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Spatial analysis of groundwater suitability for drinking and irrigation in Lahore, Pakistan

Zainab Abbas · Harold Wilson Tumwitike Mapoma · Chunli Su · Syed Zahid Aziz · Yanhua Ma · Naaz Abbas

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Abstract This study used a total of 474 groundwater samples analyzed from 2014 data to evaluate the distribution of groundwater quality in the Water and Sanitation Agency (WASA) jurisdiction of Lahore city, Pakistan. The study further assessed the variations in suitability of groundwater for drinking (emphasis on arsenic and fluoride) and irrigation using spatial correlation technique in GIS. The hydrochemical analysis revealed a predominance of Mg-Ca-HCO_3-SO_4 and Ca-Mg-HCO_3-SO_4 type. Distribution analysis indicated relatively higher salinity ($TDS_{max} = 1667$ mg/L), total hardness ($TH_{max} = 558$ mg/L), and alkalinity (${HCO_3^-}_{max} = 584$ mg/L) in the south-eastern region of the city, while the central part displayed the highest levels of SO_4 and NO_3. Also, the eastern region (north-south) of Lahore had significantly elevated As concentrations (up to 86 μg/L). The order of exceedance in terms of arsenic was Gunj Bakhsh town (17.4%), Nishter town (16.4%), Iqbal town (9.8%), Aziz Batti and Shalimar town (8.1%), and Ravi town (3%). The groundwater was classified as average saline to highly saline, except few samples in Aziz Batti/Shalimar town that were in non-saline group. Otherwise, the various indices classified the groundwater for irrigation as generally acceptable. With the various irrigation quality indices displaying discernible variations for the entire study area, it was observed from the distribution maps that the groundwater suitability for irrigation is relatively excellent in the areas away from industries and landfill locations. Also, the chloride analysis shows 98.7% of the groundwater samples belong to the very fresh and fresh water class. Thus, continued monitoring and studying the changes in groundwater quality in Lahore is imperative.

Keywords Groundwater · Hydrochemistry · Irrigation · Arsenic · Lahore city

Introduction

Most people in developing countries, including Pakistan depend on groundwater for drinking and irrigation. Increased dependence on groundwater, which is presumed to be cleaner than surface water, has resulted in over-reliance and sometimes over-exploitation of the

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Z. Abbas (✉) · S. Z. Aziz
Water and Sanitation Agency Lahore, Zahoor Elahi Road, Lahore, Punjab 54000, Pakistan
e-mail: zainababbas6@hotmail.com

Z. Abbas · C. Su · Y. Ma
School of Environmental Studies, China University of Geosciences (Wuhan), Lumo Lu 388, Wuhan 430074 Hubei, China

H. W. T. Mapoma (✉)
Physics and Biochemical Sciences, University of Malawi, Private Bag, 303, Blantyre 3, Malawi
e-mail: hmapoma@poly.ac.mw

N. Abbas
Pakistan Council of Science and Industrial Research, Feroz Road, Lahore, Punjab 54000, Pakistan

groundwater resource (Mapoma and Xie 2014; Abbas et al. 2015). Groundwater flow, rainfall, climate, geology, human activities, and over-exploitation trigger the mobilization of naturally occurring contaminants and facilitates introduction of anthropogenic pollutant into the subsurface (Rajesh et al. 2015).

Several studies on groundwater quality have been done worldwide (Abou Zakhem and Hafez 2015; Baillieux et al. 2015; Bonton et al. 2010; Ghesquière et al. 2015; Kudoda and Abdalla 2015; Pathak and Limaye 2011) and Pakistan (Abbas et al. 2015; Manzoor et al. 2006; Mullane et al. 2015; Valipour 2014; Kazi et al. 2009; Farooqi et al. 2007; Rafique et al. 2008). The characterization of groundwater quality for various purposes assists in decision-making on either management of water resource or recommending the best measures when planning to use the water.

In Pakistan, studies on groundwater contamination and the subsequent implications on the population are one of the government's greatest concerns. As such, monitoring and assessment of groundwater quality is paramount and a priority. Lahore city, which is the second largest city in Pakistan, relies on groundwater supply for development (Abbas et al. 2015). Therefore, the elevated concentrations of contaminants in groundwater such as arsenic may affect the health of the population and in turn impede the economic development. The rapid population growth rate of city increases pressure on groundwater supply capacity thereby affecting the natural balance of the aquifers.

Previous studies on groundwater in some parts of Lahore identified serious breaches on quality of groundwater for drinking (Abbas et al. 2015; Bibi et al. 2015; Farooqi et al. 2007). More importantly, these studies identified high arsenic and fluoride levels parts of Lahore city that they studied. However, the studies did not discuss much on the spatial distribution of groundwater quality for drinking and irrigation in the entire city of Lahore. The Water and Sanitation Agency of Lahore reports that the levels of groundwater in the city is decreasing by approximately 1 ft of the water table every year. This is of great concern on both quantity and quality of the groundwater. It is imperative that communities and policy makers get a clear picture of the spatial characteristics of groundwater in Lahore to facilitate in decision making on either management or proper use of the groundwater. Therefore, this study analyzed the spatial distribution of groundwater quality for drinking and irrigation using proper indices. The study takes into consideration the significance of high levels of arsenic in Lahore. Arsenic values in this region closely resemble reports in other countries in southeast Asia such as Bangladesh (Ahmed et al. 2004; Chakraborti et al. 2010; Halim et al. 2010; Rahman et al. 2013), India (Ahamed et al. 2006; Bordoloi et al. 2013; Buragohain et al. 2010), Nepal, Myanmar, Vietnam, Cambodia, Lao People's Democratic Republic, and China (Rahman et al. 2009).

The results of the study will provide baseline data on groundwater quality in the area and insight into groundwater management and monitoring. Furthermore, the paper will assist in identifying hot spots that need management and policy making through the quality distribution maps produced. The sampling and laboratory analysis were done in the months of August, September, October, and November 2014.

Study area

Lahore city lies between 31° 15′–31° 45′ N and 74° 01′–74° 39′ E in the Punjab province, Southeast Pakistan (Fig. 1). The city experiences five seasons of characteristic semi-arid and subtropical continental climate. Foggy winters (15 November–15 February), pleasant spring (16 February–15 April), summer (15 April–15 June), rainy monsoon (16 July–16 September), and dry but pleasant autumn (16 September–14 November) are distinguishing characteristics of the climate in Lahore. The mean annual maximum temperature as high as 41 °C has been recorded for the period May to June, while a mean annual minimum of 4 °C for January (the coldest month) is on record (Abbas et al. 2015). The average annual rainfall for Lahore is 510 mm (Gabriel and Khan 2010).

