International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 06 Issue: 04 | Apr 2019 www.irjet.net p-ISSN: 2395-0072

Assessing Spatial Variability of Groundwater Quality using GIS techniques in Nadia District, West Bengal

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Abstract - *Assessment of the quality of ground water is very crucial in determining suitability for drinking or irrigation purposes. Pre and post-monsoon groundwater quality data at 166 sites of Nadia district was collected from SWID, Kolkata. A strong positive correlation was found between specific conductivity and total hardness as well as chloride content of the water. Total iron content of the water was weakly correlated with total arsenic content (r=0.24**) during pre-monsoon season. Inverse Distance Weighting (IDW) and Natural Neighbor (NN) interpolation techniques were used to prepare spatial distribution maps for eight water quality parameters. Six water quality parameters such as specific conductivity, total dissolved solids, total hardness, iron, chloride and arsenic content were integrated to develop a Water Quality Index (WQI) map of the district. Standard guideline values for six parameters as recommended by World Health Organization, Central Pollution Control Board, Bureau of Indian Standards and Indian Council of Medical Research were used in computation of the WQI map. WQI in the majority of the blocks of Nadia district varied from very poor to poor during both pre and post monsoon period. Due to the declining drinking water quality in Nadia district it is high time to raise awareness at household level to improve public health.*

***Key Words*: Nadia district, Ground water quality, Inverse Distance Weighting, Natural Neighbor, Water Quality Index**

1. Introduction

Water was referred to as the "matrix of life" [1] way back to 1979. Water is a unique solvent in regards of its important physical and chemical properties like universality as a solvent, ability to form hydrogen bonds, its amphoteric nature and is referred by the Biologists as the backdrop of life as it is a major component of different molecules present in cells [2]. Investments in water supply and sanitation can be more beneficial than investment in intervention strategies because of the reduction in adverse health effects and its related cost [3]. To contribute to the water goals of the Millennium Declaration, the Johannesburg Plan of Implementation of the World Summit for Sustainable Development and Agenda 21, the UN general assembly declared the period of 2005 to 2015 as the International Decade for Action, "Water for Life". The goal during the "Water for Life Decade" was to promote efforts to fulfill international commitments in the water sphere by 2015 [4].

The demand for potable fresh water has increased drastically over the past years due to pressure of ever increasing population, modernized agriculture, urbanization, rapid industrialization and economic developments. Groundwater having lower level of contamination and wider distribution is the most preferred source for this growing need. However, the indiscriminate withdrawal of ground water has resulted in an unsustainable decline of this great resource and also reducing ground water quality in both the developing and developed nations. In India 0.4 million lives are lost annually due to lack of water, sanitation, and hygiene [5]. Globally diarrhoea and other water related infectious diseases are responsible for 4% of all deaths and 5.7% of the total burden of diseases in Disability Adjusted Life Years [6]. Water pollution is emerging as a serious problem in India as growing percentage of its groundwater reserves are contaminated by different organic and inorganic pollutants.

Water quality parameters cannot be measured at all locations within the study area because of time and cost constraints involved [7]. Therefore, at unsampled locations, prediction of values can be done using various geostatistical techniques [8, 9]. Spatial objects are generally spatially correlated, i.e., objects which are close together tend to have similar characteristics and geostatistics utilizes this concept assuming that each point influences the resulting interpolated surface only up to a certain finite lag distance. Among different interpolation approaches, Inverse Distance Weighting (IDW) interpolation makes the assumption that the measured values closest to the prediction location have more influence on the predicted value than those farther away. Greater weights are given to points closest to the prediction location, and the weights decline as distance from the point of interest increases [10]. Another method - Natural Neighbor interpolation has been shown to perform well for irregularly distributed data [11, 12]. This is a weighted average technique based on the Voronoi diagram to find out the closest subset of input samples to a query point and apply weights to them based on proportionate areas [13]. The interpolated groundwater quality maps provide an efficient tool in identifying areas affected by groundwater pollution and to obtain other relevant information about current groundwater quality scenarios that may be essential for the effective and efficient implementation of water management programs.

Development of Water Quality Index (WQI) for assessment of water quality is documented as early as 1965 [14] and subsequently modified by many researchers. Calculation of WQI involves 3 simple steps involving first selection of important parameters followed by determination of weights to each parameter from their prescribed standards and finally aggregation of the weighted values of each parameter to a single index [15, 16]. This index is considered as the most effective method of measuring water quality by many researchers [16, 17, 18, 19, 20, 21]. Rather than considering different parameters separately all the water quality parameters are combined in a mathematical equation after assigning weights to each parameter indicating its significance and impact on the index. Using this index have an advantage over the individual interpolated water quality maps as it provides a single value considering all the quality parameters at a certain location and time and thus simplifies a complex dataset into easily understandable and usable information.

Although the study area comprising of Nadia district in West Bengal, India receives heavy monsoon rainfall, year round water availability is problematic and the drinking water quality is also poor. Due to excessive exploitation, the groundwater aquifers in the region have been depleting alarmingly without subsequent recharge, the quality of limited surface water resources is deteriorating and consequently cannot be considered safe for drinking purpose. Significant amount of work has been done on the ground water quality of Nadia district focusing majorly on arsenic (As) toxicity problems. Arsenic toxicity in the district have been reported to be present in 6 villages of 4 affected blocks (Karimpur I, Karimpur II, Nabadwip and Chakdaha) as per the SOES Report [22]. However, recently, it was reported that As toxicity in groundwater of 17 blocks in the district were above 50 μg L^{-1} of As [23]. Development of a simplified and easily understandable water quality map of the district, integrating all the relevant water quality parameters is still lacking. Therefore, the present study was undertaken with the following objectives: (i) Statistical analysis of ground water quality parameters in the study area, (ii) Assessing spatial distribution of groundwater quality parameters using different geostatistical techniques, and (iii) Development of a Water Quality Index map in the study area integrating different water quality parameters.

2. Study Area

Nadia district, presently chosen as the study area is located in South Eastern part of West Bengal between 22°53' to 24°11' North latitude and 88°09' to 88°48' East longitude. It consists of 17 blocks and encompasses a geographical area of 3,927 km^2 (Fig 1).

