Geospatial assessment of groundwater quality using Water Quality Index and Inverse Distance Weighted techniques

SHUMAILA MAJEED, AMBREENA JAVAID, SARA GUL, NIMRA FAROOQ, MAHAM TAHIR
Geography Department
Kinnaird College for Women Lahore
93-Jail Road, Lahore
PAKISTAN
shumaeela78@gmail.com; ambreena.mubashir@gmail.com; sara.gull19@yahoo.com; kcitegrl123@gmail.com; maham.8@hotmail.com

Abstract: - Groundwater is the main source of domestic and industrial activities in the city of Lahore and Kasur due to meagre resources of surface water. The current study was conducted to investigate the groundwater quality for drinking purpose and to identify the hydrochemistry of groundwater using Canadian Council of Ministers for the Environment Water Quality Index and Gibb's graph. 40 water samples were taken from different areas of Lahore city and 19 samples were collected from Kasur city. These samples were tested by 15 physiochemical parameters (pH, EC, TDS, TH, Turbidity, HCO3, Cl, Ca, K, Mg and Na) and heavy metal (Zn, Cu, Fe and As). According to water quality index model results, groundwater of Lahore city lie between excellent to the marginal category, whereas the groundwater of Kasur fall under good to poor category. Evaporation and rock water interaction influence were dominant in both of the study areas, which clearly indicates the interaction between rock and percolated water geochemistry. It is recommended that the government should install more tube wells at a considerable depth to ensure contamination free and excellent drinking water at the consumer's end.

Key-Word: - Groundwater, hydro-geochemistry, water quality index (WQI), drinking water, interpolation technique (IDW).

1 Introduction

Water is the vital source of life on earth. A third fourth of the earth's surface is covered by water. It is the most precious gift of God. On the earth's surface, about 97% water is present in oceans and 3% is present in freshwater sources. Out of this 3%, only 0.01% of freshwater is accessible for drinking purpose [1]. The main sources of fresh water are rainwater, groundwater and surface water. Rainwater percolates in the soil (infiltration process) and stores itself in underground aquifers. Owing to its filtering effect, this groundwater drawn from the underground aquifer is more fine and supreme to the surface water [2]. Due to huge population growth, rapid urbanization, poor irrigation, increasing industrialization, prompt climatic changes and unsustainable use of drinking water has led this little amount of freshwater under enormous stress [3,4]. According to World Health Organization (WHO), contaminated water intake can trigger up to 80% of diseases among humans. Therefore it is essential to check the groundwater quality on regular basis and to design necessary measures to maintain its characteristics [5].

Various indices of water quality have been created around the world. A modern technique known as water quality index is used for the analysis of various water resources. It is one of the most appropriate tools for checking the quality of water and used as a significant parametric quantity for the management and analysis of water resources [6]. It is a simple, unique and the most powerful mean to elucidate the statistical data of water quality to the associated populations, management and decision makers. WQI can precisely reduce the bulk information of the groundwater assessment into a single powerful value ranging from 1 to 100. It is a unitless number emulating the collective influence of varied water quality parameters to produce a single ranking position of a water system [7]. Hydrochemistry of an area is responsible for groundwater quality. It gives a true picture of the subsurface geological environment of an aquifer [8].

Pakistan is a water stressed country, having only 1384 (m^3/capita/year) fresh water available resources [9,10]. Groundwater is used as a primary source of consumption. These groundwater sources are deteriorating in quality and quantity due to unstable government, overpopulation, unplanned urbanization, unchecked irrigation, improper dumping of waste and lack of strict government enforcement laws [11-13]. Major cities like Faisalabad, Gujrat, Karachi, Lahore, Kasur, Peshawar, Rawalpindi and Sheikhupura are declining in water quality due to the huge dumping of untreated municipal, agricultural and industrial waste [13].

The current study includes the investigation of groundwater quality of populated areas of Lahore and Kasur which has been deteriorated by the local industries and agricultural activities. The main purpose of the present study is to examine the drinking water quality through Canadian water quality index model and to analyze the groundwater hydro-geochemistry.