Lahore is in the Punjab alluvial plain, which displays similar characteristics to the arsenic laden aquifers of West Bengal and Bangladesh (Bibi et al. 2015). The city covers a total land area of 1232 km^2, which is underlain by unconsolidated alluvial deposits with intermittent clay lenses. The thickness of sedimentary aquifers is about 400 m. The well logs show that the lenses of less permeable materials are neither thick nor continuous so the aquifer is treated as a single (homogenous) unconfined layer. Various aquifer

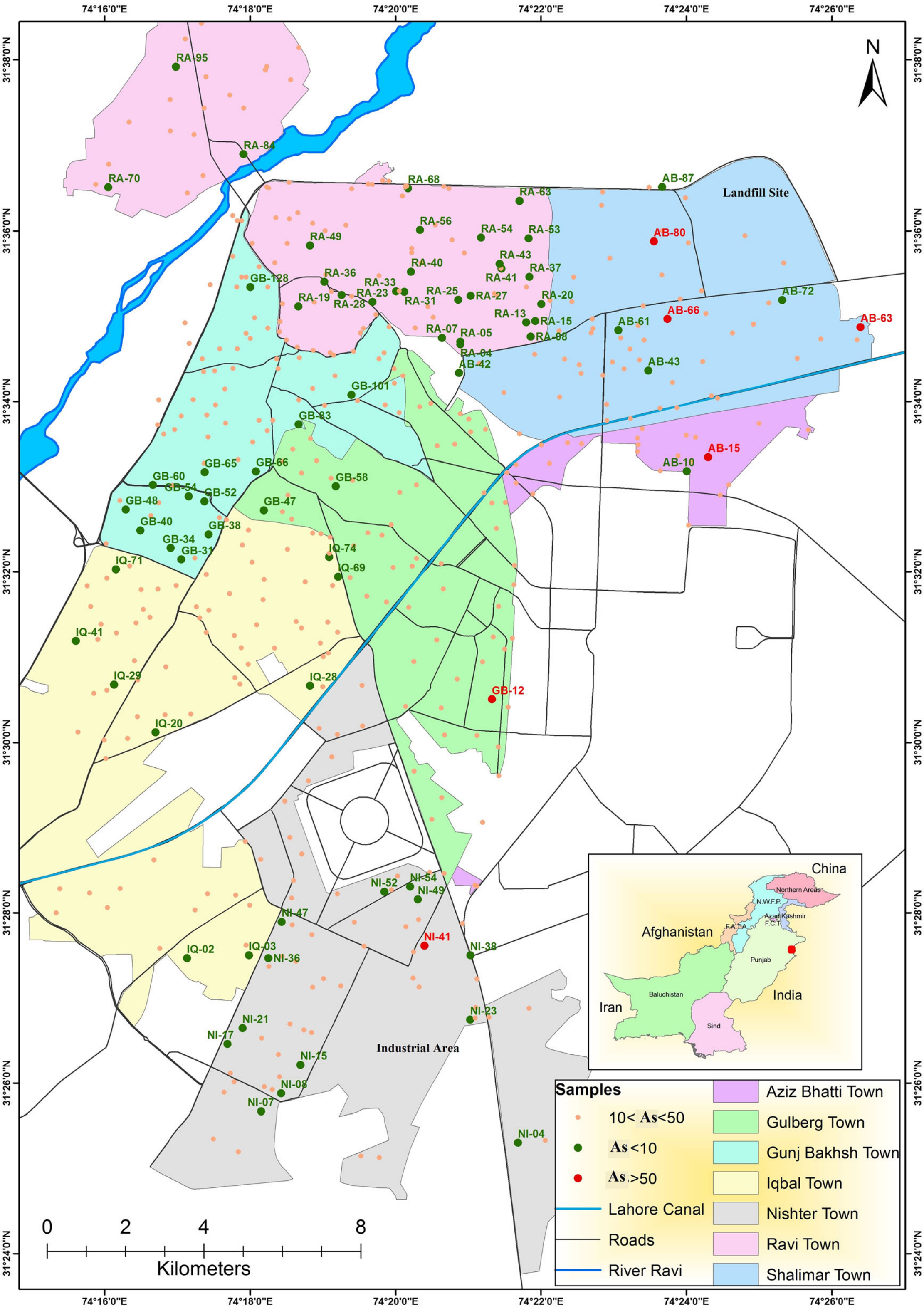

Fig. 1 Location of study area within Lahore, Pakistan showing the sampling sites classified according to levels of arsenic observed in this study

formations exist in the region. Most of these formations consist of sand, silt, and clay. Gravels of mudstone or siltstone and calcareous concretion locally known as canker exist dispersed in places. The lithological analysis from one well log agrees with other studies showing a sequential depth conformation consisting of clay, fine sand, medium sand, coarse + canker, and medium to coarse + canker (Fig. 2). Important hydrological features in the area are Ravi River in the Northwest and Bambanwala Ravi Bedian Depalpur (BRBD) canal in the East (Fig. 1). Isotopic and chemical analysis data shows that Lahore aquifer has major contributions from River Ravi, and flow path is from the river to the center of the city. The aquifer has mixed recharge from River Ravi and direct rainfall infiltration (Ahmad et al. 2002). However, there is poor management of wastewater in the city where disposal is directly into River Ravi that would result in groundwater contamination. Besides, an unconfined and poorly managed landfill is located in the northeastern part of the city that could add to pollution of the groundwater through infiltration. The abstraction of groundwater of 44.6 MGD (million gallon per day) in 1960 has increased to 784 MGD in 2010 translating to a decline of 1.27 m per year.

The current population of Lahore city is 9.24 million. Water and Sanitation Agency (WASA) of Lahore is responsible for monitoring the quality of drinking water for 6.8 million people while the remaining population is served by private urban schemes. The scope of this research was WASA jurisdiction area, which consists of seven towns (Aziz Batti, Shalimar town, Gunj Bakhsh, Gulberg, Iqbal, Nishter, and Ravi town).

Materials and methods

Sampling

The study used 474 samples from groundwater sources of depth ranging from 110 to 245 m in the study area (Fig. 1). Groundwater was purged for 10 to 15 min before sampling. Samples for major cations and anions analysis were collected in 250 and 100 ml glass bottles, respectively. Immediately after sampling, a drop of standard nitric acid (HNO_3) into the sample meant for cation analysis adjusted the pH (< 2). This procedure prevents trace elements from bacterial conversion of nitrite to nitrate. Also, a separate HCl acidified sample was preserved.

Hydrochemical analysis

All the field, titration, and analytical methods followed the prescribed APHA techniques (Rice et al. 2012). Calibrated portable meters (JENCO USA) determined the pH, turbidity, electric conductivity (EC), and total dissolved solids (TDS) in groundwater samples on-site.

The EDTA Titrimetric Method determined TH (mg $CaCO_3$ /L) and calcium (mg/L). Subtracting calcium hardness from TH determined magnesium hardness, which in turn computed the concentration of magnesium (mg/L). Similarly, APHA titration determined total alkalinity (mg/L), while subsequent titration provided results for carbonate concentrations (CO_3^{2-}) (mg/L) in the samples. Gravimetric method determined Sulfate (SO_4^{2-}) with drying of residue. Also, argentometric method determined concentration of chloride (Cl^-). This method is suitable for use in clear water.

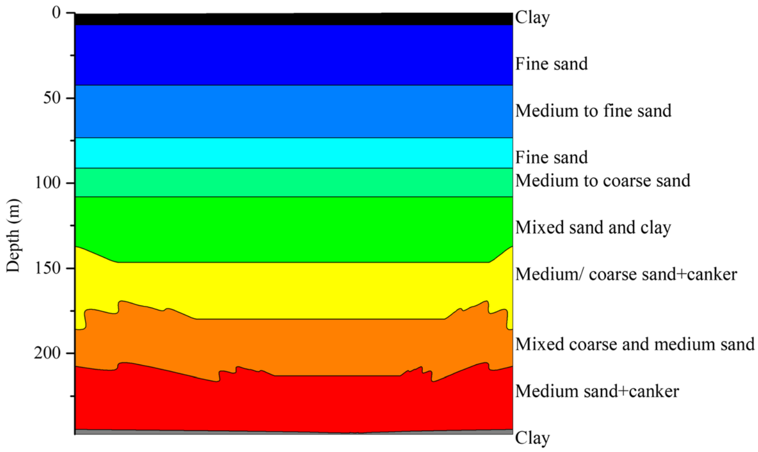

Fig. 2 The depth profile of sediment sample analyzed in the laboratory from one well showing the sequential lithological characteristics of the aquifer

A flame photometer determined Na^+ and K^+ concentrations. To minimize interference, standard addition technique was chosen to determine these two elements from the standard calibration graphs. The concentration of F^- was examined by the SPADNS method using a spectrophotometer (NOVA) at wavelength 570 nm. The inductively coupled plasma-optical emission spectroscopy (ICP) method (ICP-OES, Perkin Elmer) detected arsenic concentration in the samples. Temperature was kept constant to keep analytical accuracy when analyzing samples and standards. The colorimetric method established nitrite (NO_2) by using spectrophotometer (NOVA) at 543 nm following a standard procedure that ensures minimal interference from metal ions. Sample analysis happened on the day of sampling to prevent bacterial conversion of nitrite to nitrate. Finally, automated hydrazine reduction method determined nitrate (NO_3) levels. The analytical error (ion balance) of the dataset was less than 10%, which is desirable in groundwater quality analysis.