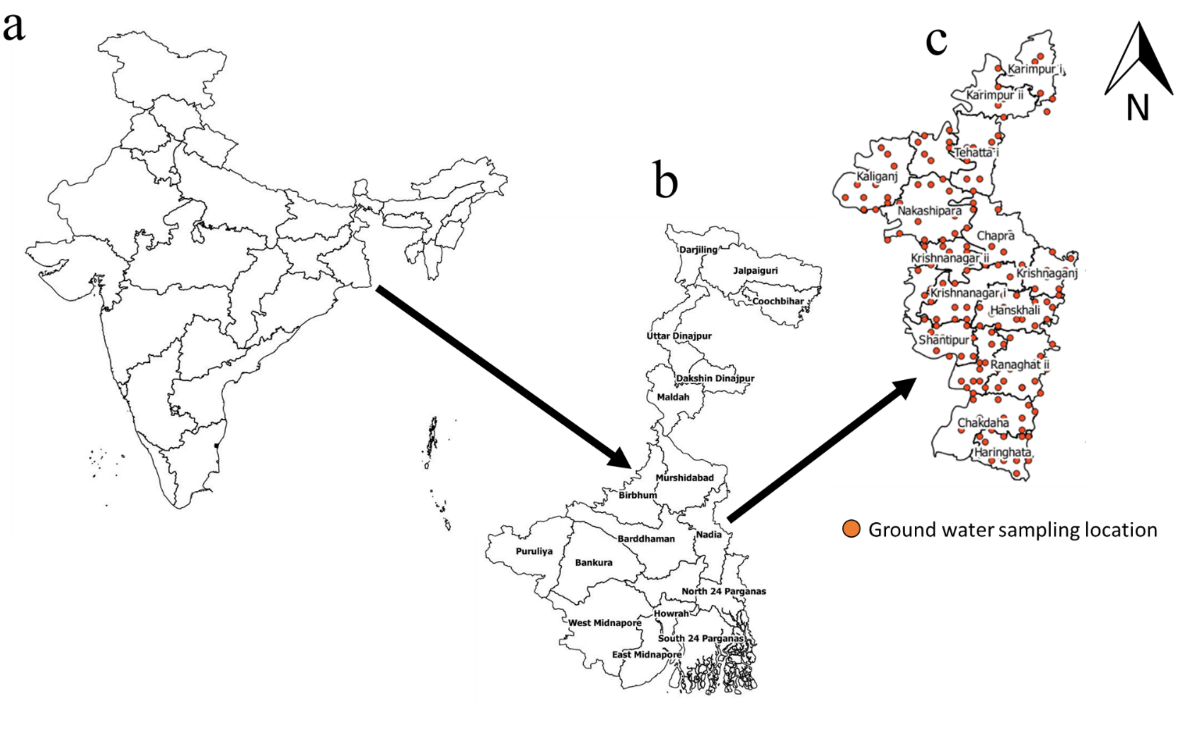

Fig 1. (a) Map of India, **(b)** map of West Bengal, **(c)** map of Nadia district with 17 assembly constituencies (blocks). Location of 166 ground water sampling points are also shown.

The major river systems flowing through the district are Jalangi, Hooghly, Churni, Mathabhanga and Ichamati. The district is bounded by Murshidabad district on the North & North West and North 24 Parganas towards South and South East. In the West, there are Burdwan and Hooghly district and Bangladesh in the East. The tropic of Cancer divides the district in two parts and is characterized by tropical monsoon with cold-dry winters and warm-humid summer. The average temperature falls to around 14°C during month of January–February and rise up to 35°C during the hottest months of April-May. The mean annual rainfall is 1500 mm, 80% of which is received during June to September. Total 16 numbers of soil series have been mapped in Nadia district under fluvial landscape, out of which 78.35% is under alluvial plain, 9.64% under flood plain & 6.44% under marshy land. Soils of the district has majority of area (82.93%) under almost none to slight erosion, followed by moderate (12.30%) erosion and moderate to severe erosion (0.31%) [24]. Apart from 16 soil series, soils of the district are taxonomically classified into three orders viz. Alfisol, Inceptisols and Entisols, 5 sub-orders and great groups, 12 subgroups and 16 families. The drainage pattern of the district reveals a regional south-eastern slope [25]. A large thickness of Gangetic alluvium of Quaternary age completely blankets the sub-surface geology in the district. Both confined and unconfined ground water aquifers are present within the explored depth of maximum 600mb gl with large yield prospect of about 150 $m^3 hr^{-1}$ [26]. The district which is a part of the Ganges delta, marked by shifting courses of the river Ganges in particular and changes of its various outlets, described as the moribund delta - meaning a delta of dead rivers [27]. In general, the district is an alluvial plain dotted with villages surrounded by clusters of groves and intersected by numerous small rivers, abandoned river courses, minor streams, bils or ox-bow lakes. The major emerging issues regarding ground water are lack of year round water availability along with the poor quality of drinking water. Overexploitation of groundwater aquifers along with limited and poorly maintained surface water availability, arsenic, iron and fluoride contamination, salinity development are adding up to the grave problem of rapidly deteriorating water quality.

3. Materials and methods

Pre-monsoon and post-monsoon groundwater quality data on eight water quality parameters such as total dissolved solid (ppm), total hardness (ppm), total iron (ppm), total chloride (ppm), total arsenic (ppm), pH, specific conductivity (µS) and depth of ground water (m) have been collected for the year of 2011 at 166 sites (Fig 1-c) located in Nadia district from the State Water Investigation Directorate, SWID, Kolkata. The criteria for suitability and non-suitability of the groundwater quality parameters were decided as per the water quality standards given by the World Health Organization, Central Pollution Control Board, Bureau of Indian Standards and Indian Council of Medical Research. All the statistical, geospatial computations and plotting of maps were done using open source R software - version 3.4.3 [28, 29] and QGIS - version 2.18.16, Las Palmas de G.C. [30].

3.1 Statistical characterization of ground water samples

The properties of water samples during both pre and post monsoon seasons were statistically examined for understanding the features of the data set. Descriptive statistics in terms of the maximum, minimum, mean, median and standard deviation values are shown in Table 1 & 2. Pearson correlation matrix was generated for investigating the dependence between multiple variables using R software package "PerformanceAnalytics" version 1.5.2 [31] for both pre and post monsoon data sets. A general property of spatial variables like the one under consideration is to have a spatial autocorrelation on both spatial and temporal scale. So to find out how much close ground water samples are in comparison with others, cluster analysis on both datasets was done using R software package "pvclust" version 2.0-0 [32]. Approximately Unbiased (AU) and Bootstrap Probability (BP) p-values were calculated for each cluster with 1000 bootstrapping to find how strong the cluster is supported by data [33]. For doing the hierarchical clustering average of the data were used as an agglomerative method and correlation was used as a distance measure.

3.2 Spatial Data interpolation

In these present study we have data on discrete point locations and for raster representation of the spatial distribution of the ground water properties two very common spatial interpolation algorithms such as Natural Neighbor (NN) and Inverse Distance Weighted (IDW) interpolation were used. NN uses a weighted average of the nearest neighbor values with weights dependent on areas or volumes also known as Voronoi polygons to predict the value in an unsampled location [34]. IDW is based on the approximation of value in an unsampled location as a weighted average within a certain distance, however weights in this case are inversely proportional to a power of distance [35]. R software packages "sp" version 1.2-7 [36, 37], "rgdal" version 1.2-16 [38], "dismo" version 1.1-4 [39] and "gstat" version 1.1-5 [40, 41] were used for doing both the interpolations. We have also used "colorRamps" version 2.3 and [42] "viridis" version 0.5.0 for [43] making color maps of the interpolated rasters.

