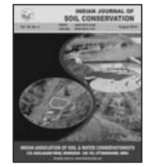
Vol. 42, No. 3, pp 260-267, 2014
Indian Journal of Soil Conservation
Online URL:http://indianjournals.com/ijor.aspx?target=ijor:ijsc&type=home



Characterization of groundwater quality for irrigation and drinking purposes using a modified groundwater quality index

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ARTICLE INFO

Article history :
Received : September, 2013
Revised : August, 2014
Accepted : October, 2014

ABSTRACT

Groundwater quality assessment is an important issue to a megacity like Delhi, where intensive agriculture, use of sewage and polluted drain water for irrigation and industrial effluents have posed a serious threat to groundwater quality. Describing overall groundwater quality over space is difficult because of multiple contaminants and its wide range of spatial variation. The present study is aimed at determination of the overall groundwater quality using a groundwater quality index after its modification and to map their spatial variation in terms of suitability for irrigation and drinking purposes. For irrigation water quality, five parameters such as electrical conductivity, sodium adsorption ratio, bicarbonate, chloride and magnesium/calcium ratio based on FAO standard and for drinking water quality, eight parameters such as sodium, calcium, magnesium, nitrate, sulphate, fluoride, total dissolved solids and hardness based on WHO standard were used. The spatial variation of groundwater quality index indicates that overall quality of Delhi groundwater is acceptable for irrigation and drinking, while highly polluted groundwater zones are mainly found at the western part. Approximately, 76.44 and 89.14% area of Delhi have groundwater suitable for irrigation and drinking purposes, respectively. Sensitivity analysis indicates that parameters, which reflect relatively poor water quality (high mean rank value) and those of significant spatial variability imply larger impacts on the index needs to be accurately assessed. The index is very robust to predict drinking water quality.

Key words :
Delhi,
FAO standards,
GIS,
Groundwater quality index,
Sensitivity analysis,
WHO standards

1. INTRODUCTION

The alluvial aquifer of Delhi is one of the heavily utilized aquifers in India and providing 50% of water requirement of Delhi. The megacity is facing both groundwater quality and quantity problems due to growing urbanization, exploding population and intensive agriculture. Delhi's groundwater level has gone down approximately by 8 m within a span of 10 years (CGWB, 2006). The groundwater recharge zones are distributed in small patches (Datta *et al*., 1996*,* Adhikary *et al*., 2014) and used as sources of contaminant migration to groundwater. The groundwater of western Delhi, especially Najafgarh block is heavily polluted from different sources (Adhikary *et al*., 2010). Open unlined drains and the pollution dumping sites in the recharge areas act as source of pollution to the groundwater (Datta *et al*., 1997). So there is an urgent need to systematically describe the overall groundwater quality that can be clearly communicated to different audiences and their spatial distribution over Delhi.

The definition of water quality is not objective but a subjective one. It depends upon desired uses. The chemical composition of groundwater is a measure of its suitability as a source of water for various uses and different uses require different standards. The groundwater quality is dependent upon different natural (precipitation, rock-water interaction, geology, geomorphology *etc*.) and anthropogenic (agriculture, industry, domestic, land use *etc.*) activities which ultimately make the groundwater vulnerable. Vulnerability is the property of the aquifer to receive and transmit contaminant from anthropogenic sources (Vrba and Zoporozec, 1994). Therefore, groundwater quality monitoring is important because we need clean water for drinking and other domestic use and irrigation to crops also.

Groundwater quality may not be attributed to a single parameter because it contains various biological, physical, chemical and radioactive attributes. These are called different indicators. It is very difficult to describe overall water quality at a particular point because of multiple contaminants. It is even more difficult to describe over space. Therefore, a groundwater quality index will be helpful to arrest the effect of multiple contaminants and by using the capability of GIS, the spatial variation of those contaminants can also be represented.

GIS based mapping of groundwater quality is an important component of a groundwater planning strategy. It can reveal potential contaminated zones and indicate suitability of water for drinking, irrigation, or other purposes (Adhikary and Biswas, 2011). It can show, quantitatively or qualitatively, certain characteristics of the sub-surface environment that determine vulnerability of groundwater to contamination (Umar *et al*., 2009). GIS can be used to identify potential areas where groundwater recharge activities can be feasible (Duraiswami *et al*., 2009) and to obtain other reliable information about current groundwater quality scenarios that may be essential for the effective and efficient implementation of water management programmes (Gupta and Srivastava, 2010).

The present study uses modified groundwater quality index proposed by Babiker *et al*. (2007) to delineate overall groundwater quality of Delhi, India. The spatial variation of irrigation and drinking water quality as it currently exists was mapped using GIS, utilizing the data generated from chemical analysis of water samples collected from the area under study. The sensitivity of the index was also tested separately for irrigation and drinking purposes.