Data analysis

A summary of data (minimum, maximum, and mean) were determined for both observed and computed water quality parameters. All statistics (ANOVA and least squared deviation) were done using SYSTAT. Tables and figures present the data summary obtained from specific hydrological software. To discern the variations in suitability of groundwater for both drinking and irrigation among towns within Lahore, various indices were computed after converting the values to meq/L, as follows:

$$\text{Sodium adsorption : SAR} = \frac{\mathrm{Na}^+}{\sqrt{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}/2}}$$

$$\text{Magnesium hazard : MH} = \frac{\mathrm{Mg}^{2+} \times 100}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}$$

$$\text{Percentage sodium : \%Na} = \frac{\mathrm{Na}^+ \times 100}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^+ + \mathrm{K}^+}$$

$$\text{Exchangeable sodium ratio/Kelly ratio : KR} = \frac{\mathrm{Na}^+}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}$$

$$\text{Permeability index : PI} = \frac{\left(\mathrm{Na}^+ + \sqrt{\mathrm{HCO}_3^-}\right) \times 100}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{2+}}$$

The geographical information system was used to analyze the spatial distribution of groundwater quality parameters as well as the computed quality indices for the study area. Kriging is the interpolation method that was used to generate the spatial maps. This method relies on the assumption that distance or direction between points reflects a spatial correlation that can be used to explain the variations in the output surfaces. Kriging enables one to optimize the method through the evaluation of the errors associated with the models. Kriging has been widely used in several studies to understand the distribution of groundwater quality (Salcedo-Sánchez et al. 2016; Bohling 2005).

Results and discussion

General hydrochemistry

Firstly, this section shows and discusses data from the field and laboratory analyses arranged according to arsenic levels to facilitate general description of groundwater physico-chemical characteristics (Table 1). Table 2 shows the variation of groundwater physico-chemistry among towns within Lahore. From Table 1, the major physico-chemical parameters varied across the groups, although the variations were not significant ($p > 0.05$). The piper plot (Fig. 3) illustrates the general groundwater characteristics in the study area. The supplementary material lists the various water facies for individual sampling points. From the piper plot (Fig. 3), it is observed that the groundwater types are predominantly of Ca-Mg-HCO_3-SO_4 and Mg-Ca-HCO_3-SO_4. The groundwater containing arsenic higher than 50 μg/L is mainly of Mg-Ca-HCO_3-SO_4 type (see "supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)"). The water types for each town are sorted according to frequency of occurrence for individual sampling points listed in "supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)" as shown in Table 2. The diversity in hydrochemical facies reflects the heterogeneous geological conditions of the aquifers in Lahore (Farooqi et al. 2007) consequently explaining the variations in hydrochemistry within and among the towns studied. The differences in local geology are important to consider when prospecting new tube-wells for drinking water in Lahore.

The concentration of cations and anions varied in different areas as shown in Tables 1 and 2. In most cases, divalent cations (Ca^{2+} and Mg^{2+}) dominate over univalent cations (Na^+ and K^+) (Tables 1 and 2). In terms of anions, the HCO_3^- dominates the group (Tables 1 and 2). It is possible that CO_2 (dissolving as HCO_3^-) from organic matter decomposition is one good

Table 1 Statistical summary of data for the entire study area group according to arsenic levels ($n = 474$)

	As < 0.01 ($n = 19$)				0.01 < As ≤ 10[a] ($n = 52$)				10 < As < 50[b] ($n = 397$)				As ≥ 50 ($n = 6$)				Overall		ANOVA	
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Mean	SD	F	p value
pH	7.8	8.2	7.9	0.1	7.8	8.3	8.0	0.2	7.0	8.3	8.0	0.2	7.8	8.1	7.9	0.1	8.0	0.2	1.166	0.322
Turbidity (NTU)	0.0	4.2	0.7	1.2	0.0	1.7	0.4	0.5	0.0	11.0	0.6	1.2	0.0	1.6	0.4	0.6	0.6	1.1	0.665	0.574
TDS (mg/L)	211	1150	407	249	179	891	398	151	166	1668	413	203	297	804	481	173	412	199	0.327	0.806
EC (μS/cm)	335	1825	651	392	284	1414	632	240	16	2010	651	315	472	1276	764	274	650	310	0.325	0.808
TH (mg CaCO3 /L)	96.0	510.0	190.4	99.0	70.0	438.0	180.6	81.1	43.0	558.0	174.9	89.8	166.0	288.0	207.7	48.4	176.6	88.8	0.478	0.698
Ca (mg/L)	20.0	99.2	41.3	19.6	16.0	112.8	40.5	18.7	6.2	116.0	37.7	19.0	30.4	50.4	39.2	7.4	38.2	18.8	0.500	0.682
Mg (mg/L)	8.2	62.9	20.9	12.7	3.8	49.0	19.0	9.8	3.8	117.6	19.3	12.7	15.4	38.9	27.1	9.0	19.5	12.4	0.889	0.447
Cl (mg/L)	12.0	125.0	32.3	26.6	15.0	90.0	37.7	18.6	8.0	220.0	38.2	30.2	15.0	59.0	28.3	16.8	37.8	28.8	0.464	0.708
NO_2 (mg/L)	0.01	0.02	0.01	0.0	0.00	0.03	0.01	0.0	0.00	1.01	0.02	0.1	0.01	0.02	0.01	0.0	0.01	0.0	0.127	0.944
NO_3 (mg/L)	7.9	23.1	15.8	4.4	1.8	24.5	15.1	5.0	0.0	100.0	15.3	7.8	6.6	22.5	15.6	5.3	15.3	7.4	0.047	0.987
HCO_3 (mg/L)	160	584	264	133	120	480	259	95	0	792	270	118	252	530	378	92	270	117	1.871	0.134[c]
SO_4 (mg/L)	6.4	20	11.9	3.4	6.5	23.0	12.6	3.5	4.1	26.0	11.9	3.5	11.9	18.5	13.7	2.5	12.0	3.5	1.039	0.375
Na (mg/L)	2.0	30.0	9.9	7.2	3.0	22.0	11.2	4.3	0.0	80.0	12.1	7.9	9.0	20.0	15.0	4.5	12.0	7.5	1.060	0.366
K (mg/L)	1.4	9.6	3.5	1.8	0.5	17.4	3.9	2.9	0.8	69.3	4.4	5.5	3.6	7.8	4.9	1.6	4.3	5.2	0.256	0.857
As (μg/L)	< 0.01	< 0.01	< 0.01		0.06	9.89	5.83	2.9	10.26	48.71	24.02	8.0	57.12	86.82	68.74	10.3	21.63	11.6	221.700	< 0.001*
F (mg/L)	0.00	1.40	0.12	0.3	0.00	1.10	0.22	0.3	0.00	1.10	0.13	0.2	0.00	0.10	0.02	0.0	0.14	0.2	3.243	0.022*

*Variations were significant

[a] WHO standard for arsenic in drinking water = 10 μg/L

[b] Threshold value for arsenic in drinking water for Pakistan and other Asian countries = 50 μg/L (Abbas et al. 2015)

[c] The p value for HCO_3 is low because sample mean (378 mg/L) for the group where As is greater than 50 μg/L was significantly higher than the other three groups of samples (LSD analysis; $p < 0.05$)

