH value using a nitric acid solution (Radojevic et al. 1999). The TDS concentration was determined, ranging between 97 an d 715 $mg.L^{-1}$ with a multiparameter instrument after calibration. To ensure reliability, the proper quality assurance process and safety measures were required, and each sample was easily handled to prevent contamination. All the used glassware was appropriately cleaned and ultrapure water from Milli-Q was utilized throughout the studies (Tiwari et al. 2017).A total of eight important elements (Al, Ba, Cd, Fe, Mn, Pb, Ni and Zn) were considered through ICP-MS (inductively coupled plasma-mass spectroscopy). To determine the ICP-confirmation MS's status, a calibration blank, and an independent calibration verification standard have been analyzed for every 10 samples. Most of the time, with comparable accuracy, the precision improved to better than 5% RSD.

HPI Specification

A model of grading called the Heavy Metal Pollution Index (HPI) enables the composite impact of individual metal on the overall quality of water (Sheykhi et al. 2012). To estimate of HPI, the unit weight (Wi) and recommended standard value (Si) of the appropriate elements were taken into consideration and these are inversely proportional to each other. The unit weight ranging from 0 to 1 has been assigned for heavy metals (Reddy 1995). The critical value of HPI is 100 according to (Prasad & Bose 2001). In this study area, the three types of HPI were taken into account. Correspondingly low HPI<15, Medium HPI 15-30, and High HPI>30 (Edet & Offiong 2002). There are several steps for calculating HPI with the following equation as per Venkata Mohan et al. (1996).

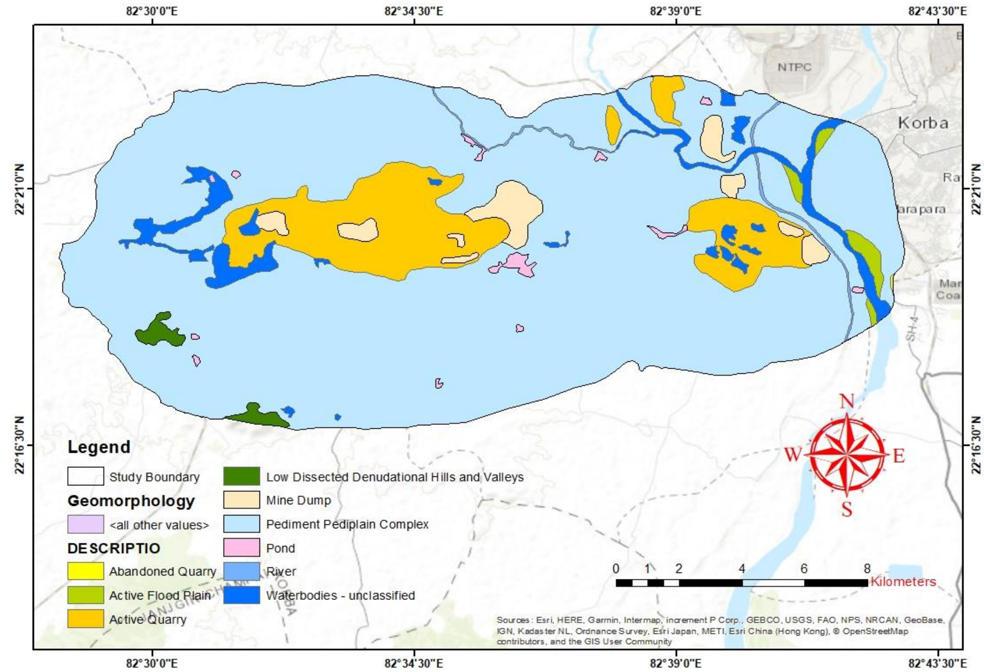


Fig. 3: Geomorphological map of the study area.

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{i=1}^{n} Wi} \qquad ...(1)$$

Where n – Number of parameters

W_i – unit weightage

Q_i – Sub-index of i^{th} parameter calculated by Equation 2.

$$\text{Qi} = \sum_{i=1}^{n} \frac{(Mi - Ii)}{(Si - Ii)} \times 100 \qquad ...(2)$$

Where Sign (-) – represents a numerical difference of two value, not used for algebraic importance

M_i – Monitored concentration

I_i – Ideal value

S_i – Standard value for the i^{th} parameter ($\mu g.L^{-1}$).

Each pollutant concentration was converted into HPI when the HPI result was calculated. A higher HPI value can be harmful to one's health.

Spatial Distribution Map

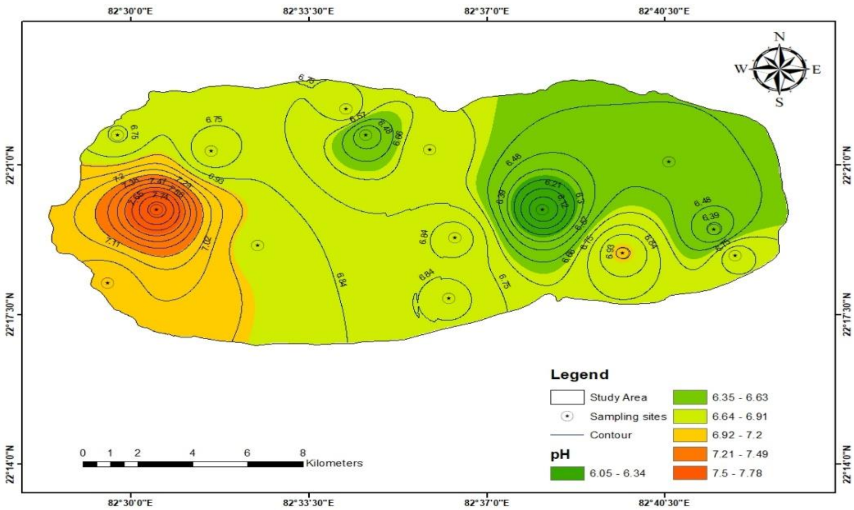
The HPI is a rating mechanism based on empirical data that determines the total influence of individual metals on water quality. The grading system gives a general sense of a rating that can be anywhere between 0 and 1, based on how significant each parameter is to the overall quality. The Toposheet number of this study area was geo-referenced with projection UTM Datum WGS-84 & Zone-45N on ArcGIS 10.8 software. The study area map was digitized on ArcGIS software. The spatial distribution of different elements was prepared with the spatial analyst tool in ArcGIS 10.8. The two different tools used to prepare the spatial distribution map with contour lines are IDW (Inverse distance weighted) interpolation and the contour option in ArcGIS software. With the help of these two modules in ArcGIS, it has drowned the spatial distribution maps for (pH, TDS), (Al, Fe, Pb, Zn, Cd), (Ba, Mn, Ni) and calculated HPI for the study area as shown in Fig. 4 and 7 respectively.

