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Assessment of Groundwater Quality of the Central Gangetic Plain Area of India Using Geospatial and WQI Techniques

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ABSTRACT

Suitability of water quality for the drinking and irrigation purposes is indispensable for the endurance of life and sustainability of the ecosystem. The present study is aimed to evaluate the groundwater quality for suitability of drinking and irrigation purposes in the central Gangetic plain area (Bhagarpur district, Bihar), India using the geo-spatial and waterqaulity index (WQI) techniques. Groundwater samples were collected randomly from 45 locations in the pre-monsoon (April -May) and post-monsoon (October-November) season respectively during the period between 2015 and 2016. The different major water quality parameters such as pH, Electrical Conductivity (EC), Total hardness, Calcium (Ca^{++}), Magnesium (Mg^{++}), Sodium(Na^+), Potassium (K^+), Chloride (Cl^-), Carbonate (CO_3^{--}), Bicarbonate (HCO_3^-), and Fluoride (F^-) were analyzed using standards methods. Sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) were estimated for suitability of irrigation uses. Pearson's correlation coefficient was calculated to measure the degree of relation between groundwater variables. The spatial variation maps of these groundwater quality parameters were generated through Inverse distance weightage (IDW) interpolation technique in Arc-GIS software. The pH value of 4.4% of the groundwater samples was found exceeding the acceptable limit established by the WHO (2011)/BIS (2012). Cl^- values ranges between 3.24 to 28.74 mg/l^{-1} in the pre-monsoon season and from 2.50 to 64.98 mg/l^{-1} in post-monsoon season. Magnesium are cross the limits (<50 mg/l^{-1}) of WHO/BIS in both the pre- and post-monsoon seasons. The F^- concentration is higher in both the pre-monsoon and post-monsoon season. The water quality index (WQI) indicates 4.44% of the pre-monsoon samples are good for drinking purposes, whereas the value increases to 31.11% during the post-monsoon in the study area. The higher value of RSC was portrayed in the entire Naugachhia block and the eastern part of the Goradih block for both the season. The higher concentration of sodicity problem is portrayed in the entire Goradih block, north-east of Gopalpur block, and south-west of Naugachhia block for both the pre-monsoon and post-monsoon season. These results will be help planners, decision makers, local peoples, and Government to take necessary measures.

INTRODUCTION

The quality of water is a vital concern for mankind since it is directly linked to human welfare (Mahalingam et al., 2014). In India, only 12% of people can access the good quality of drinking water (Singh et al., 2015). Groundwater is the most important source of water for human activities and is being threatened as a consequence of development and anthropogenic activities (Verma et al. 2017). Ascertaining the quality is crucial before its use for various purposes such as drinking; agricultural, recreational and industrial uses (Selvam et al., 2015; Mahato et al. 2016; Tiwari et al. 2017). Bhagalpur district in Bihar (India) is experiencing declining groundwater levels due to over-exploitation and is directly affected by arsenic contamination (Gouri and Choudhary, 2017). As per the report of Central Ground Water Board, (2009) 25.53% out of 35.01% of irrigated use. Several studies have been conducted in India to regulate the suitability of water for drinking and irrigational use (Kalpana and Elango 2013; Brindha and Kavitha, 2015).

The present investigation was undertaken to study the physico-chemical characteristics of the groundwater of Bhagalpur district (Bihar, India). The objective of the study is to understand the spatial and seasonal distribution of the various hydro-chemical parameters of the groundwater using the GIS. Consequently, the hydro-chemical observation of the groundwater permits us to attain imperative information on chemical weathering of rocks. The characteristics such as electrical conductivity(EC), pH, calcium (Ca^{2+}), magnesium (Mg^{2+}),sodium (Na^+), potassium (K^+), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-), fluoride (F^-), Hardness, sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) were studied. The information derived in this study may be helpful to locate groundwater quality zones suitable for different usages such as irrigation and domestic purposes.

MATERIALS AND METHODS

Study Area

The study area lies between the 25°06'561" N and 36°56'917" E, situated at 141feet above the sea level. Five blocks, namely Naugachhia, Rangra Chowk, Gopalpur, Sabour and Goradih blocks of Bhagalpur district were selected to collect the water samples. Generally, the eastern and north-eastern parts of the district received the higher amount of rainfall. The monthly temperature ranges from 29°C to 44°C, with the annual mean temperature is 31°C.The study area consists of mainly alluvial soil formation and the surface soils comprise mostly of ferruginous lime quartzite, granites, and schistose rock minerals (Verma et al. 2015). Pearl millet is the main rainy season crop along with guar, chickpea, and green gram.

Sample Collection and Analysis

Water samples were collected randomly from the dug wells (open well), hand pumps, submersible pump and deep tube well for two different seasons: pre-monsoon (April-May) and post-monsoon (October-November) season for the year of 2015 and 2016 respectively. Water samples were collected from the 45 sampling sites (Fig.1) both

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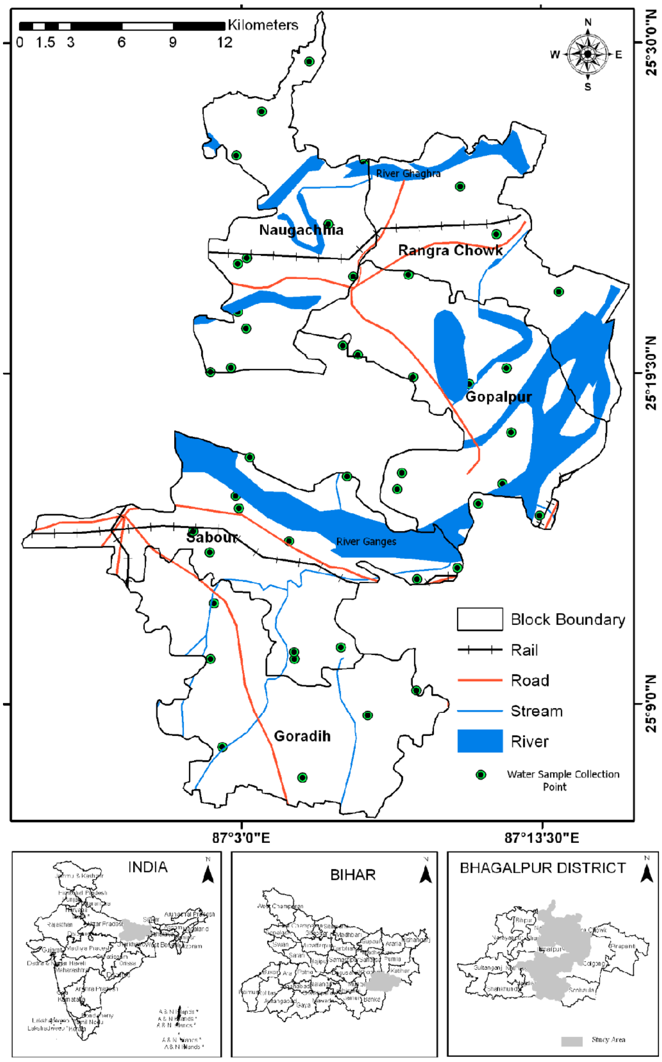

Fig.1. Location map of the study area (Central Gangetic Plain Area, India)

in the pre-monsoon and post-monsoon season respectively. The coordinates of each sampling location were recorded using a handheld Global Positioning System (GPS, GARMIN International Inc., Kansas, USA). The samples were placid in polythene containers of one liter capacity for hydro-chemical analysis after pumping out an adequate amount of water from the source. Water samples were stored in narrow mouth plastic sampling bottle and after sample collection; bottles were sealedon site with proper labeling.

Laboratory Measurement

The water samples were stowed at a temperature less than 4°C prior to analysis in the laboratory. Electrical conductivity (EC) and pH values were measured in the field using a portable conductivity and pH meter. In the laboratory, the water samples were filtered through 0.45 lm Millipore membrane filters to separate suspended particles. Acid titrations were used to determine the concentration of bicarbonate; carbonate (CO_3^{2-}) and Mohr's titration methods were used to determine the concentration of chloride in groundwater. Concentrations ofmajor anions (F^-) were determined by UV spectrophotometer. Concentration of major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) was determined by flame photometry and flame atomic absorption spectrophotometer(AAS).The initial hydro-chemical characteristics of groundwater samples and quality of drinking and irrigation water were determined using the standard analytical methods followed by American Public Health Association(APHA, 2000).