2 Materials and methods

2.1 The Study area

The area of study comprises of Lahore and Kasur District, Punjab as shown in Fig. 1. Lahore is the capital city of Punjab province, Pakistan. It is situated between 74.3572° E longitude and 31.5546° N latitude, next to the eastern bank of River Ravi. It has an estimated 1,772 km² total area with an elevation of 217 m above sea level characterized by a flat topography. The city of Lahore is expanding towards the southern side with an estimated population of 11 million, growing at the rate of 3.1% per year [10,14,15]. The average population density is 6300 persons per square kilometre. The average annual rainfall of Lahore is 240 mm and it mostly occurs in monsoon time period. There are 3 major water provision methods working in Lahore city; the water supply piped network of Water and Sanitation Agency [16], the water supply piped network of local Cantonment board and local household boreholes [10].

Whereas Kasur lies towards the south of Lahore district between 31.0701° N and 74.2701° E with an elevation of 198 m and 3,996 km² area. It lies between an alluvial plain of River Ravi and River Satluj with an estimated population of 4.1 million, growing at the rate of 2.7% per year [17,18]. The city of Kasur is well known for its industrial activities such as leather, textile and woodwork etc. The average amount of rainfall is approximately 33 mm. Currently, 43 tube wells are providing groundwater to 75% of the total population [17,19].

2.2 Sampling Program and Chemical Analysis

A field survey was carried out for the sampling of tap water from 15th February, 2017 to 5th March, 2017. A random and convenient sampling technique was adopted and each sampling area was well marked by Global Positioning System (GARMIN eTrex 10 GPS). Total 59 groundwater samples were collected from the populated area of Lahore and Kasur, 40 from Lahore city and 19 from Kasur city. For the collection of groundwater, tap water was used. The tap mouth was heated for 1 minute and then the tap water was let open for 4-5 minutes to run. The drinking water was collected in pre-cleaned polyethylene 1-litre plastic bottles and properly marked with labelling codes ("L" for Lahore and "K" for Kasur water samples). These samples were placed in the icebox at 4℃ and brought to the Kinnaird College Laboratory within 24 hours. 2 ml/L concentrated Nitric acid (HNO3) was added in the water samples to preserve them as stated by APHA-AWWA-WEF [20]. Physical parameters of groundwater like EC, pH and TDS were observed through EUTECH instruments PC510. HCO3 was measured by titration method. Turbidity was evaluated through HI 93703 turbidity meter (HANNA instrument). Whereas filtered groundwater samples were analysed for chemical variables like sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), chloride (Cl), arsenic (As), zinc (Zn), iron (Fe) and copper (Cu) using Atomic Absorption Spectrophotometer. Total hardness (TH) was calculated through mathematical expression; *Total Hardness (CaCO3) = [Ca^{2+} □ 2.5] + [Mg^{2+} □ 4.1]* [21]. For Lahore and Kasur groundwater samples, 15 physiochemical parameters are observed (pH, EC, TDS, Turbidity, total hardness, HCO3, Ca, Mg, Na, K, Cl, Zn, Cu, Fe and As) respectively. The obtained results of all the parameters are evaluated on the basis of WHO drinking water quality standards [22].