2. MATERIALS AND METHODS

Study Area and Data Collection

The National Capital Territory of Delhi lies between 28° 24′ 15″ and 28° 53′ 00″ N latitudes and 76° 50′ 24″ and 77° 20′ 30″ E longitudes covering a total area of 1483 km^2, of which 35% is under agriculture and floriculture (Fig. 1). Agricultural area occupied the northern, western and southern border of Delhi. Urbanized areas are mainly found in the central and eastern side of Delhi. The climate is semi arid with average annual rainfall of about 700.4 mm of which 84% is received from south west monsoon during the months of July, August and September. The average annual temperature is 25°C with January being the coldest month. April and May are the driest months with relative humidity of about 30% in the morning and less than 20% in the afternoon. Soils are deep and calcareous. The geology is marked by quartzite inter-bedded with mica-schist belonging to Delhi Super Group. Quartzite occurs in the central and southern part of the area while the quaternary sediments comprising older and newer alluvium cover rest of the area. Delhi is a densely populated area and subjected to many contamination sources. The groundwater availability is controlled by hydrogeological conditions characterized by occurrence of different geological formations namely Delhi (quartzite) ridge, older and younger alluvium and Yamuna flood plain.

For this study, pre-monsoon (May) groundwater samples from 74 observation wells during 2006 were collected. The locations of groundwater observation wells (Fig. 1) were determined with the help of a global positioning system (GPS). A few locations were also cross-checked with a differential GPS. Collected samples were analysed in the laboratory to measure the concentration of the quality parameters using standard procedures (Table 1). The software GS+ 8 (*Gamma Design Software,* 1988) was used for geostatistical

Table: 1
Specific methods of estimation of different hydrochemical parameters of groundwater in the study area

Parameters	Methods
EC (Electrical Conductivity)	Conductivity Bridge method (Richards, 1954)
Na (Sodium)	Flame Photometric method (Osborn and Johns, 1951)
Ca (Calcium)	EDTA titration method (Richards, 1954)
Mg (Magnesium)	EDTA titration method (Richards, 1954)
SAR (Sodium Adsorption Ratio)	$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++}+Mg^{++}}{2}}}$
HCO_3 (Bicarbonate)	Acid titration method (Hesse, 1971)
Cl (Chloride)	Mohr's titration method (Hesse, 1971)
NO_3 (Nitrate)	Kjeldahl method (Subbiah and Asija, 1956)
SO_4 (Sulphate)	Turbidity method using $CaCl_2$ (Chesnin and Yien, 1950)
F (Fluoride)	Alizarin S visual method (Crosby *et al.*, 1968)
Hardness (As calcium carbonate concentration)	EDTA titration method (Richards, 1954)
TDS (Total Dissolved Solids)	Water quality analyzer (APHA, 1995)

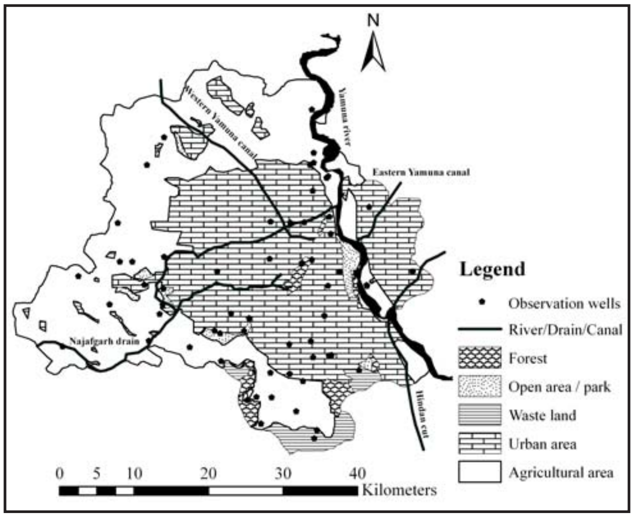

Fig. 1. Map showing the location of observation wells and land use of Delhi

analysis of data and Arc GIS 9.3 (ESRI, 2004) for generation of maps.