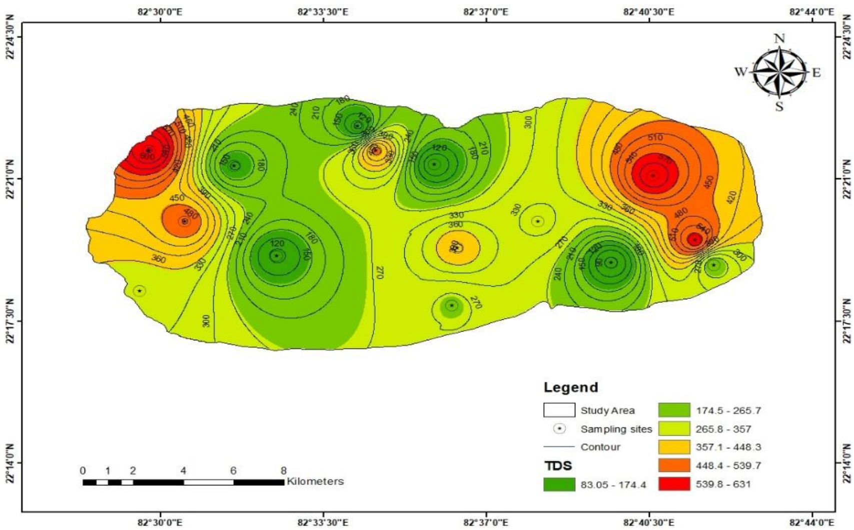
RESULTS AND DISCUSSION

Groundwater contamination

The concentration of contaminant has been determined and statistics have been listed in Table 1. The average value of all eight metals (Al, Fe, Pb, Zn, Cd, Ba, Mn, Ni) were 28.82, 658.29, 9.78, 1078, 0.09, 242.37, 111.59 & 24.86 $\mu g.L^{-1}$ in pre-monsoon season (March 2022). Only one element Cd was not exceeded its desirable limit as specified by WHO (2006) & BIS 2012 (IS 10500) at all selected sites (GW-1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 & 15).

In a previous study around KCF (Singh et al. 2017), it has been reported that the few metal concentration of


Legend
Study Area
Sampling sites
Contour
pH
6.05 - 6.34
6.35 - 6.63
6.64 - 6.91
6.92 - 7.2
7.21 - 7.49
7.5 - 7.78
Kilometers


Legend
Study Area
Sampling sites
Contour
TDS
83.05 - 174.4
174.5 - 265.7
265.8 - 357
357.1 - 448.3
448.4 - 539.7
539.8 - 631
Kilometers

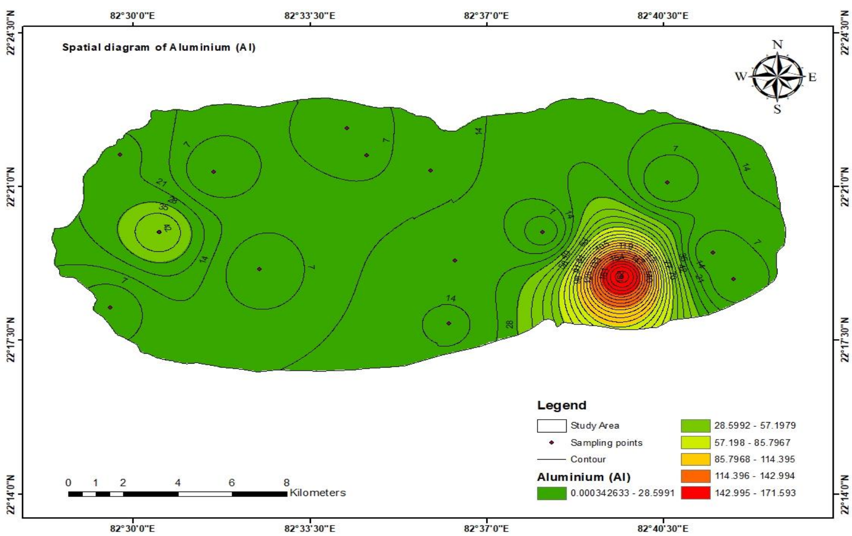

Spatial diagram of Aluminium (Al)
Legend
Study Area
Sampling points
Contour
Aluminium (Al)
0.000342633 - 28.5991
28.5992 - 57.1979
57.198 - 85.7967
85.7968 - 114.395
114.396 - 142.994
142.995 - 171.593
Kilometers

Fig. cont....