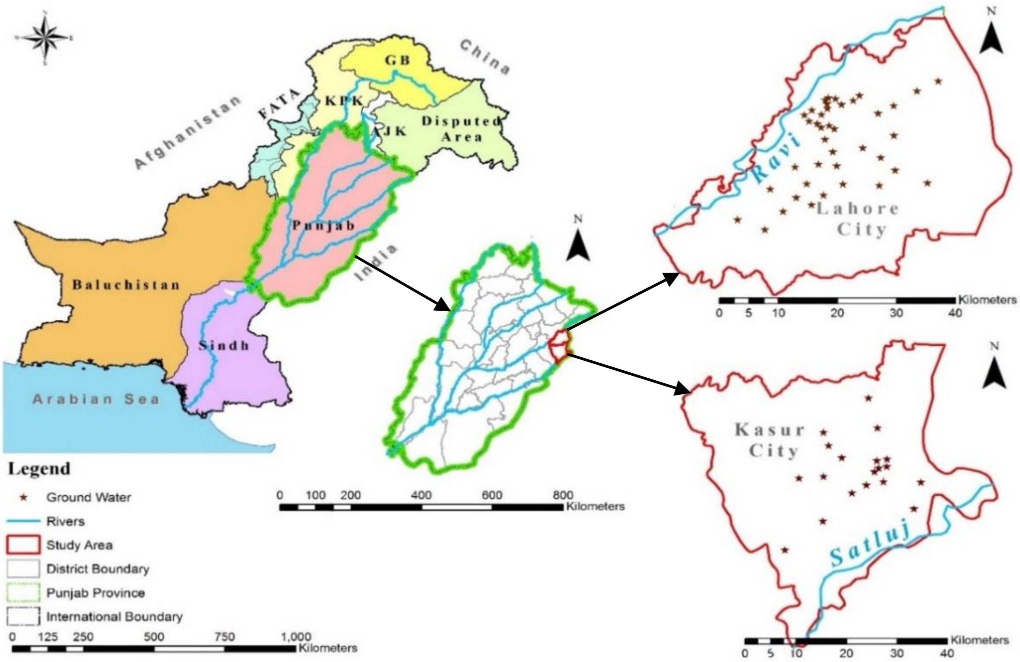


Fig. 1- Showing map of study area

2.3 Statistical analysis

Microsoft Office Excel 2013 and SPSS (*PASW Statistics ver. 18.0)* were used for all mathematical and statistical calculations. Whereas ARC Map, *ArcGIS ver. 10.1* [23] was used for the spatial maps.

2.4 Conceptualization of IDW Technique

A point layer shapefile was prepared with their attribute information. Inverse Distance Weighted (IDW) interpolation technique was used for the preparation of different thematic maps. Interpolation is a process of spatial analysis in which a new information is extracted from the original data. IDW is a unique interpolation algorithm based on assumption that the local influence of each measured point diminishes with the distance [24]. This impact can be controlled by the power value. By assigning higher power, more weight is laid on closer points and the resulting surface will be less smooth, showing more details. Whereas, lower power value will affect those points which are far apart, resulting in a more smooth surface [24,25]. The IDW interpolation is based on the following algorithm [26];

$$D_{\circ} = \frac{\sum_{i=1}^{n}(Di/h^{p})}{\sum_{i=1}^{n}(1/h^{p})} \qquad \text{(I)}$$

Where;

$$h = \sqrt{\delta^2 + \sigma^2} \qquad \text{(II)}$$

Where $D_{\circ}$ represents the interpolated value, *Di r*epresents the actual value of a location, δ represents the distance between the locations and the interpolant, *p* represents the power value (*p* = 2), *σ* represents the smoothing value (0,…1).

2.5 Conceptualization of Canadian Council of Minister of the Environment water quality index (WQI-CCME) model

Canadian Council of Minister of the Environment water quality index (WQI-CCME) is a complete and well-known model for calculating the water quality index of drinking water [27]. It is based on 3 main determinants; *Scope*, *Frequency and Amplitude*.

Determinant (D1): **Scope**

$$D1 = 100 * [\frac{\text{Failed varaibles}}{\text{Total variables}}] \qquad \text{(III)}$$

Determinant (D2): **Frequency**

$$D2 = 100 * [\frac{\text{Failed Tests}}{\text{Total Tests}}] \qquad \text{(IV)}$$

Determinant (D3): **Amplitude**

$$D3 = [\frac{nse}{(0.01*nse)+0.01}] \qquad \text{(V)}$$

where;

$$Dex = 1 - \left[\frac{\text{Deviated Amount}}{\text{Objectives j}} \right] \quad (VI)$$

$$nse = \sum_{i=1} n \left[\frac{Dex}{\text{Total Tests}} \right] \quad (VII)$$

The WQI-CCME model is calculated through;

$$\text{WQI-CCME} = 100 - \left(\frac{\sqrt{(D1)^2+(D2)^2+(D3)^2}}{1.732} \right) \quad (VIII)$$

The 1.732 divisor has been used to scale the index from 0 to 100, where 0 means the poor water class and 100 means the excellent water classification. The five categories of WQI-CCME water quality index are shown in Table 1.