3.3 Water Quality Index

Through spatial interpolation of the water sample properties in 166 locations, surface plot of different parameters have been prepared for both pre and post monsoon seasons in Nadia district. After that a single map of ground water quality index (WQI) ensembling all the ground water sample parameters was prepared for both the seasons. For computing WQI, six parameters such as specific conductivity, total dissolved solids (TDS), total hardness (TH), iron (Fe), chloride (Cl) and arsenic (As) were used. The WQI was calculated as per the formula:

$$Qi = \frac{Ci * 100}{Si}$$

$$Wi = \frac{1}{Si}$$

$$WQI = \frac{\sum_{i=1}^{n} Qi * Wi}{\sum_{i=1}^{n} Wi}$$

Where, Q_i = Quality rating for i[th] parameter, C_i = Concentration of the i[th] parameter in each sample in ppm, S_i = drinking water standards of the i[th] parameter in ppm, W_i = relative weightage of i[th] parameter, *WQI* = water quality index and *n* = number of parameters used to calculate the *WQI*. Among the six parameters taken into consideration for this study, the maximum weight was given to As followed by Fe, TH, Cl, TDS and specific conductivity. Based on the WQI values the ground water quality was classified into 5 classes such as excellent (<50), good (50-100), poor (101–200), very poor (201–300) and water unsuitable for drinking (>300). The water quality standard used for calculating WQI is shown in Table 1 & 2.

Table 1. Statistical summary of different hydrochemical parameters of the study area during Pre monsoon period

Parameter	Minimum	Maximum	Median	Mean	Standard Deviation	Remarks	Permissible limits
pH	7.34	8.45	7.94	7.94	0.29	All samples are within the limit	6.5-8.5 [3]
Specific conductivity (µS cm^{-1})	370	1960	725	751.87	188.25	65% samples are within the limit	2000 mg L^{-1} or 1000 µS cm^{-1} [44]
Total Dissolved Solids (mg L^{-1})	78	1254	461	477.29	122.06	68% samples are within the limit	1000 mg L^{-1} [45]
Total Hardness (mg L^{-1})	200	480	270	274.06	37.77	All samples are within the limit	600 mg L^{-1} [44]
Total Iron (mg L^{-1})	0.1	4.8	2.5	2.31	1.16	18 % samples are within the limit	1 mg L^{-1} [44]
Total Chloride (mg L^{-1})	20	180	60	60.83	27.80	All samples are within the limit	1000 mg L^{-1} [44]
Total Arsenic (mg L^{-1})	0.005	0.3	0.05	0.06	0.05	19 % samples are within the limit	0.05 mg L^{-1} [46]

Table 2. Statistical summary of different hydrochemical parameters of the study area during Post Monsoon period

Parameter	Minimum	Maximum	Median	Mean	Standard Deviation	Remarks	Permissible limits
pH	6.93	8.48	7.48	7.64	0.43	All samples are within the limit	6.5-8.5 [3]
Specific conductivity (µS cm^{-1})	320	1270	610	631.35	147.92	88 % samples are within the limit	2000 mg L^{-1} or 1000 µS cm^{-1} [44]
Total Dissolved Solids (mg L^{-1})	205	813	300	404.49	94.24	All samples are within the limit	1000 mg L^{-1} [45]

Total Hardness (mg L^{-1})	200	570	330	336.90	73.49	All samples are within the limit	600 mg L^{-1} [44]
Total Iron (mg L^{-1})	0.1	5	2.2	2.32	1.33	22 % samples are within the limit	1 mg L^{-1} [44]
Total Chloride (mg L^{-1})	10	170	30	40.71	26.78	All samples are within the limit	1000 mg L^{-1} [44]
Total Arsenic (mg L^{-1})	0.005	0.3	0.05	0.06	0.05	13 % samples are within the limit	0.05 mg L^{-1} [46]

4. Results and discussion

4.1 Statistical analysis of groundwater quality parameters

Statistical analysis of the hydro-chemical parameters in the ground water in terms of maximum, minimum, mean, median, and standard deviation values for both pre and post monsoon season are given in Table 1 and 2. Clustering is a procedure which involves partitioning of observations into homogenous subsets, or clusters through unsupervised learning to understand subpopulation structure in a dataset [47]. In this study for each hierarchical cluster two quantities, such as AU and BP – p values were calculated (Fig 2). AU and BP p-values are shown in red and green color, respectively. AU p-value, computed by multiscale bootstrap resampling, is a better approximation to unbiased p-value than BP value computed by normal bootstrap resampling [32]. Clusters which are strongly supported by data with AU larger than 95% are highlighted by red colored rectangles. During the pre-monsoon season, it is found that two significant clusters are present out of five clusters formed. The left side cluster has both AU and BP – p values of 1.0 (100%) meaning that total hardness, chloride content, specific conductivity and total dissolved solids will tend to be in a same cluster every time with a probability equals to 1. This result is also supported by the correlation matrix discussed in the next section, as these properties are very well correlated with correlation coefficient varying from 0.9 to 1. The right side cluster has AU-p value of 0.95 and BP-p value of 0.84, meaning that the rest of the water quality parameters such as total iron and arsenic content tend to be in the same cluster 95% or 84% times runs out of the total bootstraps, respectively. During post-monsoon season, two significant clusters are formed out of the six clusters. The left side cluster consisting of total hardness, chloride content, specific conductivity and total dissolved solids has both AU and BP-p values of 1. The right side cluster consisting of total arsenic, pH and iron content of the ground water samples and shows that in 97% or 82% of cases a random sample taken will fall in the same cluster. AU –p values are better representations than BP-p values as it is an unbiased version [32].