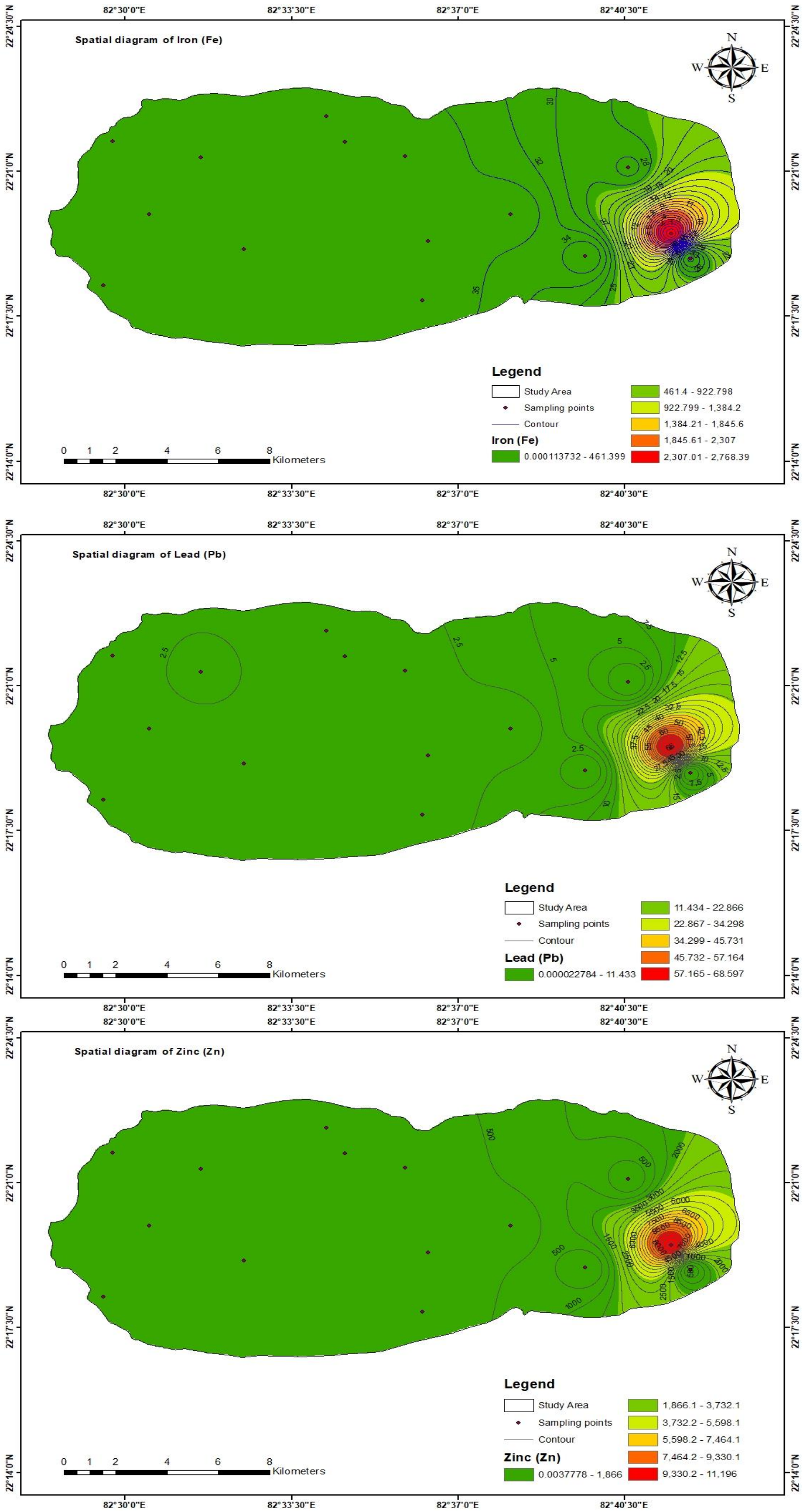
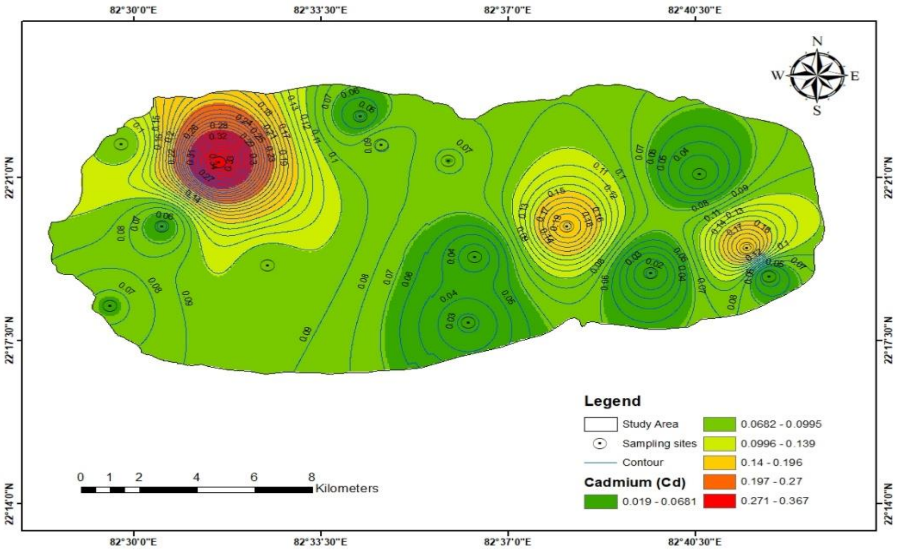
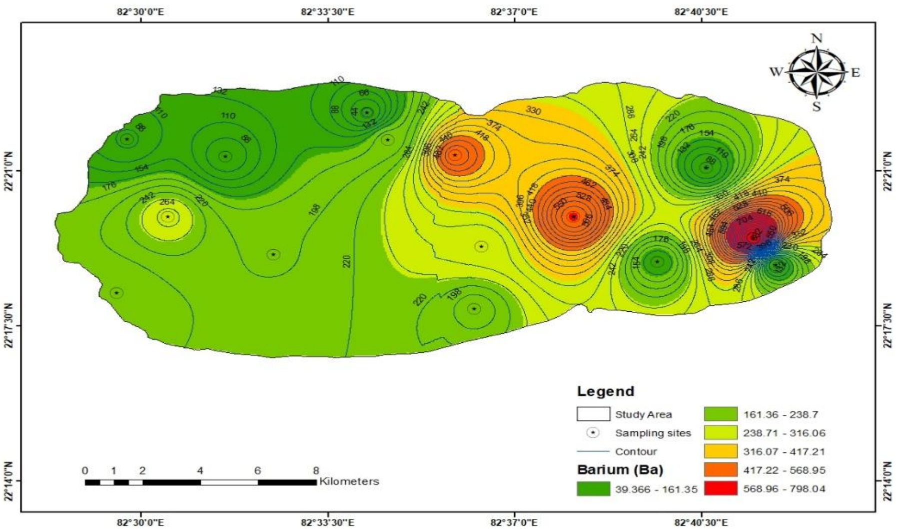