Estimation of Water Quality Index (WQI)

For calculation of water quality index (WQI) weighted arithmetic quality mean method has been adopted and following three steps have been followed (Krishna Kumar et al., 2015). In the first step, each of the twelve parameters has been assigned a weight (W_i) according to its relative importance in the overall quality of water for drinking water. The maximum weight of '5' has been assigned for its major importance in water quality assessment and the minimum weight of '1' has been given for its less importance. In the second step, the relative weight is computed from the following equation:

$$W_i = \frac{w_i}{\Sigma_{i=1}^{n} w_i}$$

Where, W_i = relative weight, w_i = Weight of each parameter, n = the number of parameters

In the third step, a quality rating scale (q_i) for each parameter is assigned by dividing its concentration in each water sample by its respective standard according to the guidelines laid down in the WHO standard (2006) and the result multiplied by 100:

$$q_i = \frac{C_i}{S_i} \times 100$$

Where, q_i = quality rating, C_i = concentration of each hydro-chemical parameter in each water sample in mg/l, S_i = Sub-index of i^{th} parameter for each hydro-chemical parameter in mg/l according to BIS standard that can be calculated as:

$$SI_i = W_i * q_i$$

For calculating WQI, SI was determined for each parameter. Finally, WQI can be calculated through sum of SI values for each sample using the equation:

$$WQI = \Sigma_{i=1}^{n} SI_i$$

Spatial and Geo-statistical Analysis

The base map of the Bhagalpur district was digitized from the Census of India map (2011) using ArcGIS software v.9.3. A point layer is prepared based on the sampling points during the period of pre-monsoon and post-monsoon season collected through GPS in GIS platform. The geographical distribution of the hydro-chemical characteristics of groundwater was executed with the assistance of spatial analyst modules in ArcGIS v9.3 software.

Spatial distribution map of water quality parameters was prepared using ArcGIS v.9.3 with spatial statistical analyst module and the inverse distance weighted (IDW) interpolation technique. IDW interpolation method was chosen for spatial modelling to regulate cell values via a linearly weighted combination of a regular sample point (Adhikary et al. 2011, 2012; Bhunia et al. 2018). The weight is a function of reverse space and the output value for a cell using IDW is inadequate to the range of the input values used to interpolate. The method implemented at an acceptable level for envisaging soil properties in gentle landscape. The sampling locations of the adjoining neighboring samples generating the best covenant between the observed data and the estimates through this method (Yao et al., 2013). The general equation of the IDW method has the following form:

$$Z_0 = \frac{\sum_{i=1}^{s} Z_i \frac{1}{d_i^k}}{\sum_{i=1}^{s} Z_i \frac{1}{d_i^k}}$$

Where, Z_0 = the estimated value at point 0, Z_i = the Z value at point i, d_i= the distance between point i and point 0, s = number of known points used in the estimation, k = specified power.

As the IDW is a weighted distance average, the average cannot be more than the highest or less than the lowest input. The paramount outcomes from IDW are attained when sampling is appropriately dense to epitomize the limited discrepancy that prerequisites to be replicated (Selvam et al., 2015). Accordingly, the IDW method is best for examination in respect of water quality data from numerous sampling points compactly spacious.

Validation

Root Mean Square Error (RMSE) is employed to scrutinize the best fit of the model by evaluating its value, and the smallest value of RMSE determines the most suitable model to the data. Accurate predictions have a value close to zero. For each water quality parameter, prediction performances were assessed by cross-validation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[Z(x_i) - Z^*(x_i)]^2}$$

In this research, the procedure for the application of methodology in the framework of GIS software for spatial analysis of groundwater quality index is illustrated in Fig.2, and the following steps (Mehrjardi et al. 2008) were followed: (i) Exploratory spatial data analysis (ESDA) was performed using ArcGIS v9.0 software for the groundwater chemistry and to study the spatial distribution of the data. (ii) Spatial interpolation for groundwater chemistry data was performed using ArcGIS v9.0 software, and the IDW model was used to generation of the groundwater chemistry maps.

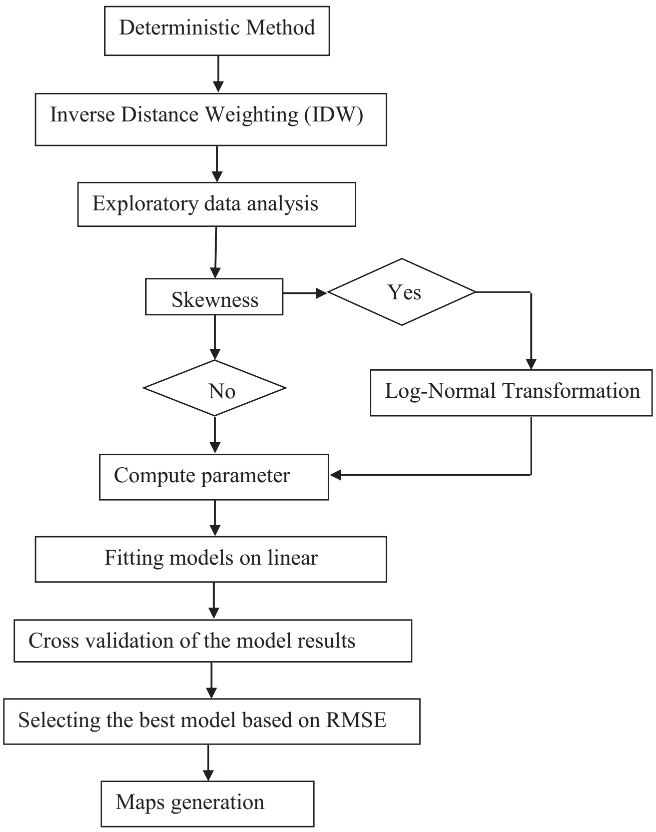

Fig.2. Flow chart of the steps followed for the deterministic analysis

RESULT AND DISCUSSION

Hydro-chemical Properties of Groundwater

The evaluation of concentration of hydro-chemical parameters such as pH, EC, Cl^-, HCO_3^-, F^- (ppm), Hardness, Ca^{++} (mg/l^{-1}), Mg^{++} (mg/l^{-1}), Na^{++} (mg/l^{-1}), K^+ (mg/l^{-1}), SAR, RSC in two season of Naugachhia, Rangra Chowk, Gopalpur, Sabour and Goradih blocks of Bhagalpur district. Maximum, minimum, mean and their standard deviation values of the analyzed variables of groundwater samples and drinking water standards are summarized in Table 1. Chemical parameters for the groundwater samples result were compared with the standard guideline values recommended by WHO (2011) (Table 2). The mean concentration of pH, EC, Cl^-, HCO_3^-, F^- (ppm), hardness, Ca^{++}, Mg^{++}(mg/l), Na^{++}(mg/l), K^+ (mg/l), SAR, RSC were 7.96,1.10, 14.89, 0.01, 1.71, 371.02, 97.46, 66.75, 10.66,2.91, 1.19, and -64.19 which include total 45 groundwater sampling points for two seasons of the year.

Acidity or basicity of a solution is determined by its pH which or this area ranged from 7.32 to 8.67 in pre-monsoon season and from 6.17 to 7.67 in the post-monsoon season. In the study area, 4.4% of groundwater samples were found exceeding the acceptable limit of WHO/BIS. In pre-monsoon season, the water in this area was slightly alkaline. High pH value persuades the development of trihalomethanes which are toxic and possesses carbonates (Shrivastava and Patil, 2002). Electrical conductivity (EC) in groundwater varies from 0.63 to 1.65 dsm^{-1} in pre-monsoon and from 0.28 to 1.21 dsm^{-1}in the post-monsoon season. EC is a good indicator of the concentration of total dissolved solids and major ions in groundwater. Chloride (Cl^-) is not adsorbed or held back by soils, therefore it moves readily with the soil-water. Cl^- concentration in groundwater found under the permissible limit in the pre and post-monsoon seasons of Bhagalpur district. Cl^- values ranges between 3.24 to 28.74 mg/l^{-1}(average14.89 mg/$l^{"1}$) in pre-monsoon season and 2.50 to 64.98 mg/l^{-1}(average 19.61 mg/$l^{"1}$) in post monsoon season. The most common toxicity from chloride is affected through irrigation water in the study area. Dissolution of salt accumulations, seawater intrusion and irrigation reoccurrence movement are normally liable for the growing chloride content in the groundwater (Verma et al. 2015). The excess of fluoride in groundwater reduce the quality of water. The observed fluoride value in pre-monsoon ranges between 0.25 to 4.57 ppm (mean±S.D.- 1.71±1.01) and 0.04

Table 1. Descriptive statistics of ground water variables in Pre-monsoon and Post-monsoon season