Geology of the Study Area

The geological map of Delhi is presented in Fig. 2. The area is transacted by a quartzite rocky ridge, called Delhi ridge which is intercalated with mica schist intruded by pegmatities and quartz veins. It is a prolongation of Aravalli Hills extending along the southern border of Delhi and ending to the north on the west bank of the Yamuna river for about 35 km. The Ridge acts as a water divide between the eastern and western parts. The alluvial formation on western side of the ridge is predominantly clay with fine grain Aeolian sand. This covers the maximum part of Delhi. Alluvial plain on the eastern side of the ridge consist mainly Yamuna sand, silt, clay with gravel. The nearly closed Chattarpur alluvial basin covering an area about 48 km^2 that is occupied by the alluvium derived from the adjacent

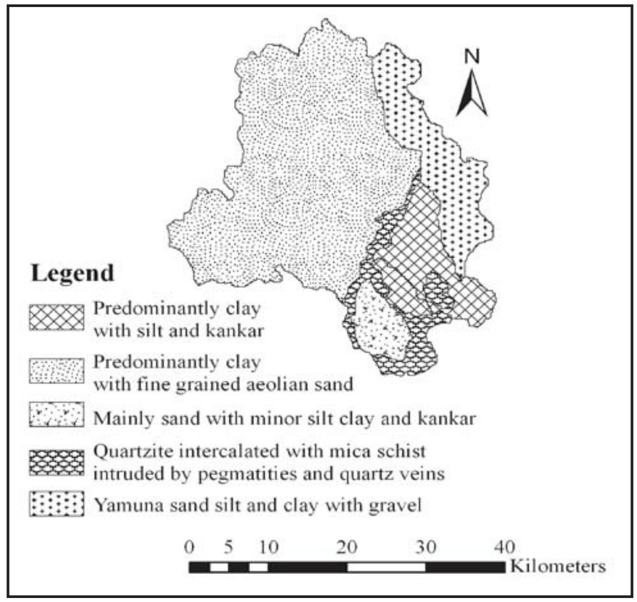

Fig. 2. General geological map of Delhi showing different geological formations

quartzite ridge. It consists mainly of sand with minor silt, clay and kankar. In between Delhi ridge and Yamuna river there is a Yamuna flood plain deposits. These are of recent origin, also termed as newer alluvium consists of predominantly clay with silt and kankar.

Standard Limits of Groundwater Quality Parameters

Certain chemical characteristics can affect the suitability of water for irrigation. But the most important are the total concentration of soluble salts, represented in terms of electrical conductivity (EC); the relative proportion of sodium to calcium and magnesium, represented by sodium adsorption ratio (SAR); bicarbonate hazard, chloride hazard and the relative proportion of magnesium to calcium (Mg/Ca ratio). To judge the irrigation water quality, the standards set by FAO (FAO, 2003) was used (Table 2).

Table: 2
Groundwater quality and their comparison with irrigation (FAO, 2003) and drinking water standards (WHO, 2004)

Parameters	Minimum	Maximum	Mean	SD	CV (%)	Irrigation standards	Drinking standards
EC (dS m^{-1})	0.44	14.46	2.04	2.41	118.35	3	-
SAR	0.60	19.22	4.61	3.75	81.38	20	-
HCO3 (me l^{-1})	1.84	16.15	6.87	2.43	35.31	8.5	-
Cl (me l^{-1})	0.70	153.55	11.54	24.08	208.76	10	-
Mg/Ca	0.19	17.24	0.90	2.01	222.12	3	-
Na (mg l^{-1})	21.00	2240.00	246.72	326.37	132.29	-	200
Ca (mg l^{-1})	8.20	1584.00	109.48	190.99	174.46	-	300
Mg (mg l^{-1})	6.48	675.60	63.38	95.32	150.39	-	300
NO_3 (mg l^{-1})	0.50	140.00	31.05	28.12	90.57	-	45
SO_4 (mg l^{-1})	0.56	1600.00	124.00	202.24	163.09	-	250
F (mg l^{-1})	0.20	5.12	0.89	0.89	99.94		1.5
TDS (mg l^{-1})	278.40	9216.00	1302.46	1541.48	118.35	-	600
Hardness (mg l^{-1})	68.00	6731.00	533.82	842.68	157.86	-	600

SD = Standard deviation, CV = Coefficient of variation

Among the different drinking water quality parameters, sodium, calcium, magnesium, nitrate, sulphate, fluoride, total dissolved solids (TDS) and hardness were considered because of their health effect. The permissible limits as per World Health Organization Standards (WHO, 2004) for drinking water quality parameters are presented in Table 2.

Generation of Groundwater Quality Index

In order to assess the combined impact of different water quality parameters on drinking and irrigation, the water quality index proposed by Babiker *et al*. (2007) was modified and used. The measured concentration is related to maximum permissible concentration using a normalized difference index.

$$CI_i = \frac{MV_i - SV_i}{MV_i + SV_i} \quad (1)$$

Where, CI_i = Contamination Index at sampling location *i*; MV_i = Measured water quality parameter at sampling location *i*; and SV_i = Maximum permissible limit of that water quality parameter set by a particular organization at i^{th} location. The CI value ranges from -1 to +1.