Spatial diagram of Iron (Fe)
Legend
Study Area
Sampling points
Contour
Iron (Fe)
0.000113732 - 461.399
461.4 - 922.798
922.799 - 1,384.2
1,384.21 - 1,845.6
1,845.61 - 2,307
2,307.01 - 2,768.39
Kilometers
Spatial diagram of Lead (Pb)
Legend
Study Area
Sampling points
Contour
Lead (Pb)
0.000022784 - 11.433
11.434 - 22.866
22.867 - 34.298
34.299 - 45.731
45.732 - 57.164
57.165 - 68.597
Kilometers
Spatial diagram of Zinc (Zn)
Legend
Study Area
Sampling points
Contour
Zinc (Zn)
0.0037778 - 1,866
1,866.1 - 3,732.1
3,732.2 - 5,598.1
5,598.2 - 7,464.1
7,464.2 - 9,330.1
9,330.2 - 11,196
Kilometers
82°30'0"E
82°33'30"E
82°37'0"E
82°40'30"E
22°24'30"N
22°21'0"N
22°17'30"N
22°14'0"N

Fig. cont....


82°30'0"E
82°33'30"E
82°37'0"E
82°40'30"E
22°21'0"N
22°17'30"N
22°14'0"N
Legend
Study Area
Sampling sites
Contour
Cadmium (Cd)
0.019 - 0.0681
0.0682 - 0.0995
0.0996 - 0.139
0.14 - 0.196
0.197 - 0.27
0.271 - 0.367
0 1 2 4 6 8
Kilometers


82°30'0"E
82°33'30"E
82°37'0"E
82°40'30"E
22°21'0"N
22°17'30"N
22°14'0"N
Legend
Study Area
Sampling sites
Contour
Barium (Ba)
39.366 - 161.35
161.36 - 238.7
238.71 - 316.06
316.07 - 417.21
417.22 - 568.95
568.96 - 798.04
0 1 2 4 6 8
Kilometers

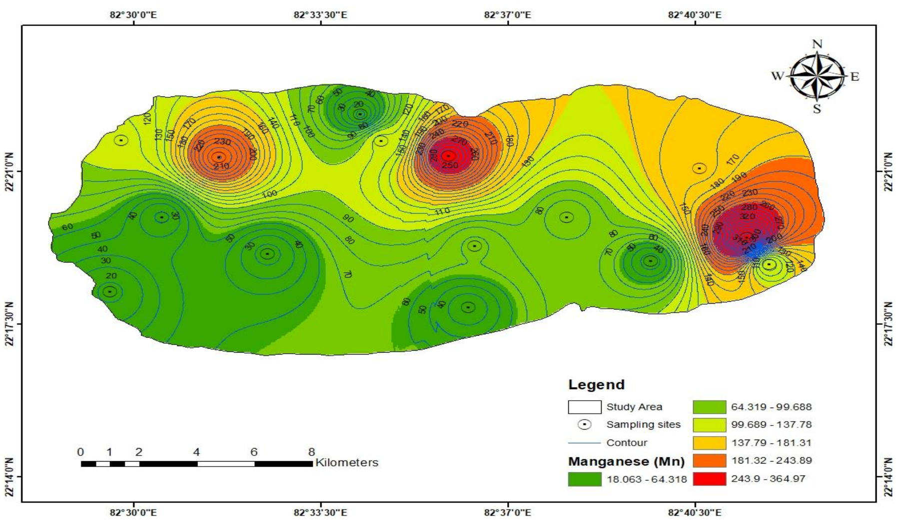

82°30'0"E
82°33'30"E
82°37'0"E
82°40'30"E
22°21'0"N
22°17'30"N
22°14'0"N
Legend
Study Area
Sampling sites
Contour
Manganese (Mn)
18.063 - 64.318
64.319 - 99.688
99.689 - 137.78
137.79 - 181.31
181.32 - 243.89
243.9 - 364.97
0 1 2 4 6 8
Kilometers

Fig. cont....

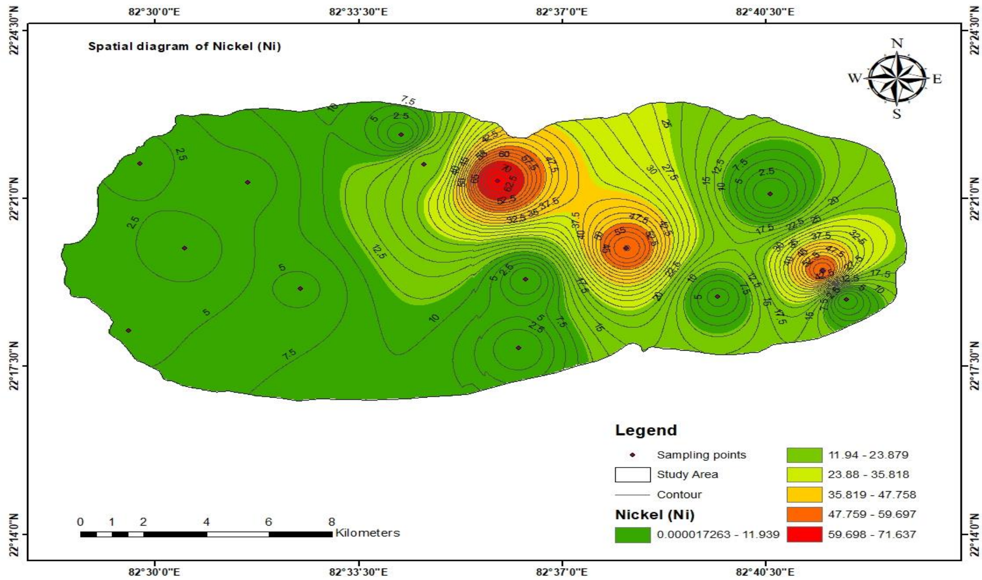


Fig. 4: Spatial distribution maps for pH, TDS, aluminum, iron, lead, zinc, cadmium, barium, manganese, and nickel respectively in the KCF region.