Parameters	Pre-monsoon							Post-monsoon						
	Mean	S.D.	Min.	Max.	Kurtosis	Skewness	95% CI	Mean	S.D.	Min.	Max.	Kurtosis	Skewness	95% CI
pH	7.96	0.29	7.32	8.67	-0.21	0.22	0.09	6.89	0.43	6.16	7.67	-1.2	0.25	0.13
EC (dsm^{-1})	1.1	0.28	0.63	1.65	-0.58	0.61	0.08	0.71	0.24	0.28	1.21	-0.28	0.5	0.07
Cl^- (mg/l)	14.89	6.95	3.25	28.74	-0.58	0.61	2.09	19.61	16.67	2.5	64.98	0.53	1.07	5.01
HCO_3^-	0.01	0.01	0	0.04	0.23	0.8	0.01	0.01	0.01	0.01	0.02	1.64	1.25	0
F^- (ppm)	1.71	1.01	0.25	4.57	0.95	0.96	0.3	1.48	1.00	0.04	4.32	1.18	1.02	0.3
Hardness	371.02	70.91	178	490	-0.01	-0.64	21.3	291.9	80.57	108	426	-0.83	-0.18	24.21
Ca^{++} (mg/l)	97.46	25.1	52.1	151.5	-0.49	0.21	7.54	78.7	23.46	40.88	131.46	-0.43	0.35	7.05
Mg^{++} (mg/l)	66.75	15.25	21.72	88.85	1.32	-1.19	4.58	52	18.08	6.79	78.24	-0.16	-0.51	5.43
Na^{++} (mg/l)	10.66	4.57	3.8	22.9	-0.46	0.59	1.37	8.6	4.09	2.8	18.5	-0.69	0.56	1.23
K^+ (mg/l)	2.91	1.05	0.5	5.1	-0.62	-0.25	0.31	2.33	0.98	0.3	4.7	-0.54	0.03	0.29
SAR	1.19	0.51	0.43	2.26	-0.89	0.5	0.15	1.08	0.51	0.38	2.21	-0.85	0.51	0.15
RSC	-164.19	31.34	-229	-101.4	-0.48	-0.04	9.42	-131	31.43	-189.66	-64.21	-0.68	-0.22	9.44

Table 2. Comparison of groundwater samples with BIS and WHO standards

Parameters	Bureau of Indian standards (2012)		World Health Organization Standard (2011)		% of Samples above Maximum Permissible limit	
	Highest desirable limit	Maximum Permissible limit	Highest desirable limit	Maximum Permissible limit	Monsoon	
					Pre-	Post-
pH	6.5 -8.5	6.5 -9.2	6.5 – 8.5	6.5 -9.2	4	Nil
EC (dS/m)	1.5	3.0	1.5	3.0	Nil	Nil
Cl^- (mg L^{-1})	250	1000	200	600	Nil	Nil
HCO_3^-	-	-	-	500	Nil	Nil
F^- (mg L^{-1})	-	-	-	1.5	51	40
Hardness	200	600	-	500	Nil	Nil
Ca^{2+} (mg L^{-1})	75	200	75	200	Nil	Nil
Mg^{2+} (mg L^{-1})	30	100	50	100	Nil	Nil
Na^+ (mg L^{-1})	-	-	-	200	Nil	Nil
K^+ (mg L^{-1})	-	-	-	10	Nil	Nil

to 4.32 ppm (mean±S.D.- 1.48±1.00) in pre-monsoon season and post-monsoon respectively.53% of the total samples in pre-monsoon and post-monsoon season was recorded exceeding the acceptable limits of WHO/BIS standards. It may be due to the dissolution of micaceous content in the alluvium. Much of the fluoride content entering the human body causes mild type of dental fluorosis (Amalraj and Pius, 2013). The concentration of bicarbonate varies from 0.0 to 0.04 mg/l in pre-monsoon and from 0.0 to 0.02 mg/l in post-monsoon season. The bicarbonates are perhaps acquired from weathering of silicate rocks, dissolution of carbonate precipitates atmospheric and soil CO_2 gas (Tiwari and Singh, 2014). The total hardness of the groundwater samples was calculated between 178.0 to 490.0 mg/l and 108.0 to 426.0 mg/l in pre-monsoon and post-monsoon season respectively. The Calcium (Ca^{++}) and Magnesium (Mg^{++}) ions existent in the groundwater are probably attained from percolating of calcium and magnesium-bearing, rock-forming silicates, dolomite, limestone, gypsum and anhydrides (Adhikary et al. 2012; Sharma et al. 2017). Calcium is one of the most sample constituent observe in normal water in higher magnitudes in the rocks. The concentration of Ca^{++} varied from 52.10 to 151.50 mg/l^{-1} (mean±S.D.- 97.46±25.1) and 40.88 to 131.46 mg/l^{-1} (mean±S.D.- 78.75±23.46) in pre-monsoon and the post-monsoon season respectively. The concentration of Mg^{++} was estimated between 21.72 and 88.85 mg/l^{-1}in pre-monsoon and between 6.79 and 78.24 mg/l^{-1}in post-monsoon season. Magnesium exceed the permissible limit (<50 mg/l^{-1} according to WHO / BIS) in both pre and post-monsoon season.86.67 % of the Mg^{++} exceeds the permissible limit prescribed by WHO in pre-monsoon season. High absorption of Mg^{++} may intensification the hardness of water, the possessions of which were elucidated past. The sodium (Na^+) content in the study area has shown variations from 3.80 to 22.90 mg/l in pre-monsoon and 2.80 to 18.50 mg/l in in post monsoon season. The high concentration of Na^+ among the cationic concentrations reflects dissolution of soil salts stored by the influence of evaporation. The high concentrations of Na^+ suggest river water percolation in the Gangetic plain. Sodium adsorption ratio (SAR) and Residual sodium carbonate (RSC) represent the quality of water for the use of irrigation purposes. The observed value of the SAR ranges between 0.46 to 2.26 in pre-monsoon and 0.38 to 2.21 in post monsoon season. RSC contemplates the concentrations of calcium, magnesium, carbonate and bicarbonate of water (Eaton, 1950). The observed RSC values in the study area is varied from -229.18 to -101.36 in pre-monsoon and -189.66 to -64.21 in the post-monsoon season. The higher RSC value in water clues to an increase in the absorption of sodium on soil particles (Eaton, 1950).

Correlation Analysis

The pearson's correlation coefficient was calculated to measure the degree of relation between groundwater quality variables. The greater the value of correlation coefficient is better and more useful the regression variables (Patil and Patil, 2010). The high positive correlation was observed in pre-monsoon period between Ca^{++} and Hardness (r = 0.492), EC and Cl^- (r =1.00), Mg^{++} and Hardness (r = 0.937), SAR and Na^+ (r = 0.960), RSC and Hardness (r = 0.850), RSC and Mg^{++} (r = 0.612) at 0.005 level of significant (Table 3).

In post-monsoon period highly positive correlation coefficient was found between Ca^{++} and Hardness (r = 0.411), Mg^{++} and Hardness (r= 0.957), SAR and Na^+ (r= 0.955), RSC and Ca^{++} (r= 0.822), RSC and Mg^{++} (r= 0.673), and RSC and Hardness (r= 0.858). The results indicate that the physico-chemical parameters of good to moderate quality for irrigation and correlation among the variables shown in Table 4.

Table 3. Pearson's correlation coefficient of groundwater quality (Pre-monsoon period)

Parameters	pH	EC	Cl^-	HCO_3^-	F^-	Hardness	Ca^{++}	Mg^{++}	Na^{++}	K^+	SAR	RSC
pH	1.000	0.231	0.231	0.280	0.455	0.147	0.330	0.034	0.157	0.101	0.076	0.281
EC		1.000	1.000	0.027	0.059	0.041	0.040	0.030	0.033	0.182	0.035	0.047
Cl^-			1.000	0.027	0.059	0.041	0.040	0.030	0.033	0.182	0.035	0.047
HCO_3				1.000	0.049	0.121	0.154	0.076	0.223	0.139	0.158	0.160
F^-					1.000	0.167	0.037	0.174	0.058	0.021	0.015	0.114
Hardness						1.000	0.492	0.937	0.065	0.288	0.164	0.850
Ca^{++}							1.000	0.156	0.201	0.073	0.025	0.877
Mg^{++}								1.000	0.007	0.356	0.176	0.612
Na^{++}									1.000	0.125	0.960	0.158
K^+										1.000	0.172	0.114
SAR											1.000	0.106
RSC												1.000

Table 4. Pearson's correlation coefficient of groundwater quality (Post-monsoon period)

Parameters	pH	EC	Cl^-	HCO_3^-	F^-	Hardness	Ca^{++}	Mg^{++}	Na^{++}	K^+	SAR	RSC
pH	1.000	0.320	0.057	0.140	0.449	0.241	0.232	0.188	0.106	0.211	0.026	0.281
EC		1.000	0.191	0.001	0.100	0.071	0.019	0.071	0.233	0.110	0.219	0.055
Cl^-			1.000	0.137	0.005	0.187	0.004	0.202	0.014	0.040	0.064	0.119
HCO_3^-				1.000	0.086	0.058	0.134	0.020	0.190	0.091	0.135	0.112
F^-					1.000	0.243	0.025	0.257	0.061	0.070	0.008	0.166
Hardness						1.000	0.411	0.957	0.207	0.244	0.029	0.858
Ca^{++}							1.000	0.131	0.122	0.058	0.102	0.822
Mg^{++}								1.000	0.186	0.284	0.001	0.673
Na^{++}									1.000	0.066	0.955	0.198
K^+										1.000	0.116	0.120
SAR											1.000	0.075
RSC												1.000

Principal component analysis (PCA)

PCA is powerful techniques for pattern recognition that association between variables of a large set of data. PCA extracts the eigen values and eigenvectors from the covariance matrix of original variables through reducing dimensionality of variables. PCA was executed on the correlation matrix of the groundwater dataset, with the intention of identifying a reduced set of factors that could capture the variance of a dataset. Table 5 and 6 summarizes the PCA results including the loading, eigen values and variance elucidated by each principal component (PCs) of pre-monsoon and post- monsoon session respectively. Finally, it was concluded that PCA analysis yielded five principal components of which PC1 and PC2 accounting for 55.34 and 23.45% of total variance respectively are mainly responsible for controlling geochemistry of groundwater with both session. This is because 67.8% of physico-chemical parameters analyzed in the study area and have strong loading fall under these two components.

