Arab J Geosci (2015) 8:2699–2711
DOI 10.1007/s12517-014-1415-x

ORIGINAL PAPER

GIS applicability to assess spatio-temporal variation of groundwater quality and sustainable use for irrigation

Partha Pratim Adhikary · H. Chandrasekharan · S. M. Trivedi · Ch. Jyotiprava Dash

Received: 15 March 2013 / Accepted: 2 April 2014 / Published online: 22 April 2014

Abstract Sustainable and safe use of groundwater requires periodical monitoring of its quality. Because of the presence of multiple contaminants, spatial variation of overall groundwater quality is difficult to describe. The present study describes the overall groundwater quality for irrigation using a multi-criteria quality assessment system and sustainability of water use by incorporating the aspect of temporal variation of groundwater quality. The GIS-based multi-criteria system effectively amalgamated different quality parameters into an easily understandable format and assessed the spatial variation of groundwater quality for irrigation in west Delhi, India. The rate of spatial increment of poor quality groundwater within the study period was 3.7 km^2 per year. It has been observed that there is deterioration of groundwater quality from south-west to east, along the general groundwater flow direction, and improvement of groundwater quality from west to north-east, due to less urbanization and availability of groundwater recharge zones with good quality water. Temporal variation of groundwater quality is high ($V > 20$ %) at northern part, moderate ($V = 10–20$ %) at middle and southern parts, and less ($V < 10$ %) at some pockets of southern part of the study area. The overall groundwater quality coupled with its variation reveals that while the groundwater use is mostly unsustainable in the southern part, groundwater sustainability is constrained by relatively poor and variable quality in western and northern fringes of the study area.

P. P. Adhikary (✉) · C. J. Dash
Central Soil and Water Conservation Research & Training Institute, Research Centre, Koraput, Odisha 763002, India
e-mail: ppadhikary@gmail.com

H. Chandrasekharan · S. M. Trivedi
Indian Agricultural Research Institute, PUSA, New Delhi 110012, India

Keywords Delhi · GIS · Groundwater quality · Spatial variation · Sustainable use · Temporal variation

Introduction

Optimum planning for judicious use of water resources is important to meet the demand of the ever-growing population in a city like Delhi, where demand of fresh water always exceeds supply. The study area forms a part of peri-urban areas, west Delhi, wherein rapid change of agricultural pattern, increase of agro-based industry, and use of polluted drain water for irrigation cause significant deterioration in the quality of groundwater (Adhikary et al. 2010). The contaminated groundwater cannot cleanse itself of degradable wastes very rapidly as flowing surface water does (Poonam and Namita 2001). Groundwater movement being very slow hinders effective dilution and dispersion of contaminants. It may take hundreds to thousands of years for contaminated groundwater to cleanse itself of degradable wastes on a human time scale.

The concept of sustainable use appeared in the early 1980s, which was based on judicious resource utilization to sustain over a long period. Sustainable groundwater use is commonly defined as development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley and Leake 2004). In recent years, research on sustainable management of groundwater resources has got international spotlight (Xu et al. 2005; Qureshi et al. 2010). The groundwater resources need a sustainable use to maintain them for future generations and to meet the constraining factors in water management (Sophocleous 2005). Besides the contaminant load in groundwater, other factors like soil information and socioeconomic condition of the groundwater users also play significant roles to achieve the water resources sustainable development (Kawy 2012). Kritsotakis and Tsanis

(2009) developed a surface-groundwater integrated program for the sustainable water resources management. Sustainability issue regarding groundwater use can easily be addressed when a single parameter governs the quality, but in practical sense, it is very complicated because of multiple constituents.

Groundwater quality is the manifestation of combine impact of various biological, physical, chemical, and radioactive attributes. However, for irrigation purpose, chemical attribute plays the most significant role. The overall chemical quality of groundwater is very difficult to describe over space because of multiple contaminants. Therefore, multiple criteria are necessary to ascertain the combined effect of various contaminants on groundwater quality. The distribution of combined groundwater quality over space can be described by either traditional system or the spatial interpolation capability of geographic information system (GIS).

The efficacy of traditional system has generally been limited to the difficulty in acquiring useful information over vast areas and the lack of means to effectively process and analyze the acquired data (Dengiz et al. 2010). In addition to these, the vastness of various factors associated with each feature under study makes the manual methods too expensive and time consuming (Aronoff 1989). During the last decade, GIS has received much attention in applications related to resources on large spatial scales (Chandio et al. 2012).

GIS is an important component for groundwater resources management and can help to identify and map the zones of contaminated plumes in the aquifer (Arnous and El-Rayes 2012), and delineate the areas suitable for drinking and irrigation purposes (Adhikary et al. 2012). Certain characteristics of the subsurface environment can be shown quantitatively or qualitatively to determine the vulnerability of groundwater to contamination (Al Hallaq and Elaish 2012). Apart from delineating groundwater potential zones (Pradhan 2009; Manap et al. 2012; Manap et al. 2013), GIS can also be used to identify potential areas where groundwater recharge activities can be feasible (Khodaei and Nassery 2013; Kaliraj et al. 2013), and to obtain other reliable information about current groundwater quality scenarios, essential for effective and efficient implementation of water management programs (Babiker et al. 2007; Neshat et al. 2013).

In this study, authors intended to describe the overall groundwater quality for irrigation using a multi-criteria system of different chemical quality parameters. Additionally, the aspect of temporal variation of groundwater quality was incorporated to address the extent of water use sustainability. Capabilities of GIS were used to implement the multi-criteria and temporal aspect for mapping the areas suitable for sustainable use of groundwater for irrigation.

Materials and methods

Study area

The study area is situated between 76° 50′ 24″ and 77° 02′ 15″ E and 28° 39′ 41″ and 28° 30′ 19″ N, and covers almost 189 km^2 (Fig. 1). Najafgarh drain flows along the southern and eastern boundary, and Kultana Chhudani Bupania drain along the northern boundary of the study area. The climate is subtropical semiarid with an average annual rainfall and evaporation value of about 700.8 and 2,565 mm, respectively (average of 30 years). Southwest monsoon (July to September) contributes 84 % of total rainfall. The monthly mean temperature ranges from 21 to 41 ºC, while the annual mean temperature is 31.5 ºC.

Soil and hydrogeology

The study area consists mainly of alluvial formation. Soils are coarse loamy, mixed, hyperthermic, and Typic Haplustepts. Most of the soils come under Palam series comprising of very deep, yellowish brown alluvial soils with the presence of calcium carbonate concretions to the extent of 10–15 % by volume. The surface soils comprise mostly of ferruginous lime quartzite, granites, and schistose rock minerals. Weathering of plagioclase feldspar and hornblende is mainly responsible for the development of high SAR and salinity (CGWB 2006).