3 Results and discussion

A comparison of selected parameters in the groundwater of Lahore and Kasur along with WHO permissible limits are shown in Fig. 2. The physiochemical characteristics of the drinking water are statistically examined and the output such as minimum, maximum, range, standard deviation and mean are provided in Table 2.

3.1 Groundwater physical components

The pH in the study area of Lahore ranges from 7.3-8.3, which is slightly alkaline in nature (Fig. 3a). This alkalinity of groundwater is due to the presences of HCO3 ions which are formed by the composition of H2O and CO2, thus affecting the pH of water [28]. Whereas the pH of Kasur ranges from 5.2-7.1 (Fig. 3b), indicating acidic and corrosive water due to anthropogenic activities. Electric conductivity (EC) is the water capability to pass the electrical current. Higher values of EC in groundwater mark higher amount of salts in it. The amount of EC ranges between 400-2500 (μS/cm) and 630-1830 (μS/cm) in Lahore and Kasur city as shown in Fig. 3c-d. In Lahore, 45% of groundwater samples fall within the prescribed limits of WHO 2011 (1000 μS/cm). Whereas in Kasur, only 42% of water samples fall within the limits set by WHO.

The Total dissolved solids (TDS) is the amount of movable charged ions in the given volume of water. It is directly connected to the purity and purification system of drinking water. It ranges between 290-1800 mg/L and 570-1972 mg/L in Lahore and Kasur city (Fig. 3e-f). Only 10% of water samples in Lahore and 37% in Kaur are exceeding the WHO limits (1400 mg/L). The highest values of TDS are observed at L2 in Lahore and K6 in Kasur. An anthropogenic effect like percolation of domestic sewage and septic tanks might be the reason for increased TDS in groundwater [8].

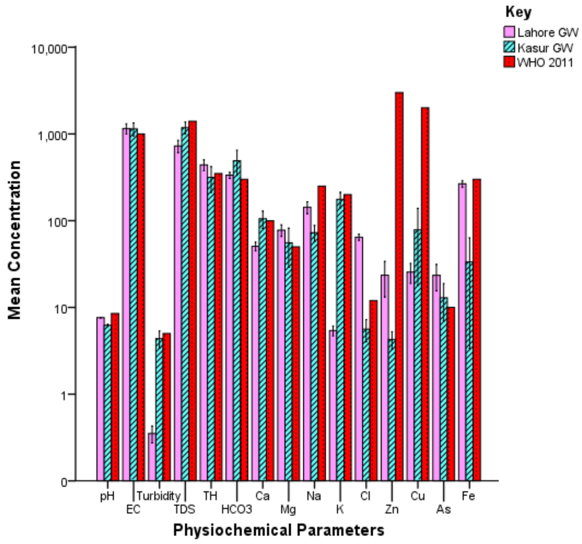


Fig. 2- A comparison of selected parameters in the groundwater of Lahore and Kasur along with WHO permissible limits.

Turbidity is the measure of the virtual clarity of a drinking water [29]. The turbidity of all sampling sites in Lahore is within the limits of WHO (5 NTU). Whereas only one site K19 (5.88 NTU) in Kasur is exceeding the prescribed limit. This might be due to the presence of biomass in water supply, sediments mobilization, precipitation of minerals in water and insufficient groundwater filtration [30].

The total hardness (TH) of the groundwater ranges between 193-1230 mg/L and 220-1390 mg/L in Lahore and Kasur city (Fig. 3g-h). Only 17.5% of groundwater samples in Lahore and 16% of groundwater samples in Kasur are within the WHO acceptable limits (300 mg/L). According to Lenntech TH classification [21], all of the water samples in Lahore and Kasur fall under very hard water type (>180 mg/L), which reveals the natural hydrogeological formation of the groundwater. Very hard water type may affect human health like stomach disorder, heart, kidney and bladder diseases etc [31-33].