The pH

The study blocks have been categorized into five classes of pH value based on the geometric interval, such as <6.4, 6.4 – 6.7, 6.7 – 7.0, 7.0 – 7.4 and >7.4. The lower value of pH (less than 6.4) was observed in the Goradih block, south of Sabour block, south of Gopalpur, west and north-west of Naugachhia block in pre-monsoon season (Fig 3). In post-monsoon season, the lower pH value was recorded in west and north-west of Naugachhia block, north-west of Sabour block, and east of the Goradih block (Table 7). The RMSE value for the pH is estimated of 0.32 and 0.42 for the pre-monsoon and post-monsoon season respectively (Table 7).

Electrical conductivity (EC)

The geographical dissemination of EC within the study area has been illustrated in Fig.4. In pre-monsoon season, the distribution of EC was observed in north and north-west part of Goradih block, south of Sabour block, north-east of Gopalpur block, and small pockets of east Naugachhia block. I post-monsoon season, the higher concentration of EC was observed in the central part of Naugachhia block, east of the Gopalpur block, south-east of Rangra Chowk block and south of Sabour block. The result of the analysis also showed the similar location for the higher concentration of EC in both the season (Table 7). The lower concentration of EC was observed in the west of Naugachhia block and south of Goradih block in pre-monsoon season. Consequently, the lower concentration of EC was portrayed in the north-west of Naugachhia block, north-east of Gopalpur block, and south of Goradih block in the post-monsoon season. Higher EC value may be the clue of river water intrusion in the study area. The result also showed the general increase in salinity in Gopalpur and Rangra Chowk block during the post-monsoon season. The RMSE value of the IDW model is calculated as 0.31 for both the pre-monsoon and post-monsoon season (Table 8). However, the spatial variation of EC can be attributed mainly to the accumulative influence of riverine flood, chemical fertilizers, and pesticides being used in enormous magnitudes to increase the agricultural production (Goyal and Chaudhary, 2010).

Table 5. Loadings of experimental variables on principal components eigen value and variances for groundwater dataset in Pre-monsson period

Variables	Principal components				
	PC1	PC2	PC3	PC4	PC5
pH	0.213	-0.021	0.182	0.167	-0.166
EC	0.168	-0.574	0.343	0.018	0.06
Cl^-	0.168	-0.574	0.343	0.018	0.06
CO_3^-	-0.283	-0.275	-0.261	-0.618	0.248
HCO_3^-	-0.135	-0.116	-0.115	0.111	0.127
F^- (ppm)	0.134	0.01	0.01	0.202	-0.47
Hardness	-0.46	-0.032	-0.032	0.173	0.119
Ca^{++}	-0.399	-0.123	-0.123	-0.069	-0.591
Mg^{++} mg/L	-0.368	0.011	0.011	0.222	0.361
Na^{++} mg/L	-0.101	-0.284	-0.284	0.344	-0.015
K^+ mg/L	0.1	-0.218	-0.218	-0.414	-0.297
SAR	0.028	-0.316	-0.316	0.4	0.043
RSC	0.505	0.091	0.091	-0.059	0.288

Table 6 Loadings of experimental variables on principal components eigen value and variances for groundwater dataset in Post-monsoon period

Variables	Principal components				
	PC1	PC2	PC3	PC4	PC5
pH	0.327	-0.04	0.637	0.237	0.302
EC	0.11	-0.228	0.369	-0.088	-0.047
Cl^-	-0.123	-0.158	0.351	-0.726	-0.159
CO_3^-	-0.001	0.010	0.010	-0.001	-0.001
HCO_3^-	-0.108	0.132	0.133	-0.23	-0.604
F^- (ppm)	0.192	0.009	0.415	0.17	-0.187
Hardness	-0.485	-0.135	0.152	0.023	0.262
Ca^{++}	-0.326	-0.113	0.104	0.454	-0.456
Mg^{++} mg/L	-0.418	-0.11	0.131	-0.114	0.419
Na^{++} mg/L	-0.229	0.648	0.183	0.002	0.049
K^+ mg/L	0.115	0.089	0.138	0.186	-0.114
SAR	-0.076	0.641	0.126	-0.053	0.083
RSC	0.48	0.145	-0.153	-0.265	0.087

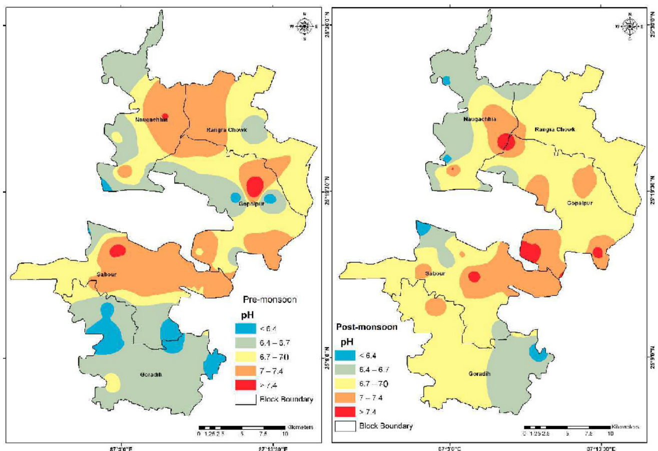

Fig.3. Spatial variation of pH **(a)** Pre-monsoon (left), and **(b)** Post-monsoon (right)

Chloride (Cl^{-1})

High concentration of chloride in groundwater used to instigate from natural as well as anthropogenic causes. Spatial distribution of chloride in pre-monsoon and post-monsoon season is portrayed in Fig.5. The study area has been categorized into five classes, namely (i) less than 5.0 mg/l^{-1} (ii) 5.0 – 9.6 mg/l^{-1} (iii) 9.6 – 18.0 mg/l^{-1}, (iv)

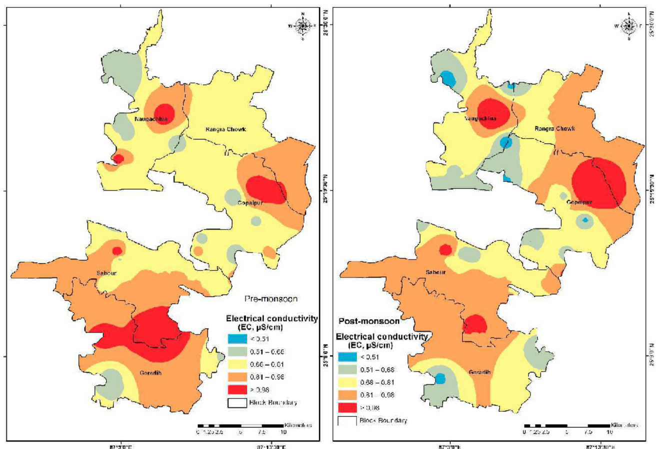

Fig. 4 Spatial variation of EC **(a)** Pre-monsoon (left), and **(b)** Post-monsoon (right)

Table 7 Delineated area under different concentration limits of groundwater quality parameters for irrigation purpose in the study area