The CI values were then ranked between 1 and 10 by keeping -1 of CI as rank 1, 0 as 5 and 1 as 10.1 indicate no contamination and 10 indicate maximum contamination. The following polynomial function can thus be used to rank the contamination level between 1 and 10:

$$R_i = 0.5CI_i^2 + 4.5CI_i + 5 \quad (2)$$

Where, R_i is the rank at sampling location *i*.

After giving the rank, the Groundwater Quality Index at i^{th} location ($GWQI_i$) was calculated as

$$GWQI_i = 100 - \frac{1}{N}\sum_{i=1}^{N} R_i W_i \quad (3)$$

Where, W_i is the relative weight of i^{th} parameter corresponds to mean ranking value of that parameter.

The index values were spatially interpolated using ordinary kriging (OK) method to get the final drinking and irrigation water quality map for the entire study area. As the normalized CI values rank between 1 and 10, therefore, rank 5 represents the middle value. So, mean GWQI for different purposes were generated using 5 as the observed value for all the quality parameters. Thus the generated index represents the 'cut-off' value *i.e.* above which water quality is suitable and below which it is unsuitable for that particular use. The composite irrigation water quality and drinking water quality maps were generated showing locations that fell within 'suitable' and 'unsuitable' ranges.

Sensitivity Analysis

In general, a sensitivity analysis is carried out to test the overall responsiveness of the output to a certain input parameter (Oyarzun *et al*., 2007). It is the study of the effects of imposed inputs variations on the output of that analysis (Lodwick *et al*., 1990). The sensitivity analysis points out the critical parameters that need to be investigated and scrutinized via field studies and data gathering. Additionally, sensitivity analysis can be viewed as a way to assess the uncertainty effect of the input parameters on the output. Here input parameter removal sensitivity measure (Lodwick *et al*., 1990) is used to test the impacts of removing any of the input parameters from the computation of the GQI. It tests the sensitivity of the output index to the removal of one or more of the input parameters from the analyses expressed in terms of a variation index (V_i):

$$V_i(\%) = \frac{|GWQI - GWQIR_i|}{GWQI_i} \times 100 \quad (4)$$

Where, GWQI is the groundwater quality index obtained by using all the input parameters and $GWQIR_i$ is the index obtained after removing i^{th} input parameter.

3. RESULTS AND DISCUSSION

Groundwater Quality Parameters for Irrigation

The exploratory data statistics for various groundwater quality (Table 2) show that the salinity (as measured by EC) of most of the Delhi groundwater samples is lower than 3 dS m^{-1}, which made the water suitable for irrigation. The mean salinity is 2.04 dS m^{-1}, which is even lower than 3 dS m^{-1}. The range, mean, standard deviation and CV values reveal that there is a considerable variation of EC in the water samples. Alkali hazard of the irrigation water is determined by SAR. If the proportion of Na is low, the alkali hazard is low. The SAR values vary from 0.60 to 19.22 with a mean value of 4.61 indicating low alkali hazard in the groundwater of Delhi. The bicarbonate is an important anion in irrigation water as regards to calcium and a lesser degree to magnesium. It brings about a change in soluble sodium percentage in irrigation water, hence regulate the sodium hazard. Groundwater bicarbonate concentration vary from 1.84 to 16.15 me l^{-1}. The average value (6.87 me l^{-1}) is also less than the maximum permissible limit of FAO (8.5 me l^{-1}). The variation of bicarbonate in the samples is comparatively low indicated by its low CV (35.31%) value. Chlorides occur in all natural waters in widely varying concentrations. The chloride content normally increases as the mineral content increases (Sawyer and McCarty, 1978). The chloride ion occurs in natural waters in fairly low concentrations, unless the water is brackish or saline (Fetter, 1999). In the study area, chloride concentration ranges from 0.70 me l^{-1} to 153.55 me l^{-1} with a mean value of 11.54 me l^{-1} which is higher than the FAO standard of permissible limit for irrigation. The concentration of magnesium ion is more important than that of calcium ion for irrigation water and their ratio serves as an index for irrigation water quality. The Mg/Ca ratio of the groundwater samples shows a wide range of 0.19 to 17.24. But the mean value is very low (0.90). The variation of chloride and Mg/Ca is very high as CV values are 208.76 and 222.12%, respectively.

Groundwater Quality Parameters for Drinking

The groundwater quality parameters for drinking are also given in Table 2. The threshold concentration of sodium in water depends on the associated anion and the temperature of the solution. The sodium concentration varies between 21 and 2240 mg l^{-1}. The mean value (246.72 mg l^{-1}) is more than acceptable WHO drinking water quality standard. The groundwater is low in both calcium and magnesium range from 8.2 to 1584 mg l^{-1} and 6.48 to 675.6 mg l^{-1}, respectively. The average values are 109.48 mg l^{-1} and 63.38 mg l^{-1}, respectively which are even lower than their permissible limits for drinking water standard.