The Alwar quartzite of Delhi system, exposed in the area, belongs to Precambrian age. The quartzites are pinkish to grey in color, hard, compact, highly jointed, fractured, and weathered. These appear with interbeds of mica-schist and are intruded locally by pegmatite and quartz veins. The basement or hard rock appears at 300-m-below ground level. The water quality in general is poor due to the presence of saline aquifer at shallow depth (CGWB 2006).

Natural vegetation and land use

Natural vegetation comprises of dry deciduous trees, shrubs, and grasses. The land use has been changed significantly over the years due to urbanization. Out of the total area, nearly 75 % is cultivated, and the rest is occupied by habitats, roads, ponds, forests, and so on. This area was well covered earlier with dense vegetation. Pearl millet is the main *rainy* season crop along with guar, chickpea, and green gram. These are followed by wheat and mustard in *winter*. Farmers are now shifting towards floriculture and vegetable cultivation owing to nearness of Delhi. Tube well is the main sources of irrigation, and the boring depth ranges from 20 to 30 m (CGWB 2006).

Sampling and analytical techniques

Ninety three groundwater samples from hand pumps and dug wells, situated at different locations of the study area (Fig. 1),

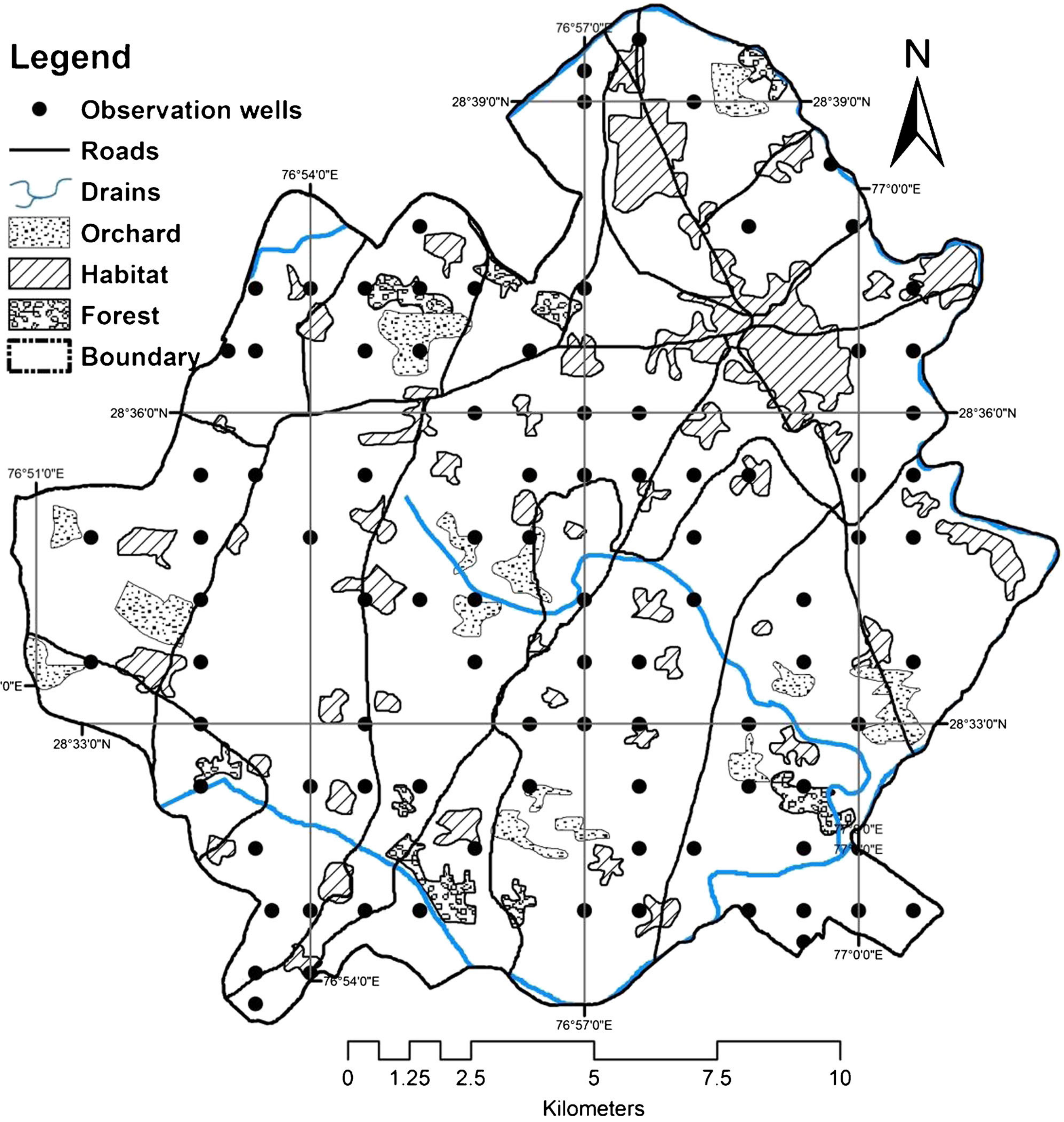


Fig. 1 Map of the study area showing the location of observation wells

were collected for the years 1997, 2004, 2006, and 2007. Geographical coordinates of each sampling location were recorded using a handheld Global Positioning System (GPS). A few locations were also cross-checked with a differential GPS. In the case of hand pumps, purging was done for 10 min to flush out the stagnant water retained in pipes. For dug wells, it was checked that the well has been used daily to ensure not to sample stale and stagnant water. The sampled water was stored in soda lime glass storage bottles sealed with bromobutyl synthetic rubber stopper. The collected samples were analyzed in the laboratory to measure the concentration of the hydrochemical parameters using standard procedures (APHA 1995).

Formulation of multi-criteria system to determine the overall groundwater quality and spatial analysis with GIS

Based on the actual concentration of chemical parameters in the groundwater, and their cutoff values for irrigation use, set by FAO (2003), a multi-criteria system was formulated

(Table 1) to determine the overall groundwater quality. Among the various chemical constituents, the most important for irrigation water quality are the total concentration of soluble salts, represented by electrical conductivity (EC); the relative proportion of sodium to calcium and magnesium, computed as sodium adsorption ratio (SAR); carbonate hazard, represented by residual sodium carbonate (RSC), chloride hazard; and the relative proportion of magnesium to calcium (Mg/Ca ratio). Grouping of good, medium, and poor quality water for irrigation owing to the presence of multiple pollutants in groundwater is presented in Table 1. Spatio-temporal thematic maps of these five quality parameters were prepared and classified based on the concentration of pollutants using ordinary kriging interpolation technique of ArcGIS. These five thematic maps were overlaid based on the multi-criteria, and composite irrigation water quality maps for all the years were prepared.