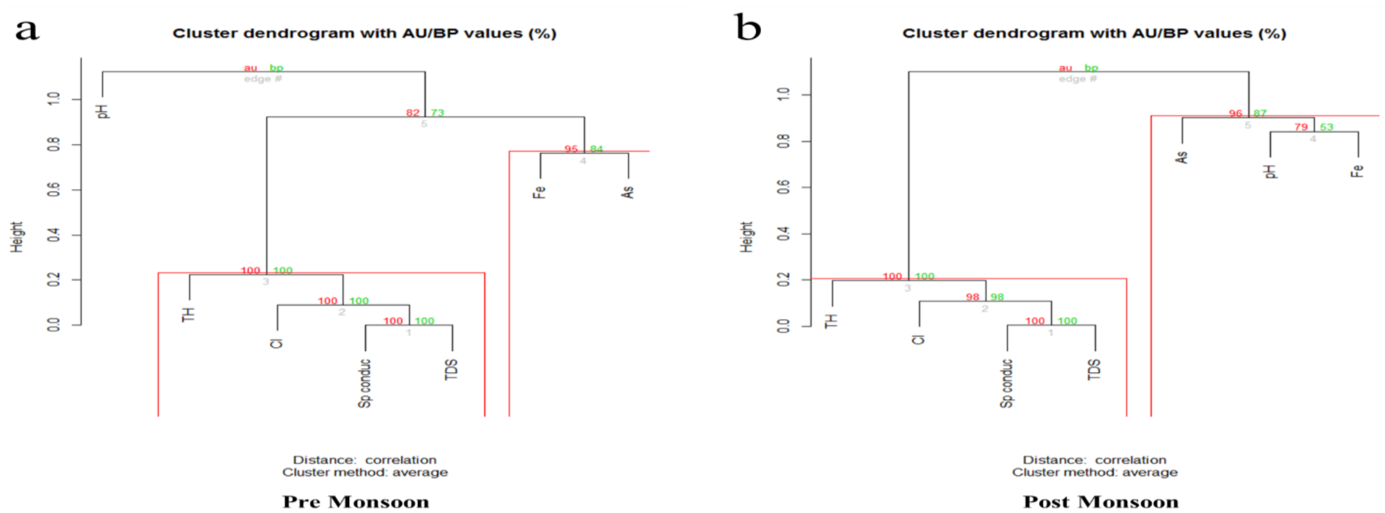

Fig 2. Hierarchical cluster analysis of the samples showing cluster dendrogram with Approximately Unbiased (AU) and Bootstrap Probability (BP) p-values for **(a)** Pre Monsoon and **(b)** Post Monsoon period.

4.2 Correlation coefficient matrix

Correlation coefficient matrix of water quality parameters for both pre and post monsoon seasons are shown in Fig 3. Diagonal elements of each Figure represent the frequency distribution or histogram of each variable. The bottom plot of each diagonal element represent the bivariate scatter plots along with a best fitted line between respective row and column variable. The correlation coefficient between two variables and their significance level is shown on the top of each diagonal element.

During pre-monsoon season, pH of the ground water was shown to be negatively correlated with specific conductivity and total dissolved solids with a weak correlation coefficient of -0.20. A weak negative correlation was also found between pH and chloride content with correlation coefficient of -0.29. Specific conductivity as well as total dissolved solids were found to have strong positive correlation with total hardness and chloride content of the water with correlation coefficient of 0.77 and 0.91, respectively. A positive correlation coefficient of 0.79 was found between total hardness of water and chloride content. Total iron content of the water was shown to have weakly correlated with total arsenic content with a correlation coefficient of 0.24.Similar to pre-monsoon season during post-monsoon period also similar trend was found. Ground water pH was shown to have weak negative correlation with specific conductivity, total dissolved solids and chloride content with a correlation coefficient of -0.19. Additionally, pH was also strongly and negatively correlated with the total hardness with a correlation coefficient of -0.46. It also had a very weak positive correlation with total iron content. In case of specific conductivity, positive correlation coefficient of 0.83 and 0.90 was found with total hardness and chloride content, respectively. Total hardness was positively correlated with chloride content and total dissolved solids with a correlation coefficient of 0.75 and 0.83, respectively. A positive correlation coefficient of 0.89 was found between chloride and total dissolved solids content. However, in the post-monsoon period, total iron and arsenic content in ground water did not show any significant correlation like pre-monsoon period.

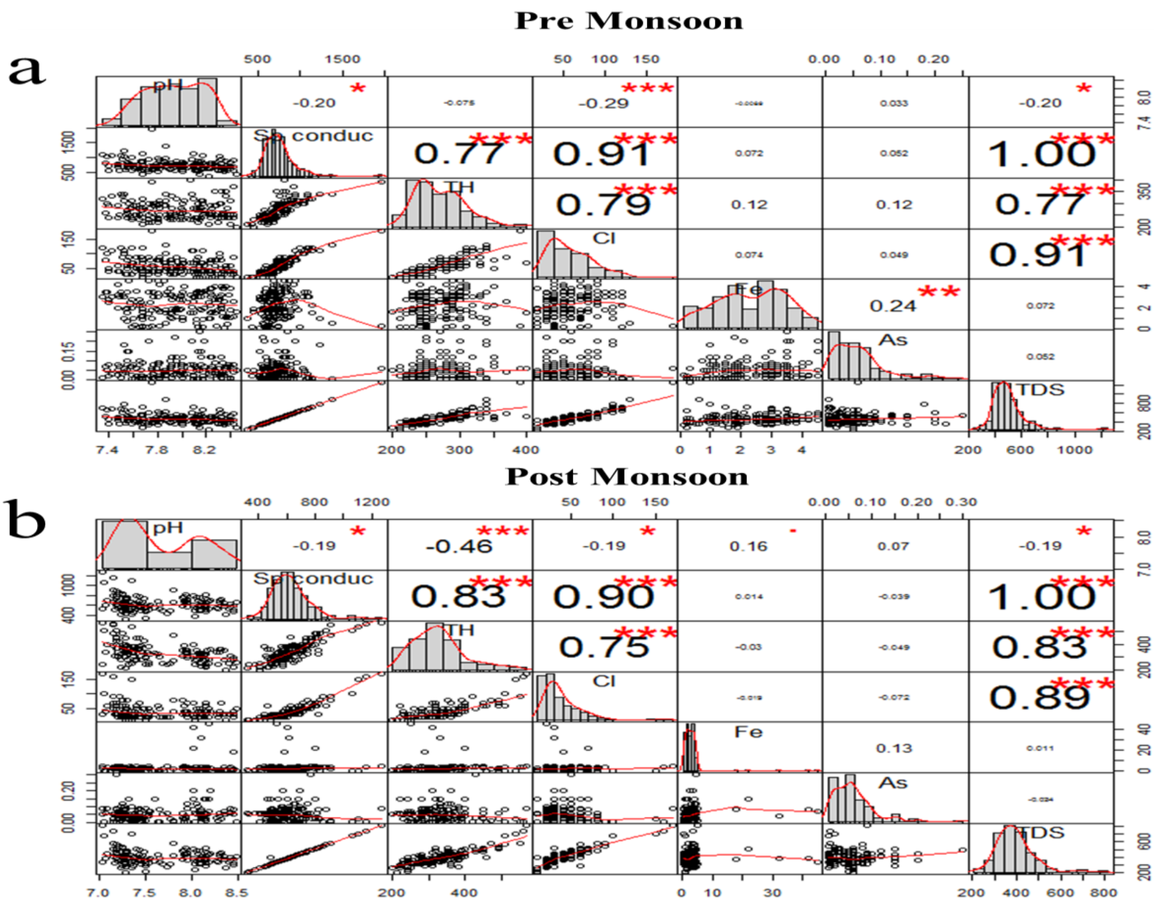

Fig 3. Correlation coefficient matrix of different water quality parameters during **(a)** Pre Monsoon and **(b)** Post Monsoon period. Level of significance are shown by symbols "***", "**", "*" corresponding to p-values of 0.001, 0.01 & 0.05, respectively.