Nitrate concentration in groundwater is normally used to be low but can reach high levels as a result of anthropogenic activities (WHO, 2004). The nitrate level is generally low ranging from 0.50 to 140.00 mg l^{-1} with excess load in few pockets. The mean value of 31.05 mg l^{-1} is lower than tolerance limit. Sulphates occur naturally in numerous minerals and are used commercially, principally in the chemical industry. They are discharged into water in industrial wastes and through atmospheric deposition; however, the highest levels usually occur in groundwater and are from natural sources. In general, the daily intake of sulphate is from drinking-water, air and food but in areas with drinking-water supplies containing high levels of sulphate, drinking-water may constitute the principal source of intake (WHO, 2004). The wide range (56 to 1600 mg l^{-1}) and high CV (163.09 %) indicate that there is considerable variation of sulphate in Delhi groundwater but the average value (124 mg l^{-1}) is within permissible limit of drinking water quality. The Fluorine concentration varies from 0.20-5.12 mg l^{-1}. Out of total analysed samples, 24.3% contained F level lower than 0.5 mg l^{-1}, 55.4% from 0.5 to 1.0 mg l^{-1}, 9.5% from 1.0 to 1.5 mg l^{-1} and only 10.8% contained >1.5 mg l^{-1}. The mean value (0.89 mg l^{-1}) is lower than maximum permissible limit of drinking water standard.

TDS is a parameter related to EC. The importance of EC and TDS lies in their effect on the corrrosivity of a water sample and in their effect on the solubility of slightly soluble compounds such as $CaCO_3$. TDS is comprised of inorganic salts and small amounts of organic matter that are dissolved in water. It reflects the level of minerals that are present in water in dissolved form. TDS in water vary considerably in different geological regions owing to differences in the solubility of minerals (WHO, 2004). TDS ranges from 278.40 to 9216 mg l^{-1}. According to WHO standards, the desirable limit for TDS in drinking water is 600 mg l^{-1}. Even though some samples showed low TDS readings, the mean value (1302.46 mg l^{-1}) is beyond acceptable limits. High TDS values of Delhi groundwater was also observed by Kumar *et al*. (2006). Hardness of water depends on the concentration of substances such as Ca and Mg. Hardness in water is caused by dissolved Ca and, to a lesser extent, Mg. It is usually expressed as the equivalent quantity of $CaCO_3$ (WHO, 2004). The hardness of water reflects the nature of the geological formations with which it has been in contact (Sawyer and McCarty, 1978). Public acceptability of the degree of hardness may vary considerably from one community to another depending on local conditions. The taste of water with hardness in excess of 500 mg l^{-1} is tolerated by consumers in some instances. The hardness value of the groundwater samples of Delhi ranges from a minimum of 68 mg l^{-1} to a maximum of 6731 mg l^{-1} with a mean value of 533.82 mg l^{-1} which is lower than the maximum permissible limit WHO recommendations (600 mg l^{-1}).

Composite Groundwater Quality of Delhi Derived Through Index

Groundwater quality for particular use in an area is the manifestation of combined impact of multiple chemicals present there. The numerical output called the groundwater quality index (GWQI) will account the overall health of the groundwater. Based on use, the index may be of different types *viz.* irrigation water quality index (IWQI), drinking water quality index (DWQI) *etc.*

Fig. 3 shows that the Delhi groundwater quality for irrigation is generally good. The average index value of 49.25 is much higher than the cut off value of 29.73. The descriptive statistics of rank values of five quality parameters (Table 3) used to compute IWQI indicate that bicarbonate, EC and chloride dictate the spatial pattern of irrigation water quality due to their higher rank values over other. The high CV value of chloride rank indicates that the salt deposit in the study area is not homogeneous. This heterogeneity may be attributed to variations of geological materials and anthropogenic activities like agriculture, industry *etc.* (Datta *et al*., 1996). Western part of Delhi shows the availability of poor quality groundwater for irrigation and the quality is improving as one move from west to east and south-east. This is due to long term