Temporal variation of groundwater quality and sustainability of groundwater use for irrigation

The temporal variation of groundwater quality at a particular point was determined by measuring the temporal coefficient of variation (a measure of variability in time and expressed as (standard deviation/mean)*100) of each groundwater quality parameters of that point. The overall variation (V) of groundwater quality at each well was then calculated as:

$$V = \frac{1}{N}\sum_{i=1}^{N} CV_i \qquad (1)$$

Table 1 Criteria table for irrigation water quality rating using five predominant groundwater quality parameters prevailed in the study area

EC (dS m^{-1})	Cl (me L^{-1})	Mg/Ca	RSC (me L^{-1})	SAR	Quality
<2.25	<12	<1.5	<1.25	<10	Good
				10 to 18	Good
				18 to 26	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		1.5 to 3.0	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		>3.0	RSC	SAR	Poor
	12 to 20	<1.5	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		1.5 to 3.0	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		>3.0	RSC	SAR	Poor
	>20	Mg/Ca	RSC	SAR	Poor
2.25 to 5.00	<12	<1.5	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		1.5 to 3.0	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		>3.0	RSC	SAR	Poor
	12 to 20	<1.5	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		1.5 to 3.0	<1.25	SAR	Medium
			1.25 to 2.5	SAR	Medium
			>2.5	SAR	Poor
		>3.0	RSC	SAR	Poor
	>20	Mg/Ca	RSC	SAR	Poor
>5.00	Cl	Mg/Ca	RSC	SAR	Poor

Mg/Ca Ratio between magnesium and calcium; *RSC* Residual sodium carbonate; *SAR* Sodium adsorption ratio

Table 2 Criteria table for sustainable use of groundwater for irrigation using overall quality of groundwater and degree of temporal variation of groundwater quality

Groundwater quality	Temporal variability	Sustainable use
Good	Low	Sustainable
	Moderate	Sustainable
	High	Doubtful
Medium	Low	Doubtful
	Moderate	Doubtful
	High	Unsustainable
Poor	Low	Unsustainable
	Moderate	Unsustainable
	High	Unsustainable

Where CV_i is the variation coefficient of the i^{th} parameter, and N is the total number of parameters. The overall variation was then separated into two types: long-term variation, showing the variation for 10 years, and short-term variation, depicting the variation for 3 years. Short- and long-term temporal variation maps were generated from the point data using kriging interpolation technique. The temporal variation maps were then integrated with the recent (year 2007) groundwater quality map, using the sustainability criteria as depicted in Table 2 that the sustainability of water use increases when groundwater quality improves and variation decreases.

Spatial autocorrelation of groundwater quality parameters

Concentration of chemical constituents in groundwater, measured at several locations with discrete values, can be considered as random. But they show a certain degree of spatial correlation with themselves. Therefore, to know the randomness of the sample points, the arrangement pattern of the wells was analysed. Moreover, the spatial autocorrelation analysis was carried out using GS + software to understand the correlation between the points and to visualize the spatial variability of the groundwater quality.

Spatial variability of groundwater quality parameters

Spatial variability is expressed as a semivariogram which is a graphical representation of the mean square variability between the two neighboring points of distance h as shown in Eq. 2:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(H)} [z(x_i + h) - z(x_i)]^2 \tag{2}$$

Where *γ(h)* is the semivariogram expressed as a function of the magnitude of the lag distance or separation vector h between the two pints, *N(h)* is the number of observation pairs separated by distance h, and $z(x_i)$ is the random variable at location x_i. The experimental semivariogram was fitted to a theoretical model, based on highest R^2 and lowest RSS, to determine the three parameters, such as the nugget (C_0), the sill ($C + C_0$), and the range (A_0). Surface maps of all the groundwater quality parameters were prepared using ordinary kriging method. Ordinary kriging estimates the value of groundwater quality parameters at unsampled locations using weighted linear combinations of known parameters located within a neighborhood, centered around that particular point.

Cross validation of the predicted maps

The accuracy and uncertainty of the groundwater quality maps were evaluated with cross-validation approach (Davis 1987). Mean absolute error (MAE) and mean squared error (MSE) measure the accuracy of prediction, whereas goodness-of-prediction (G) measures the effectiveness of prediction. MAE is expressed as the sum of the residuals:

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} \left(z_{o,i} - z_{p,i}\right) \cong 0 \tag{3}$$

Table 3 Statistical summary of the Moran's I, the measure of spatial autocorrelation

Parameters	Moran's I											
	Minimum				Maximum				Average			
	1997	2004	2006	2007	1997	2004	2006	2007	1997	2004	2006	2007
EC	−0.22	−0.17	−0.15	−0.15	0.74	0.79	0.73	0.74	0.13	0.14	0.13	0.13
Cl	−0.18	−0.22	−0.24	−0.22	0.44	0.64	0.72	0.77	0.07	0.11	0.13	0.15
Mg/Ca	−0.29	−0.24	−0.11	−0.11	0.12	0.11	0.36	0.38	−0.03	−0.03	0.04	0.04
RSC	−0.17	−0.17	−0.20	−0.17	0.46	0.43	0.40	0.39	0.06	0.04	0.07	0.06
SAR	−0.21	−0.21	−0.10	−0.10	0.67	0.59	0.77	0.77	0.12	0.11	0.12	0.12

Table 4 Best-fit semivariogram models and semivariogram parameters of groundwater quality variables in the study area for the years 1997, 2004, 2006, and 2007

Parameters	Semivariogram model	Nugget, C_0				Sill, $C_0 + C$				Range, A_0 (km)			
		1997	2004	2006	2007	1997	2004	2006	2007	1997	2004	2006	2007
EC (dS m^{-1})	Spherical	0.01	0.01	0.84	0.82	8.43	10.47	10.98	10.78	6.72	7.23	7.95	8.01
Cl (me L^{-1})	Spherical	26.28	33.56	47.24	76.17	446.25	553.42	739.15	708.73	7.26	7.77	7.88	8.37
Mg/Ca	Exponential	0.02	0.01	0.01	0.01	0.59	0.59	0.53	0.52	4.61	4.32	5.01	5.07
RSC (me L^{-1})	Exponential	35.55	45.37	62.9	72.2	135.34	192.41	214.64	225.95	12.66	13.50	30.96	32.81
SAR	Exponential	0.01	0.01	0.01	0.10	14.67	13.70	16.62	32.48	5.89	5.94	6.64	6.83
STV	Spherical	39.62				46.24				11.51			
LTV	Spherical	52.96				59.09				11.03			

STV Short-term variation; *LTV* Long-term variation

Where $z_{o,i}$ is the observed value at location i, $z_{p,i}$ is the predicted value at location i, and N is the number of pairs of observed and predicted values. MAE values near to zero indicate better prediction. The MAE measure, however, does not reveal the magnitude of error; hence, MSE is used as squaring the difference at any point that gives an indication of the magnitude:

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left(z_{o,i} - z_{p,i}\right)^2 \cong \text{minimun} \tag{4}$$

The G measure indicates the effectiveness of a prediction, relative to that of sample mean.

$$G = 1 - \left[\frac{\sum_{i=1}^{N}\left(z_{o,i} - z_{p,i}\right)^2}{\sum_{i=1}^{N}\left(z_{o,i} - \bar{z}\right)^2}\right] \times 100 \tag{5}$$

Where $\bar{z}$ is the sample mean. G=100 indicates perfect prediction, while negative values indicate that the predictions are less reliable than using sample mean as the predictor.

