Hydrogeochemistry and Water Quality Index in the Assessment of Groundwater Quality for Drinking Uses

Article in Water Environment Research · July 2015

DOI: 10.2175/106143015X14212658613956

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Hydrogeochemistry and Water Quality Index in the Assessment of Groundwater Quality for Drinking Uses

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ABSTRACT: The present investigation is aimed at understanding the hydrogeochemical parameters and development of a water quality index (WQI) to assess groundwater quality of a rural tract in the northwest of Bardhaman district of West Bengal, India. Groundwater occurs at shallow depths with the maximum flow moving southeast during pre-monsoon season and south in post-monsoon period. The physicochemical analysis of groundwater samples shows the major ions in the order of $HCO_3 > Ca > Na > Mg > Cl > SO_4$ and $HCO_3 > Ca > Mg > Na > Cl > SO_4$ in pre- and post-monsoon periods, respectively. The groundwater quality is safe for drinking, barring the elevated iron content in certain areas. Based on WQI values, groundwater falls into one of three categories: excellent water, good water, and poor water. The high value of WQI is because of elevated concentration of iron and chloride. The majority of the area is occupied by good water in pre-monsoon and poor water in post-monsoon period. *Water Environ. Res.*, **87,** 607 (2015).

KEYWORDS: groundwater, hydrogeochemistry, water quality index, rural tract, Bardhaman district, West Bengal, India.

doi:10.2175/106143015X14212658613956

Introduction

The quality of groundwater depends on the composition of recharge water, the interaction between the water and the soil, the rock with which it comes in contact in the unsaturated zone, and the residence time and reactions that occur within the aquifer (Freeze and Cherry, 1979; Fetter, 1994; Appelo and Postma, 2005). Quality is also affected by various anthropogenic activities. Quality has become an important concern particularly in rural areas where the population is widely dependent on groundwater for drinking purposes. Undesirable groundwater quality reduces the economy and restrains the improvement in living conditions of rural people. Therefore, it has become necessary for systematic assessment and monitoring of groundwater quality to examine its suitability for drinking and to adopt appropriate measures for protection.

Various geostatistical concepts were used to better understand complex data sets of the water quality parameters (Isaaks and Srivastava, 1989; Suk and Lee, 1999; Kumar and Ahmed 2003). Use of a water quality index (WQI) is one of the most effective approaches to communicate information on the quality of any water to decision makers. The WQI is a mathematical equation used to transform large numbers of water quality data into a single number (Stambuk-Giljanovic, 1999). It promotes understanding of water quality issues by integrating complex data and generating a score that describes water quality status (Reza and Singh, 2010).

The area under investigation is a rural where residents depend on groundwater for drinking and domestic purposes. The objective of this paper is to discuss the suitability of groundwater for human consumption based on compliance of physicochemical data with reference to drinking water standards and computed WQI values. These studies are the first attempts with respect to quality management of groundwater in the Bardhaman district of West Bengal.

Study Area Setup

This study was carried out in the Kanksa-Panagarh area, located in the northwestern part of the Bardhaman District of West Bengal. The area, comprising approximately 181 km^2, is bounded within latitudes 23°24′30″ N to 23°32′33″ N and longitudes 87°21′14″ E to 87°28′24″ E in the Survey of India (SOI) topographical survey sheets 73M/6 and 73M/7 (Figure 1). The climate is semiarid with a temperature range of 12°C in winter and 39°C in summer. However, minimum temperatures can fall to 6°C in winter, and the maximum temperature can increase up to 45°C because of hot winds in summer. The average annual rainfall varies from 1100 to 1350 mm. Significant rainfall occurs during the Southeast monsoon, from mid-June to mid-October.

The area is surrounded by the Kunur Nadi, a tributary of the Ajay River in the northeast and the Damodar River in the southeast. The area has an undulating topography with elevation (altitude) ranges from 52.37 m to 74.75 m above mean sea level (MSL). The area is mostly covered by a blanket of alluvium and laterite. The alluvial cover of unconsolidated sediments, ranging in age from middle cretaceous to recent, overlies a semi-consolidated basement of the lower and upper Gondwanas (Table 1). The thickness of the unconsolidated sediments ranges from 31.5 m in the northwest to 177 m in the southeast (Das & Biswas, 1969). The unconsolidated sediments include granular zones of variable thickness consisting of very coarse to fine sand; sandy clay; lateritic gravels; and quartz

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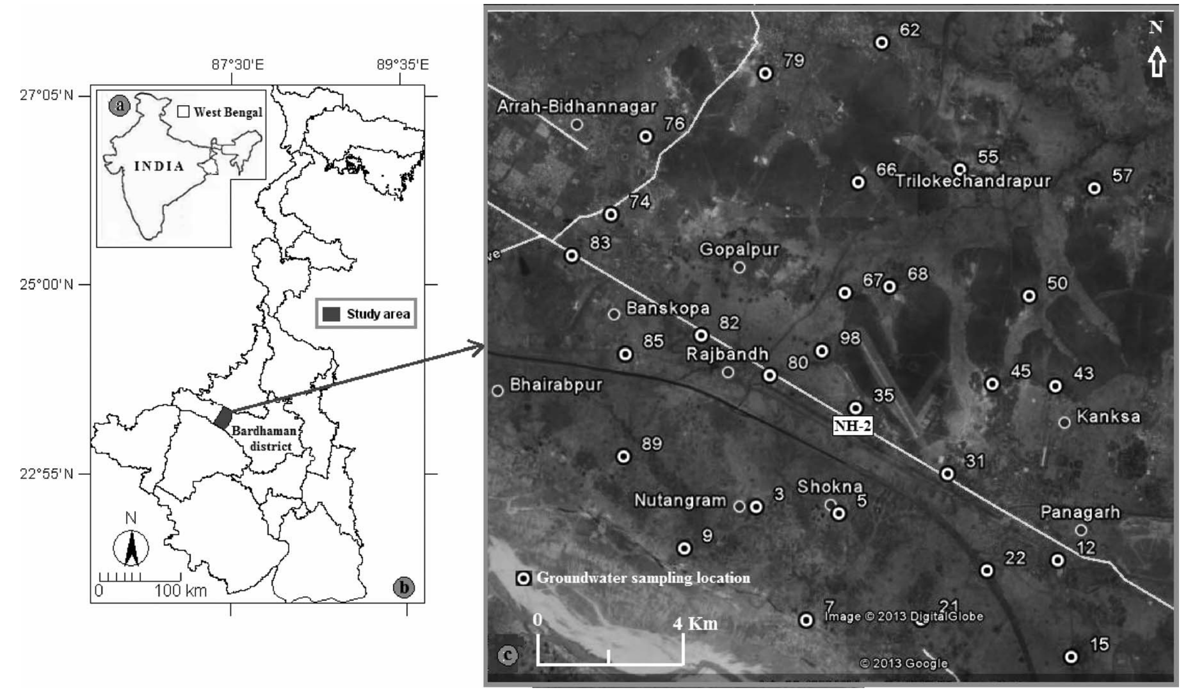

Figure 1—Location map of the study area.

pebbles. The groundwater occurs in these granular zones under unconfined conditions in shallow aquifers within 37 m below ground level (bgl). Groundwater in semiconfined to confined conditions in deeper aquifers (31 to 118 m bgl) were also recorded in the eastern area (Das and Biswas, 1969). Here, impervious beds like clay, shale, and argillaceous limestone overlie the water saturated granular zones comprising of coarse to fine sand and pebbles. The impervious layers separating different granular zones in the east pinch out to the west, and, thus, the different zones become hydraulically interconnected with the near surface granular zones (Das and Biswas, 1969).