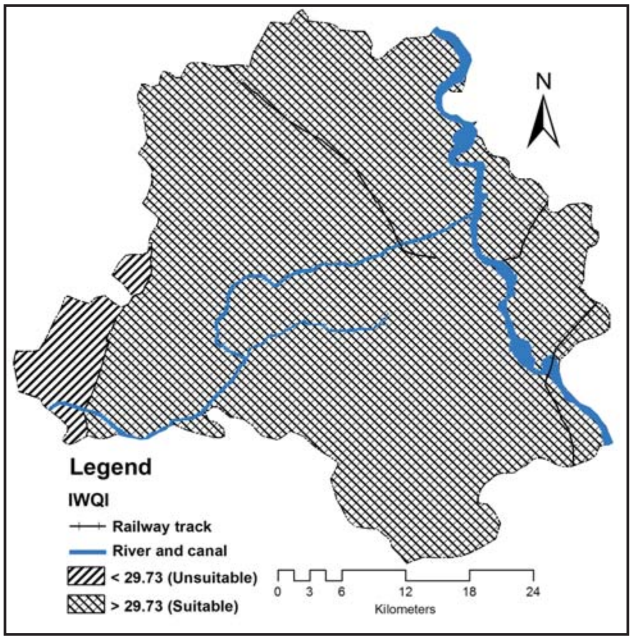

Fig. 3. Groundwater quality index map showing the spatial distribution of irrigation water quality in Delhi

Table: 3
Summary statistics of rank values groundwater quality parameters used to derive groundwater quality index for irrigation. The mean rank values were used as weighing factor for respective quality parameters

Parameters	Minimum	Maximum	Mean	SD	CV (%)
EC (dS m^{-1})	2.19	8.55	4.14	1.47	35.44
SAR	1.23	5.15	2.40	0.88	36.58
HCO_3 (me l^{-1})	2.31	6.44	4.43	0.72	16.35
Cl (me l^{-1})	1.47	9.33	3.67	2.15	58.51
Mg/Ca	1.43	8.41	2.35	1.05	44.71

agricultural practice in west Delhi results salt movement from surface to groundwater.

To judge overall drinking water quality, eight parameters were considered. Table 4 indicate that, owing to their high mean rank values, TDS, sodium, hardness, nitrate and fluoride ions mainly dictate the spatial distribution of drinking water quality over Delhi. Though the mean rank value of nitrate and fluoride may be less than TDS, sodium and hardness, their effect will obviously be high on drinking water quality because of their direct health effect. Fig. 4 shows that entire western and north-western Delhi is under poor groundwater condition, not fit for drinking. The intensive agriculture and indiscriminate use of agrochemicals like nitrogenous fertilizer in western Delhi may be the main reason for this (Adhikary *et al*., 2010). The eastern and southern Delhi is highly urbanized therefore reduce the natural recharge to groundwater. So the migration of pollutants through these areas is naturally low. The industrial disposal to rivers is a point source and has direct effect on surface water bodies but agricultural pollution being a non-point source and with its present magnitude certainly have greater impact on groundwater pollution. Area wise distribution (Table 5) of groundwater quality indicate that approximately 76.44 and 89.14% area of Delhi have groundwater underneath suitable for irrigation and drinking purposes, respectively.

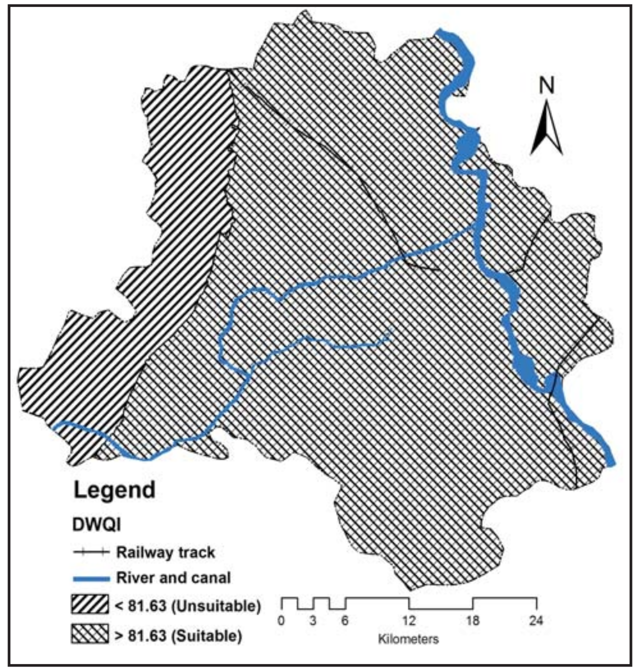

Fig. 4. Groundwater quality index map showing the spatial distribution of drinking water quality in Delhi

Table: 4
Summary statistics of rank values groundwater quality parameters used to derive groundwater quality index for drinking