Results and discussion

Spatial interdependence of groundwater quality parameters

Spatial autocorrelation measures the level of interdependence between the different variables and the nature and strength of that interdependence. The result of pattern analysis indicated that the sampling points were arranged in a complete spatial randomness. The probability of finding nine other points within a specified distance of any point showed an exponential growth with distance (Babiker et al. 2007). The spatial autocorrelation coefficients or the Moran's I values for the five groundwater quality parameters are summarized in Table 3. As per the result, Mg/Ca ratio and RSC showed a very weak positive autocorrelation or close to randomness (average Moran's I>0, but very close to zero), whereas EC, chloride, and SAR showed a weak negative autocorrelation (average Moran's I<0, but close to zero). So,

Table 5 Performance of kriging maps of the groundwater quality parameters for irrigation in the study area for the years 1997, 2004, 2006, and 2007 along with their temporal variation

Parameters	MAE				MSE				G			
	1997	2004	2006	2007	1997	2004	2006	2007	1997	2004	2006	2007
EC (dS m^{-1})	0.014	0.047	0.221	0.004	0.011	0.014	0.049	0.002	36.21	33.97	35.55	37.00
Cl (me L^{-1})	0.186	0.146	0.162	0.134	0.026	0.008	0.047	0.006	29.81	26.87	24.92	30.16
Mg/Ca	0.098	0.047	0.138	0.022	0.004	0.018	0.092	0.007	8.92	2.44	11.37	9.06
RSC (me L^{-1})	0.182	0.214	0.226	0.174	0.044	0.052	0.055	0.016	5.86	10.14	12.74	11.84
SAR	0.112	0.125	0.108	0.098	0.047	0.028	0.016	0.012	20.14	16.29	12.38	22.18
STV	0.086				0.024				28.19			
LTV	0.048				0.012				32.22			

MAE Mean absolute error; *MSE* Mean squared error; *G* Goodness of prediction

Table 6 Descriptive statistics of groundwater quality parameters for irrigation in the study area for the years 1997, 2004, 2006, and 2007

Parameters	Minimum				Maximum				Mean				SD			
	1997	2004	2006	2007	1997	2004	2006	2007	1997	2004	2006	2007	1997	2004	2006	2007
EC (dS m^{-1})	1.80	2.42	1.98	2.04	11.80	13.24	14.96	14.99	5.49	6.47	6.41	6.64	2.97	3.25	3.23	3.20
Cl (me L^{-1})	8.41	11.34	5.26	2.36	85.80	95.65	98.85	95.58	30.18	35.59	35.89	34.78	20.62	23.61	23.06	23.30
Mg/Ca	0.64	0.66	0.60	0.62	4.22	4.61	4.99	5.00	1.76	1.69	1.68	1.67	0.77	0.75	0.71	0.71
RSC (me L^{-1})	−34.16	−36.64	−48.93	−51.78	3.66	3.04	2.53	2.36	−12.45	−15.32	−18.46	−18.48	10.12	9.74	11.11	11.39
SAR	3.03	3.50	2.62	4.28	17.25	17.43	18.64	26.19	8.50	8.96	8.90	12.79	3.85	3.73	3.98	5.55

all the groundwater quality parameters were independent to each other and distributed randomly within the study area.

Semivariogram and groundwater quality parameters

Spherical model for EC, Cl, short-, and long-term variation of groundwater quality and exponential model for Mg/Ca, RSC, and SAR were found best fit. Table 4 shows the semivariogram parameters (nugget, sill, and range) of groundwater quality variables for all the 4 years and temporal variations of groundwater quality. For EC and chloride, the range varied from 6.72–8.01 and 7.26–8.37 km, respectively. Therefore, EC and chloride at two locations were spatially correlated with each other with a lag distance of less than 8 km; beyond this, they were randomly distributed. Mg/Ca and SAR were spatially correlated for a shorter lag distance. They became random beyond 5.07 and 6.83 km, respectively. RSC showed comparatively higher spatial correlation distance. Beyond 32.81 km, it distributed randomly in space. The temporal variations of groundwater quality showed spatial randomness beyond 11 km.

Nugget (C_0) indicates the micro-scale variability and measurement error for the respective groundwater quality parameters, whereas sill (C) indicates the amount of variation which can be defined by spatial correlation structure. For all the groundwater quality parameters except RSC, nugget component was less than 10 % of the total variation. For RSC, it varied between 19 and 24 %. So the spatial correlation structure of the quality parameters was very good. Out of the total variation, nugget component was nearly 50 % for the temporal variability component, which shows that the micro-scale variation of this property was relatively high. SAR was found to be the best in terms of spatial correlation structure.

Cross validation

Evaluation indices resulting from cross-validation of spatial maps of groundwater quality parameters are presented in Table 5. G value was greater than zero for all the quality parameters, which indicated that the spatial prediction using semivariogram parameters was better than assuming mean of observed value as the standard value for any unsampled location. The semivariogram parameters obtained from fitting of experimental semivariogram values were reasonable to describe the spatial variation. Inclusion of more number of samples might have led to better fitting of experimental semivariogram. The MAE and MSE were consistently hovered around zero, also indicated higher predictability and less uncertainty.

Spatio-temporal variation of individual groundwater quality parameters

EC

The EC ranged from 1.80–11.80, 2.42–13.24, 1.98–14.96, and 2.04–14.99 dS m^{-1}, with average values of 5.49, 6.47, 6.41, and

Table 7 Delineated area under different concentration level of individual groundwater quality parameter based on the suitability for irrigation purpose

Parameters	Area (% of total study area)											
	Low level				Medium level				High level			
	1997	2004	2006	2007	1997	2004	2006	2007	1997	2004	2006	2007
EC	49.1	37.7	35.1	28.7	22.3	23.0	26.1	29.7	28.7	39.3	38.8	41.5
Cl	37.4	35.4	27.9	31.2	27.2	23.0	25.0	23.1	35.4	41.6	47.1	45.7
Mg/Ca	30.3	38.6	44.7	47.2	55.9	48.6	42.6	40.9	13.8	12.7	12.8	11.8
RSC	86.0	80.1	86.7	97.9	12.6	18.9	12.1	2.1	1.4	1.1	1.2	0.0
SAR	79.2	78.4	72.9	36.9	20.8	21.6	25.1	54.6	0.0	0.0	2.0	8.5