The groundwater is being exploited in the study area through shallow tube wells for drinking and domestic purposes. The present investigation concentrated on groundwater occurring under unconfined conditions.

Methodology

In this investigation, water level at 98 tube wells was measured from the ground surface during November to December 2011 for the post-monsoon period and during May to June 2012 for the pre-monsoon period. The maximum depth recorded was 37 m bgl. Several steps were taken to construct a water table contour map. First, the water-level data measured from the ground surface are converted to the water table elevations (water level height above the mean sea level). The water table elevation with respect to mean sea level (MSL) at tube wells was determined with the help of global position system (GPS) and shuttle radar topography mission (SRTM) data. A handheld global positioning system (GPS, Model GARMIN GPSMAP 78s) was used to determine the tube well locations (longitude and latitude). The reduced level of the tube well points was computed from the SRTM data and cross checked against the contour data of SOI Toposheets. The water table elevation data

Table 1—Stratigraphy of the area around Kanksa-Panagarh, Bardhaman district, West Bengal (after Das and Biswas, 1969).

System	Age	Lithology	Thickness range
Quaternary	Recent	Sand, ferruginous, yellow, fine to coarse, silt, greyish yellow clay	Unconsolidated sediments, 31.5 m to more than 177 m from northwest to southeast
	Pliocene to Pleistocene	Sand, ferruginous, yellow; litho-margic clay, yellow clay; laterite and calcareous nodules	
Tertiary	Middle Cretaceous to Miocene	Sand and pebbles, greyish white; sticky clay; red, green, and white clays; calcareous and carbonaceous shales; bluish grey, grey, and greyish black claystones with lenses of peat or lignite at paces; siltstones and sandstones with layers of argillaceous and arenaceous limestone	

were computed by subtracting water level data (bgl) from the reduced level values. The water table contour maps for both seasons were constructed using triangulation with linear interpolation method with the help of GIS software (Surfer). A contour interval of 1 m was chosen to avoid overcrowding the map with contour lines.

Groundwater samples were collected from 28 representative tube wells (Figure 1) during the post-monsoon (Po) and pre-monsoon (Pr) periods. The samples were collected after 10 minutes of pumping and stored in properly washed polyethylene bottles at 4°C until the analyses were finished. Each of the groundwater samples was analyzed for various physicochemical parameters such as pH; electrical conductivity at 25°C; total dissolved solids (TDS); total hardness as $CaCO_3$ (TH); turbidity; total alkalinity as $CaCO_3$ (Alk); major cations—sodium (Na^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}); major anions—bicarbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-) and sulphate (SO_4^{2-}); components such as fluoride (F^-), phosphate (PO_4^{3-}), phenol as C_6H_5OH; and heavy metals such as iron (Fe), manganese (Mn), copper (Cu), arsenic (As), zinc (Zn), lead (Pb) cadmium (Cd), nickel (Ni), and mercury (Hg). Test methods followed are the standard procedures recommended by American Public Health Association (2005). The quality of analytical data was examined by computing the balance of positive and negative ions. Almost all groundwater samples of the pre- and post monsoon seasons showed good charge balance, typically less than 10%. The analytical data obtained were processed for statistical analyses using AquaChem v.2011.1 and Excel 2007 software. The geochemistry of groundwater was analyzed by major cation and anion concentrations and correlation analysis among various physiochemical parameters. The suitability of groundwater of the study area was examined based on percent compliance of the measured data with respect to Indian Standard (BIS, 1991) and WHO (1993).

To get a comprehensive picture of overall quality of groundwater, the WQI was used. WQI is defined as a rating reflecting the composite influence of different water quality parameters on the overall quality of water. The Indian standard specified for drinking water (BIS, 1991) was used for the calculation of WQI. The WQI was computed through three steps. First, each of the 13 parameters (pH, TDS, total hardness, HCO_3, Cl, SO_4, NO_3, F, Ca, Mg, Fe, Mn, and Zn) was assigned a weight (w_i) according to its relative importance in the overall quality of water for drinking purposes (Table 2). The maximum weight 5 was assigned to nitrate because of its major importance in water quality assessment; minimum weight 1 was assigned to zinc because of its insignificant role. Other parameters such as pH, TDS, total hardness, HCO_3, Cl, SO_4, F, Ca, Mg, Fe, and Mn were assigned weights between 1 and 5 based on their relative significance in the water quality evaluation. Second, the relative weight (Wi) of the chemical parameter was computed using the following equation:

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

Where,

W_i is the relative weight,
w_i is the weight of each parameter, and
n is the number of parameters.

Table 2—Relative weight of chemical parameters.

Chemical parameters[a]	Indian Standard[b]	Weight (w_i)	Relative weight (W_i) $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
pH	6.5–8.5	4	0.0952
Total dissolved solids (TDS)	500–2000	4	0.0952
Total hardness (TH)	300–600	2	0.0476
Bicarbonate	244–732	3	0.0714
Chloride	250–1000	3	0.0714
Sulphate	200–400	4	0.0952
Nitrate	45–100	5	0.1190
Fluoride	1–1.5	4	0.0952
Calcium	75–200	2	0.0476
Magnesium	30–100	2	0.0476
Iron	0.3–1.0	4	0.0952
Manganese	0.1–0.3	4	0.0952
Zinc	5–15	1	0.0238
		$\sum w_i = 42$	$\sum W_i = 1.000$

[a] Chemical parameters in mg/L.
[b] Lower value indicates desirable limit, and higher value indicates permissible limit in absence of alternate source (Bureau of Indian Standards, 1991).

Calculated relative weight (W_i) values of each parameter are given in Table 2. 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 guidelines (BIS, 1991), and the result is multiplied by 100:

$$q_i = (C_i/S_i) \times 100$$

Where,

q_i is the quality rating,
C_i is the concentration of each chemical parameter in each water sample in mg/L, and
S_i is the Indian drinking water standard for each chemical parameter in mg/L.