4.3 Generation of Surface Maps of various Groundwater Quality Parameters

Spatial distribution maps of various groundwater quality parameters are useful in assessing the usability of the water for different purposes. In the present study, groundwater quality maps on eight groundwater quality parameters such as pH, specific conductivity, TDS, total hardness, depth, arsenic, chloride and iron were prepared for both pre-monsoon and post-monsoon period for the study area to understand the spatial variability of these parameters. The following section discusses about the spatial distribution characteristics of these groundwater quality parameters in the district.

4.3.1 pH

The pH value of water is a very important indication of its quality. The pH of groundwater in the study area varied from 7.92 to 8.42, thus indicating a general alkaline nature of groundwater in the district. Though the values of pH at all the 166 sites were found to be within the permissible limit for drinking water (7.5-8.5), but at many sites it is very close to upper permissible limit recommended by WHO. Spatial variations of pH are shown in Fig 4-a. Both NN and IDW produced same kind of results. A considerable variability in the district is seen from pre-monsoon to post-monsoon season. During pre-monsoon period higher ground water pH was found in parts of Karimpur-II, Nabadwip, Krishnanagar-I & II, Hanskhali, Krishnaganj and Haringhata block. During post-monsoon period, ground water pH increased in the southern part of the district particularly, Shantipur, Hanskhali, Ranaghat-II, Chakdaha and Haringhata block. In other parts, the pH remained low.

4.3.2 Specific Conductivity

Specific conductivity is a measure of dissolved solids in groundwater and it varied in the study area from 370 µS to 1960 µS during pre-monsoon period and 320 µS to 1270 µS during post monsoon period. According to Hander's classification scheme [35] the groundwater of Nadia district can be characterized as having medium to slightly high salinity (Fig 4-b). As can be seen from the NN interpolated map, during pre-monsoon season specific conductivity was found to be higher at Ranaghat and Krishnaganj. However, with IDW interpolation higher EC value was shown in the northern part of the district. During post-monsoon, EC value decreased in the study area well below the permissible limit (780µS). Although higher EC was found near Nakashipara block in both NN and IDW interpolated maps.

4.3.3 Total Dissolved Solids (TDS)

To ascertain the suitability of ground water for any purposes, it is essential to classify the ground water depending upon their hydrochemical properties, among which TDS plays a significant role. The desirable limit of TDS value is 500 ppm and water with more than 1000 ppm of dissolved solids usually gives disagreeable taste or makes the water unsuitable for other use (BIS). If the water contains less than 500 ppm of dissolved solids, it is generally satisfactory for domestic use and for many industrial purposes. The spatial map of TDS in the study area (Fig 4-c) reveals that during pre-monsoon period considerable portion of northern part of the district, particularly Karimpara-I & II and Tehatta-I along with Krishnaganj and Ranaghat- I block showed higher TDS value in the ground water having TDS value more than the desirable limit for drinking. However, during post-monsoon period ground water quality improved in respect to the TDS value except Karimpara-I & II block and Nakashipara block which showed higher TDS values.

4.3.4 Total Hardness

The hardness of water is due to the presence of two cations in water such as calcium and magnesium. The total hardness of water may be divided into 2 types, carbonate or temporary hardness and bicarbonate or permanent hardness. The temporary hardness produced by the bi-carbonates of calcium and magnesium can be removed by boiling the water. However, the hardness caused mainly by the sulphates and chlorates of calcium and magnesium cannot be removed by boiling and is therefore known as permanent hardness. Total hardness is the sum of the temporary and permanent hardness. Water that has a hardness of less than 75 ppm is considered soft. The maximum allowable limit of TH for drinking purpose is 500 ppm and the most desirable limit is 100 ppm as per the WHO international standard. Total hardness of ground water varied in the study area from 200 ppm to 480 ppm during pre-monsoon period and 200 ppm to 570 ppm during post monsoon period. From the interpolated surface map of TH (Fig 4-d) it was revealed that during pre-monsoon season TH was well below the permissible limit in the whole district. Although, in Karimpur – I & II, Tehatta-I, Krishnaganj, Hanskhali, Ranaghat – I and parts of Haringhata block TH was towards the higher side. Whereas during the post monsoon season, TH of ground water was found to increase in the northern part of the district.

4.3.5 Total iron

As per WHO norms the desirable limit for Iron in drinking water is 1.0 ppm. The concentrations of iron in ground water varied from 0.1 to 4.5 ppm during pre-monsoon period and 0.1 to 5.0 ppm during the post-monsoon period. The surface maps of iron concentration both for pre-monsoon and post-monsoon (Fig 5-a) reveal that most part of the district has iron