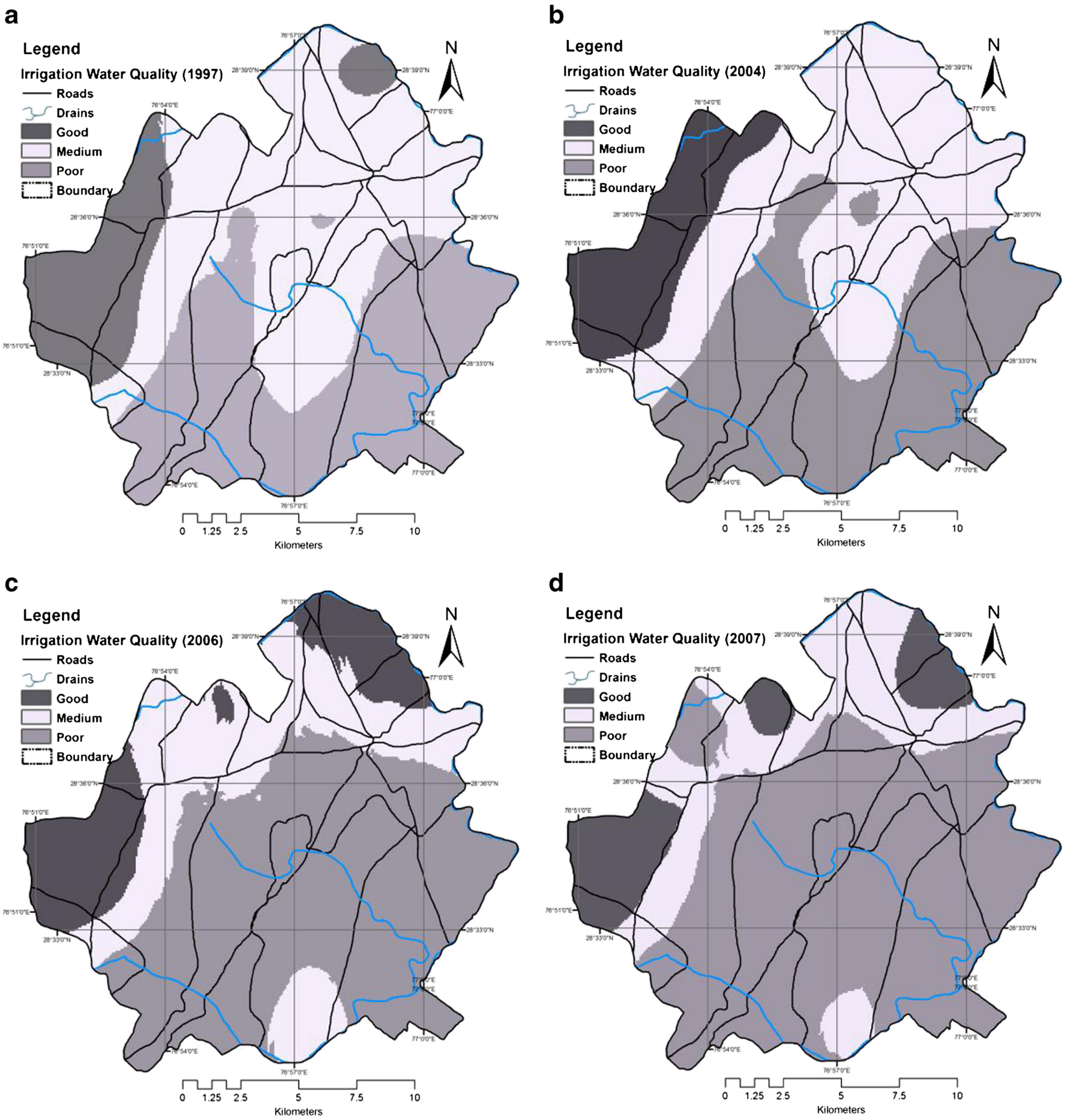


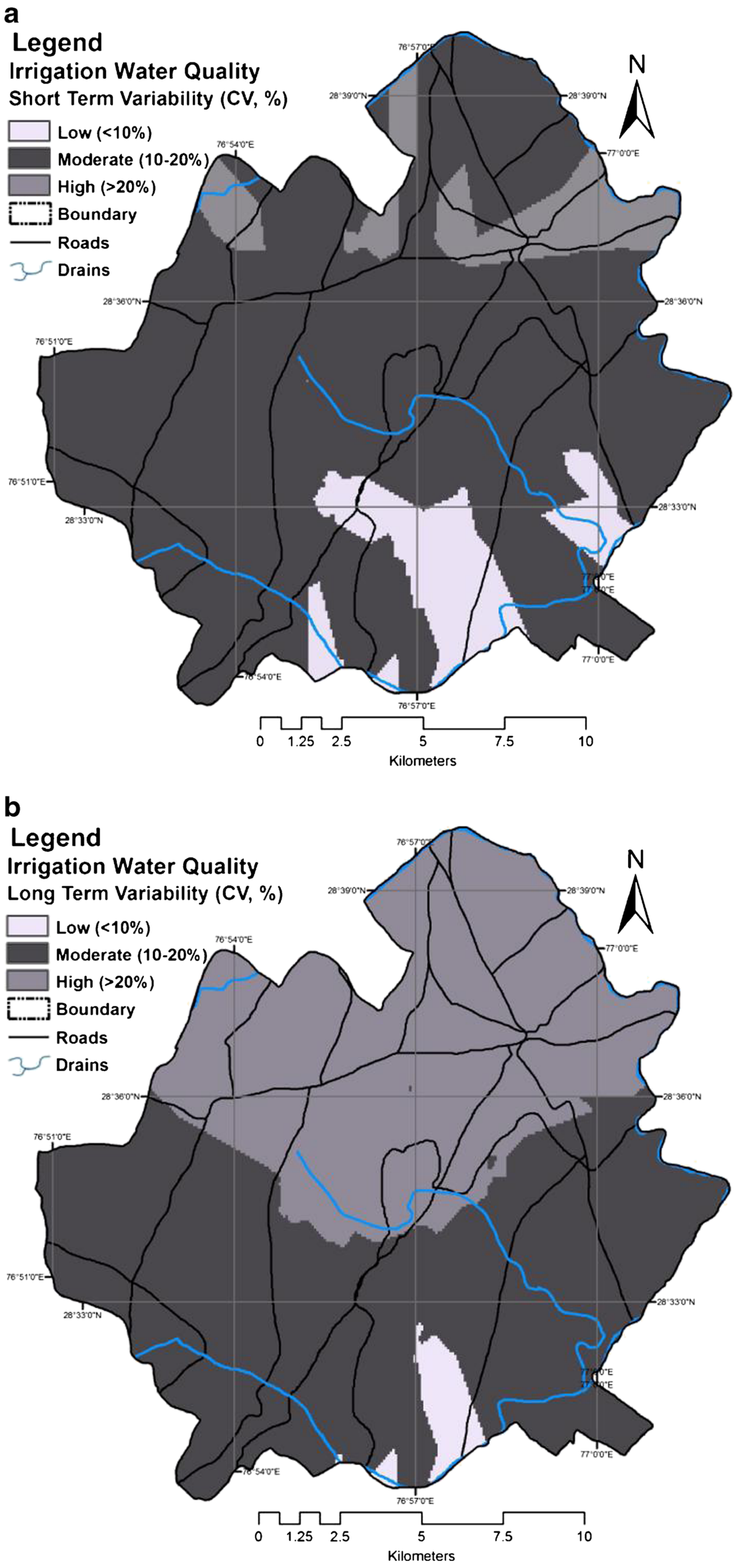
Fig. 2 Map displaying the spatial variation of overall groundwater quality for irrigation in the study area for the years **a** 1997, **b** 2004, **c** 2006, and **d** 2007