Table 1: Summary of dissolved metals compared with standard values specified by WHO (2006) and BIS (2012) (IS 10500) for drinking (unit: $\mu g.L^{-1}$) except pH & TDS.

Metals	Mean	Min	Max	Std. Dev.	WHO (2006)	BIS (2012) (IS 10500)		Percent Exceeded desirable limit	Percent Exceeded per. limit
						Requirement	Permissible limit		
pH	6.77	6.05	7.78	0.38	7.0-8.5	6.5-8.5	NR*	Nil	Nil
TDS	323.4	83	631	190.64	500-2000	500	2000	20%	Nil
Al	28.83	1.03	171.62	43.78	100-200	30	200	13.33%	Nil
Ba	242.37	39.36	798.4	214.97	300	700	NR*	20%	Nil
Cd	0.09	0.02	0.37	0.09	3	3	NR*	Nil	Nil
Fe	658.29	69.85	2769.6	709.29	300	300	NR*	Nil	6.67%
Mn	111.59	18.06	365.1	107.58	100	100	NR*	40%	6.67%
Pb	9.78	0.09	68.63	17.58	10	10	NR*	6.67%	Nil
Ni	24.86	1.13	71.65	24.96	20	20	NR*	26.67%	Nil
Zn	1078	13.01	11201.2	2880.55	4000	5000	15000	6.67%	Nil

NR*- No relaxation

such as Ba, Fe, Ni, Mn and Al exceeded their desirable limit in groundwater samples caused by mining and related activities such as leaching from overburden, dump materials & waste effluents from the coal mine. The concentration range of metals with mean value is expressed in $\mu g.L^{-1}$ is listed in Table 1. Origin 9 pro software was used to prepare the map for mean, maximum, and minimum values of metal presented by box-whisker plots are shown in Fig. 5. In case of three metal concentrations such as Al, Mn and Ni have exceeded their desirable limit at several locations as specified by BIS 2012 (IS 10500) and rest elements (Fe, Pb, Zn, Cd & Ba), also exceeded the desirable limit only at few locations.

The Mn concentration ranged between 18.06 to 365.09 $\mu g.L^{-1}$ with its mean value of 111.59 $\mu g.L^{-1}$, 46.67% of samples exceeded the desirable limit of 100 $\mu g.L^{-1}$ as per WHO (2006) & BIS 2012 (IS 10500) and only one sample (GW-10) exceeded the maximum permissible limit of 300 $\mu g.L^{-1}$ as per given by BIS 2012 (IS 10500).

The Ni concentration ranged between 1.3 $\mu g.L^{-1}$ to 71.65 $\mu g.L^{-1}$ with an average of 24.84 $\mu g.L^{-1}$. About 26.67%

(4 samples) of total groundwater samples exceeded its desirable limit as given by WHO (2006) & BIS 2012 (IS 10500). The rest of the four elements concentrations such as of Ba, Zn, Fe and Pb were determined of which 93.37% of groundwater were not exceeded the acceptable limit as specified by WHO (2006) & BIS 2012 (IS 10500) for drinking purposes and only 6.67% of all four elements concentration exceeded their desirable limits as per given by BIS (2012). The only one element i.e., Cd concentration was not exceeded its desirable limit and acceptable limit as per WHO (2006) & BIS 2012 (IS 10500) standards. 100% of groundwater samples lay within acceptable limits as given by WHO (2006) & BIS 2012 (IS 10500) in the pre-monsoon season.

Statistical Correlation of the Groundwater Quality Parameters

According to the correlation matrix between metal content and estimated HPI, Ni and pH have a strong negative correlation (r > -0.538). However, a strong positive correlation between Pb and Fe (r > 0.99), Zn and Fe (r > 0.995) and Zn and Pb (r > 0.998) were established. While HPI is positively correlated with Fe (r > 0.947), Pb (r >0.967), and Zn (r > 0.963) as listed in Table 2.

This high level of correlation indicates that Fe, Pb, and Zn loading has made a significant contribution to heavy metal concentration in various samples examined more than the other selected elements, and they were also responsible for the high level of HPI obtained for different sites in the study area, asserting that Fe, Pb, and Zn pollution in groundwater.

Hierarchical Cluster Analysis (HCA)