Table 2 Summary and comparative analysis of water quality among towns calculated using SYSTAT while groundwater types were obtained from Aquachem 2011 software

	pH	Turbidity	TDS	EC	TH	Ca	Mg	Cl	NO_2	NO_3	HCO_3	SO_4	Na	K	As	F
		(NTU)	(mg/L)	(μS/cm)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(μg/L)	(mg/L)
Aziz Batti and Shalimar town (ABST) (*n* = 87) (Ca-Mg-HCO_3-SO_4; Mg-Ca-HCO_3-SO_4; Ca-HCO_3-SO_4)																
Minimum	7.8	< 0.01	231.8	15.7	74.0	6.2	3.8	13.0	< D.L	5.3	192.0	54.0	4.0	1.6	0.06	< D.L
Maximum	8.3	5.3	1040.7	1652.0	430.0	79.2	59.0	125.0	0.032	26.5	792.0	215.0	29.0	9.0	73.4	0.70
Mean	8.1	0.3	429.0	664.2	186.3	37.8	22.0	34.6	0.011	17.7	335.8	127.1	13.2	4.2	25.2	0.13
SD	0.2	0.7	156.6	242.3	77.9	13.8	11.2	22.1	0.005	4.7	111.3	29.4	5.1	1.6	13.3	0.19
% Exceedance		1.15	1.2	23.0			1.15			0.00	8.05	0.72			8.05	
Gunj Burksh town (GBT) (*n* = 138) (Ca-Mg-HCO_3-SO_4; Mg-Ca-HCO_3-SO_4; Ca-Mg-HCO_3-SO_4-Cl; Mg-Ca-HCO_3-SO_4-Cl)																
Min	7.8	< 0.01	170.7	271.0	70.0	6.7	5.7	10.0	< D.L	< D.L	104.0	45.0	2.0	1.7	< 0.01	< D.L
Max	8.3	11.0	1266.3	2010.0	558.0	116.0	117.6	185.0	0.083	38.1	760.0	260.0	80.0	69.3	64.0	1.10
Mean	8.0	0.7	439.3	698.3	194.0	40.4	21.9	46.5	0.013	13.4	257.0	126.5	13.1	5.6	22.8	0.18
SD	0.2	1.5	228.8	363.4	108.3	23.4	15.1	36.3	0.010	6.7	117.3	41.2	9.6	8.1	10.3	0.26
% Exceedance		2.17	3.6	31.9			4.35			0.00	17.4				17.39	
Iqbal town (IQT) (*n* = 82) (Ca-Mg-HCO_3-SO_4; Ca-Mg-HCO_3-SO_4-Cl; Mg-Ca-HCO_3-SO_4; Ca-HCO_3-SO_4)																
Min	7.0	< 0.01	172.6	274.0	43.0	10.4	3.8	10.0	0.001	< D.L	130.0	41.0	< D.L	0.5	< 0.01	< D.L
Max	8.3	7.5	1149.7	1911.0	532.0	111.2	62.9	220.0	0.150	37.4	584.0	243.0	33.0	9.6	48.7	0.70
Mean	8.0	0.7	389.5	626.5	145.6	32.3	15.8	37.5	0.015	14.4	248.5	110.6	10.7	2.8	22.0	0.09
SD	0.2	1.2	182.0	315.8	88.5	18.0	10.6	34.4	0.021	8.3	97.4	31.2	5.4	1.7	10.8	0.15
% Exceedance		2.44	1.2	26.8			2.44			0.00	9.76				9.76	
Nishter town (NIT) (*n* = 67) (Mg-Ca-HCO_3-SO_4; Ca-Mg-HCO_3-SO_4; Ca-HCO_3-SO_4)																
Min	7.2	< 0.01	296.1	470.0	68.0	12.8	3.8	16.0	0.002	2.2	214.0	65.0	7.0	0.8	< 0.01	< D.L
Max	8.2	2.3	1667.8	1695.0	334.0	60.0	98.0	127.0	0.038	34.0	620.0	200.0	34.0	7.7	86.8	0.60
Mean	7.9	0.5	516.9	807.0	166.5	34.0	20.6	33.4	0.013	17.1	356.3	121.3	15.8	3.9	19.9	0.09
SD	0.2	0.6	215.6	278.6	70.5	12.4	14.0	18.7	0.005	5.2	107.4	26.5	6.2	1.7	12.9	0.16
% Exceedance		0.0	1.5	49.3			0.00			0.00	20.9				16.42	
Ravi town (RAT) (*n* = 100) (Ca-Mg-HCO_3-SO_4; Ca-Mg-HCO_3-SO_4-Cl; Ca-Mg-SO_4-HCO_3)																
Min	7.8	< 0.01	165.6	28.5	76.0	16.0	5.8	8.0	0.001	< D.L	80.0	48.0	1.0	1.1	< 0.01	< D.L
Max	8.3	5.6	737.1	1170.0	438.0	112.8	37.4	90.0	1.010	24.3	388.0	230.0	48.0	37.3	39.1	1.40
Mean	7.9	0.6	307.6	485.3	176.3	43.2	16.2	31.5	0.021	14.5	191.7	113.5	7.9	4.0	17.8	0.14
SD	0.1	0.9	132.6	212.8	71.2	18.2	7.2	18.8	0.100	4.6	59.8	35.4	6.4	5.0	10.4	0.27
% Exceedance		1.00	0	10.0			0.00			0.00	4.00				3.00	
WHO value		5	1000	750		200	50	250		50	< 250	250	200	100	1.0	1.5

% exceedance is based on the WHO threshold value; the most frequent groundwater types (in decreasing order) were computed using Aquachem 2011

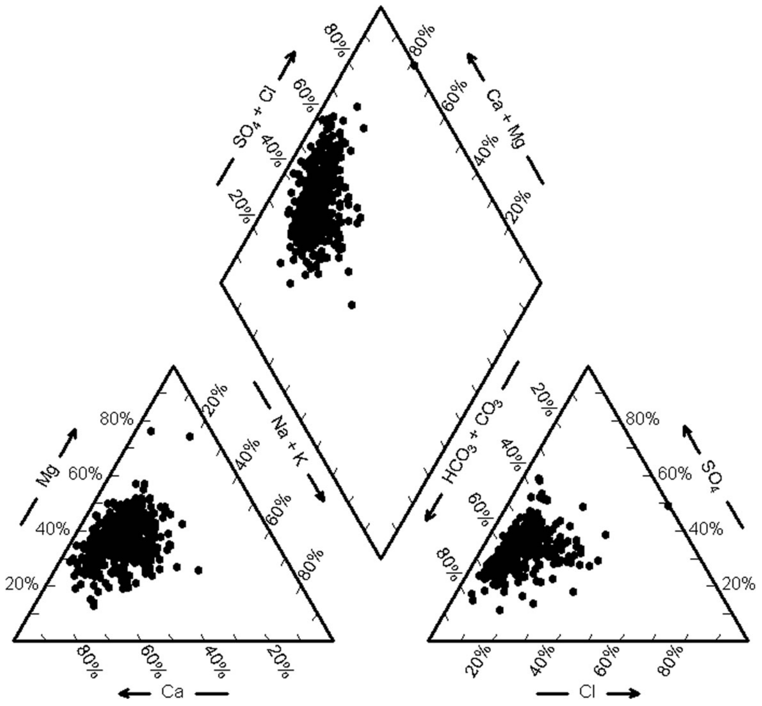

Fig. 3 Piper diagram used to identify the general groundwater types in Lahore

supplement to observed alkalinity although organic matter in aquifer sediments was not measured in this study. Besides decomposition product from overburden materials, atmospheric CO_2 can find its way into the groundwater by diffusion. Above all, it is stated earlier in this paper that the aquifer is rich in sedimentary rocks whose dissolution could account for the elevated HCO_3 levels. Therefore, carbon dioxide dissolution and carbonate weathering can increase HCO_3^- concentration in groundwater, although alkaline conditions favor precipitation of carbonate minerals (e.g., calcite) over dissolution (Mapoma et al. 2014; Farooqi et al. 2007).