For computing WQI, the sub index (SI) is first determined for each chemical parameter, as given below:

$$SI_i = W_i \times q_i$$

$$WQI = \sum SI_{i-n}$$

Where,

SI_i is the sub index of i^{th} parameter;
W_i is relative weight of i^{th} parameter;
q_i is the rating based on concentration of i^{th} parameter, and
n is the number of chemical parameters.

The computed WQI values are classified into five categories: excellent water (WQI < 50); good water (WQI = 50–100); poor water (WQI = 100–200); very poor water (WQI = 200–300); and water unsuitable for drinking (WQI > 300).

The GIS was integrated to generate a map that includes information relating to water quality and its distribution over the study area. The spatial analysis was carried out using ILWIS Academic version 3.3 GIS software. All the chemical parameters

Table 3—Status of the water table during post- and pre-monsoon periods.

	Water table below ground level (m)		Water table with respect to mean sea level (m)	
	Post-monsoon 2011	Pre-monsoon 2012	Post-monsoon 2011	Pre-monsoon 2012
Maximum	17	19.6	69.93	68.97
Minimum	2.48	3.44	45.5	43.37
Average	7.73	9.98	54.56	52.31

with their location details, concentration values and weight (W_i) were included separately into the attribute table of GIS. Then by applying the above expression in GIS functions menu, q_i and S_i were calculated. Finally, the WQI values were calculated by the summation of all S_i. All these values were then interpolated by moving the average algorithm with an inverse distance method to generate a WQI value map. The logic behind choosing the average inverse distance method is that points that are close to an output pixel obtain large weights; while points that are farther away from an output pixel obtain small weights. Values of points that are close to an output pixel are thus of greater importance to the output pixel value than the values of points which are farther away. The values for the output pixels are the weighted averages of input point values. Finally, slicing options are applied using these ranges of values with four groups of water quality classes to generate a spatial distribution of water quality map (Chakraborty et al., 2007).

Results and Discussion

Groundwater Flow. A summary of the water table data of the study area is presented in Table 3. The water table (MSL) ranges from 45.5 to 69.93 m during post-monsoon and 43.37 to 68.97 m during pre-monsoon period. The depth of the water table from the ground level varies from 2.48 to 17 m and 3.44 to 19.6 m during post-monsoon and pre-monsoon periods, respectively.

Groundwater elevation contour maps of both the seasons (Figure 2) reveal that groundwater troughs exist in the south-central part of the area near Natungram village and in the southeastern part near Panagarh; groundwater moves towards these depressions from the surrounding region. Local groundwater mounds, from which groundwater moves away in all directions, are also observed at various locations in both seasons. The groundwater contour pattern of both seasons are similar except for a decline of the water table during pre-monsoon of approximately 1 to 7 m. The remarkable difference between the contours of these two periods may occur because pre-monsoon groundwater mounds are slightly flattened compared with post-monsoon. Signficant groundwater flow directions are towards south, southwest, and southeast during post-monsoon period and southeast, southwest, and south during pre-monsoon period. In the central and southern parts of the area, the

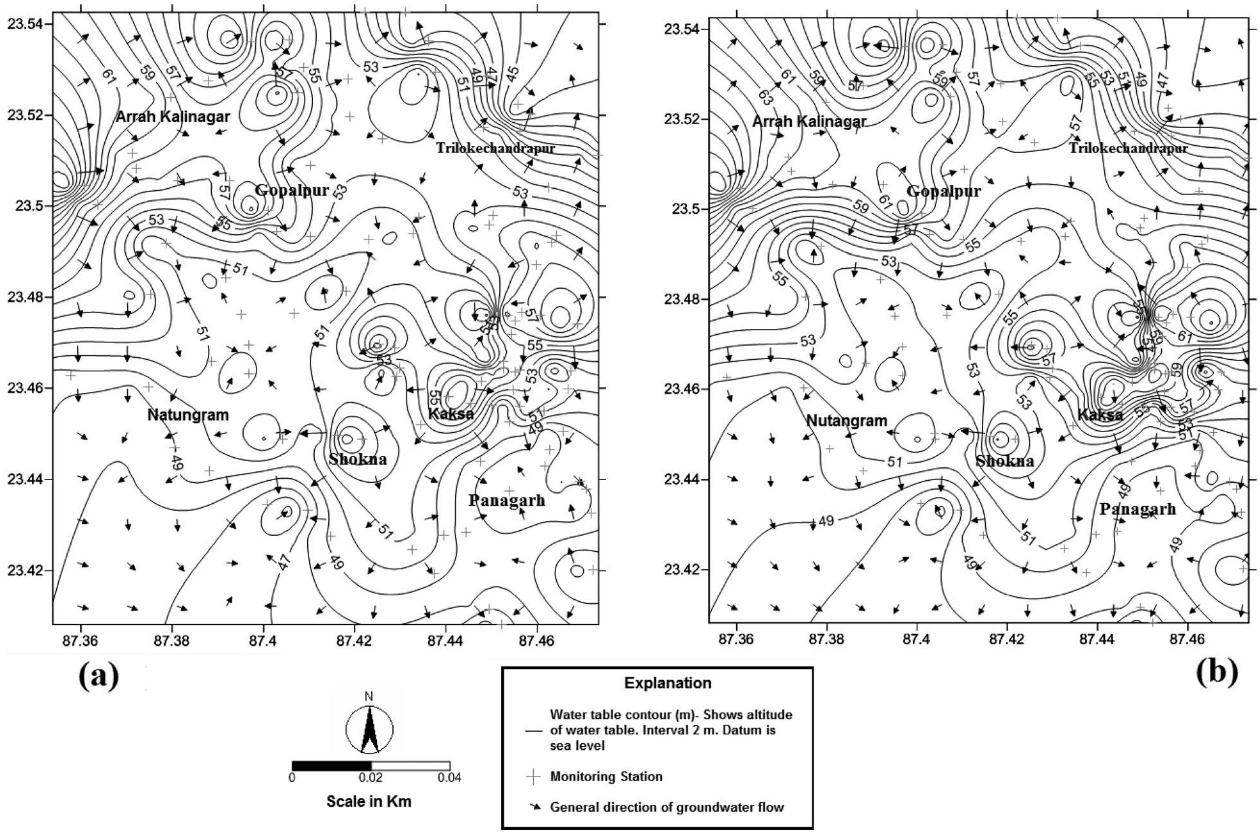

Figure 2—Water table contour maps: (a) pre-monsoon and (b) post-monsoon.

Table 4—Basic statistics of the physicochemical parameters of groundwater samples.