Parameters	Minimum	Maximum	Mean	SD	CV (%)
Na (mg l^{-1})	1.68	9.11	4.55	1.77	38.98
Ca (mg l^{-1})	1.19	8.30	2.64	1.15	43.53
Mg (mg l^{-1})	1.15	6.81	2.09	0.98	47.15
NO_3 (mg l^{-1})	1.08	7.44	3.71	1.63	44.00
SO_4 (mg l^{-1})	1.02	8.55	2.96	1.60	54.17
F (mg l^{-1})	1.85	7.61	3.53	1.21	34.28
TDS (mg l^{-1})	3.42	9.34	5.87	1.43	24.31
Hardness (mg l^{-1})	1.73	9.11	4.04	1.38	34.20

Table: 5
Area wise (km^2) distribution of groundwater quality suitable for irrigation and drinking in Delhi predicted through GWQI

Parameters	Irrigation (km^2)	Human drinking (km^2)
Suitable	1133.61 (76.44%)	1321.9 (89.14%)
Unsuitable	349.39 (23.56%)	161.1 (10.86%)

Sensitivity Analysis

To investigate the influence of the significant parameters required to compute IWQI and DWQI, sensitivity analysis was conducted. This entailed removing each parameter from the index calculation and comparing the indices to the original. The objective is to observe whether or not any one parameter changed the index so much that it is no longer correlated with the original indices. The removal of bicarbonate and EC from the IWQI cause maximum variation to the index (Table 6) whereas chloride, SAR and Mg/Ca has less effect on the output. It is interesting to note that bicarbonate and EC have higher average rank values showing more sensitive to the output. This is true because average rank value was used as the weighing factor to compute the index. The index of variation for all the groundwater quality parameters used to compute the index is very high. This indicates that the index may not be so robust to predict overall groundwater quality for irrigation of different locations and from different data sets.

Table 6:
Results of the sensitivity analysis after removing each quality parameters from groundwater quality index for irrigation

Parameters removed	Index of Variation (%) Minimum	Maximum	Mean	SD
EC ($dS\,m^{-1}$)	12.16	144.07	37.48	25.66
SAR	4.03	44.73	11.34	7.48
HCO_3 ($me\,l^{-1}$)	13.79	94.31	40.79	15.77
Cl ($me\,l^{-1}$)	5.68	51.12	15.24	10.07
Mg/Ca	4.30	36.51	10.17	6.10

For DWQI, the magnitude of index of variation is low as compare to the same for IWQI (Table 7). TDS is maximum sensitive to DWQI followed by magnesium, calcium and sodium. Anions are showing less sensitive than cations. Although nitrate is showing less average sensitivity to DWQI but its wide range indicating that it is potentially very sensitive. The sensitivity analysis for drinking water quality reveals that regardless of which parameter is removed, the index is still significantly correlated. This suggests that DWQI is not strongly driven by one particular parameter, but rather by the combination of all parameters. This insensitivity to independent parameters makes the index robust to predict drinking water quality.

Table: 7
Results of the sensitivity analysis after removing each quality parameters from groundwater quality index for drinking

Parameters removed	Index of variation (%) Minimum	Maximum	Mean	SD
Na ($mg\,l^{-1}$)	0.04	3.56	1.11	0.81
Ca ($mg\,l^{-1}$)	0.16	2.84	1.31	0.52
Mg ($mg\,l^{-1}$)	0.99	3.09	1.75	0.48
NO_3 ($mg\,l^{-1}$)	0.01	4.01	0.84	0.75
SO_4 ($mg\,l^{-1}$)	0.05	2.97	1.01	0.48
F ($mg\,l^{-1}$)	0.02	2.42	0.74	0.59
TDS ($mg\,l^{-1}$)	1.74	5.92	3.34	0.99
Hardness ($mg\,l^{-1}$)	0.01	2.60	0.46	0.42

4. CONCLUSIONS

The aim of this study was to map and evaluate the overall groundwater quality of Delhi using a groundwater quality index. Spatial distribution of groundwater quality indices were carried out through GIS and geostatistical techniques. Highly polluted groundwater zones were mainly found at the western part of the study area but overall groundwater quality is acceptable. Approximately, 76.44 and 89.14% area of Delhi have groundwater suitable for irrigation and drinking purposes, respectively. Sensitivity analysis indicates that parameters which reflect relatively poor water quality (high mean rank value) and those of significant spatial variability imply larger impacts on the GWQI and must be carefully and accurately analysed. The index is very robust to predict drinking water quality but not so robust to predict irrigation water quality.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. G.C. Saha, Officer In-Charge, State Unit Office, Delhi, Central Ground Water Board (CGWB) for providing the groundwater quality data of NCT of Delhi.

REFERENCES

Adhikary, P.P. and Biswas, H. 2011. Geospatial assessment of groundwater quality in Datia district of Bundelkhand. *Ind. J. Soil Cons.*, 39(2): 108-116.