With respect to Na^+, Fig. 4 shows excess of Cl^- over Na^+(stoichiometric ratio $\neq 1$), which implies minimal external sources of Na^+ and aids in dismissing halite dissolution as a significant source of Na^+. Whenever the plot of Na vs Cl falls on the 1:1 line, it signifies halite dissolution, which is not the case in this study. The other probable source of Na^+ could be a result of cation exchange. The other sources of Na^+ could be cation exchange and industrial activities. Similarly, wastewater pollution and human activities such as agriculture and industries contribute to elevated chlorides in the system.

Fig 5a, b depicts detailed hydrochemical evolution scenarios. Despite differences in correlation with TDS, both cations and anions display a discernible increase with increase in salinity. The linear relationship between TDS and major groundwater quality descriptors is significant with higher regression coefficients for Na^+ and HCO_3^-($p < 0.05$). Although the observed correlation between Na^+ and TDS is strong, the salinity is more dependent on Ca^{2+} and Mg^{2+}, while HCO_3^- and SO_4^{2-} dominate over Cl^- (Fig. 5a, b). This observation affirms earlier findings in Lahore (Abbas et al. 2015) that noted the prevalence of $Mg\text{-}HCO_3$ or $Ca\text{-}HCO_3$ type in almost all samples studied. With these observations, cation

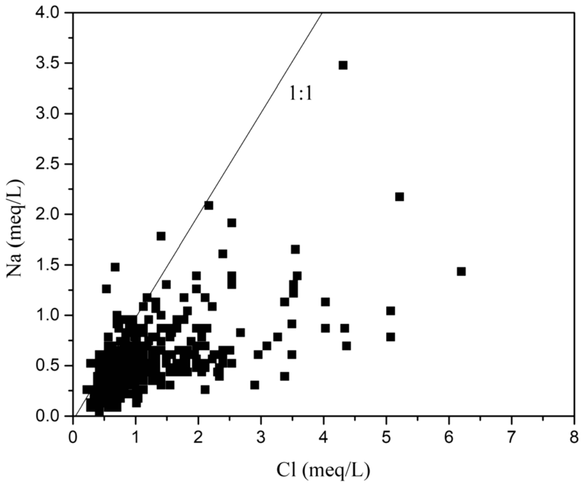

Fig. 4 Sodium as a function of chloride used to confirm the excess relationship and possible halite dissolution

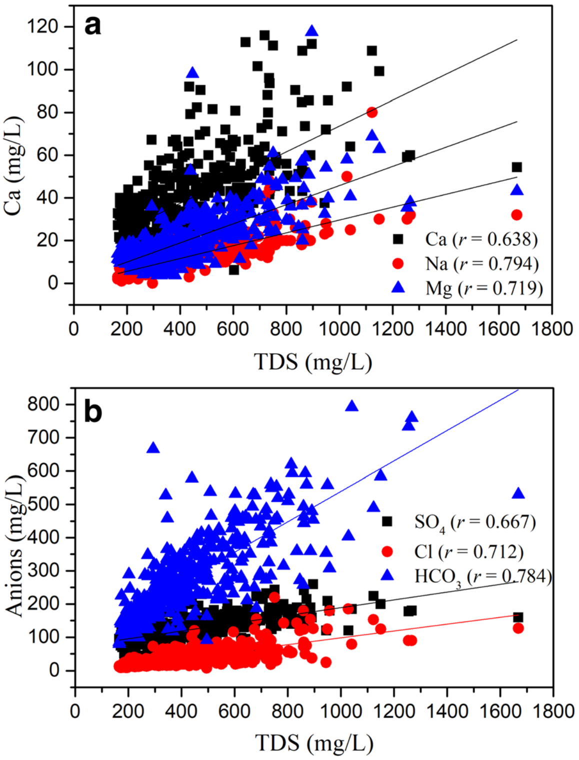

Fig. 5 Variation of TDS with cations (**a**) and anions (**b**)

exchange between divalents and monovalent is plausible, although minimal as shown earlier. This necessitates further experimental studies to confirm the mechanisms.

Although ANOVA did not identify the significant differences among the four groups in terms of HCO_3^- concentrations, LSD analysis showed that the average HCO_3 value for As > 50 μg/L group was significantly higher ($p < 0.05$) (Table 1). Traces of NO_2^- in all but three samples (99.37%) ("supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)") is a sign of bacterial activities as it is the end product of aerobic decomposition of organic nitrogenous matter (Abbas et al. 2015). This calls for further studies in the area.

Spatial variations in drinking water quality

This section discusses the groundwater quality variations among towns within Lahore city. The values were compared with the WHO (2011) standards and identifies towns with disparities. Overall, pH and turbidity values were within the acceptable range for human consumption. When using a threshold limit of less than 1000 mg/L TDS in drinking water, 44.7% of the total samples exceeded this value ($166 \leq \text{TDS} \leq 1668$ mg/L). Groundwater with higher salinity is unsuitable for drinking, and palatability depends on the element contributing most to the overall salinity. In some samples, higher values exceeding the WHO threshold values for alkalinity (Table 2) is apparent (see "supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)"). High alkalinity observed in 50.0% of total samples ("supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)") is unacceptable particularly for children (Abbas et al. 2015). In Lahore, groundwater is distributed to consumers by the Integrated Water Supply System, and such high alkalinity may adversely impact on the circulation system by enhancing scale formation through carbonate precipitation and impinge on water flow regime. However, the Langelier saturation index (LSI), computed in Aquachem 2011 ($-35.6 < \text{LSI} < -33.9$), recognized the water as undersaturated with respect to calcium carbonate. The index range (LSI < 0) dismissed any evidence of scale forming potential of groundwater in the studied samples. Furthermore, there were no traces of carbonates (CO_3^{2-}) detected in all the samples. Chloride and SO_4^{2-} values were both below the WHO limit value of 250 mg/L, respectively, except some samples in GBT (Table 2 and "supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)").

Table 2 shows groundwater quality according to different parts of the study area. The spatial distribution map for TDS, alkalinity, TH, SO_4^{2-}, NO_3^-, and As is presented in Figs. 6 and 7. The distribution characteristics of TDS and HCO_3^- are similar, and higher concentrations are found mainly in the central, south-eastern, and north-eastern regions of the study area (Fig. 6a, b). Nishter town recorded the highest salinity (and highest exceedance) value, while the lowest occurred in Ravi town. Similarly, the highest mean value for alkalinity is eminent in Nishter town, while Ravi town recorded the lowest mean alkalinity value (Table 2). TH has a sporadic (high to low) distribution throughout the area (Fig. 6c). High SO_4^{2-} and NO_3 concentrations are mainly in the central part (Fig. 7a, b), while). The Ravi town had the highest mean NO_2^- value observed. The highest mean value for NO_3 was determined for Aziz Batti and Shalimar town. There was a weak inverse relationship between NO_3 and NO_2^- ($r = -0.02$, $p = 0.61$) which suggests little significance of NO_2^- oxidation to NO_3^-. As stated earlier, this needs further confirmation in the next studies. It is possible that NO_3^- is controlled by