Table 1- WQI-CCME categorization scheme.

Category	WQI-CCME	Description
Excellent	95-100	Water quality is safe with a virtual absence of threat and conditions very much near to natural levels.
Good	80-94	Water quality is safe with few degree of threats and conditions rarely deviate from desirable or natural levels.
Fair	65-79	Water quality is usually safe but occasionally impaired and conditions sometimes deviate from desirable or natural levels.
Marginal	45-64	Water quality is repeatedly threatened and conditions frequently deviate from desirable or natural levels.
Poor	0-44	Water quality is constantly threatened and conditions usually deviate from desirable or natural levels.

Table 2- Descriptive statistics of ground water in the study area of Lahore (n=40) and Kasur (n=19)

	pH	**EC** (µS/cm)	**Turb.** (NTU)	**TDS** (mg/L)	**HCO3** (mg/L)	**T.H** (mg/L)	**Ca** (mg/L)	**Mg** (mg/L)	**Cl** (mg/L)	**Na** (mg/L)	**K** (mg/L)	**Zn** (µg/L)	**Cu** (µg/L)	**As** (µg/L)	**Fe** (µg/L)
Kasur City															
Mean	6.2	1144.0	4.4	1183.4	316.2	490.7	105.3	55.5	72.7	176.5	5.6	4.3	78.3	12.9	33.4
Std. Dev	0.4	404.6	2.0	392.5	217.2	329.1	49.6	55.1	32.2	74.7	3.4	2.1	125.2	12.3	62.4
Range	1.9	1200	9.2	1402	756	1170	160	207	110	253	9.7	10	354	46	227
Min	5.2	630	1.65	570	12	220	50	5	25	81	2.4	2	1	1	3
Max	7.1	1830	10.83	1972	769	1390	210	212	135	334	12.1	12	355	47	230
Lahore City															
Mean	7.6	1154.0	0.4	726.3	334.6	440.5	50.8	77.8	64.5	142.7	5.4	23.6	25.5	23.5	266.4
Std. Dev	0.2	493.9	0.2	374.2	85.9	197.1	18.7	38.0	16.8	70.1	2.2	32.6	20.9	24.9	74.4
Range	1	2100	1.56	1510	390.4	1037	81	204	67	212	10	169	70	98	310
Min	7.3	400	0.2	290	154.5	193	28	30	38	30	3	1	4	2	70
Max	8.3	2500	1.76	1800	544.9	1230	109	234	105	242	13	170	74	100	380
WHO 2011	**6.5-8.5**	**1000**	**5**	**1400**	**350**	**300**	**100**	**50**	**250**	**200**	**12**	**3000**	**2000**	**10**	**300**

3.2 Groundwater chemical components

3.2.1 Major Cations

The dominant cations fall in the order Na > Mg >Ca > K in Lahore and Na > Ca > Mg > K in Kasur city. Magnesium and sodium are the most dominating cations in both of the study areas. Magnesium ranges between 30-234 mg/L in Lahore (Fig. 4c) and 5-212 mg/L in Kasur city (Fig. 4d). 90% of ground water samples in Lahore and 26% of ground water samples in Kasur are exceeding the WHO limits (50 mg/L). The higher levels of magnesium in drinking water may occur due to leaching of dolomite rocks which may end up in ground water. High magnesium levels in drinking water may cause laxative effects among humans [4,32]. The amount of calcium ranges between 28-109 mg/L in Lahore (Fig. 4a) and 50-210 mg/L in Kasur (Fig. 4b). Only 5% of water samples in Lahore and 32% of water samples in Kasur are above the allowable limits of WHO. Calcium in ground water is derived from the percolation of carbonate minerals like dolomite and calcite. Excess of calcium may cause stone formation in bladder and kidneys, which may cause irritation in urinary passages of human beings [32].