Parameters	Concentration limits	Pre-monsoon season		Post-monsoon season	
		Area (km^2)	Area (%)	Area (km^2)	Area (%)
EC (dsm^{-1})	<0.51	0.34	0.05	4.65	0.72
	0.51-0.68	8.87	1.37	13.02	2.01
	0.68-0.81	378.58	58.53	277.96	42.98
	0.81-0.98	212.32	32.83	309.21	47.81
	>0.98	46.66	7.21	41.93	6.48
	<0.51	0.34	0.05	4.65	0.72
pH	<6.4	35.98	5.56	12.53	1.94
	6.4-6.7	188.32	29.12	123.41	19.08
	6.7-7.0	262.36	40.56	398.25	61.58
	7.0-7.4	151.58	23.44	97.41	15.06
	>7.4	8.53	1.32	15.17	2.35
HCO_3^-	<0.0022	7.42	1.15	40.09	6.20
	0.0022-0.0035	119.36	18.45	88.36	13.66
	0.0035-0.0057	412.98	63.85	389.69	60.25
	0.0057-0.0095	86.23	13.33	102.32	15.82
	>0.0095	20.78	3.21	26.31	4.07
Cl^- (mg/l)	<5.00	0.62	0.10	6.87	1.06
	5.0-9.8	48.64	7.52	66.21	10.24
	9.8-18	185.58	28.69	198.25	30.65
	18-34	313.31	48.44	354.38	54.79
	>34	98.62	15.25	21.06	3.26
F^- (ppm)	<0.71	22.04	3.41	62.37	9.64
	0.71-1.2	119.58	18.49	111.45	17.23
	1.2-1.8	408.21	63.12	370.32	57.26
	1.8-2.8	56.36	8.71	58.54	9.05
	>2.8	40.58	6.27	44.09	6.82
Hardness	<240	12.34	1.91	26.32	4.07
	240-310	82.96	12.83	419.59	64.87
	310-360	415.57	64.25	126.78	19.60
	360-380	105.61	16.33	48.20	7.45
	>380	30.29	4.68	25.88	4.00
Ca^{++} (mg/l)	<54	78.54	12.14	16.58	2.56
	54-70	276.32	42.72	185.21	28.64
	70-88	209.39	32.37	341.47	52.80
	88-110	71.28	11.02	84.65	13.09
	>110	11.24	1.74	18.86	2.92
Mg^{++} (mg/l)	<27	13.65	2.11	9.45	1.46
	27-43	219.25	33.90	39.64	6.13
	43-57	335.45	51.87	422.38	65.31
	57-69	52.36	8.10	129.67	20.05
	>69	26.06	4.03	45.63	7.06
Na^{++} (mg/l)	< 5.1	29.67	4.59	35.87	5.55
	5.1-6.4	34.52	5.34	45.12	6.98
	6.4-8.7	297.49	46.00	276.87	42.81
	8.7-12	223.29	34.52	207.45	32.07
	> 12	61.80	9.56	81.46	12.59
K^+ (mg/l)	< 1.5	8.32	1.29	71.75	11.09
	1.5-2.3	114.23	17.66	284.06	43.92
	2.3-2.7	298.82	46.20	213.24	32.97
	2.7-3.5	185.94	28.75	69.41	10.73
	> 3.5	39.46	6.10	8.31	1.28
SAR	<0.6	12.23	1.89	10.14	1.57
	0.6-0.88	108.47	16.77	85.98	13.29
	0.88-1.2	349.68	54.07	367.19	56.77
	1.2-1.7	122.64	18.96	139.78	21.61
	> 1.7	53.75	8.31	43.68	6.75
RSC	< 99	59.32	9.17	21.27	3.29
	99 - 120	208.35	32.21	211.15	32.65
	120 - 130	249.87	38.63	207.09	32.02
	130 - 150	97.98	15.15	119.68	18.50
	> 150	31.25	4.83	87.58	13.54

18.0 – 34.0 mg/l^{-1} (v) more than 34.0 mg/l^{-1}. The most of the study area is covered by more than 18mg/l Cl^{-1} in both the pre-monsoon and post-monsoon season. The maximum value of Cl^- was recorded in the north of Goradih, south of Sabour block and north-east of Gopalpur block and some small pockets were observed in the Naugachhia block in pre-monsoon season. A very small portion of lower $Cl^–$ concentration was recorded for both the pre-monsoon and post-monsoon season. The RMSE value of IDW model was calculated as 7.80 and 18.07 for the pre-monsoon and post-monsoon season respectively (Table 8). The high $Cl^–$ concentration in the groundwater was because of the collective outcome of silicate weathering, usage of sewage water for irrigation, and undiscerning practice of fertilizers and new agro-chemicals.

Bicarbonate (HCO_3^-)

The mean value of bicarbonate for the pre-monsoon and post-monsoon season is estimated as 0.001 mg/l and 0.0006 mg/l respectively (Table 7). The maximum concentration of bicarbonate is recorded in the south of Sabour block, the central part of Goradih block and north-west of Gopalpur block in pre-monsoon season (Fig. 6). In the post-monsoon season, the highest concentration was observed in the south of Goradih and Sabour block, north-west of Gopalpur and central part of Rangra Chowk block in post-monsoon season. There is a small dissimilarity found in the seasonal and geographical dispersal of HCO_3^{-1} but very momentous at assured locations, which may be because of mingling of geologically existent salt patches in the soil profile and due to increase in the water table (Selvam et al., 2013).

Fluoride (F^-)

Spatial distribution of Fluoride ($F^–$) content in the study area for the pre-monsoon and post-monsoon season is illustrated in Fig.7. The maximum F^- value has been recorded in the south, south-east of Gopalpur block, and north-east of Sabour block in both the pre-monsoon and post-monsoon season respectively. Consequently, the low concentration of F^- has been portrayed in the east of Goradih block and small pocket at the east in Rangra Chowk and Gopalpur block in both seasons (Fig.7). Most of the part in Naugachhia, Rangra Chowk, Gopalpur and Sabour block having the medium concentrations (1.2 – 1.8 ppm) of F^- content.

Hardness

Hardness of the water depends on the concentration of substances such as calcium and magnesium (Verma et al. 2017). The mean hardness value of the study area is calculated as 371.02 mg/l. The estimated mean and RMSE error of the hardness is calculated as -1.55 and 84.95 respectively in the pre-monsoon season and -1.54 and 98.52 respectively in the post-monsoon season (Table 8). The spatial distribution map of hardness is portrayed in Figure for the pre-monsoon season and post-monsoon season respectively. The result of the analysis showed maximum hardness values were concentrated in the west and north-west of Naugachhia block, north-east of Goradih block in both seasons. A small part at east of Rangra Chowk block and central part of Gopalpur block were recorded least hardness value in the pre-monsoon season. In post-monsoon season, the entire Rangra Chowk, Gopalpur, Sabour andsouth-west of Goradih block were recorded least concentration of hardness (Fig.8).

Calcium (Ca^{++})

The highest desirable level of calcium in drinking water is 75 mg/

Table 8. Model summary based on IDW Interpolation Method

Physio-chemical properties of groundwater	Pre-monsoon		Post-monsoon	
	Mean	RMSE	Mean	RMSE
pH	0.02	0.32	0.005	0.42
EC	0.023	0.31	0.08	0.31
$Cl^–$	0.59	7.80	1.79	18.07
HCO_3^-	0.001	0.009	0.0006	0.004
F^-	0.11	1.05	0.09	1.01
Hardness	-1.55	84.95	-1.54	98.52
Ca^-	1.59	31.53	1.05	28.43
Mg^-	-0.76	16.98	-0.63	21.08
Na^-	-0.12	5.02	-0.11	4.46
K^+	0.06	1.07	0.07	0.98
SAR	-0.02	0.56	-0.01	0.57
RSC	0.83	40.25	0.42	40.02

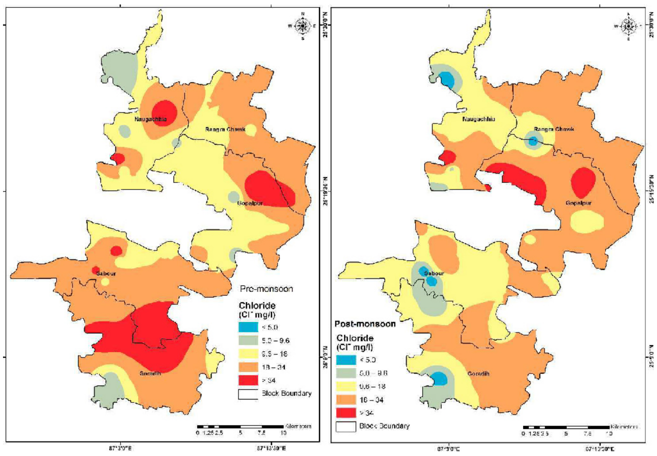

Fig. 5 Spatial variation of Chloride (a) Pre-monsoon (left), and (b) Post-monsoon (right)

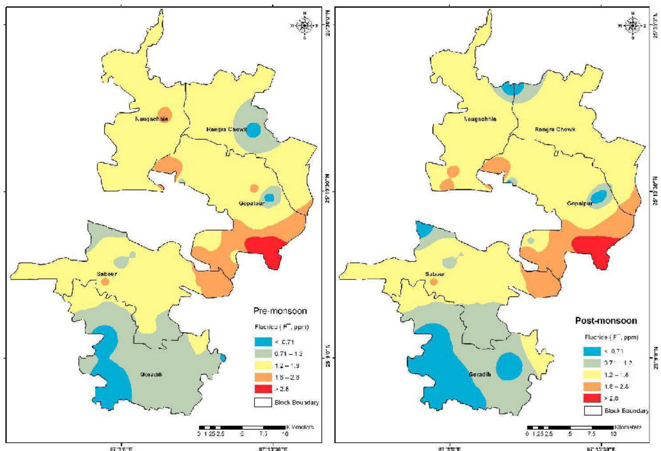

Fig. 7 Spatial variation of Fluoride (a) Pre-monsoon (left), and (b) Post-monsoon (right)