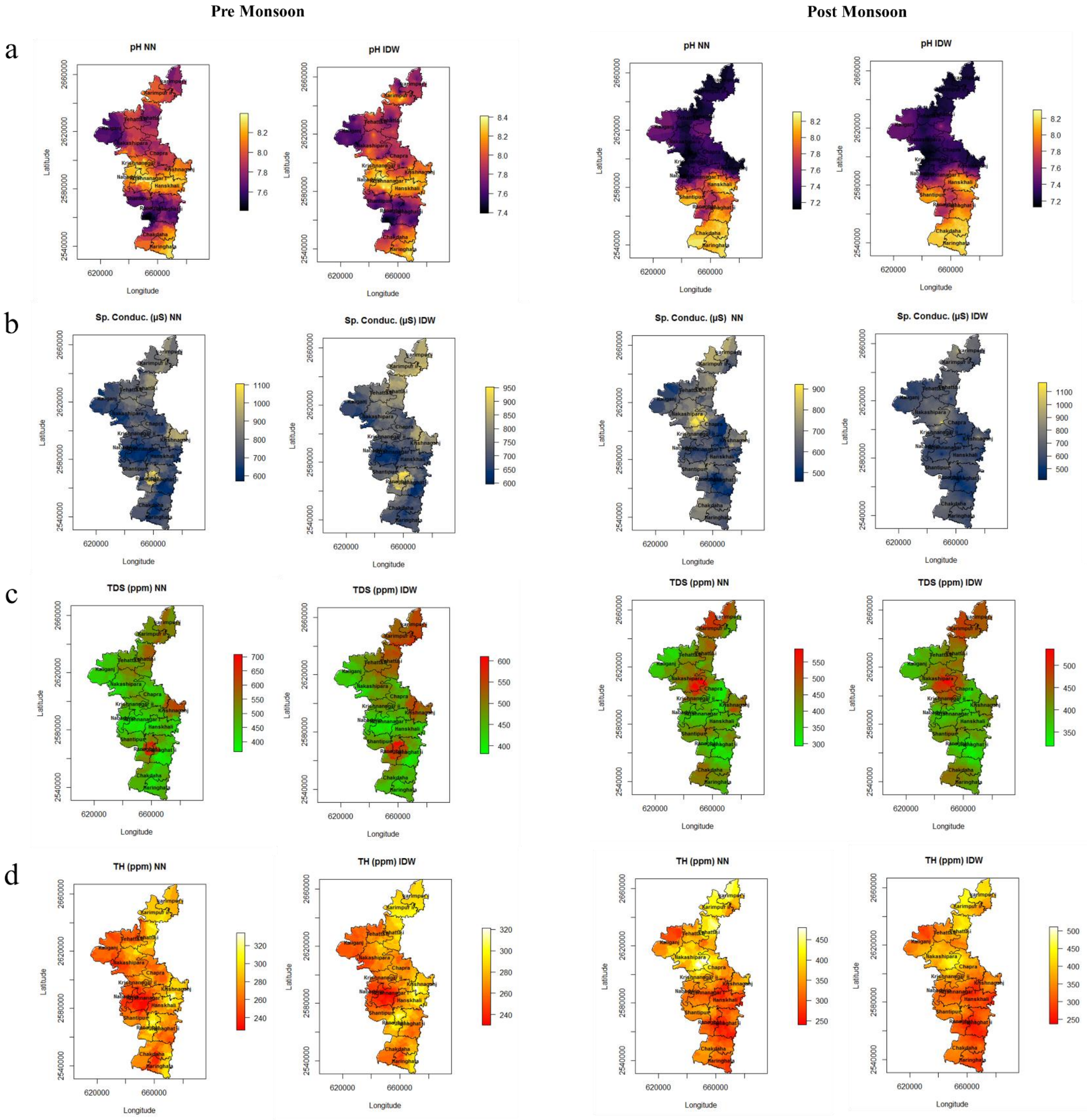

Fig 4. Ground water quality maps prepared by Natural Neighbor (NN) and Inverse Distance Weighted (IDW) interpolation during both Pre and Post Monsoon season for **(a)** pH, **(b)** Specific conductivity (µS), **(c)** Total Dissolved solids (TDS) in ppm and **(d)** Total Hardness (TH) in ppm.

concentration more than 1.5 ppm. During pre-monsoon period two highly toxic patch was identified in the district having iron concentration near to 3.5 ppm. One patch was covering parts of some blocks like Chapra, Kishanganj, Krishnanagar – I & II, Hanskhali while another toxic patch was found in parts of Tehatta- I & II and Nakashipara block. However, during post-monsoon season the iron toxicity was found to be slightly lower than pre-monsoon season in these blocks. In Nakashipara block a large patch of iron toxicity in ground water was seen to be developed as particularly shown in NN interpolated map. However, in IDW interpolated map higher iron concentration was seen in parts of Krishnanagar-II, Hanskhali, Krishnaganj, Chapra and Tehatta-I & II blocks.

4.3.6 Total Chloride

Chloride is one of the most important parameter in assessing the water quality and higher concentration of chloride indicates higher degree of organic pollution. According to WHO, the permissible limit of chloride in drinking water is 200 ppm. Spatial distribution map of chloride in the study area for pre monsoon season as well as post monsoon season reveal that the chloride concentrations in the groundwater at all the sites are much lower than the permissible limit for drinking and irrigation purposes (Fig 5-b). During pre-monsoon period chloride concentration was found to be towards the higher side in Karimpur-I, Tehatta-I, Krishnaganj and Ranaghat block particularly in case of NN interpolated map. Significant differences in interpolated chloride concentration was found between NN and IDW interpolation, particularly in case of IDW interpolated map more number of blocks in northern part of the district is seen to have higher chloride concentration. During pre-monsoon season the upper limit of interpolated chloride concentration was lower in case of IDW than that of NN interpolated one. In the post monsoon season however the upper limit of interpolated chloride concentration was found to be higher in IDW than NN interpolation. In both the interpolated maps higher chloride concentration was seen in the Nakashipara block during post-monsoon. The chloride concentration in the district varies from 20 to 180 ppm in the pre-monsoon period and 10 to 170 ppm in the post monsoon period. Therefore, groundwater can be used for drinking and irrigation purposes. Both the pre-monsoon and post-monsoon surface maps of the chloride reveal that chloride concentration is well below the permissible limit in the study area.

4.3.7 Total Arsenic

Arsenic in natural water is present predominantly in two forms: arsenate [As(V)] and arsenite [As(III)]. The acceptable level as defined by WHO for maximum concentrations of arsenic in safe drinking water is 0.01 ppm. The arsenic concentration in the study area varied from 0.005 to 0.25 ppm during pre-monsoon period and 0.005 to 0.3 ppm during post-monsoon period. The surface maps for both pre and post monsoon period are presented in Fig 5-c. The figures reveal that during pre-monsoon period most part of the district is falling under moderate arsenic contamination zone with arsenic concentration between 0.01 to 0.05 ppm. A small part of the district is falling under high arsenic contamination zone having arsenic concentration more than 0.05 mg/l. High arsenic toxicity during pre-monsoon period is seen in blocks like Karimpur-I & II, Tehatta-I, Nakashipara, Chapra, Shantipur, Ranaghat-II, Chakdaha and Haringhata blocks. However, during post-monsoon period, the area showing arsenic toxicity in ground water increased. Additionally, arsenic toxicity became prevalent in Kaliganj, Krishnanagar-I & II, Nabadwip, Haringhata and Krishnaganj blocks.

4.3.8 Depth of ground water table

Although the depth of ground water table does not affect the ground water quality directly, having a map of the same can help in delineating areas showing low water availability. The fluctuation in the level of the water table may be attributed to the changes in weather cycles and precipitation patterns, streamflow and geologic changes, etc. If the rate of recharge is lower than the exploitation in the bore well, then a "cone of depression" is created around it. Overexploitation of ground water can lower down the water table to an extent that the wells may dry and lose their capacity to supply water. However, luckily the ground water is recharged by the processes stated earlier and the rate of replenishment may vary depending upon the geologic and hydrologic conditions of the aquifer if not the water is overexploited obviously. The surface map of ground water depth in the district reveal that during both pre and post monsoon period, the ground water is near to 100 m in the whole district (Fig 5-d). Not much variation was found in the interpolated maps of depth of ground water in pre and post monsoon period. During both the season depth of water table was found to be lower in Tehatta-I, Krishnaganj, Krishnanagar-I, Hanskhali, Chakdaha and Haringhata blocks. Only minor changes was found in Krishnanagar-I and Nabadwip blocks between these two seasons.