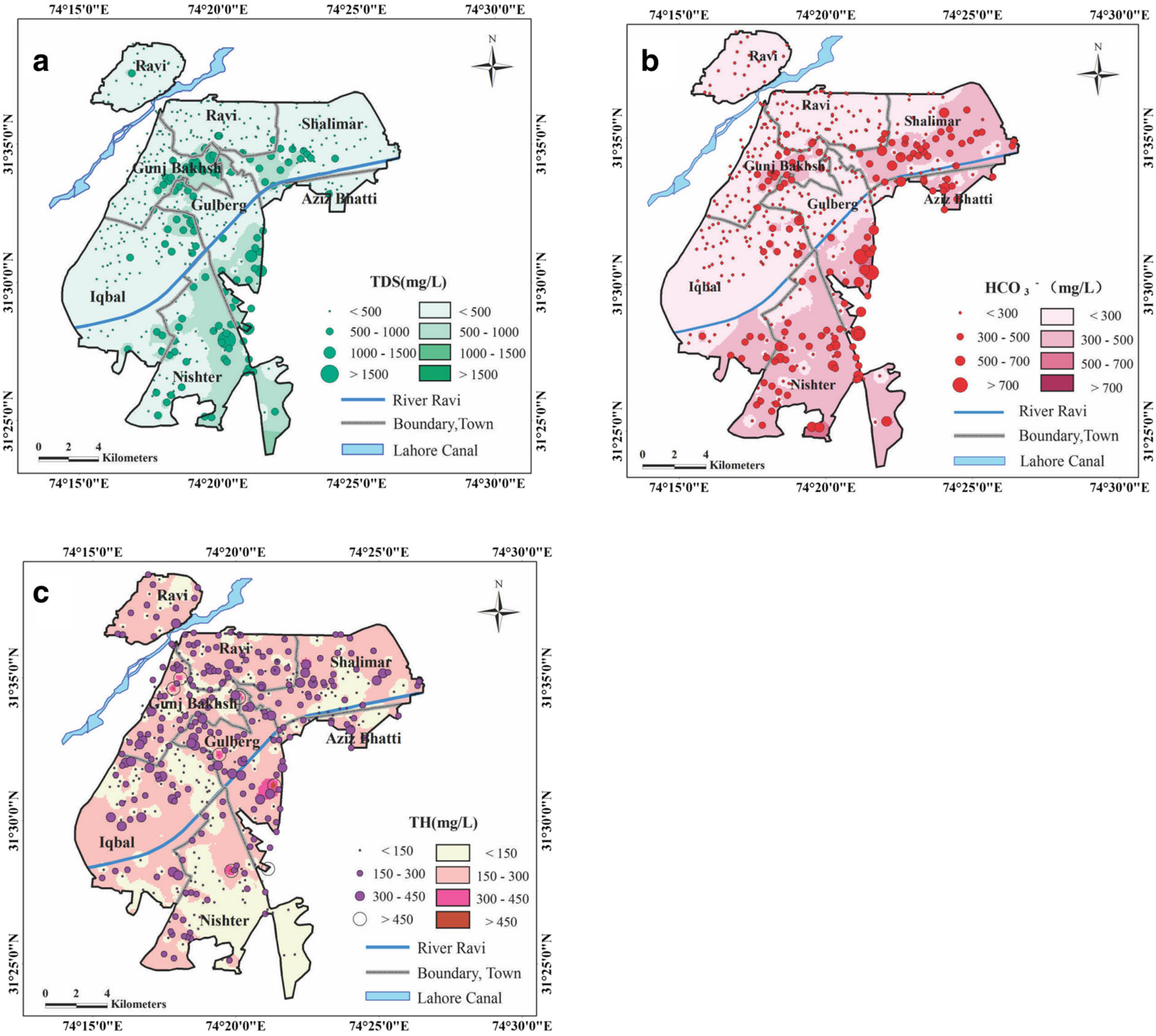

Fig. 6 Spatial distribution maps of TDS (**a**), HCO$_3^-$ (**b**), and TH (**c**) in the study area showing areas of high concentrations against those displaying low concentrations in Lahore city. Names of towns are included based on Fig. 1

dissolution process rather than evaporation as the correlation between nitrate and chloride was also poor ($r = 0.07$, $p = 0.15$) (Abou Zakhem and Hafez 2015). However, infiltrating water from River Ravi that is laden with wastewater effluents contributes NO$_3$ into the aquifer.

Table 1 shows that As co-varied with HCO$_3^-$ and alkaline earth metals (Na$^+$ and K$^+$) in terms of mean values across the groups. The correlation analysis confirmed this observation ($r = 0.8$, 0.7, and 0.5, respectively, $p < 0.05$). From the summary of results (Table 1), As in majority of the samples exceeds the WHO recommended value (As = 10 μg/L). Six out of 474 samples (representing 1.27% of total samples) showed values of arsenic above 50 μg/L ("supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)"); only 15% of the samples were within permissible range (< 10 μg/L). This is further illustrated in the distribution map (Fig. 7c). The map shows that the eastern region (north-south) displayed relatively higher As distribution. From the supplementary material, sample (NI-41) of Nishter town (industrial area) has the highest value of As (86 μg/L). On average, Gunj Bakhsh town exceeded the limit by the most (17.4%) followed by Nishter town area (16.4%). The lowest exceedance (3%) was for Ravi town. The HCO$_3^-$ dominated groundwater facies