Parameters	Pre-monsoon					Post-monsoon				
	Min	Max	AM	Med	SD	Min	Max	AM	Med	SD
pH	5.9	7.7	7.05	7.2	0.58	5.5	7.2	6.45	6.57	0.59
EC	50	820	311.18	270	191.94	43	540	250.79	210	144.65
TDS	30	452	172.36	155	105.51	30	396	169.86	148	97.09
TH	10.1	341	133.18	121.2	89.18	8	336	127.64	112	86.01
Turbidity	<1	130	20.9	2.5	39.72	<1	172	34.56	18	48.93
Alkalinity	12.2	355	128	118.3	91.56	8	313.6	115.73	105.9	85.56
Na^{+}	3.1	61.7	19.09	15.35	15	3.5	46.7	17.23	12	13.73
K^{+}	1.5	13.6	3.77	2.6	3.06	0.81	20	3.52	2.15	3.7
Ca^{2+}	3.1	92.5	37.55	32.9	26.13	2.4	91.2	35.39	32.8	23.74
Mg^{2+}	<0.02	26.3	9.5	10.7	6.18	0.48	26	9.45	8.64	7.16
HCO_3^-	14.9	433.1	157.55	144.3	110.43	9.8	382.6	142.95	129.2	102.82
Cl^-	4.9	96	15.77	10.8	17.36	6.1	79.6	17.2	13.25	14.86
NO_3^-	<0.4	38	9.21	7.15	10.82	<0.4	32.7	8.89	7	8.87
SO_4^{2-}	<1	44.6	14.13	10.4	13.62	<1	26.3	9.96	6	7.35
F^-	<0.1	0.6	0.3	0.3	0.14	<0.1	0.7	0.25	0.2	0.17
Fe	0.05	14	1.65	0.29	3.69	0.11	16.8	3.07	0.69	4.6
Mn	<0.02	0.8	0.17	0.11	0.18	<0.02	0.82	0.13	0.07	0.19
Zn	<0.02	1.35	0.26	0.08	0.4	<0.02	18.3	0.98	0.06	3.64

Min = minimum; max = maximum; AM = arithmetic mean; med = median; SD = standard deviation; TDS = total dissolved solids; TH = total hardness. Electrical conductivity (EC) in µS/Cm, turbidity in NTU, all other parameters in mg/L).

contours in both the periods are widely spaced, indicating permeability of the near-surface sedimentary formation. In the northwestern and eastern parts of the area, the contours are closely spaced, which is likely because of the less permeable nature of the formations transmitting groundwater.

Compliance of Physicochemical Data Respecting Drinking Water Standards. The basic statistics of groundwater chemistry are presented in Table 4. The percent compliance of the physicochemical data with respect to Indian Standard (BIS, 1991) and WHO (1993) for suitability for drinking water is summarized in Table 5.

The pH shows slightly acidic to alkaline nature (Pr 5.9 to 7.7, Po 5.5 to 7.2) of groundwater in the study area. The maximum values of electrical conductivity are 820 µS/Cm (Pr) and 540 µS/Cm (Po), indicating low to moderate mineralization in the area. With respect to TDS (maximum values Pr 452 mg/L, Po 396 mg/L), the groundwater is hydrochemically freshwater suitable for drinking. The turbidity values at some locations were high (Pr < 1 to 130 NTU, median 2.5 NTU and Po < 1 to 172 NTU, median

Table 5—Comparison of groundwater quality with drinking water standards (TDS = total dissolved solids; TH = total hardness; EC = electrical conductivity) (Bureau of Indian Standards, 1991; World Health Organization, 1993).

Parameters	Indian standard (desirable limit)	Percent compliance		WHO limit	Percent compliance	
		Pre-monsoon	Post-monsoon		Pre-monsoon	Post-monsoon
pH	6.5–8.5	82.1	60.7	7–8	64.3	25
EC	–	–	–	–	–	–
TDS	500	100	100	1000	100	100
TH	300	96.4	96.4	–	–	–
Turbidity	5	71.4	46.4	–	–	–
Alkalinity	200	71.4	82.1	–	–	–
Na^{+}	–	–	–	200	100	100.00
K^{+}	–	–	–	–	–	
Ca^{2+}	75	89.3	92.9	75	89.3	92.9
Mg^{2+}	30	100	100	30	100	100
HCO_3^-	–	–	–	–	–	–
Cl^-	250	100	100	250	100	100
NO_3^-	45	100	100	50	100	100
SO_4^{2-}	200	100	100	250	100	100
F^-	1	100	100	1.5	100	100
Fe-Tot	0.3	53.6	28.6	0.3	53.6	28.6
Mn-Tot	0.1	60.7	75	0.1	60.7	75
Zn-Tot	5	100	96.4	3	100	96.4

Note: Electrical conductivity in µS/Cm, turbidity in NTU, all other parameters in mg/L.

18 NTU). The TDS content is within permissible limit at maximum sites (Pr 82.1% and Po 57.1%). The higher values of turbidity in groundwater, particularly during post-monsoon samples, might be caused by enhanced erosion of host rocks and leaching from lateritic soil. Apart from one sample, the total hardness of groundwater is within the safe limit for drinking; the groundwater is soft to moderately hard at maximum locations. The alkalinities (maximum values Pr 355 mg/L and Po 313.6 mg/L) are within the permissible limit.

The major ion chemistry reveals that Ca^{2+} is the most leading cation, and HCO_3^- is the most dominant anion in both the seasons. The array of abundance of cations was recorded as Ca>Na>Mg in pre-monsoon and Ca>Mg>Na in post-monsoon period; the relative order of anions as HCO_3>Cl>SO_4 was observed in both the seasons. The overall concentration pattern of the major ions may be ordered as HCO_3>Ca>Na>Mg>Cl>SO_4 and HCO_3>Ca>Mg>Na>Cl>SO_4 in pre- and post-monsoons, respectively. All the major cations and anions show values within the permissible and safe limits with respect to Indian and WHO standards. The concentration of Cl^- was high (greater than 10 mg/L) at places in the study area. In West Bengal, India, the chloride (Cl^-) concentration in uncontaminated water is less than 10 mg/L, and it ranges between 30 and 300 mg/L in the domestic/septic tank wastewater (McArthur et al., 2012). This indicates that the high Cl^- concentration in groundwater of the present study area might be from the domestic and household septic tanks. The influence of wastewater on groundwater quality is a well-documented concern worldwide (Foster et al., 2011). In rural areas, most domestic supply, and much irrigation water, is derived from shallow (< 50 m) wells, many of which are close to either septic tanks or pit latrines (McArthur et al., 2012). Possible sources of contaminated chloride are de-icers, evaporites, landfill leachate, agricultural chemicals, industrial chemicals, recharge from village ponds, mixing with saline water, and domestic wastewater. The present study area is located in the northwestern part of Bardhaman district of West Bengal, India. In the area, de-icers are not used; the evaporate deposits at shallow depths, and landfill sites at or near the study area are not reported. The use of agricultural chemicals is light, and no chemical industries emerge in the study area. Village ponds are small, and chloride concentrations are found within the normal limit. There is no question of intrusion of saline water because the sea is far away from the study area. By exclusion, it may be concluded that the contaminant chloride in the study area derives from domestic wastewater. In field studies, chloride-contaminated sites are in close proximity to household septic tanks.