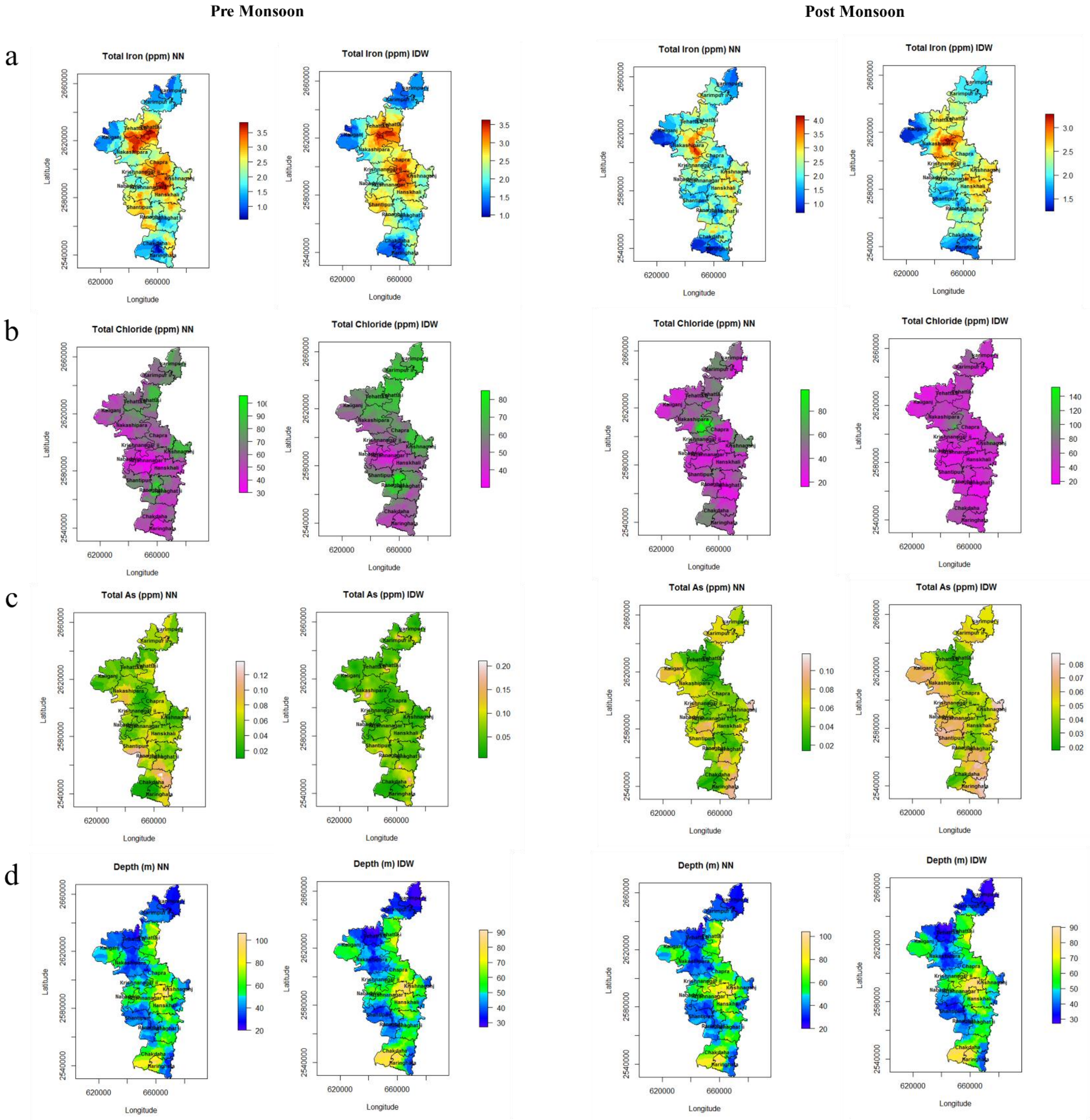

Fig 5. Ground water quality maps prepared by Natural Neighbor (NN) and Inverse Distance Weighted (IDW) interpolation during both Pre and Post Monsoon season for **(a)** Total iron content in ppm, **(b)**, Total Chloride content in ppm, **(c)** Total arsenic (As) content in ppm and **(d)** Depth (m) of ground water table.