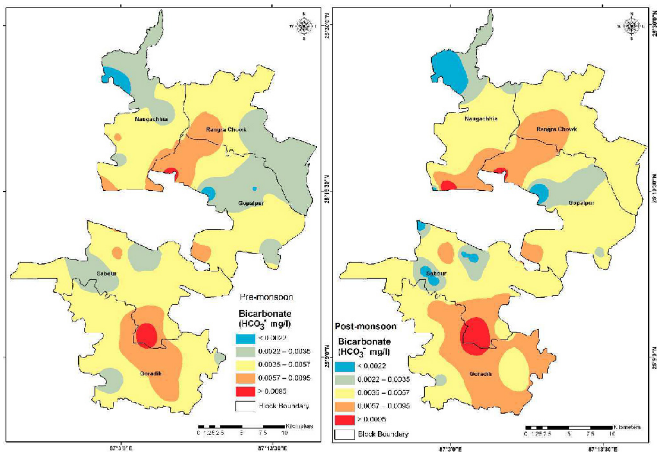

Fig. 6. Spatial variation of Bicarbonate **(a)** Pre-monsoon (left), and **(b)** Post-monsoon (right)

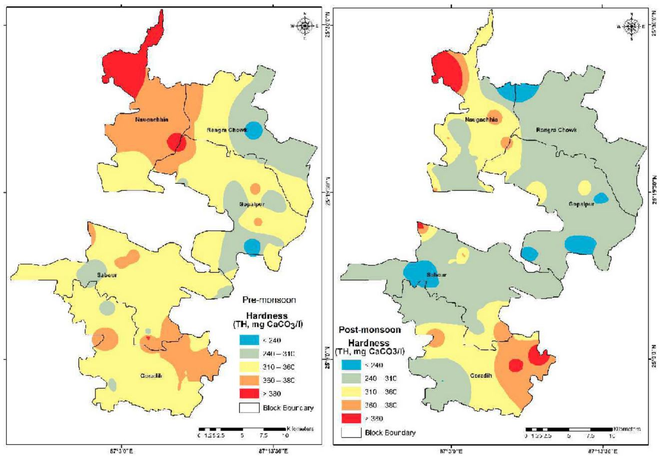

Fig. 8 Spatial variation of Hardness **(a)** Pre-monsoon (left), and **(b)** Post-monsoon (right)

l and the maximum permissible limit is 200 mg/l^{-1}(BIS, 2012). The maximum allowable is deliberated generally in the nonexistence of any other source of water for drinking. Ca^{++} content in surface water ranged from 52.1 – 151.5 mg/l^{-1}. Thus 82.22% were between the highest desirable limit and the maximum permissible limit for Ca^{++}. The maximum concentration of Ca^{++} was portrayed in the west of Naugachhia block, north-west of Gopalpur block, north-west and south of Sabourblock and north of Goradih block in the pre-monsoon season. Conversely, in the post-monsoon season, accumulation of Ca^{++} was illustrated in the west of Naugachhia and Sabour block, and east of the Goradih block. The low concentration of Ca^{++} was found in the entire Rangra Chowk block, east of Gopalpur block, and west of Goradih block for both the pre-monsoon and post-monsoon season (Fig.9).

Magnesium (Mg^{++})

Among the groundwater samples, three samples were more than 30 mg/l^{-1} for magnesium. However, all groundwater samples were within 100 mg/l which is the maximum allowable limit for magnesium in drinking water according to BIS (2012). The maximum concentration of Mg^{++} is observed in the central and north-west of Naugachhia block, small pockets at the north-west of Gopalpur and west of Rangra Chowk block in the pre-monsoon season. However, the lower Mg^{++} are recorded in the east of Ragnra Chowk, at central and east of Gopalpur block, and south-west of Sabour block. In the post-monsoon season, the maximum concentration of Mg^{++} are observed in the north-west of Naugachhia and Gopalpur block, west of Rangra Chowk block, south of Sabour block and the entire Goradih block; whereas, the lower value of Mg^{++} are found in the south of Gopalpur and west of Sabour block (Fig.10).

Sodium (Na^{+})

The observed sodium (Na^{+}) concentration ranged from a minimum value of 3.8 mg/l to a maximum value of 22.9 mg/l. The spatial distribution map of the study area illustrated in Goradih, east and south-east of Sabour, noth-west of Gopalpur, south and north of Naugachhia block in both seasons (Fig.11). The lowest concentration of Na^{+} was observed in the small pockets of the study area. Most of the part in Gopalpur, Rangra Chowk and Sabour block having a medium value of Na^{+}. The RMSE value is estimated of 5.02 and 4.46 for the pre-monsoon and post-monsoon seasons, respectively (Table 6).

Potassium (K^{+})

The mean observed value of potassium (K^{+}) is calculated as 2.91mg/l and 2.33 mg/l for the pre-monsoon and post-monsoon season respectively. The spatial distribution map showed that the maximum concentration of K^{+} were found in the east of Rangra Chowk,Goaplpur, Goradih and Sabour block in the pre-monsoon season. On the other hand, in post-monsoon season the maximum value was recorded in the south-east of Rangra Chowk, east of Gopalpur and south of Sabour block (Fig. 12). The least value of K^{+} was observed in the central of

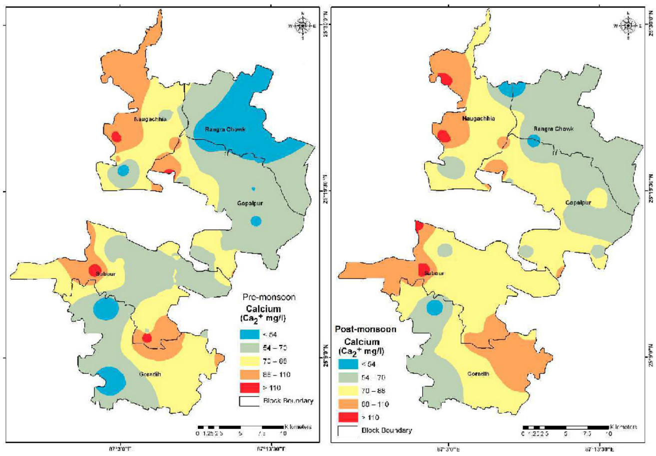

Fig.9. Spatial variation of Calcium (a) Pre-monsoon (left), and (b) Post-monsoon (right).

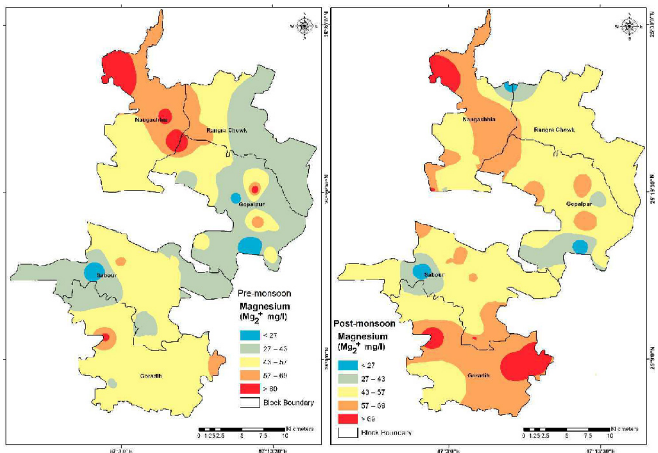

Fig.10. Spatial variation of magnesium (a) Pre-monsoon (left), and (b) Post-monsoon (right).

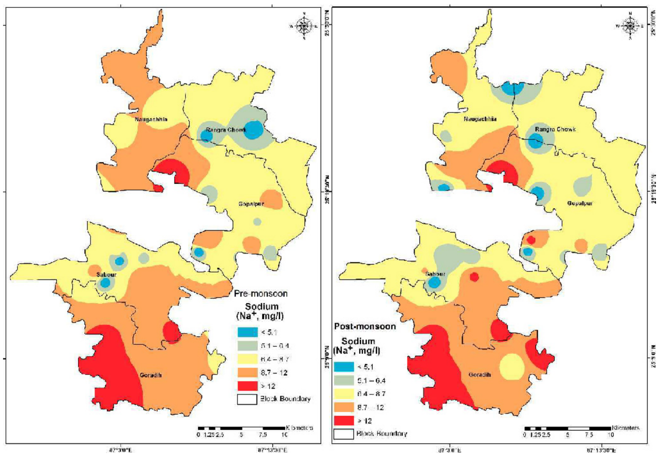

Fig.11. Spatial variation of Sodium (a) Pre-monsoon (left), and (b) Post-monsoon (right).

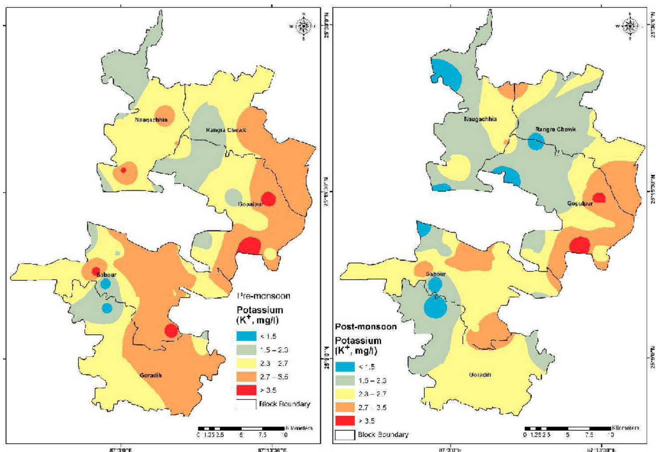

Fig.12. Spatial variation of Potassium (a) Pre-monsoon (left), and (b) Post-monsoon (right).