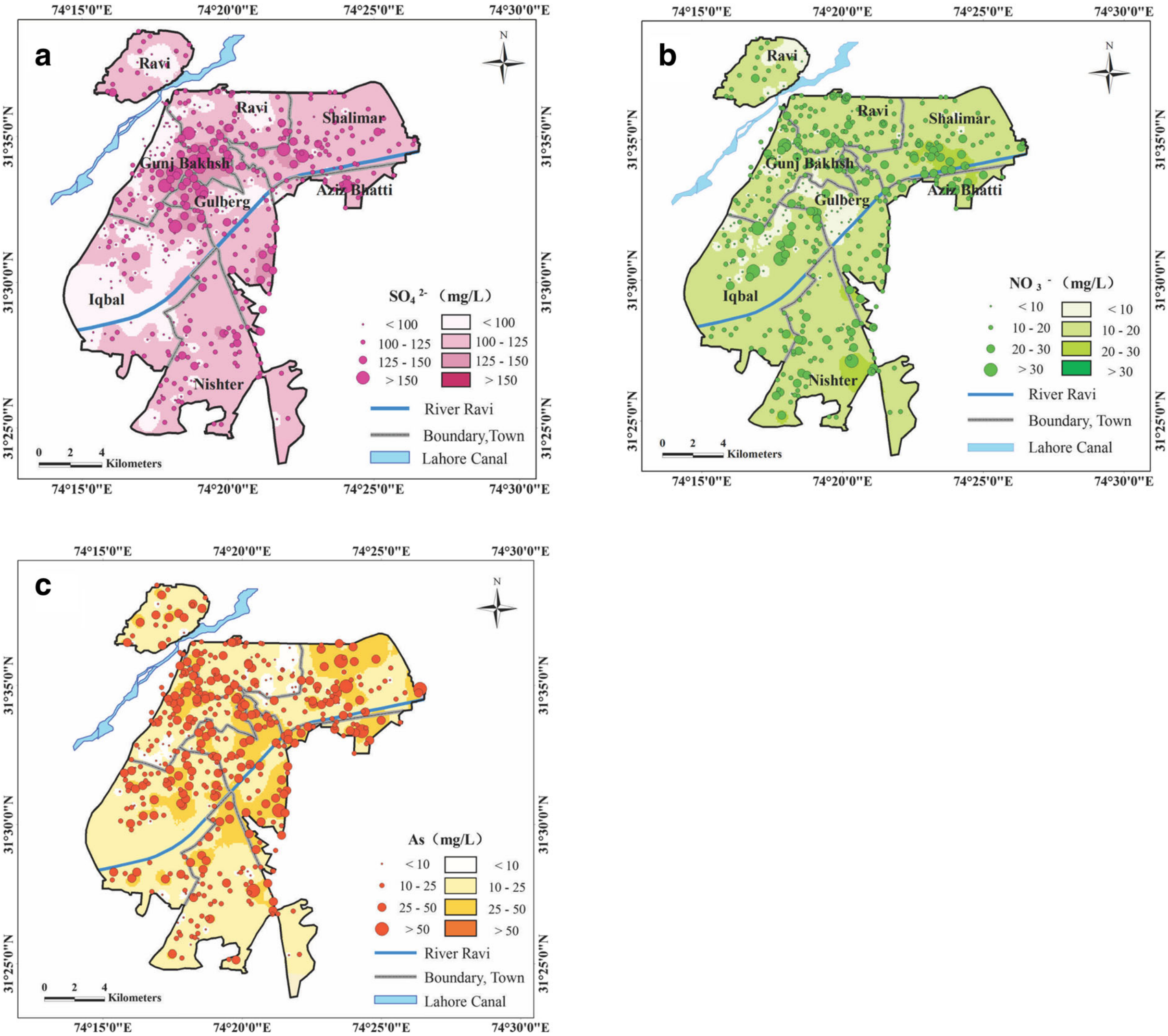

Fig. 7 Spatial distribution maps of SO_4^{2-} (**a**), NO_3^- (**b**), and As (**c**) within the confines of the latitudes and longitudes of the study area

observed in all towns in Lahore is conducive for As mobilization. Similarly, the pH observed for all samples in this study is ideal for arsenic mobilization. However, the average arsenic value (Table 1) observed is relatively lower than most of the cases reported in arsenic laden regions (Bangladesh, China, India, and West Bengal) (Smedley and Kinniburgh 2002). However, the situation seriously threatens the health of the population that solely depends on groundwater for drinking in the city.

Fluoride ranged from below detection limit (< D.L) to 1.4 mg/L comparably lower than the 1.5 mg/L prescribed by WHO guidelines (WHO 2011). The results echo those of earlier studies (Farooqi et al. 2007; Abbas et al. 2015). In the right amounts, fluoride is an essential element for human health; therefore, there is need for constant monitoring of fluoride levels in potable groundwater. Fluoride was found highest in Gunj Bakhsh town while the lowest mean value is for Iqbal and Nishter towns.

The industries occupying the northeast and southeast and a solid waste dumpsite located in the northeast parts of Lahore (Fig. 1) may have an impact on groundwater quality through leaching processes (Aiman et al. 2016). Leachates from landfill and seepage from wastewater drains are increasing pollutants in ground water of Lahore. As mentioned earlier (and illustrated in Figs. 6a, b and 7a, respectively), the eastern region of Lahore has the highest distribution of TDS, HCO_3^-, and

SO_4^{2-}, which may be attributed to industrial activities, poor solid waste, and wastewater management.

Irrigation water quality distribution

Salinity values

As mentioned earlier, salinity refers to total amount of dissolved inorganic solids in natural water. Thus, an increase in TDS and overall chemical load of the water is a predictor of salinization. The excessive dissolved ions, especially Na^+, HCO_3^-, and CO_3^{2-} in irrigation water affect the soil fertility and crop yield. It is established already in this paper that there are higher salinity values in the city. The WHO recommends that irrigation water should not exceed a TDS value of 450 mg/L with values greater than 2000 mg/L classified as unsuitable. The maximum value observed in this study is 1667 mg/L, which is not bad (Zouahri et al. 2015). The maximum EC value in all the cities is 2010 μS/cm falling in the category of highly saline water. The EC plot shows some highly saline groundwater samples in the city (Fig. 8). As earlier shown (Table 2), Nishter town had the highest percent of groundwater samples exceeding the WHO limit value for drinking in terms of EC. This is no surprise that the same town surpasses the other towns in number of samples falling within the highly saline water (Fig. 8). Increased EC results in decreased water intake by the plants and therefore reduction in productivity. Groundwater samples in GBT, Iqbal, and Nishter fall either in average salinity (C2) or highly saline (C3). Only a few samples in Aziz Batti/Shalimar and Ravi towns had groundwater falling within the non-saline group (C1). However, there were no samples with salinity values in the class of very highly saline (C4) and extremely saline water (C5). In places were irrigation is practiced in the city of Lahore, it is better to be aware of which groundwater abstraction point to use. If no option is available in terms of abstraction points, implementing mitigation measures to obviate the effect of high salinity is a necessary.

Sodium adsorption ratio and magnesium hazard

In terms of sodium adsorption ratio (SAR), the values were found to show that the groundwater is suitable for irrigation SAR (< 9) (Fig. 8). The distribution of SAR values is clearly shown in Fig. 9a. The eastern margin of the city is characterized by relatively higher values of SAR. This is where Nishiter town is located with the highest mean SAR. It is further observed that certain samples (27.2%) in all studied towns exceeded the MH limit value of 50% on individual basis (see "supplementary material (http://doi.pangaea.de/10.1594/PANGAEA.847769)"). Furthermore, ABST showed the highest average and a wider range of MH values while RAT had the lowest mean MH value. Most of the groundwater for RAT fall within the acceptable region for irrigation in terms MH (Fig. 9b) unlike other towns. A high MH value indicates higher Mg^{2+} compared to Ca^{2+} ions, which may affect the soil quality by converting it to alkaline conditions and thereby decreasing crop yield. In this case, the eastern region is more prone to development of alkaline soil conditions

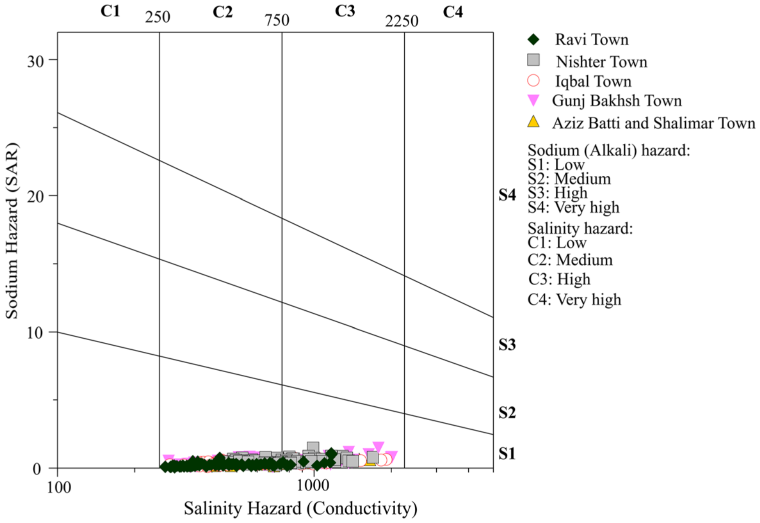

Fig. 8 Wilcox diagram illustrating the suitability of groundwater for irrigation in Lahore city based on SAR and salinity hazard criteria