Phosphate (< 0.05 mg/L) and phenol (< 0.001 mg/L) in groundwater were less than the detection limit. The NO_3^- and F^- contents are within the safe limits for drinking uses; maximum concentrations during pre- and post-monsoon periods are found as 38 mg/L and 0.6 mg/L and 32.7 and 0.7 mg/L, respectively. The heavy metals aresenic, cadmium, copper, lead, mercury, and nickel were found below the detection limits. Concentration of iron varied from 0.05 to 14 mg/L and 0.11 to 16.8 mg/L with compliances of 53.6% and 28.6% in pre- and post-monsoon samples, respectively; the lateritic nature of soil and host rocks likely caused the elevated iron concentration in groundwater. Except for agricultural activities no other major anthropogenic activities are being carried out in the study area which could be assigned responsible for elevated concentration of iron, rather the water-rock interaction might be the explanation for higher values of iron. The groundwater in the study area occurs at shallow depths under unconfined conditions in quaternary sediments in the upper part of the unconsolidated sediments (Table 1). In this zone, continuous sequences of ferruginous sand, lateritic gravel, and laterite, with minor clay, has been intersected. The interaction of rainwater during infiltration with the iron-rich sediments was primarily responsible for the high iron content in groundwater. Manganese concentrations greater than the desirable limit was found in 39.3% and 25% of sampling sites during pre- and post-monsoon periods, respectively, and this may be because of some localized effects. Except for one post-monsoon sample, zinc concentrations were found to be within the safe range of drinking water standards during both the seasons.

Correlation Analysis. A widely used correlation criterion between two variables is the simple correlation coefficient which indicates the sufficiency of one variable to predict the other (Davis, 1986). This coefficient is used to determine the correlation between the variables when the dependent (x) is only influenced by the independent (y) and vice versa (Voudouris et al., 2000). In this study, the correlation matrix of 15 variables for the pre- and post-monsoon seasons was computed using AquaChem v.2011.1 software and is presented in Table 6 and Table 7, respectively. Each table shows the degree of a linear association between any two of the parameters, as measured by the simple correlation coefficient (r). A linear regression method calculates the coefficient (r), as given below:

$$r = \frac{\sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n}}{\sqrt{\left[\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}\right]}\sqrt{\left[\sum_{i}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n}\right]}}$$

Where, x and y are the variables, and n is the number of water parameters.

The value of r ranges from –1 to +1; r = +1 indicates strongest positive linear correlation and r = –1 reveals strongest negative linear correlation.

The correlation among parameters in the pre- and post-monsoon seasons has shown approximately an analogous trend. Strong (r > 0.9) to good (r = < 0.9 to > 0.5) correlations between the various physicochemical parameters have been observed: (1) electrical conductivity with TDS, total hardness, Alk, Ca^{2+}, Mg^{2+}, HCO_3^- , Na^+ and SO_4^{2-}; (2) TDS with total hardness, Alk, Ca^{2+}, Mg^{2+}, HCO_3^-, Na^+, and SO_4^{2-}; (3) total hardness with Alk, Ca^{2+}, Mg^{2+}, HCO_3^-, Na^+, and SO_4^{2-}; (4) Ca^{2+} with Mg^{2+}, HCO_3^-, and SO_4^{2-}; (5) Mg^{2+} with HCO_3^- and SO_4^{2-}; and (6) HCO_3^- with SO_4^{2-}. This correlation indicates that all of them have originated from the same source.

Electrical conductivity and TDS are strongly correlated (pre-monsoon r = 0.990; post-monsoon r = 0.965), consistent with the fact that conductivity increases as the concentration of all dissolved constituents/ions increases. Electrical conductivity exhibits strong (r > 0.9) and good (r = < 0.9 to > 0.5)

Table 6—Correlation coefficient matrix of physicochemical parameters of pre-monsoon groundwater samples (TDS = total dissolved solids; TH = total hardness; EC = electrical conductivity; WQI = water quality index).

Variable	pH	EC	TDS	TH	Alk	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	HCO_3^{-}	Cl^{-}	NO_3^{-}	SO_4^{2-}	Fe	Mn	WQI
pH	1	0.757	0.762	0.816	0.842	0.459	0.102	0.776	0.841	0.841	−0.012	−0.28	0.357	0.098	0.351	0.221
EC		1	**0.99**	**0.972**	**0.922**	0.802	0.171	**0.96**	**0.917**	**0.937**	0.338	−0.095	0.596	−0.119	0.468	0.039
TDS			1	**0.97**	**0.927**	0.826	0.222	**0.955**	**0.925**	**0.944**	0.369	−0.09	0.555	−0.098	0.484	0.063
TH				1	**0.94**	0.682	0.13	**0.99**	**0.938**	**0.951**	0.235	−0.125	0.609	−0.145	0.413	0.007
Alk					1	0.679	0.142	**0.906**	**0.947**	**0.998**	0.029	−0.266	0.499	−0.077	0.525	0.085
Na						1	0.221	0.667	0.662	0.71	0.614	−0.107	0.312	−0.022	0.591	0.129
K							1	0.076	0.253	0.152	0.233	−0.011	−0.067	0.354	−0.075	0.352
Ca								1	0.881	**0.919**	0.254	−0.091	0.652	−0.184	0.36	−0.041
Mg									1	**0.952**	0.166	−0.206	0.45	−0.038	0.509	0.12
HCO_3										1	0.083	−0.262	0.498	−0.081	0.528	0.082
Cl											1	0.23	−0.011	−0.029	0.134	0.014
NO_3												1	−0.104	−0.171	−0.237	−0.201
SO_4													1	−0.199	0.164	−0.119
Fe														1	0.052	**0.98**
Mn															1	0.231
WQI																1

Note: Concentrations in meq /L; **bold** = strong correlation ($r > 0.9$).

correlations with total hardness, Ca^{2+}, Mg^{2+}, HCO_3^{-}, Na^{+}, SO_4^{2-} during both the pre- and post-monsoon seasons, indicating that most of the ions were involved in various physicochemical reactions, such as oxidation-reduction and ion exchange in the groundwater aquifer system (Subba Rao, 2002). The WQI has also been incorporated in the correlation matrix to examine the role of water parameters in the WQI values. The iron is strongly correlated with WQI (pre-monsoon $r = 0.98$, and post-monsoon $r = 0.988$); chloride also shows good correlation ($r = 0.532$) with WQI during post-monsoon period.