Na and K maintain the natural osmotic pressure in human cells. Potassium is required for the protein synthesis and insulin secretion [34]. The concentration of K in groundwater varies from 3-13 mg/L in Lahore (Fig. 4g) and 2.4-12.1 mg/L in Kasur (Fig. 4h). Only one sample (L30) in Lahore city is slightly higher than the prescribed WHO limits (12 mg/L). Whereas Na ranges from 30-242 mg/L with an average mean value of 142.7 mg/L in Lahore (Fig. 4e) and 81-334 mg/L with a mean value of 176.5 mg/L in Kasur (Fig. 4f). 23% of water samples in Lahore and 37% of water samples in Kasur are exceeding the WHO prescribed limits (200 mg/L). The elevated concentration of Na in the groundwater may be derived from anthropogenic activities and rock-water interaction. Higher levels of Na in drinking water might be detrimental to the person suffering from kidney and cardiac diseases [8,31].

3.2.2 Major anions

Among the anions concentration, HCO3 is the most dominant ion followed by Cl in both of the studied areas. The concentration of HCO3 in the groundwater ranges between 154.5-544.9 mg/L in Lahore (Fig. 5a) and 12-769 mg/L in Kasur city (Fig. 5b). 35% of groundwater samples from Lahore and 36% of groundwater samples from Kasur are above the WHO acceptable limits (350 mg/L). Mineral weathering and dissolution of carbon dioxide gas into the groundwater may be the reasons of elevated concentrations of HCO3 [35]. Whereas Cl concentration varies from 38-105 mg/L in Lahore (Fig. 5c) and 25-135 mg/L in Kasur (Fig. 5d). All samples of Lahore and Kasur city are within the acceptable limits of WHO (250 mg/L).

3.2.3 Heavy metals

The heavy metals in the groundwater observe the order Fe > Cu > Zn > As in Lahore and Cu > Fe > As > Zn in Kasur city. The amount of Zn varies between 1 to 170 µg/L in Lahore (Fig. 6a) and 2 to 212 µg/L in Kasur (Fig. 6b). Whereas the concentration of Cu in Lahore (Fig. 6c) ranges between 7 to 74 µg/L and 1 to 355 µg/L in Kasur (Fig. 6d). All groundwater samples of both the areas are within the acceptable limits of WHO. The amount of Fe in the groundwater fluctuated between 70 to 380 µg/L in Lahore (Fig. 6e) and 3 to 230 µg/L in Kasur area (Fig. 6f). Fe concentration is exceeding in 42% of the water sample of Lahore city from WHO acceptable limits (300 µg/L).

High concentrations of Fe in the groundwater are due to the industrial growth and immoderate use of iron-based fertilizers in the agricultural lands of Lahore district. The contribution of arsenic ranges from 2 to 100 µg/L in Lahore (Fig. 6g) and 1 to 47 µg/L in Kasur city (Fig. 6h). 45% of the groundwater samples in Lahore and 42 % of groundwater samples of Kasur are exceeding the WHO limits (>10 µg/L). High levels of As in Lahore and Kasur city are due to the growing anthropogenic activities like metallic industries and excessive use of arsenic containing agricultural pesticides [36]. Elevated concentration of As in groundwater might cause severe health effects such as cancer development in liver, bladder, lungs and kidneys [37].