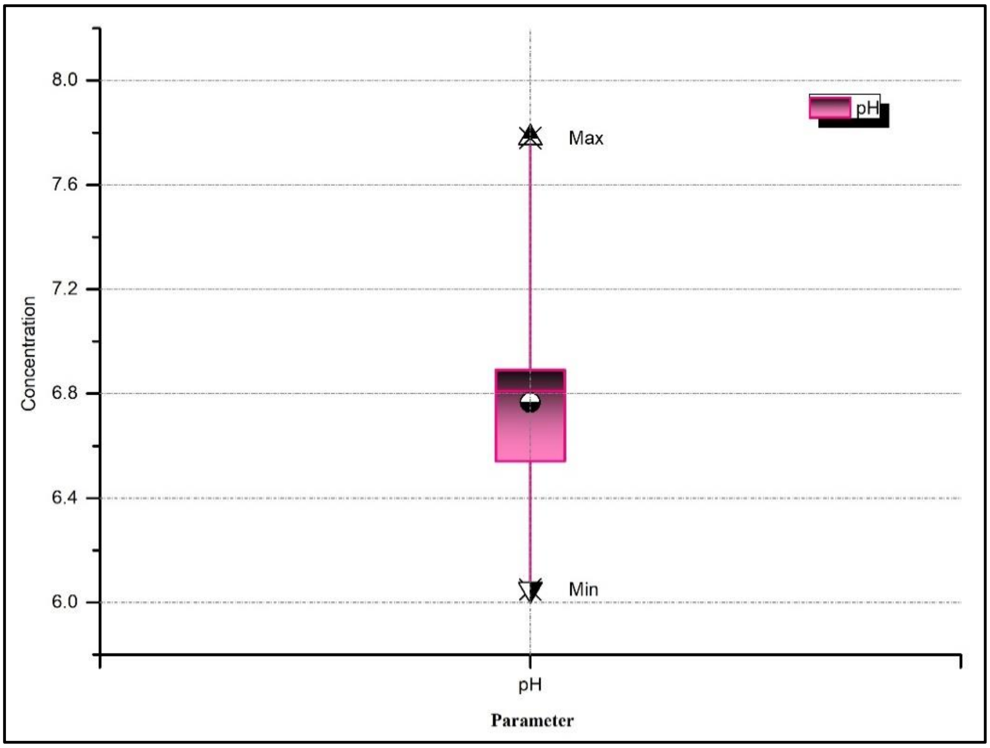
Cluster analysis is a set of multivariate approaches for identifying real data clusters or stations. Water sample classification and the development of geochemical models have both been done with the help of the effective geochemical data analysis technique known as HCA (Meng & Maynard 2001; Singh et al. 2005, 2016). After normalizing the data set to Z-scale, Ward's linkage approach (Ward 1963) was used to perform HCA on the heavy metal parameters of 15 groundwater samples using PAST 4.03 software as shown in Fig. 6. The dendrogram is split into different groups, each of which has several sub-groups and singletons. It might, however, be divided into two major clusters for the purposes of interpretation. Cluster-I is made up of 14 members, with the majority of the groundwater samples (GW- 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14 and 15) coming from the KCF region of Chhattisgarh, India. This group comprises 93.33 % of the water samples examined and is distinguished by relatively low Ba (<700 $\mu g.L^{-1}$), pH, TDS, Al, Fe, Cd, Mn, Pb, and Zn concentrations. Cluster-II is made up of 1 member, which is primarily made up of groundwater samples (GW-10) taken in the KCF region. The variable dendrogram reveals two major clusters. This category accounts for 6.67 % of all tested samples and is characterized by greater Ba (>700 $\mu g.L^{-1}$), TDS, Fe, Mn, Pb, and Zn concentrations. The higher concentrations in sample (GW-10) indicate that water quality has been influenced by mining and anthropogenic factors. Cluster-I consists of 10 metals such as pH, TDS, Al, Ba, Cd, Fe, Mn, Pb, and Ni. Cluster-II contains only Zn, which behaves differently than the other dissolved elements in groundwater.

Heavy Metal Pollution Index

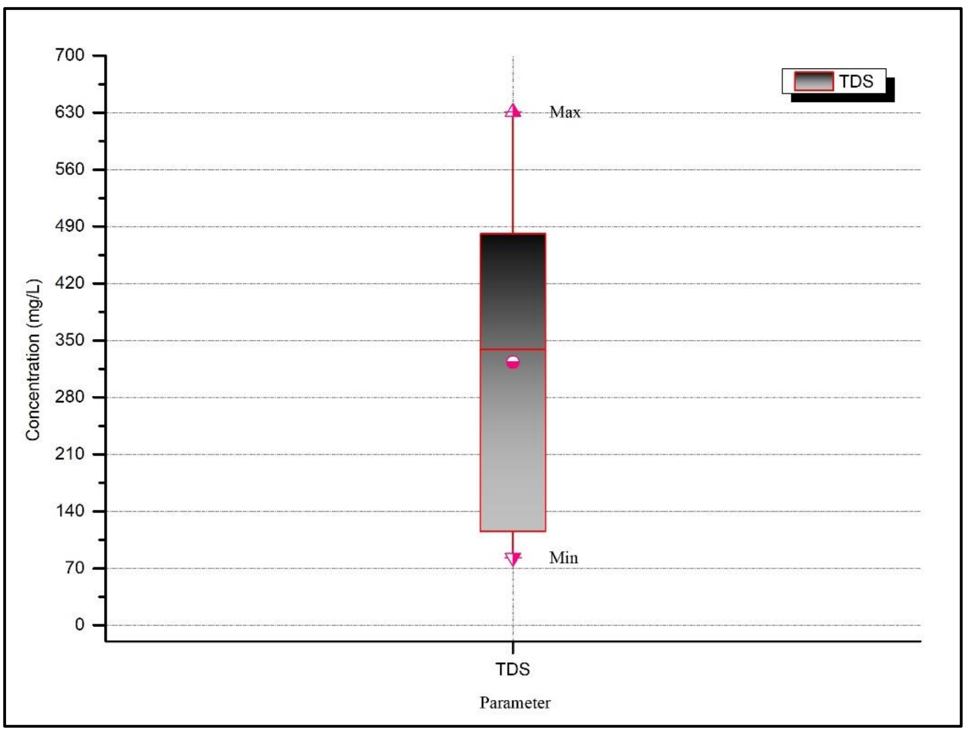
The concentration of heavy metals such as Al, Ba, Cd, Mn, Ni, Zn, Fe, and Pb was taken into account for the calculation of HPI of groundwater samples collected at the KCF mine. The HPI value was determined and ranges from 1.06 to 177.99 with a mean value of 21.52 (see Table 3). The

Table 2: Correlation matrix between heavy metals and calculated HPI of groundwater sample in KCF region, Chhattisgarh, India.