Water Quality Index. The WQI value and water type of the individual samples are presented in Table 8 and Figure 3. The WQI ranges from 15.3 to 475.9 and 18.2 to 584.3 for pre- and post-monsoon seasons, respectively. During pre-monsoon, 46.4% of groundwater samples were "excellent"; 35.7% were "good"; and 7.1% were "poor". In post-monsoon, 32.1% of water samples were "excellent"; 25% were "good"; 21.4% were "poor"; and 10.7% were "very poor". In addition, 10.7% of samples were "unsuitable for drinking" in both the seasons (Table 9). The dissolved ions in groundwater affected WQI values, particularly K, Mg, HCO_3, Cl, NO_3, SO_4, Fe, and Mn during post-monsoon period and Na, K, Mg, Cl, Fe, and Mn during pre-monsoon period. High iron concentration in groundwater caused high WQI values; high chloride concentrations also contributed to high WQI values typically during the post-monsoon period. These affects are evident from the correlation coefficients of WQI with respect to iron and chloride (Table 6 and Table 7). Iron shows strong correlation with WQI values ($r > 0.9$) in both the seasons. The post-monsoon samples reveal a greater percent of poor to very poor quality, 32.1%, compared to pre-monsoon 7.1% (Table 9). This may be explained by the observed higher values mainly of iron in many post-monsoon samples compared to pre-monsoon samples. The WQI values (Table 8) show that the quality of groundwater at some locations (sample numbers 7,

Table 7—Correlation coefficient matrix of physicochemical parameters of post-monsoon groundwater samples (TDS = total dissolved solids; TH = total hardness; EC = electrical conductivity; WQI = water quality index).

Variable	pH	EC	TDS	TH	Alk	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	HCO_3^{-}	Cl^{-}	NO_3^{-}	SO_4^{2-}	Fe	Mn	WQI
pH	1	0.799	0.834	0.891	**0.925**	0.552	0.053	0.853	0.867	**0.919**	0.022	−0.172	0.409	0.026	0.346	0.123
EC		1	**0.965**	**0.919**	0.882	0.741	0.043	**0.925**	0.804	0.894	0.376	0.126	0.528	0.01	0.451	0.126
TDS			1	**0.948**	**0.921**	0.793	0.114	**0.928**	0.881	**0.937**	0.345	0.074	0.582	0.084	0.537	0.21
TH				1	**0.965**	0.618	−0.044	**0.981**	**0.924**	**0.974**	0.086	−0.081	0.505	−0.064	0.512	0 .059
Alk					1	0.671	−0.017	**0.929**	**0.927**	**0.996**	0.026	−0.156	0.487	−0.035	0.557	0.09
Na^{+}						1	0.27	0.558	0.667	0.684	0.578	0.159	0.347	0.221	0.632	0.341
K^{+}							1	−0.108	0.086	−0.003	0.345	0.447	0.252	0.507	−0.095	0.498
Ca^{2+}								1	0.834	**0.942**	0.084	−0.08	0.513	−0.146	0.467	−0.029
Mg^{2+}									1	**0.927**	0.08	−0.076	0.44	0.11	0.546	0.231
HCO_3^{-}										1	0.048	−0.151	0.485	−0.045	0.557	0.081
Cl^{-}											1	0.511	0.099	0.508	0.048	0.532
NO_3^{-}												1	0.023	0.263	−0.206	0.251
SO_4^{2-}													1	0.107	0.281	0.174
Fe														1	−0.069	**0.988**
Mn															1	0.074
WQI																1

Note: Concentrations in meq /L; **bold** = strong correlation ($r > 0.9$).

Table 8—Computation of water quality index (WQI) for individual groundwater samples (pr = pre-monsoon; po = post-monsoon).

Sample No	WQI-Pr	Water type	WQI-Po	Water type
3	68.8	Good water	65.2	Good water
5	25.9	Excellent water	23.2	Excellent water
7	48.4	Excellent water	111.8	Poor water
9	136.2	Poor water	132.5	Poor water
12	49.4	Excellent water	55.3	Good water
15	65.5	Good water	416.2	Water unsuitable for drinking
21	46.8	Excellent water	43.1	Excellent water
22	53.2	Good water	66.5	Good water
31	66.6	Good water	50.9	Good water
35	475.9	Water unsuitable for drinking	292.9	Very poor water
43	26.8	Excellent water	231.7	Very poor water
45	348.4	Water unsuitable for drinking	584.3	Water unsuitable for drinking
50	59.9	Good water	131.5	Poor water
55	50.4	Good water	282.7	Very poor water
57	15.3	Excellent water	22.6	Excellent water
62	118.0	Poor water	137.7	Poor water
66	19.3	Excellent water	18.2	Excellent water
67	64.2	Good water	55.8	Good water
68	94.9	Good water	108.4	Poor water
74	30.1	Excellent water	27.7	Excellent water
76	427.0	Water unsuitable for drinking	469.9	Water unsuitable for drinking
79	20.0	Excellent water	19.2	Excellent water
80	49.5	Excellent water	36.3	Excellent water
82	33.0	Excellent water	28.4	Excellent water
83	33.1	Excellent water	42.7	Excellent water
85	50.8	Good water	61.1	Good water
89	84.8	Good water	74.7	Good water
98	41.4	Excellent water	128.5	Poor water
	Minimum = 15.3, Maximum = 475.9		Minimum = 18.2, Maximum = 584.3	

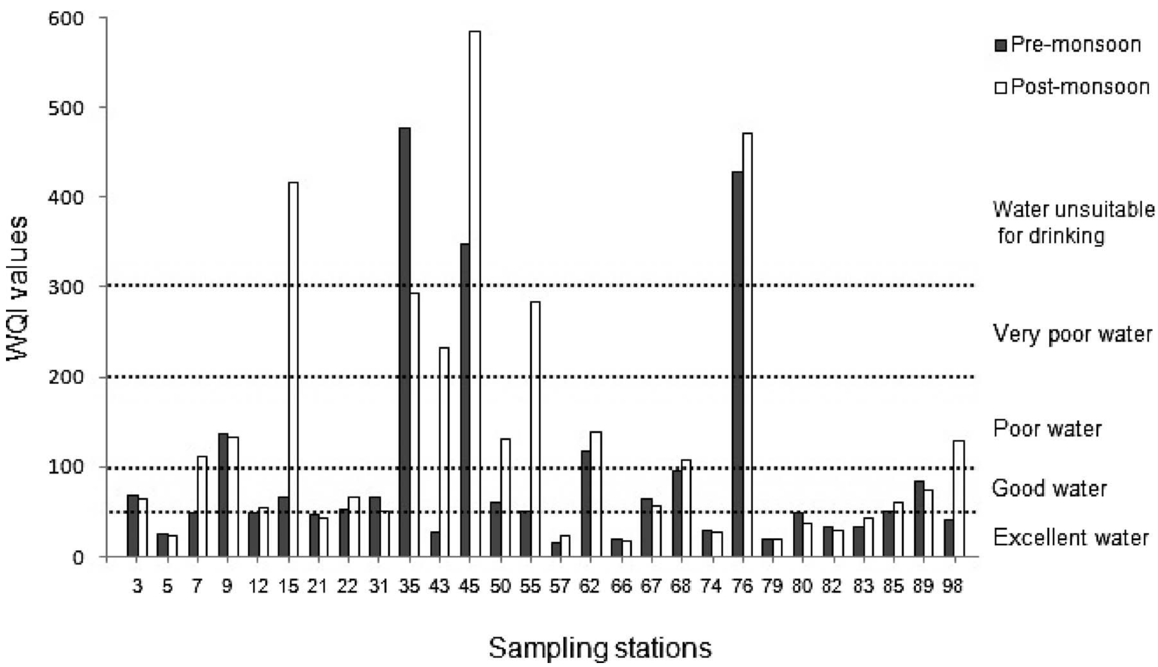

Figure 3—Water quality index (WQI) of groundwater at different locations of the study area (dotted lines represent the range of different categories of water quality).