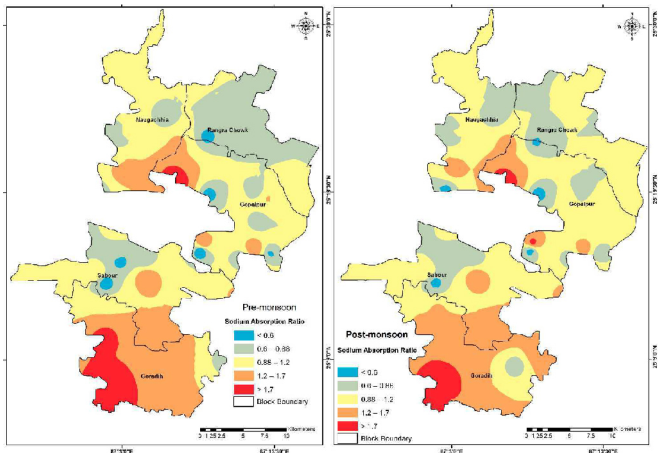

Fig.13. Spatial variation of Sodium absorption ration (a) Pre-monsoon (left), and (b) Post-monsoon (right).

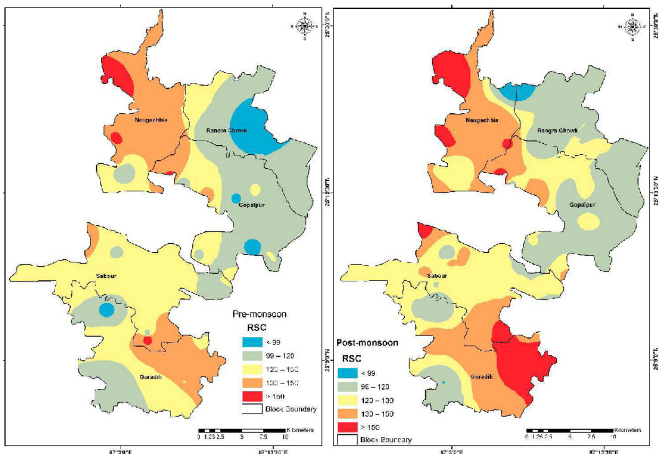

Fig.14. Spatial variation of Residual sodium carbonate (a) Pre-monsoon (left), and (b) Post-monsoon (right).

Rangra Chowk, west of Gopalpur, north-west of Goradih and Naugachhia block.

Sodium Absorption Ratio (SAR)

There is a substantial association between sodium absorption in irrigation water and the amount of which sodium is riveted by the soils. Alkali threat of the irrigation water is dogged by SAR. If the ratio of Na is high, the alkali menace is also high and vice-versa. SAR values of groundwater composed from the study area categorized into (i) less than 0.60, (ii) 0.60 – 0.88, (iii) 0.88 – 1.2, (iv) 1.2 – 1.7, and (v) more than 1.7 (Fig. 13).The higher concentration of sodicity problem is portrayed in the entire Goradih block, north-east of Gopalpur block, and south-west of Naugachhia block for both the pre-monsoon and post-monsoon season (Table 7). The low concentration of SAR is portrayed in the east and central of Rangra Chowk block, the northern part of Sabour block, and small pockets in Gopalpur block in the pre-monsoon season. In the pre-monsoon season, the low concentration of sodicity is illustrated in the north and central part of Rangra Chowk, north-east and south-west of Naugachhia block, small pockets in the east and west of Gopalpur block, thenorthern part of Sabour blockand small pockets at the east of Goradih block.

Residual Sodium Carbonate (RSC)

Classification of water based on RSC in both the pre-monsoon and post-monsoon seasons are illustrated in Figure 14. The higher value of RSC was portrayed in the entire Naugachhia block and the eastern part of the Goradih block for both the season. Consequently, the lower RSC value was recorded in the Rangra Chowk and Gopalpur block and small pockets at south-west and north-east of Goradih block. This is also perceived that the higher value of RSC associated with the low salinity and vice-versa. This ensued because calcium carbonate and bicarbonates (i.e., accountable for high RSC) were less solvable in water than chloride salts (i.e., liable for high EC).

Water Quality Index

The water quality assessment index (WQI) has been developed to abridge water quality data in a simply expressible and comprehensible setup with less evidence than the raw data. The estimated WQI values range from 47.26 to 178.96 (mean ± S.D. –93.71±31.75) in the pre-monsoon season and from 19.71 to 175.29 (mean ± S.D. - 74.86±37.04) in post-monsoon season. The value of WQI has been classified based on the geometric interval in ArcGIS software. The study area has been classified into (i) good (WQI <55), (ii) moderate (WQI 55 - 75), (iii) poor (WQI 75 – 90), (iv) very poor (WQI 90 - 105) and (v) unsuitable (WQI >105) (Table 9). Based on the groundwater quality index, 4.44% of the samples fall under good, 28.89% fall under moderate and very poor category, 13.33% fall under poor category and 24.44% under very poor for drinking purpose category in the pre-monsoon season. In the post-monsoon season, 31.11% of the samples fall under good, 20% fall under the medium, 24.44% fall under the poor condition, and 11.11% come under the very poor condition and 13.33% fall under unsuitable.

The result of the analysis also showed 6.20 % of the study area falls under good water quality condition, 26.68% falls under medium WQI, 34.25% falls under poor WQI, 21.96% falls under very poor WQI and 10.91% comes under unsuitable WQI in the pre-monsoon season (Fig 15). In post-monsoon season, 7.10% of the study area falls under good WQI, 9.68% falls under medium WQI, 23.01% comes under poor WQI, 42.96% falls under very poor WQI and 17.25% comes under unsuitable WQI.

Table 9 Delineated area of groundwater quality for irrigation purpose in the study area

WQI Index value	Pre-monsoon season Area (km^2)	Area (%)	Post-monsoon season Area (km^2)	Area (%)	Suitability Index
<55	17.13	2.65	16.79	2.60	Good
55-75	181.65	28.09	43.98	6.80	Moderate
75-90	258.65	39.99	178.27	27.56	Poor
90-105	144.74	22.38	323.37	50.00	Very Poor
>105	44.60	6.90	84.36	13.04	Unsuitable

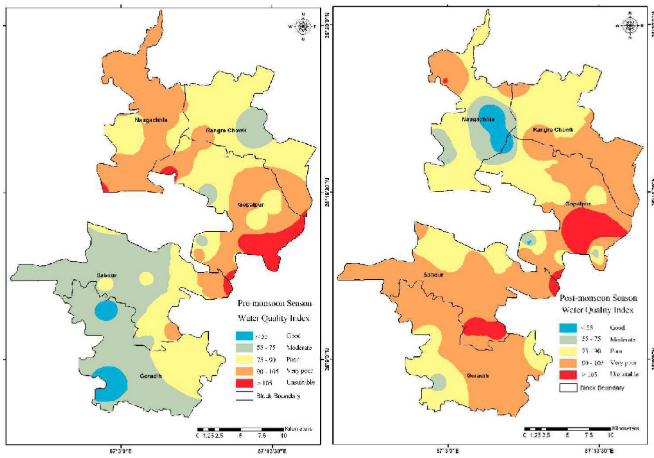

Fig. 15. Water quality index in pre-monsoon (left side) and post-monsoon season (right side).

CONCLUSIONS

Groundwater is a valuable natural resource and an imperative part of the hydrological cycle (Brindha and Kavitha, 2015). In contrast with the surface water effluence, the groundwater pollution is challenging to regulate in the Gangetic plain of Bhagalpur district in Bihar (India). The results of the chemical analysis indicate that the leading cations in the study area are calcium and magnesium and the dominant anions are bicarbonate and sulphate. The fluoride concentration of 51% of water samples in the pre-monsoon season and 40% of water samples in post-monsoon season are found to be more than the acceptable limits of WHO/BIS during both sampling sessions. Hydrochemical analysis exposes that groundwater in Bhagarlpur is slightly alkaline nature excluding for some type samples in post-monsoon period. From correlation coefficient studies among different parameters, it is clear that with Mg and Hardness, SAR and Na, RSC and Hardness, Ca and Hardness, RSC and Mg, and EC and Cl^-, show very good positive correlation the pre-monsoon while in post-monsoon session good positive correlation are found between Ca and Hardness, Mg and Hardness, SAR and Na, RSC and Ca, RSC and Mg, and RSC and Hardness.

The GIS-based multi-criteria scheme efficiently combined various groundwater quality parameters into an easily tacit set-up. The groundwater quality descent is found in the central and southern part of the study area that is concomitant with the riverine plain and intensive agricultural activities.