	pH	TDS	Al	Ba	Cd	Fe	Mn	Pb	Ni	Zn	HPI
pH	1.000										
TDS	-0.113	1.000									
Al	0.313	-0.252	1.000								
Ba	-0.368	0.198	-0.140	1.000							
Cd	-0.388	-0.040	-0.296	0.261	1.000						
Fe	-0.313	0.372	-0.145	0.684	0.266	1.000					
Mn	-0.429	0.176	-0.254	0.558	0.524	0.660	1.000				
Pb	-0.283	0.315	-0.132	0.715	0.339	0.990	0.682	1.000			
Ni	-0.538	-0.025	-0.164	0.853	0.296	0.427	0.636	0.456	1.000		
Zn	-0.302	0.341	-0.128	0.721	0.299	0.995	0.658	0.998	0.458	1.000	
HPI	-0.400	0.248	-0.166	0.838	0.400	0.947	0.759	0.967	0.665	0.963	1.000


8.0
7.6
7.2
6.8
6.4
6.0
Concentration
Max
Min
pH
pH
Parameter

(a) pH


700
630
560
490
420
350
280
210
140
70
0
Concentration (mg/L)
TDS
Max
Min
TDS
Parameter

(b)TDS

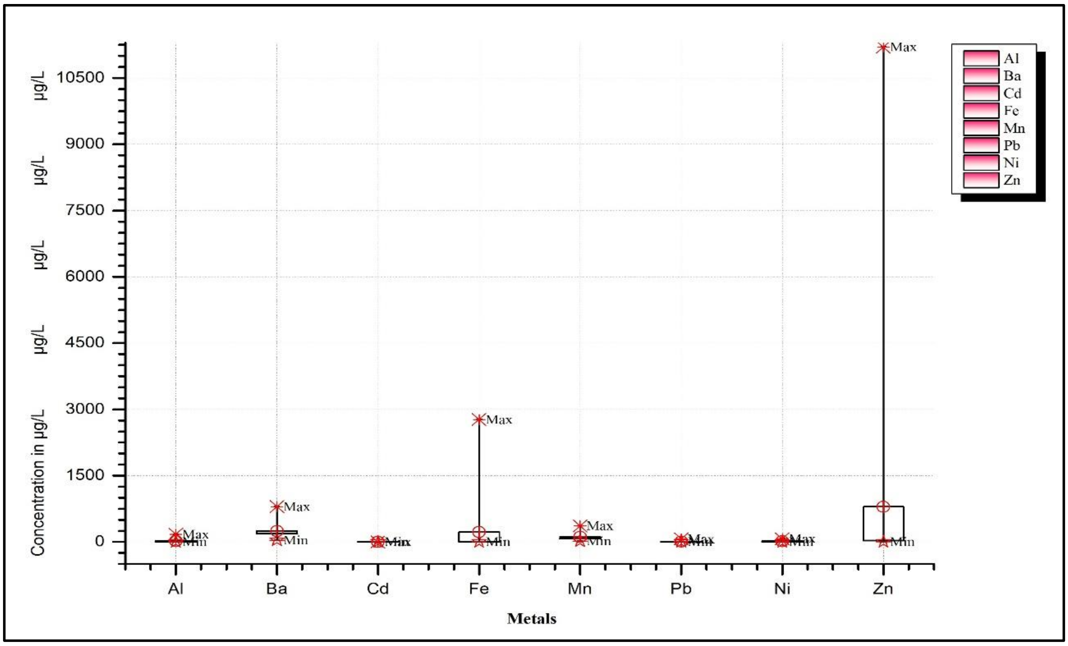


Fig. 5: Box-whisker plots for (a) pH, (b) TDS (unit in mg.L^{-1}), and (c) heavy metals (unit in µg.L^{-1}).

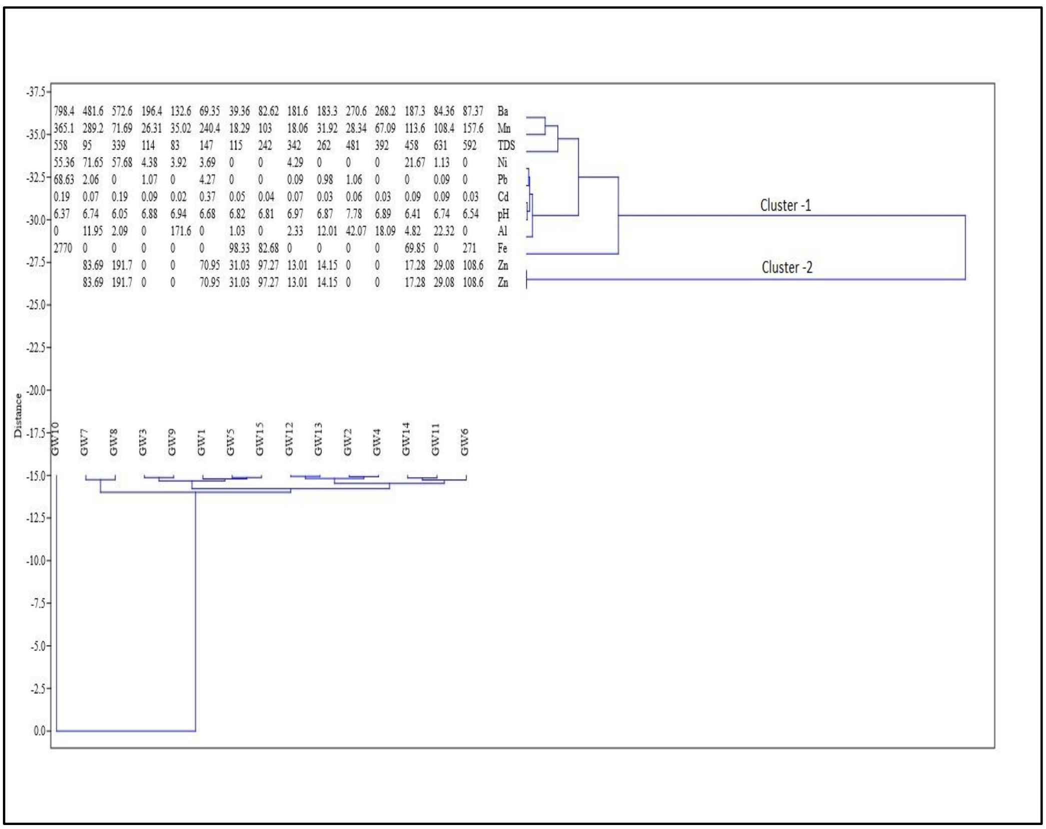


Fig. 6: Dendrogram map showing clustering metals variables and sampling sites.