Table 9—Water quality index (WQI) range and percentage of different water types (Pr = pre-monsoon; Po = post-monsoon).

WQI range	Water type	Percentage of samples Pr	Po
< 50	Excellent water	46.4	32.1
50–100	Good water	35.7	25.0
100–200	Poor water	7.1	21.4
200–300	Very poor water	0	10.7
> 300	Water unsuitable for drinking	10.7	10.7

15, 43, 55, and 98) deteriorated in the post-monsoon period. This deterioration likely occurred as iron leached out of the lateritic soil and rocks because of monsoon precipitation.

The spatial distribution of water types during the pre- and post-monsoon seasons are presented in Figure 4 and Figure 5, respectively. The area covered by various water types are calculated from the WQI maps and given in Table 10. The distribution of the water types show that majority of the area is covered by "good water" (67.12 sq km) in pre-monsoon and by "poor water" (61.69 sq km) in post-monsoon period. The area occupied by excellent water in pre-monsoon (58.31 sq km) is also greater than post-monsoon (33.35 sq km). "Excellent water" occurs primarily in the northwestern and southern area in both the seasons.

This assessment of groundwater quality using WQI values is the first such attempt in the Bardhaman district of West Bengal. The results obtained in this study cannot be compared with previous works and findings because no previously published data exists. However, the findings may be compared with the works carried out by researchers in different parts of India (Chakraborty et al., 2007; Ramakrishnaiah et al., 2009; Vasanthavigar et al., 2010; Srinivas Rao and Nageswararao, 2013). Chakraborty et al. (2007) used the WQI in assessment of groundwater quality of Malda district, West Bengal. The study showed that the range of WQI values was 68.32 to 621.03; "very poor" and "water unsuitable for drinking" accounted for 26% and 17%, respectively of the analyzed groundwater samples. These two water categories contained high concentration of heavy metals, such as Cu, Cd, Mn, Fe, Cr, and As. The quality of groundwater of Tumkur Taluk, Karnataka State was examined by Ramakrishnaiah et al. (2009) using WQI. The study revealed that WQI ranged from 89.21 to 660.56. The high value of WQI was caused by higher contents of Fe, NO_3, TDS, hardness, F, HCO_3, and Mn in groundwater. The assessment of groundwater quality in Thirumanimuttar sub-basin, Tamil Nadu, by Vasanthavigar et al. (2010) found WQI values of 37.94 to 298.96 and 41.35 to 291.94 for pre- and post-monsoon seasons, respectively. The pre-monsoon samples exhibited a greater percentage of poor quality compared to post monsoon samples. Chloride and electrical conductivity were identified as main parameters for the high values of WQI. Rao and Nageswararao (2013) applied WQI in the assessment of groundwater quality for human consumption in Visakhapatnam City, Andhra Pradesh. The investigation recorded WQI values in the range of 28 to 267. The study found that 16%, 14%, and 12% of groundwater samples pertaining to pre-monsoon, monsoon, and post-monsoon seasons were of "poor quality"; and 2%, 6%, and 4% of groundwater samples during these seasons, respectively, were of "very poor quality". They concluded that "poor quality" was attributed to high contents of TDS, NO_3, and Cl; and "very poor quality" was because of high values of hardness, Ca, Mg, Cl, NO_3, and TDS.

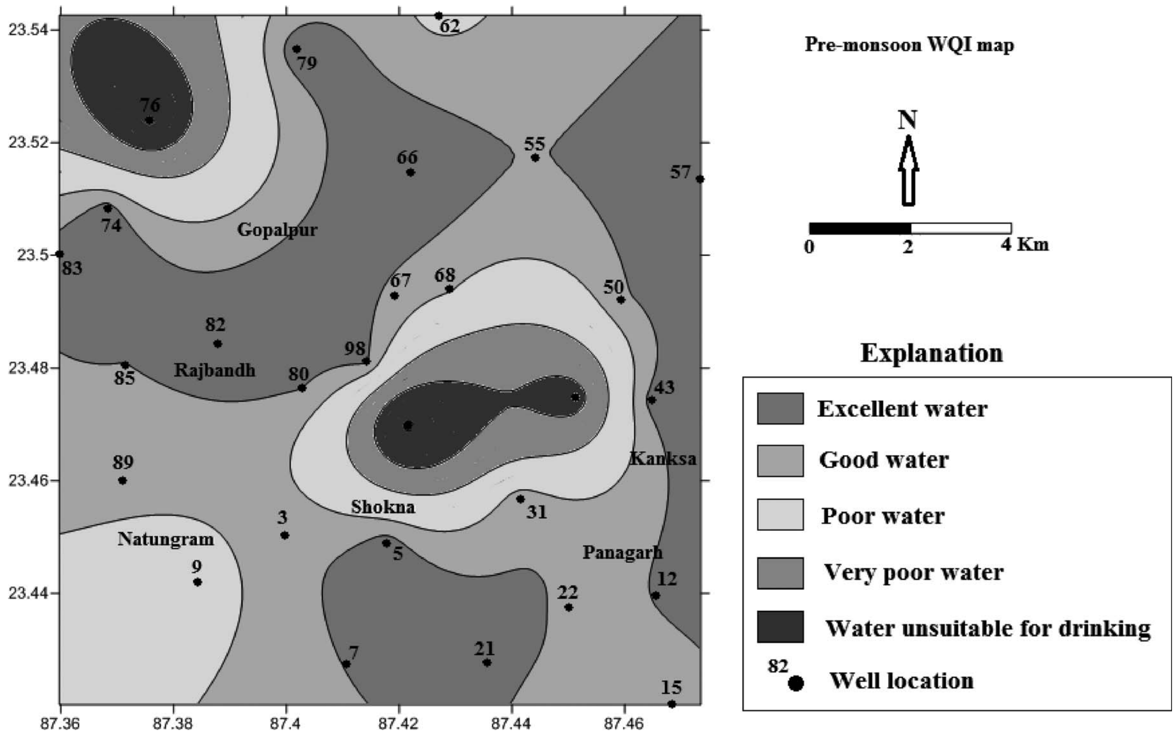

Figure 4—Water quality index (WQI) map of pre-monsoon period.