Adhikary, P.P., Chandrasekharan, H., Chakraborty, D. and Kamble, K. 2010. Assessment of groundwater pollution in west Delhi, India using geostatistical approach. *Environ. Monit. Assess.,* 167: 599-615.

Adhikary, P.P., Chandrasekharan, H., Dash, J. and Jakhar, P. 2014 Integrated isotopic and hydrochemical approach to identify and evaluate the source and extent of ground water pollution in west Delhi, India. *Ind. J. Soil Cons.,* 42(1): 17-28.

APHA. 1995. *Standard methods for the examination of water and wastewater*, 19th edn. APHA, Washington DC, USASS.

Babiker, I.S., Mohamed, M.A.A. and Hiyama, T. 2007. Assessing groundwater quality using GIS. *Water Resour. Manage*., 21: 699-715.

CGWB. 2006. *Ground water year book, National Capital Territory, Delhi*. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India.

Chesnin, L. and Yien, C.H. 1950. Turbidimetric determination of available sulphates. *In: Proc. Soil Science Society Agriculture*, 14: 49-151.

Crosby, N.T., Dennis, A.L. and Stevens, J.G. 1968. An evaluation of some methods for the determination of fluoride in potable waters and other aqueous solutions. *Analyst*, 93: 643-652.

Datta, P.S., Bhattacharya, S.K. and Tyagi, S.K. 1996. ^{18}O studies on recharge of phreatic aquifers and groundwater flow paths of mixing in the Delhi area. *J. Hydrol*., 176: 25-36.

Datta, P.S., Deb, D.L. and Tyagi, S.K. 1997. Assessment of groundwater contamination from fertilizers in the Delhi area based on ^{18}O, NO_3 and K^+ composition. *J. Contamin. Hydrol*., 27: 249-262.

Duraiswami, R.A., Dumale, V. and Shetty, U. 2009. Geospatial mapping of potential recharge zones in parts of Pune city. *J. Geol. Soc. Ind.*, 73: 621-638.

ESRI. 2004. *Using Arc GIS geostatistical analyst*. Environmental Systems Research Institute, Redlands, California, New York, USA, 300 p.

FAO. 2003. *The irrigation challenge: Increasing irrigation contribution to food security through higher water productivity from canal irrigation systems*. IPTRID Issue Paper 4, IPTRID Secretariat, Food and agricultural Organization of the United Nations, Rome.

Fetter, C.W. 1999. *Contaminant hydrogeology*. USA: Prentice Hall, 500 p.

Gamma Design Software, LLC 1988. *GS+*. Michigan, USA.

Gupta, M. and Srivastava, P.K. 2010. Integrating GIS and remote sensing for identification of groundwater potential zones in the hilly terrain of Pavagarh, Gujarat, India. *Water Int.,* 35(2): 233-245.

Hesse, P.R. 1971. *A text book of soil chemical analysis*. John Murray Publishers Ltd., *50 Albemarle Street,* London, WIX4 BD.

Kumar, M., Ramanathan, A.L., Rao, M.S. and Kumar, B. 2006. Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. *Environ. Geol*., 50: 1025-1039.

Lodwick, W.A., Monson, W. and Svoboda, L. 1990. Attribute error and sensitivity analysis of map operations in geographical information systems: Suitability analysis. *Int. J. Geogr. Inf. Syst.*, 4(4): 413-428.

Osborn, G.H. and Johns, H. 1951. The rapid determination of sodium and potassium in rocks and minerals by flame photometry. *Analyst,* 76: 410-415.

Oyarzun, R., Arum, J., Salgado, L. and Marin˜o, M. 2007. Sensitivity analysis and field testing of the RISK-N model in the Central Valley of Chile. *Agri. Water Manage*., 87: 251-260.

Richards, L.A. 1954. *Diagnosis and improvement of saline-alkali soils*. Agricultural Handbook No. 60, USDA.

Sawyer, C.N. and McCarty, P.L. 1978. *Chemistry for environmental engineering*. NY: Mc-Graw Hill, 532 p.

Subbiah, B.V. and Asija, G.L. 1956. A rapid procedure for the determination of available nitrogen in soils. *Curr. Sci.,* 25: 259-260.

Umar, R., Ahmed, I. and Alam, F. 2009. Mapping groundwater vulnerable zones using modified Drastic approach of an alluvial aquifer in parts of central Ganga plain, western Uttar Pradesh. *J. Geol. Soc. Ind.*, 73: 193-201.

Vrba, J. and Zoporozec, A. 1994. *Guidebook on mapping groundwater vulnerability*, IAH International Contribution for Hydrogeology, Heise, Hannover, v.16, 131p.

WHO. 2004. *Guidelines for drinking water quality*. Third edition. World Health Organization, Geneva.