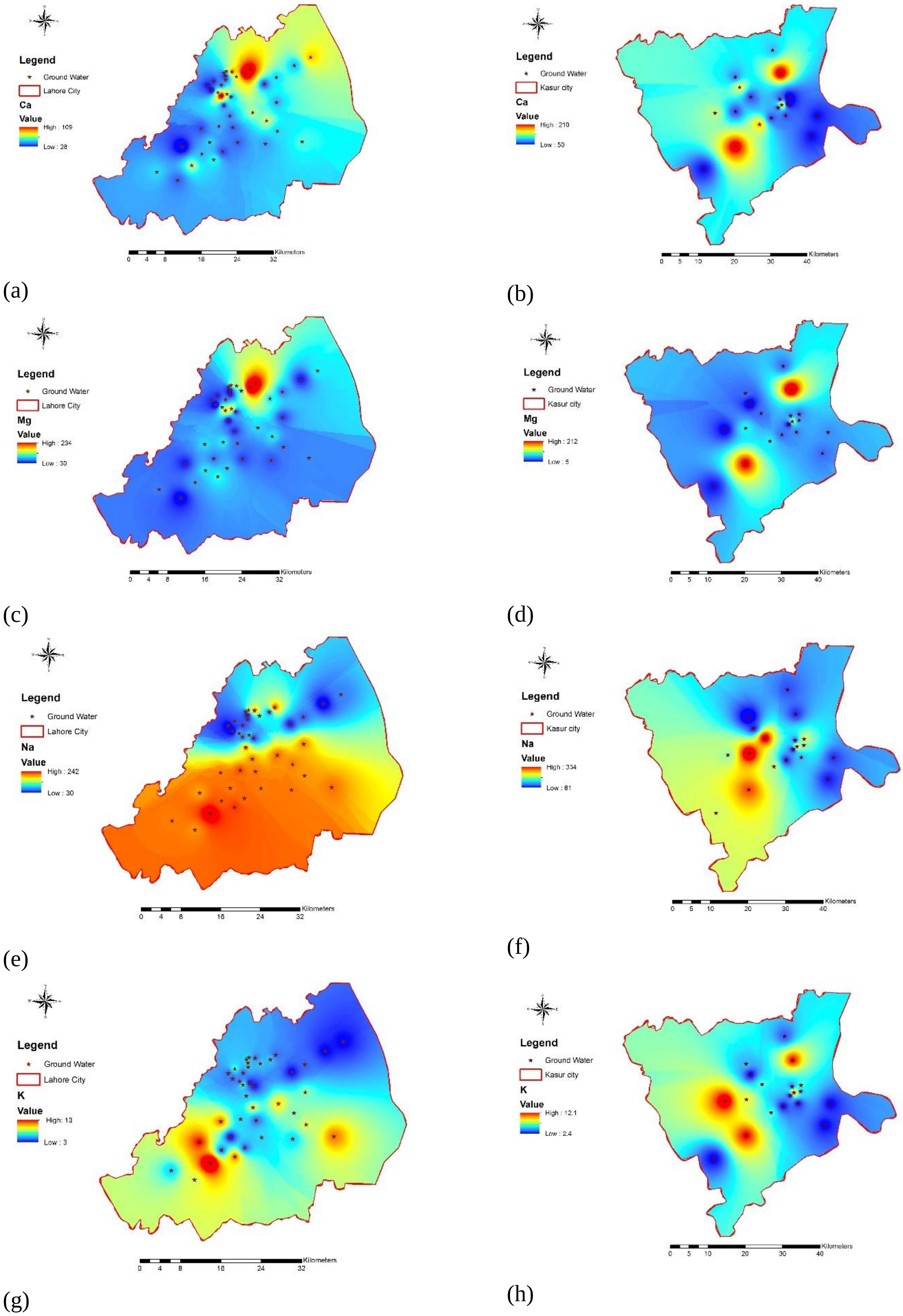


Fig. 4 - Spatial distribution of cations in the study area of Lahore and Kasur city