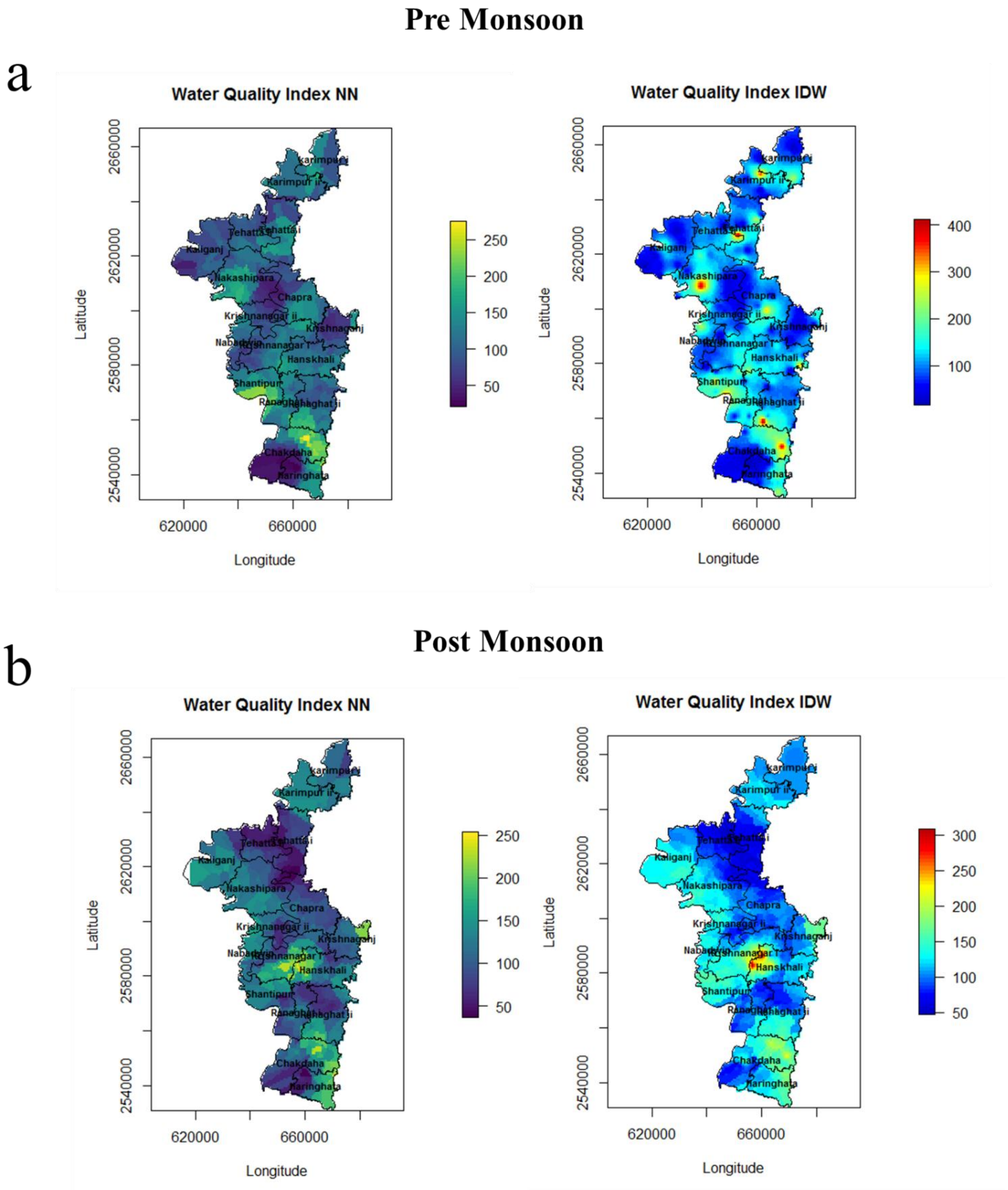

Fig 6. Water Quality Index maps during **(a)** Pre Monsoon and **(b)** Post Monsoon period as interpolated by Natural Neighbor (NN) and Inverse Distance Weighted (IDW) interpolation.

4.4 Water Quality Index (WQI) map

Interpolated surface maps of different water quality parameters provide information about the spatial distribution of different parameters and help in identifying thrust areas with respect to that particular parameter. However, the user may be interested in knowing the suitability of ground water for consumption considering all the relevant water quality parameters together rather than a single parameter alone. Therefore six water quality parameters were combined by weighted water quality index method as discussed in the methodology section in details.

During the pre-monsoon period the water quality in the district varied broadly from excellent water to unsuitable for consumption with values from <50 to around 400 as found by both NN and IDW interpolation (Fig 6-a). From NN interpolated maps water quality was found to be excellent in parts of Kaliganj, Chapra, Nakashipara, Krishnanagar-II, Krishnaganj, Chakdaha and Haringhata blocks. However in Karimpur-I & II, Tehatta-I & II, Nabadwip, Hanskhali, Krishnanagar-I, Ranaghat-I & II and Shantipur blocks along with some part of Tehatta –I, Nakashipara and Chapra blocks the water quality was found to be poor. In some pockets particularly at the center of Chakdaha and southern part of Shantipur block water quality was very poor. Although IDW interpolated map also produced similar results, in this case interpolated water quality values were towards higher limit than interpolated with NN interpolation algorithm. In case of IDW interpolated maps some small patches were highlighted with WQI value > 300 and thereby identified as having ground water unsuitable for consumption. This situation was found in blocks like Chakdaha, Ranaghat-II, Nakshipara, Tehatta-I & II and Karimpur – I & II.

During the post-monsoon season WQI value varied from <50 to around 300 in the study area (Fig 6-b). In case of NN interpolated maps ground water quality was found to be excellent in major parts of Tehatta-I & II blocks along with some less area in Karimpur-I, Krishnanagar-II, Ranaghat-II, Chakdaha and Haringhata block having WQI < 50. However, in rest parts of Karimpur-I, Ranaghat-II, Krishnanagar-II, Chakdaha and Haringhata blocks besides Karimpur-II, Kaliganj, Chapra, Nakashipara, Nabadwip, Krishnanagar-I, Krishnaganj, Hanskhali, Shantipur and Ranaghat-I blocks water quality was found to be poor. In some small parts of Krishnaganj, Krishnanagar-I, Hanskhali, Ranaghat-II, Chakdaha and Haringhata block water quality was very poor with WQI near to 250. Like pre-monsoon period, in post monsoon also IDW interpolation predicted higher values of WQI than NN interpolation. In the IDW interpolated map during post-monsoon period areas showing high WQI > 300 were found in small pockets of Krishnanagar-I and Hanskhali block and ground water is therefore unsuitable for consumption in these blocks. Therefore, the ground water quality in the district based on six parameters was shown to improve from pre-monsoon to post-monsoon period.

5. Conclusions

In the present study it was revealed that water quality varied broadly covering the full range from excellent to very poor in the district during both pre and post monsoon period. However in major portion of the district ground water was of excellent to good quality. In Chakdaha and Ranaghat –II blocks only ground water quality was found to be very poor during both the seasons. Considering two types of interpolation methods, there was considerable variation between both the methods as they differ in their sample weights. In case of natural-neighbor method only the single sampled value that was closest to the point of interest was assigned highest weight. Whereas in case of inverse distance weighting, samples that were closer to the point of interest were given larger weights. The spatial map of TDS for both pre-monsoon and post-monsoon period of the study area revealed that most part of the district have TDS values ranging from 400-500 ppm. Chloride concentration during both the pre-monsoon and post-monsoon is well below the permissible limit in the study area (below 100 ppm). Most part of the district is falling under moderate arsenic contamination zone having arsenic concentration between 0.01 to 0.05 ppm. The surface maps of iron concentration for both pre-monsoon and post-monsoon revealed that most portion of the district has iron concentration more than 3 ppm, therefore making the water unsafe for drinking purpose. The surface map of the TH concentration during wet season revealed that only at small patches the TH concentration is higher than the permissible limit, whereas for dry season, the TH concentration is well within the limit. The surface map of pH for both wet and dry season showed that pH in the district is within permissible limit. Regarding specific conductivity the groundwater was found to have medium to slightly high level of salinity. The cluster analysis of ground water quality parameters revealed that the water samples were having very similar quality parameters in terms of the total hardness, total dissolved solids, chloride content and specific conductivity and formed a strong cluster as supported by the data with AU and BP – p values of 1. During both the season pH of the ground water was shown to have a negative correlation with specific conductivity and total dissolved solids. Specific conductivity of the ground water samples also showed having a strong positive correlation with total hardness and chloride content. However, total iron content of the water was weakly correlated with total arsenic content, particularly during pre-monsoon season.

ACKNOWLEDGEMENT

The authors of this paper extend their sincere thanks to State Water Investigation Directorate, SWID, Kolkata for providing the ground water quality data of Nadia district.This research was carried out at Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia. The authors received no direct funding for this research from any government or private funding agency.

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