Table 8 Delineated area under different level of overall groundwater quality for irrigation in the study area

Groundwater Quality	Area (km^2)			
	1997	2004	2006	2007
Good	38.6 (20.4)$^{\#}$	44.5 (23.5)$^{\#}$	44.1 (23.4)$^{\#}$	23.3 (12.3)$^{\#}$
Medium	85.1 (45.0)$^{\#}$	70.5 (37.3)$^{\#}$	54.8 (29.0)$^{\#}$	59.4 (31.5)$^{\#}$
Poor	65.4 (34.6)$^{\#}$	74.0 (39.2)$^{\#}$	90.1 (47.7)$^{\#}$	106.3 (56.2)$^{\#}$

[#] Data within the parenthesis indicate percent delineated area

Fig. 3 Map displaying the degree of temporal variability of groundwater quality for irrigation across the study area: **a** Short-term variability and **b** long-term variability



6.64 dS m^{-1} for the years 1997, 2004, 2006, and 2007, respectively (Table 6). The range, mean, and standard deviation values revealed considerable spatial dispersion. During 1997, 28.7 % of the area was prone to high groundwater salinity, but in 2007, the same has been increased to 41.5 % (Table 7). Highly saline groundwater plumes were mostly found at southwestern and southeastern parts of the study area, covering the villages of Daurala, Ghalibpur, Raota, Ghummanhera, Raghopur, Badusarai, and Kangan Heri. From there, they were drifting towards more urbanized central and northeastern directions. The high salinity was mainly attributed to high chloride content (Adhikary et al. 2009). Low saline groundwater was found at northern and western edges of the study area, suitable for irrigating most of the crops on light to medium textured soils and semitolerant crops on heavy textured soils.

Chloride

High chloride in groundwater used to originate from natural as well as anthropogenic sources. Irrigation with such water can cause severe crop damage. Wells having high chloride concentration were located towards southern, southeastern, and southwestern parts of the study area. Good quality water was expected near Mitraon, Surkhpur, Jharoda Kalan, Qazipur, and few pockets in the eastern part. The similarity of spatial distribution between EC and chloride confirmed the fact that high salinity was mainly attributed to high chloride concentration in the groundwater (Adhikary et al. 2009). Chloride content of the groundwater samples varied from 8.41–85.80, 11.34–95.65, 5.26–98.85, and 2.36–95.58 me L^{-1} for the years 1997, 2004, 2006, and 2007, respectively (Table 6). The spatio-temporal variation of chloride revealed that during 1997, only 35.4 % of the study area was affected by high chloride problem, but in 2007, 45.7 % of the area became unsafe (Table 7). These waters were suitable for irrigating chloride tolerant crops only. This high level of chloride in the groundwater was due to cumulative effect of silicate weathering, use of sewage water for irrigation, and indiscriminate use of fertilizers and other agrochemicals.

Magnesium/Calcium ratio

Descriptive statistics of Mg/Ca ratio in the study area are presented in Table 6. It ranged from 0.64–4.22, 0.66–4.61, 0.60–4.99, and 0.62–5.00 with average values of 1.76, 1.69, 1.68, and 1.67 for the years 1997, 2004, 2006, and 2007, respectively. The spatio-temporal variation of Mg/Ca ratio showed that within a period of 10 years, the areal distribution of high Mg hazard has been decreased from 13.8 % in 1997 to 11.8 % in 2007 (Table 7). The decrement of medium level of Mg/Ca ratio was very sharp. In 1997, 55.9 % of the study area was under medium Mg hazard, which has been decreased to 40.9 % during 2007. The decrement of Mg/Ca ratio was due to either slowing down of the dissolution of magnesium or increase of calcium concentration in the groundwater. Critical analysis of the data revealed that both magnesium and calcium concentrations in the groundwater have been increased over time, but the rate of increment of calcium was more than that of magnesium. The sources of Ca and Mg in the groundwater were calcite ($CaCO_3$), dolomite ($CaCO_3 \cdot MgCO_3$), and silicate minerals. The dissolution of Ca and Mg from silicate minerals and dolomite was nearly the same and contributed at the same rate in the solution form. But the dissolved calcium from calcite minerals further increased the concentration of Ca. The spatial distribution of Mg/Ca ratio was scattered and mainly concentrated in few pockets. During 1997, two pockets at southern and eastern parts of the study area showed high hazard, but during 2007, the southern zone has been shifted to central part of the study area.