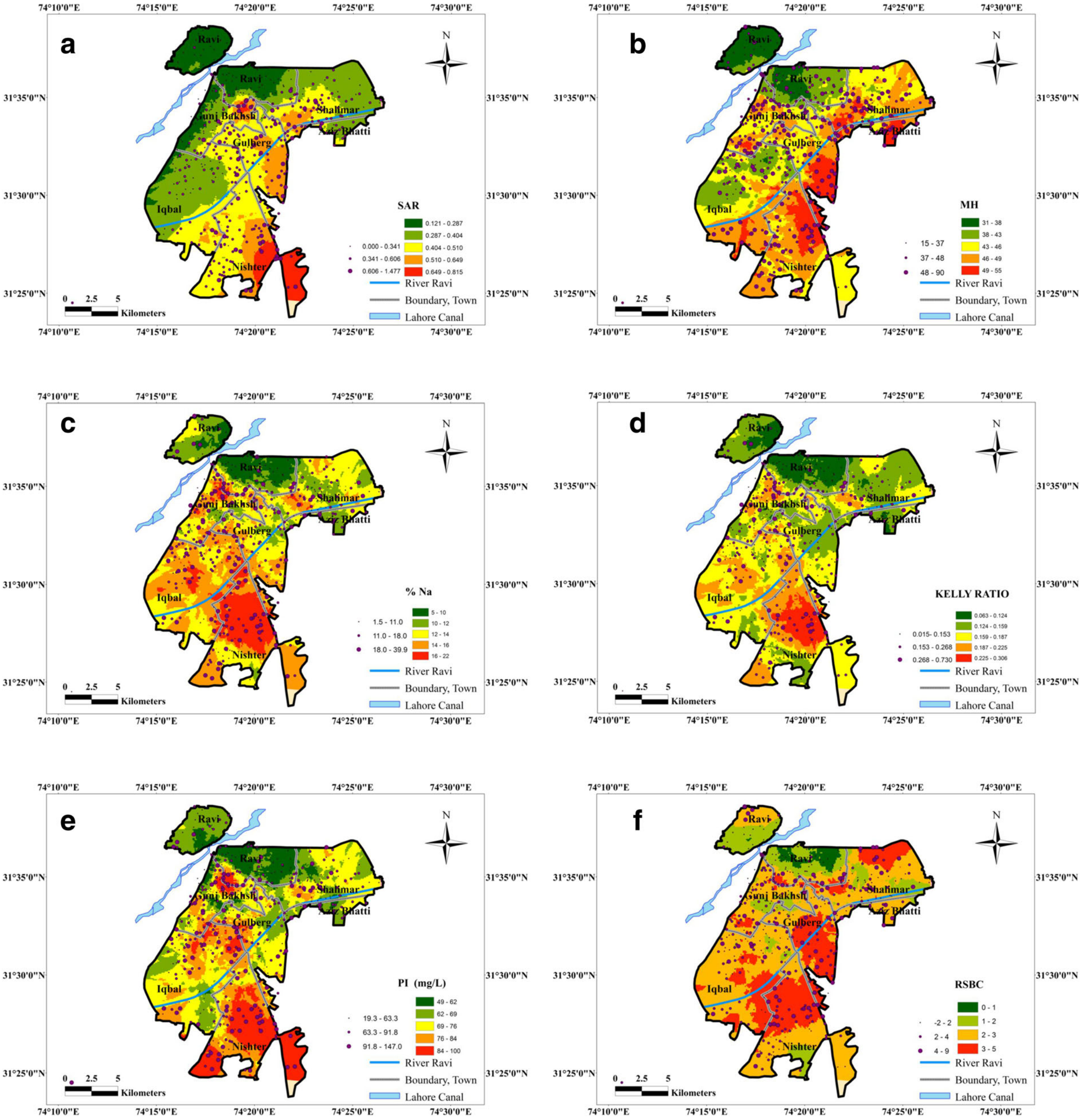

Fig. 9 Distribution maps for the irrigation water indices for SAR (**a**), MH (**b**), %Na (**c**), KI (**d**), PI (**e**), and RSBC (**f**) for Lahore city

unlike the northwestern margin (Fig. 9b). Therefore, it is better to identify properly the areas within the towns that have high risk of magnesium for irrigation.

Percent sodium (%Na) and exchangeable sodium ratio (ESR)

Most groundwater samples (%) indicate a %Na within the excellent water class for irrigation, i.e., %Na < 20. Except for one sample in NIT falling in the permissible region (40–60%), the remaining samples were on average classified as excellent for irrigation in terms of %Na (Fig. 9c). In the supplementary material, it shows that the highest mean %Na is observed for NIT while the lowest is for RAT. However, it should be noted that the southern part of the city is relatively poor in terms of %Na than the northern part. Despite this distribution, the results rule out issues of poor permeability of soils due to excess Na in relation to Ca and Mg and hence the water being safer for irrigation (Zouahri et al. 2015; Rajesh et al. 2015). Coupled to %Na, the ESR or Kelly Index (KI) (Fig. 9d) supports the conclusion that groundwater in all towns in Lahore is suitable for irrigation. This relies on the fact that waters with a KI > 1 are unsuitable for irrigation while those of KI less than 1 are suitable. In this study, the average KI in all samples from the five towns was less than 1 with the northern region better than the southern part (industrial area).

Permeability index (PI)

Long-term use of water for irrigation affects soil permeability influenced by Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- contents of the soil. The PI predicts the possible impact of water quality on soil permeability. The PI is classified into first class (PI > 75%), second class (25 < PI < 75%), and third/unsuitable (PI < 25%). In this study, suitability for irrigation varies among (and within) the towns based on PI values observed (Fig. 9e). However, most samples for all towns belonged to the second class and some samples in the first class. These two classes define groundwater as good for irrigation (Fig. 9e). In terms of distribution, it is noted that the mean PI values for IQT and NIT belong to the first class while those of ABST, GBT, and RAT falling in the range of second class. The PI distribution observed for the southern part of the city explains the poor quality of groundwater in the area relative to the northern part in that good permeability is prone to increased infiltration of polluting chemicals. None of the groundwater samples from these towns had their PI less than 25% (unsuitable).

Risk related to bicarbonate

Residual sodium bicarbonate (RSBC) value of less than 5 meq/L classifies water samples as satisfactory for irrigation. In this study, most samples had RSBC values less than 5 meq/L except few samples (8.2%) (Fig. 9f). Overall, the RSBC values among towns indicate mean values below the RSBC prescribed upper limit of 5 meq/L (Gupta and Gupta 1987). Despite having some values higher than 5 meq/L, the groundwater remains within suitable range with maximum value falling below 10 meq/L. The areas in the center and eastern margin where industries are located as well as the northeastern margin of the city (where a landfill is found) have RSBC comparably higher. These areas coupled with poor wastewater management result in increased contamination of the groundwater through infiltrating water.

Risk related to chloride

Whenever the chloride ion concentration in irrigation water is higher than 4 meq/L, toxicity problems to plants may occur (Zouahri et al. 2015). The Cl^- toxicity affects sensitive crops such as maize. In this study, majority of the groundwater samples had Cl^- concentration less than 4 meq/L and a few between 4 and 10 mg/L (Table 2). Since none of the groundwater samples from the five towns exceeded 10 meq/L, the groundwater remains within the category of good water for irrigation. But, precautionary measures are necessary for the samples with Cl between 4 and 10 meq/L before using the water for irrigation. It is also noted that majority of samples (52.3%) fall within the very fresh water group ($0.14 > Cl^- > 0.85$), 46.4% classified as fresh water ($0.85 < Cl^- < 4.23$ meq/L), and the remaining few (1.3%) falling within the fresh brackish ($4.23 < Cl^- < 8.46$) category (Zouahri et al. 2015; Stuyfzand 1989). The second group of samples (fresh brackish) requires careful consideration when planning to use for irrigation in Lahore.

Conclusions

From the 474 groundwater samples in Lahore city (WASA jurisdiction), the study highlights the bicarbonate (HCO_3) type of groundwater dominated by Ca^{2+} and Mg^{2+}, in that order. The eastern area (north-south) of the city was relatively elevated in terms of cations and anions. This area is dominated by industrial activities and a waste dumpsite in the northeastern part. The study shows that geogenic processes inherently influence the variation in groundwater quality. However, the elevated Cl and NO_3 indicate influence of industrial, poor wastewater, and landfill management on the quality of the groundwater. The activities explain the spatial distribution of the groundwater suitability for drinking and irrigation. Despite this, the groundwater in the city remains suitable for irrigation except where 1.3% of the water remains classified as fresh-brackish water. Proper management of solid waste, wastewater, and regulation of industrial activities could lessen the burden on groundwater quality violations.

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