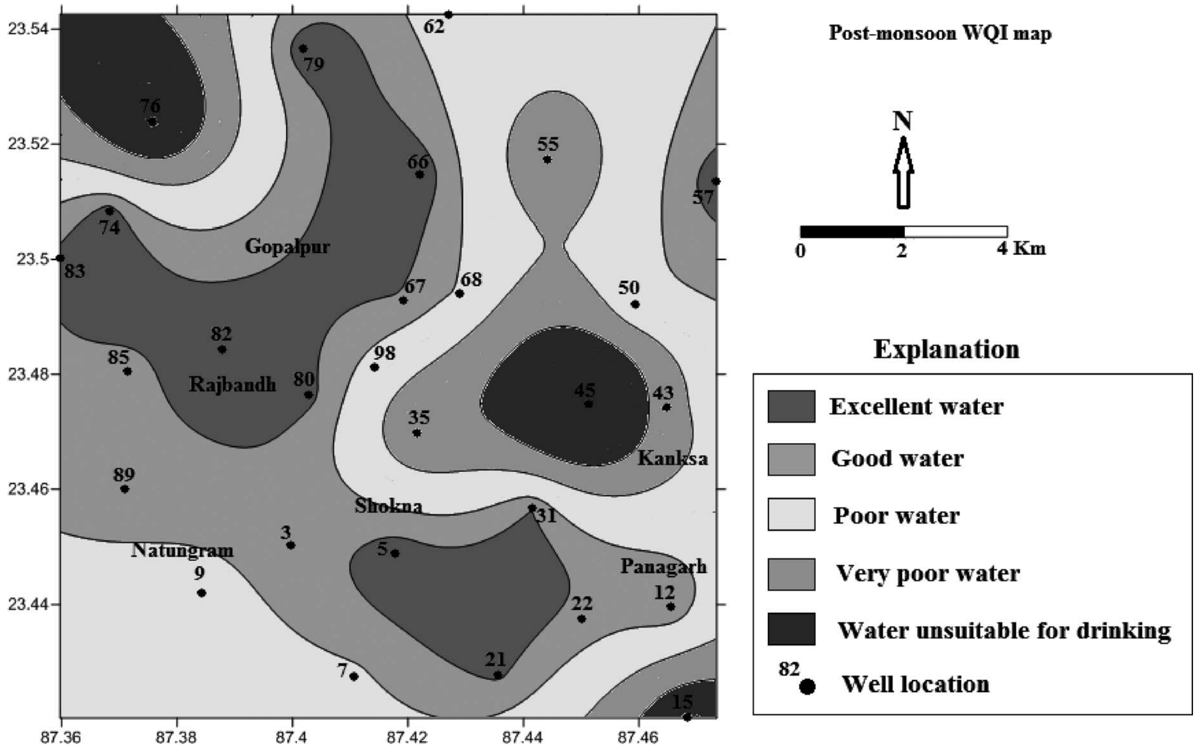

Figure 5—Water quality index (WQI) map of post-monsoon period.

All of these studies proved the usefulness of WQI method in the assessment of drinking water quality.

The findings in the present study may be summarized as: WQI values ranged from 15.3 to 475.9 in pre-monsoon period and 18.2 to 584.3 in post-monsoon period; Na, K, Mg, Cl, Fe, and Mn during pre-monsoon period and Na, K, Mg, HCO_3, Cl, NO_3, SO_4, Fe, and Mn during post-monsoon period contributed to the WQI values. High iron content in groundwater led to high WQI values; chloride also significantly increased WQI values at some locations, typically during the post-monsoon period.

Conclusions

Groundwater occurs at shallow aquifers under unconfined conditions within a depth of 37 m from the surface. Groundwater primarily flows south, southwest, and southeast directions during post-monsoon period and southeast, southwest, and south during pre-monsoon period.

The major ions may be ordered on abundance as $HCO_3>Ca>Na>Mg>Cl>SO_4$ and $HCO_3>Ca>Mg>Na>Cl>SO_4$ in pre- and post-monsoon periods, respectively. Apart from high concentrations of iron at several sites and chloride and manganese at some locations, the chemical composition of groundwater of the study area shows compliance with drinking water standards. The high concentration of iron may be ascribed to leaching from lateritic soil and host rocks, and higher values of chloride may be attributed to anthropogenic inputs from improper sanitation systems. High concentrations of manganese may be because of some localized effects; these waters may be consumed after proper treatment. The typical method of iron and manganese treatment system uses oxidation and filtration. The oxidant chemically oxidizes the iron or manganese to form particles. The filter then removes the iron or manganese particles. Oxidation using chlorine or potassium permanganate is frequently applied in small groundwater systems (http://www.nesc.wvu.edu/). The chloride in water may be reduced by the methods such as demineralization, reverse osmosis, coagulation, precipitation, electro dialysis, and other approaches. Recent studies showed the suitability of *Parthenium* sp. dried biomass as a sorbent which is capable of achieving up to 40% reduction in the chloride content (Apte Sagar et al., 2011).

In this study, the computed values of WQI vary from 15.3 to 475.9 for pre-monsoon and 18.2 to 584.3 for post-monsoon season. According to the WQI values, groundwater at only three locations in pre- and post monsoon periods were found unsuitable for drinking (WQI $>$ 300).

Dissolved ions such as Na, K, Mg, HCO_3, Cl, NO_3, SO_4, Fe, and Mn during post-monsoon period and Na, K, Mg, Cl, Fe, and Mn during pre-monsoon period affected WQI values. High iron content was responsible for the high WQI values recorded at several sampling sites. The concentration of chloride also was a significant constituent for high WQI values at some places during post-monsoon period.

Table 10—Area covered by different water types.

	Area, sq km	
Water type	**Pre-monsoon**	**Post-monsoon**
Excellent water	58.31	33.55
Good water	67.12	49.46
Poor water	32.68	61.69
Very poor water	13.92	21.88
Water unsuitable for drinking	8.97	14.42

The distribution pattern of water types based on WQI indicates that "good water" dominates the area during pre-monsoon, and "poor water" during post-monsoon period. This situation suggests that a greater amount of leaching and subsequent infiltration of pollutants to the shallow aquifer zone occurs during monsoons.

Acknowledgments

The author (AKB) thanks the Director, CSIR-Central Mechanical Engineering Research Institute (CSIR-CMERI), Durgapur for giving permission to publish this paper. The author (AKB) acknowledges financial support in the form of in-house project from CSIR-CMERI.

Submitted for publication March 24, 2014; revised manuscript submitted November 19, 2014; accepted for publication January 12, 2015.

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