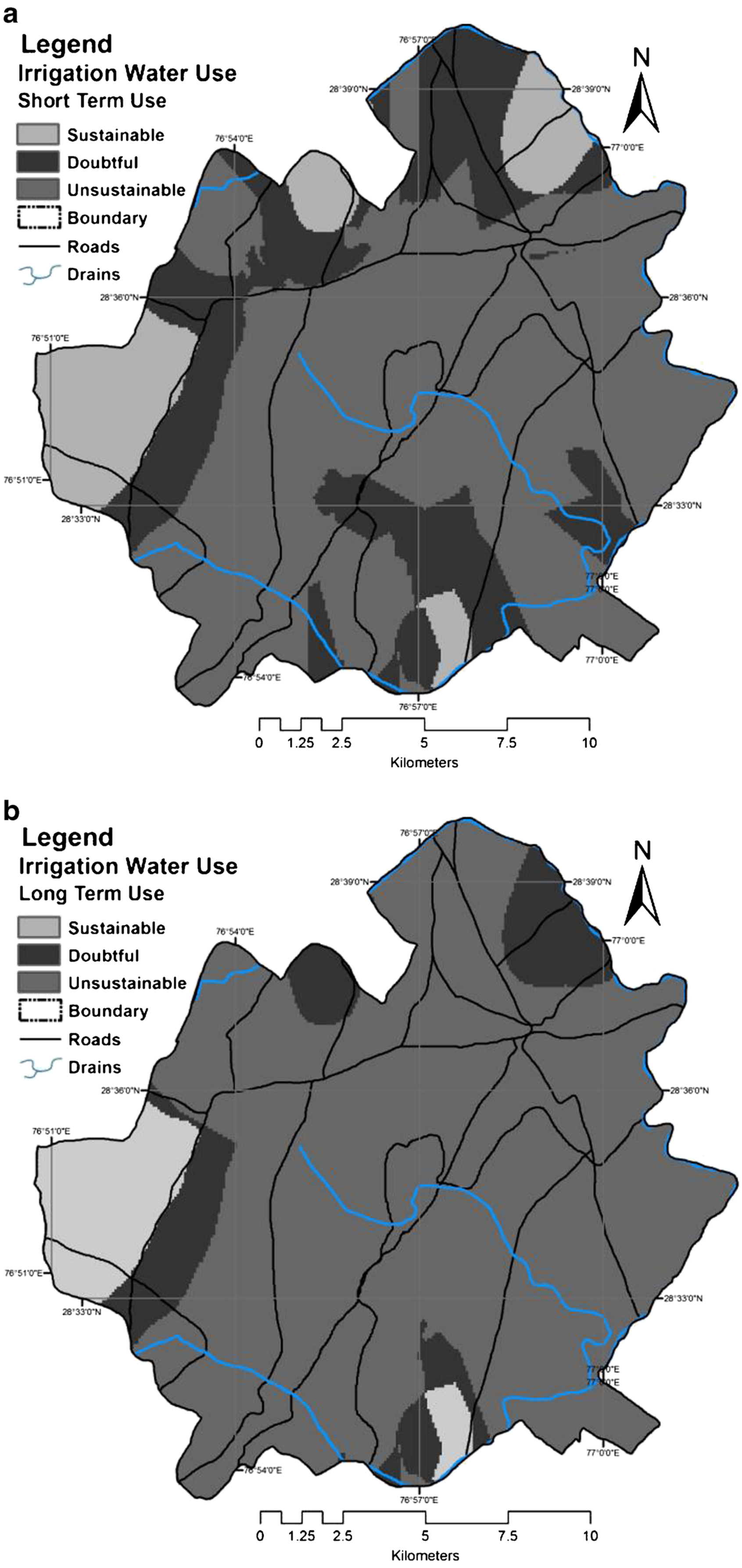
RSC

High value of RSC in water leads to an increase in the absorption of sodium on soil particles (Eaton 1950). The development of alkaline soils may be expected when water containing (CO_3^{--} + HCO_3^{-}) higher than (Ca^{++} + Mg^{++}) is used for irrigation. High concentrations of bicarbonate ions tend to precipitate as carbonate of calcium and, to some extent, magnesium, therefore, reducing the concentrations of calcium and magnesium, increasing the relative proportion of sodium. The interesting finding is that, in the study area, the carbonate hazard has been decreased over time. In 1997, nearly 1.4 % of the study area was unsafe in terms of RSC values, but in 2007, the bicarbonate hazard was absent (Table 7). The RSC values ranged from −34.16–3.66, −36.64–3.04, −48.93–2.53, and −51.78–2.36 me L^{-1} for the years 1997, 2004, 2006, and 2007, respectively (Table 6). The average values for all the years were well below the maximum permissible limit (2.5 me L^{-1}). Only few pockets at the northern border of the study area showed bicarbonate hazard leaving rest of the area with medium or no hazard. It was also observed that the RSC value was high where the salinity was low. This happened because calcium carbonate and bicarbonates (responsible for high RSC) were less soluble in water than chloride salts (responsible for high EC).

Table 9 Delineated area under different levels of variability of overall groundwater quality for irrigation in the study area

Variability	Short-term variability		Long-term variability	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Low	14.8	7.8	4.5	2.4
Moderate	154.6	81.8	98.6	52.2
High	19.7	10.4	85.8	45.4

Fig. 4 Sustainability of groundwater use for irrigation in west Delhi: **a** Short-term use and **b** long-term use



SAR

There is a significant relationship between sodium concentration in irrigation water and the extent to which sodium is absorbed by the soils. Alkali hazard of the irrigation water is determined by SAR. If the proportion of Na is high, the alkali hazard is also high. SAR values of groundwater collected from the study area varied from 3.03–17.25, 3.50–17.43, 2.62–18.64, and 4.28–26.19 for the years 1997, 2004, 2006, and 2007, respectively (Table 6). Spatial and temporal analysis of the groundwater samples revealed that during 1997 and 2004, total study area was under S_1 and S_2 (USDA Classification) classes, but in 2007, the same has been reduced to 91.5 % (Table 7). Although the sodicity problem is not so severe, the rate of increment of S_2 class is alarming. The spatial distribution of SAR showed that high sodicity was evidenced at southwestern part of the study area, and the migration of plume was directed to north and northeast.

Overall groundwater quality for irrigation

Figure 2 illustrates pictorially of the spatial variation of groundwater quality for irrigation as good, medium, and poor, and their temporal pattern during the last 10 years. Good quality water can be used for irrigation with little precautionary measures, medium quality water can also be used with some precautions, and it is better not to use poor quality water. Good quality groundwater was mainly strewn at western and northern fringes of the study area, while poor quality groundwater was located at southern and central parts. From the multi-criteria map, it has been found that within a span of 10 years there was a spatial decrement of 8.1 and 13.5 % area for good and medium quality groundwater, respectively, and 21.6 % spatial increment for poor quality groundwater (Table 8). The rate of increment of poor quality groundwater was 3.7 km^2 per year. During 2007, the areal extent of groundwater unsuitable for irrigation was approximately 106.3 km^2. So there is an urgent need of taking precautionary measures to improve the current situation.

Two gradients of groundwater quality were observed in the study area (Fig. 2). First, there was a deterioration of groundwater quality from southwest to east, along the general groundwater flow direction, attributed mainly to the shallow groundwater table (fast contaminant percolation) in the east. In addition to that, the eastern and southern parts of the study area were characterized by high urbanization, leading to increased chance of anthropogenic contamination. Highly polluted Nafafgarh drain water at southern and eastern border of the study area also contributed for groundwater pollution. The second gradient was the improvement of groundwater quality from west to northeast. Low level of urbanization and availability of groundwater recharge zones with good quality water were the reasons behind it.

Table 10 Delineated area under sustainable/unsustainable use of groundwater for irrigation in the study area

Use	Short-term use		Long-term use	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Sustainable	23.4	12.4	13.7	7.2
Doubtful	58.6	31.0	25.4	13.5
Unsustainable	107.1	56.6	149.9	79.3

Temporal variation of groundwater quality and sustainability for irrigation use

Temporally, groundwater quality was highly variable (V> 20 %) at northern part, moderately variable (V=10-20 %) at middle and southern parts, and less variable (V<10 %) at some pockets at southern part of the study area. The trend was same for both short- and long-term variation with different degree of variability (Fig. 3). When variation was considered for 3 years (2004–2007), groundwater of only 10.4 % area was under high variability. But for 10 years (1997–2007) duration, the spread of high variability was calculated as 45.4 % of the study area (Table 9). This spread of high variability at northern part was attributed to the practice of different types of irrigation schedule, mixing of groundwater of variable chemical concentration through different wells, and use of variable amount of agrochemicals and other anthropogenic activities like presence of high number of industrial waste disposal sites.