Water samples in both the season (except fluoride) has been found to be suitable for drinking and irrigation purpose. There is no gamble of salinity menace. For most of the parameters, more than 85% of the total number of samples are within allowable limits of drinking as well as irrigation use, with a very little exceptions.

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References

Adhikary, P.P. and Biswas, H. (2011) Geospatial assessment of groundwater quality in Datia district of Bundelkhand. Indian Jour. Soil Conserv., v.39(2), pp.108–116.

Adhikary, P.P., Dash, C.J., Chandrasekharan, H., Rajput, T.B.S., Dubey, S.K. (2012) Evaluation of groundwater quality for irrigation and drinking using GIS and geostatistics in a peri-urban area of Delhi, India. Arab. Jour. Geosci., v.5, pp.1423–1434.

Agarwal, E., Rajat, A., Garg, R.D., Garg, P.K. (2013) Delineation of groundwater potential zone: an AHP/ANP approach. Jour Earth Syst. Sci., v.122(3), pp.887–898.

Amalraj, A. and Pius, A., (2013) Health risk from fluoride exposure of a population in selected areas of Tamil Nadu South India. Food Science and Human Wellness, v.2(2), pp.75-86.

APHA (2000) Standard Methods for Examination of Water and Waste water, 20th Ed. American Pub. Health Assoc., Washington D.C.

Bhunia, G.S., Shit, P.K., Maiti, R. (2018) Comparison of GIS-based interpolation methods for spatial distribution of soil organic carbon (SOC). Jour. Saudi Soc. Agricul. Sci., v.17, pp.114-126. DOI: 10.1016/ j.jssas.2016.02.001

BIS (Bureau of Indian Standards)(2012) Indian standard drinking water specification, Second Revision ISO: 10500:2012, Bureau of Indian Standards, Drinking Water Sectional Committee, FAD25. New Delhi, India.

Brindha, K. and Kavitha, R. (2015) Hydrochemical assessment of surface water and groundwater quality along Uyyakondan channel, south India. Environ. Earth Sci., v.73, pp.5383–5393.

Dengiz, O., Ozcan, H., Koksal, E.S., Baskan, O., Kosker, Y. (2010) Sustainable natural resource management and environmental assessment in the Salt Lake (Tuz Golu) Specially Protected Area. Environ. Monit. Assess., v.161, pp.327–342.

Eaton, E.M. (1950) Significance of carbonates in irrigation waters. Soil Sci., v.69, pp.123–133.

Gouri, K. and Choudhary, S.K. (2017) Fluoride Contamination in Groundwater Sources of Bhagalpur Municipal Corporation Area, Bhagalpur, Bihar. IOSR Jour. Environ. Sci., Toxicology and Food Technology (IOSR-JESTFT), v.11(1), pp.45-49.

Goyal, S.K., Chaudhary, B.S. (2010) GIS based study of Spatio-Temporal changes in groundwater depth and quality in Kaithal district of Haryana, India. Jour. Indian Geophys. Union, v.14(2), pp.75-87.

Jha, A.K. and Kumar, U. (2014) A case study of arsenic and fluoride contamination in groundwater of Bhagalpur District. Jour. Chem. Pharma. Res., v.6(11), pp.735-738.

Kalpana, L. and Elango, L. (2013) Assessment of Groundwater quality for drinking and irrigation purposes in Pambar River Sub-Basin, Tamil Nadu. Indian Jour. Environ. Protect., v.33(1), pp.1–8.

Krishna Kumar, S., Bharani, R., Magesh, N.S., Godson, P.S., Chandrasekar, N. (2015) Hydrogeochemistry and groundwater quality appraisal of part of south Chennai coastal aquifers, Tamil Nadu, India using WQIand fuzzy logic method. Appld Water Sci., v.4, pp.341–350.

Mahalingam, B., Ramu, Magdum, Deepali Bhauso, Jayashree, P. (2014) Assessment of Groundwater Quality Using GIS Techniques: A Case Study of Mysore City. Internat. Jour. Engg. Innovative Tech., v.3(8), pp.117-122.

Mahato, M.K., Singh, P.K., Tiwari, A.K. (2016) Hydrogeochemical evaluation of groundwater quality and seasonal variation in East Bokaro coalfield region, Jharkhand. Jour. Geol. Soc. India, v.88(2), pp.173-184.

Mandour, R.A. (2012) Human health impacts of drinking water (surface and ground) pollution Dakahlyia Governorate, Egypt. Appld. Water Sci., v.2(3), pp.157–163.

Marko, K., Al-Amri, N.S., Elfeki, A.M.M. (2014) Geostatistical analysis using GIS for mapping groundwaterquality: case study in the recharge area of Wadi Usfan, westernSaudi Arabia. Arab. Jour Geosci., v.7, pp.5239–5252

Mehrjardi, R.T., Jahromi, M.Z., Mahmodi, S., Heidari, A. (2008) Spatial distribution of groundwater quality with geostatistics (case study: Yazd-Ardakan Plain). World Appld. Sci. Jour., v.4(1), pp.9–17.

Patil, V.T., Patil, P.R. (2010) Physicochemical analysis of selected groundwater samples of Amalner town in Jalgaon district, Maharashtra, India, Electronic Jour. Chem., v.7(1), pp.111–116.

Selvam, S., Manimaran, G., Sivasubramanian, P. (2013) Hydrochemical characteristics and GIS-based assessment of groundwater qualityin the coastal aquifers of Tuticorin corporation, Tamilnadu, India. Appld. Water Sci., DOI:10.1007/s13201-012-0068-8

Selvam, S., Venkatramanan, S., Singaraja, C. (2015) A GIS-based assessment of water quality pollution indices for heavy metal contamination in Tuticorin Corporation,Tamilnadu, India. Arab. Jour Geosci., pp.1-16. DOI: 10.1007/s12517-015-1968-3.

Sharma, D.A., Rishi, M.S., Keesari, T. (2017) Evaluation of groundwater quality and suitability for irrigation and drinking purposes in southwest Punjab, India using hydrochemical approach. Appld. Water Sci., v.7, pp.3137–3150. DOI: 10.1007/s13201-016-0456-6

Shrivastava, V.S., Patil, P.R. (2002) Tapti river water pollution by industrialwastes: A statistical approach. Nat. Environ. Pollut. Tech., v.1(3), pp.279-283.

Singh, A., Sharma, C.S., Jeyaseelan, A.T., Chowdary, V.M. (2015) Spatio–temporal analysis of groundwater resources in Jalandhar district of Punjab state, India. Sustain. Water Resour. Manag., v.1, pp.293–304.

Singh, A.K., Gupta, V.K., Sharma, B., Singla, B., Kaur, P., Walia, G. (2015) What are we drinking? Assessment of water quality in an urban city of Punjab, India. Jour. Family Medicine and Primary Care. v.4(4), pp.514-518. DOI:10.4103/2249-4863.174267.

Tiwari, A.K., Singh, A.K. (2014) Hydrogeochemical investigation and groundwater quality assessment of Pratapgarh district, Uttar Pradesh. Jour. Geol. Soc. India, v.83(3), pp.329-343.

Tiwari, A.K., Ghione, R., Maio, M. De, Lavy, M. (2017) Evaluation of hydrogeochemical processes and groundwater quality for suitability of drinking and irrigation purposes: a case study in the Aosta Valley region, Italy. Arab Jour. Geosci., v.10, pp.264.

Tiwari, A.K., Singh, P.K., Mahato, M.K. (2016) Environmental geochemistry and a quality assessment of mine water of the West Bokaro coalfield, India. Mine Water Environ., v.35(4), pp.525–535.

Verma, D.K., Bhunia, G.S., Shit, P.K., Kumar, S., Mandal, J., Padbhushan, R. (2017) Spatial variability of groundwater quality of Sabour block, Bhagalpur district (Bihar, India). Appld. Water Sci. v.7(4), pp.1997–2008. DOI:10.1007/s13201-016-0380-9.

Verma, D.K., Kumar, S., Mandal, J., Padbhushan, R. (2015) Evaluating quality of groundwater collected from intensively cropped areas in Sabour block of Bhagalpur district, Bihar, India. Ecol., Environ. Conserv., v.21, pp.53-59.

WHO (2006) Guidelines for drinking-water quality, vol 1, Recommendations, 3rd edn. World Health Organization, Geneva.

WHO (2011) Guidelines for drinking-water quality, 4th edn. World Health Organization, Geneva.

Wongsasuluk, P., Chotpantarat, S., Siriwong, W., Robson, M. (2014) Heavy metal contamination and human health risk assessment in drinking water from shallow groundwater wells in an agricultural area in Ubon Ratchathani province, Thailand. Environ. Geochem. Health., v.36(1), pp.169–182.

Yao, X., Fu, B., Lü, Y., Sun, F., Wang, S., Liu, M. (2013) Comparison of Four Spatial Interpolation Methods for Estimating Soil Moisture in a Complex Terrain Catchment. Schumann GJ-P. (Ed.), PLoS ONE. v.8(1), pp.e54660. DOI:10.1371/journal.pone.0054660.

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