Table 3: The calculated HPI value of the KCF region.

S No.	Sampling code	HPI values	Class
1.	GW-1	19.35	Medium
2.	GW-2	3.89	Low
3.	GW-3	6.91	Low
4.	GW-4	1.06	Low
5.	GW-5	1.79	Low
6.	GW-6	1.71	Low
7.	GW-7	42.69	High
8.	GW-8	33.82	High
9.	GW-9	3.52	Low
10.	GW-10	177.99	High
11.	GW-11	2.91	Low
12.	GW-12	4.36	Low
13.	GW-13	8.02	Low
14.	GW-14	13.38	Low
15.	GW-15	1.35	Low

calculated HPI was higher at three sites (GW-6, 7 & 10) in pre-monsoon (March 2022). The calculated HPI value for the study area (14 sites) comes within the critical pollution index of 100 and only one site (GW-10) HPI value exceeded the critical pollution index value.

With HPI calculation, it was found the result that 73.33% of groundwater samples have low HPI values, 6.67% of water samples had medium HPI, and the rest 20% lay in high HPI values. In the case of a high calculated HPI value, it was associated with open-cast mining with transportation routes only. The spatial distribution diagram of HPI drowns is shown in Fig 7. The groundwater of the eastern side of the selected study area has had high HPI value and some area of the KCF region was likely affected with high HPI values and the rest area were having low HPI value.

CONCLUSIONS

Based on pH concentration, the groundwater samples were close to being neutral to alkaline in nature. The groundwater is safe based on TDS concentration for drinking in the KCF region. The concentration of dissolved different elements like Al, Ba, Cd, Mn, Ni, Zn, Fe and Pb exceeded their desirable limits at a few locations only but their HPI values have laid within the critical pollution index value of 100 in the pre-monsoon season, KCF region Chhattisgarh. HPI has a positive correlation with Fe ($r > 0.9471$), Pb ($r > 0.9666$), and Zn ($r > 0.9634$), indicating that Fe, Pb, and Zn have contributed significantly to heavy metal concentrations in groundwater. A cluster analysis was also performed, and it was divided into two clusters. Cluster-1 contains 14 water samples (93.33 %) and is distinguished by low Ba

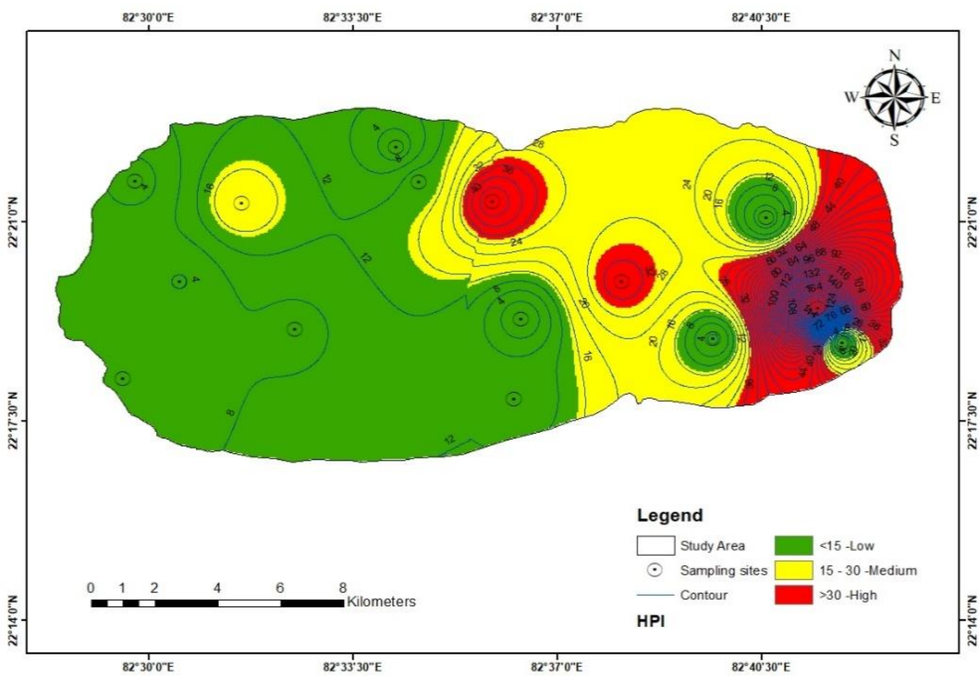


Fig. 7: Spatial distribution maps for HPI in the study region.

(700 μg.L^{-1}), pH, TDS, Al, Fe, Cd, Mn, Pb, Ni, and Zn concentrations. Cluster-II has one member (6.67 %), which is primarily made up of groundwater samples (GW-10) collected in the KCF region. An empirical evaluation system called the HPI is used to assess how particular metals generally affect the quality of water. With HPI calculation, it was found that 73.33% of groundwater samples have low HPI values, 6.67% of water samples had medium HPI, and the rest 20% lay in high HPI values. In the case of a high calculated HPI value, it was associated with open-cast mining with transportation routes only. The spatial distribution of HPI reflects that of metals, with high values of HPI in the eastern part of KCF region. It was discovered that the groundwater in the eastern part of the study area was most likely contaminated by heavy metal leaching from open-pit mining and transit routes. It was determined that the drinking water in the KCF region is of good quality in terms of heavy metals. Given the significant growth in socioeconomic activity in the study area, continuous monitoring of groundwater quality for heavy metals is deemed required.

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