Thus, the multi-year data has been provided a tool for estimating the degree of temporal variation of groundwater quality in the study area. This, combined with groundwater quality results, has been helped to delineate regions underlain by relatively fair and stable groundwater quality. Figure 4 pictorially demonstrates the areas where groundwater can be used for irrigation on sustainable basis. Based on spatial distribution and temporal variation of groundwater quality for irrigation use, it has been found that groundwater of 12.4 % of the study area is sustainable when short term variation was considered. The sustainable area has been decreased to 7.2 % when long-term variation was considered (Table 10). Maximum area is under unsustainable in terms of groundwater use for irrigation, because of high pollution level and high variability of the groundwater in the study area. There are some doubtful areas situated at the outer edges of sustainable areas. The groundwater of these regions can be used consciously for longer time periods unless intrusion of new pollutants to the groundwater system is recognized.

Conclusions

The GIS-based multi-criteria system effectively synthesized different groundwater quality parameters into an easily understood format. This has been provided a way to summarize the overall groundwater quality in a manner that can be clearly communicated to different audiences and to understand whether overall quality of groundwater posed a potential threat to particular use. The proposed GIS-based multi-criteria system delineated the spatial variation of groundwater quality for irrigation of west Delhi, India, and indicated that the water quality of the area was generally poor. The rate of spatial increment of poor quality groundwater within the study period was 3.7 km^2 per year. Two gradients of groundwater quality were observed in the study area. First, there was a deterioration of groundwater quality from southwest to east, along the general groundwater flow direction, attributed mainly to the shallow groundwater table in the east and the increase of input of pollutants from urban areas. The second gradient was the improvement of groundwater quality from west to northeast due to low level of urbanization and availability of groundwater recharge zones with good quality water. Groundwater quality was highly variable (V>20 %) at northern part, moderately variable (V=10-20 %) at middle and southern parts, and less variable (V<10 %) at some pockets at southern part of the study area. Integration of multi-criteria and temporal variation indicated that in the western and northern fringes of west Delhi the sustainable use of groundwater was constrained by relatively poor and variable groundwater quality.

Acknowledgments The financial assistance given by Council for Scientific and Industrial Research, New Delhi in the form of Senior Research Fellow and the facilities provided by Indian Agricultural Research Institute, New Delhi to carry out the work is highly acknowledged. Authors also acknowledge the anonymous reviewers for meticulous review and improvement of the manuscript.

References

Adhikary PP, Chandrasekharan H, Chakraborty D, Kumar B, Yadav BR (2009) Statistical approaches for hydrogeochemical characterization of groundwater in West Delhi, India. Environ Monit Assess 154:41–52

Adhikary PP, Chandrasekharan H, Chakraborty D, Kamble K (2010) Assessment of groundwater pollution in west Delhi, India using geostatistical approach. Environ Monit Assess 167:599–615

Adhikary PP, Dash CJ, Chandrasekharan H, Rajput TBS, Dubey SK (2012) Evaluation of groundwater quality for irrigation and drinking using GIS and geostatistics in a peri-urban area of Delhi, India. Arab J Geosci 5:1423–1434

Al Hallaq AH, Elaish BSA (2012) Assessment of aquifer vulnerability to contamination in Khanyounis Governorate, Gaza Strip—Palestine, using the DRASTIC model within GIS environment. Arab J Geosci 4:833–847

Alley WM, Leake SA (2004) The journey from safe yield to sustainability. Ground Water 42:12–16

APHA (1995) Standard methods for the examination of water and wastewater, 19th edn. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, Washington

Arnous MO, El-Rayes AE (2012) An integrated GIS and hydrochemical approach to assess groundwater contamination in West Ismailia area, Egypt. Arab J Geosci. doi:10.1007/s12517-012-0555-0

Aronoff S (1989) Geographic information system: a management perspective. WLD, Ottawa

Babiker IS, Mohamed MAA, Hiyama T (2007) Assessing groundwater quality using GIS. Water Resour Manag 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

Chandio IA, Matori ANB, WanYusof KB, Talpur MAH, Balogun AL, Lawal DU (2012) GIS-based analytic hierarchy process as a multicriteria decision analysis instrument: a review. Arab J Geosci. doi:10.1007/s12517-012-0568-8

Davis BM (1987) Uses and abuses of cross-validation in geostatistics. Math Geol 19:241–248

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

Eaton FM (1950) Significance of carbonates in irrigation waters. Soil Sci 69:123–133

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

Kaliraj S, Chandrasekhar N, Magesh NS (2013) Identification of potential groundwater recharge zones in Vaigai upper basin, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique. Arab J Geosci. doi:10.1007/s12517-013-0849-x

Kawy WAMA (2012) Use of spatial analyses techniques to suggested irrigation scheduling in Wadi El Natrun Depression, Egypt. Arab J Geosci 5(6):1199–1207

Khodaei K, Nassery HR (2013) Groundwater exploration using remote sensing and geographic information systems in a semi-arid area (Southwest of Urmieh, Northwest of Iran). Arab J Geosci 6:1229–1240

Kritsotakis M, Tsanis IK (2009) An integrated approach for sustainable water resources management of Messara basin, Crete, Greece. Eur Water 27(28):15–30

Manap MA, Nampak H, Pradhan B, Lee S, Sulaiman WNA, Ramli MF (2012) Application of probabilistic-based frequency ratio model in groundwater potential mapping using remote sensing data and GIS. Arab J Geosci. doi:10.1007/s12517-012-0795-z

Manap MA, Sulaiman WNA, Ramli MF, Pradhan B, Surip N (2013) A knowledge driven GIS modelling technique for prediction of groundwater potential zones at the Upper Langat Basin, Malaysia. Arab J Geosci 6:1621–1637

Neshat A, Pradhan B, Pirasteh S, Shafri HZM (2013) Estimating groundwater vulnerability to pollution using modified DRASTIC model in the Kerman agricultural area. Iran Environ Earth Sci. doi:10.1007/s12665-013-2690-7

Poonam T, Namita J (2001) A comparative study of some physico–chemical parameters of some irrigated with recycled and tub well water. Indian J Environ Protect 21:525–528

Pradhan B (2009) Ground water potential zonation for basaltic watersheds using satellite remote sensing data and GIS techniques. Cent Eur J Geosci 1:120–129

Qureshi AS, McCornick PG, Sarwar A, Sharma BR (2010) Challenges and prospects of sustainable groundwater management in the Indus basin, Pakistan. Water Resour Manag 24:1551–1569

Sophocleous M (2005) Groundwater recharge and sustainability in the high plains aquifer in Kansas, USA. Hydrogeol J 13:351–365

Xu YQ, Mo XG, Cai YL, Li XB (2005) Analysis on groundwater table drawdown by land use and the quest for sustainable water use in the Hebei Plain in China. Agric Water Manag 75:38–53