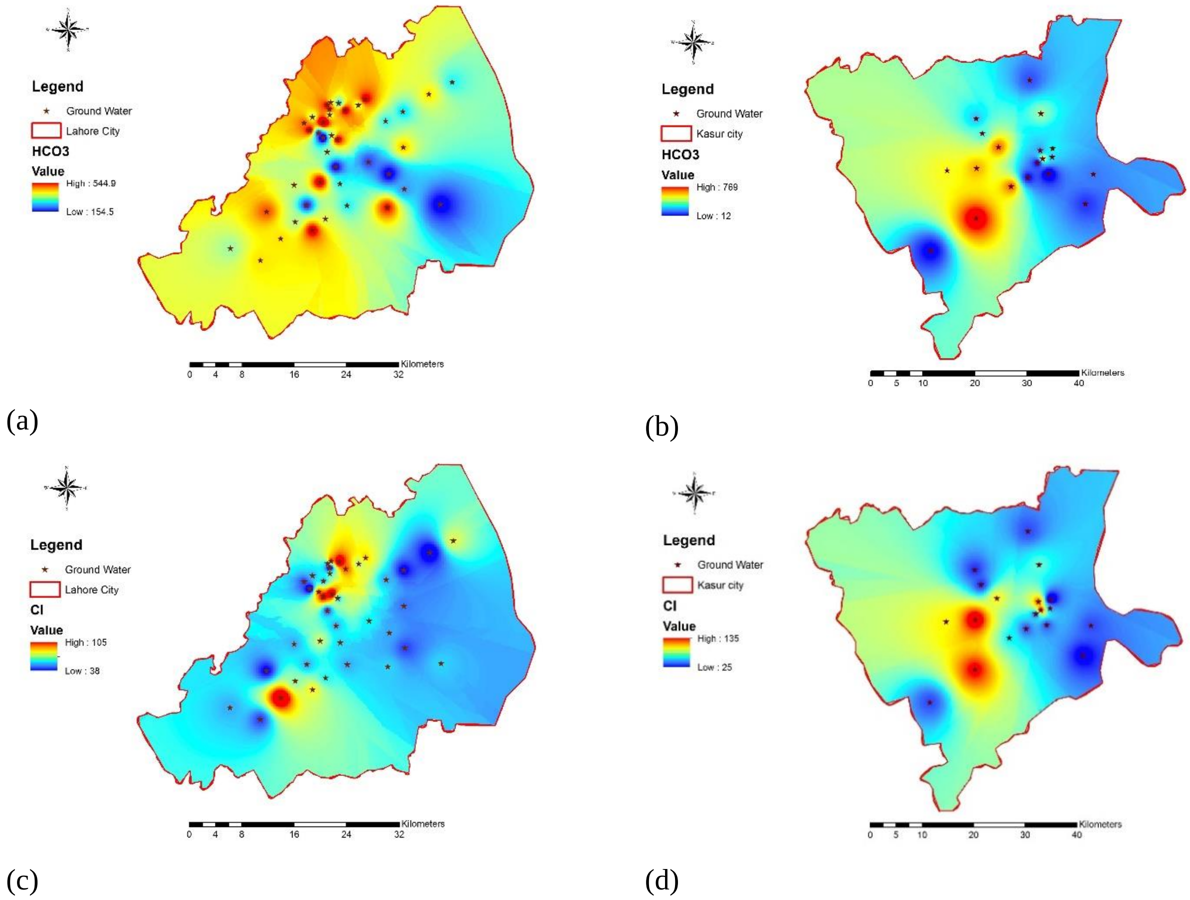


Fig. 5- Spatial distribution of anions in the study area of Lahore and Kasur city

3.3 The WQI-CCME model analysis

The guidelines of Canadian Council of Ministers of the Environment Water Quality Index (WQI-CCME) is a valuable and convenient method for the analysis of water quality dataset [38]. It can be easily perceived by the local citizens, decision makers, planner, water suppliers and managers [30]. For WQI-CCME model analysis, drinking water standards of WHO 2011 are used. Five different water categories (Excellent: dark blue, Good: sky blue, Fair: green, Marginal: orange and Poor: red) are shown in the spatial distribution maps of the study area (Fig. 7a-b). According to index model outcomes of Lahore city, the groundwater samples lie between excellent to marginal classification (Fig. 8). Only 2.5% of the groundwater samples fall under excellent water category, 25% fall under good water category, 62.5% fall under fair water category and 21% in marginal water category as shown in Table 3. None of them falls under poor water category due to the installation of new pipelines and water filtration plants at various places.

Whereas in Kasur city the groundwater samples lie between good to poor classification (Fig. 8). 47.5% fall into good water category, 21% in fair water category, 21% in marginal water category, 10.5% in poor water class and none of them fall into excellent water classification (Table 3). This might be due to the dumping of untreated industrial wastewater, broken groundwater pipelines, poor sanitation system, wastewater irrigation, immoderate use of fertilizers and pesticides. Magesh et al. (2013) observe the similar pattern of good to poor water classification in Dindigul district, Tamil Nadu, India.

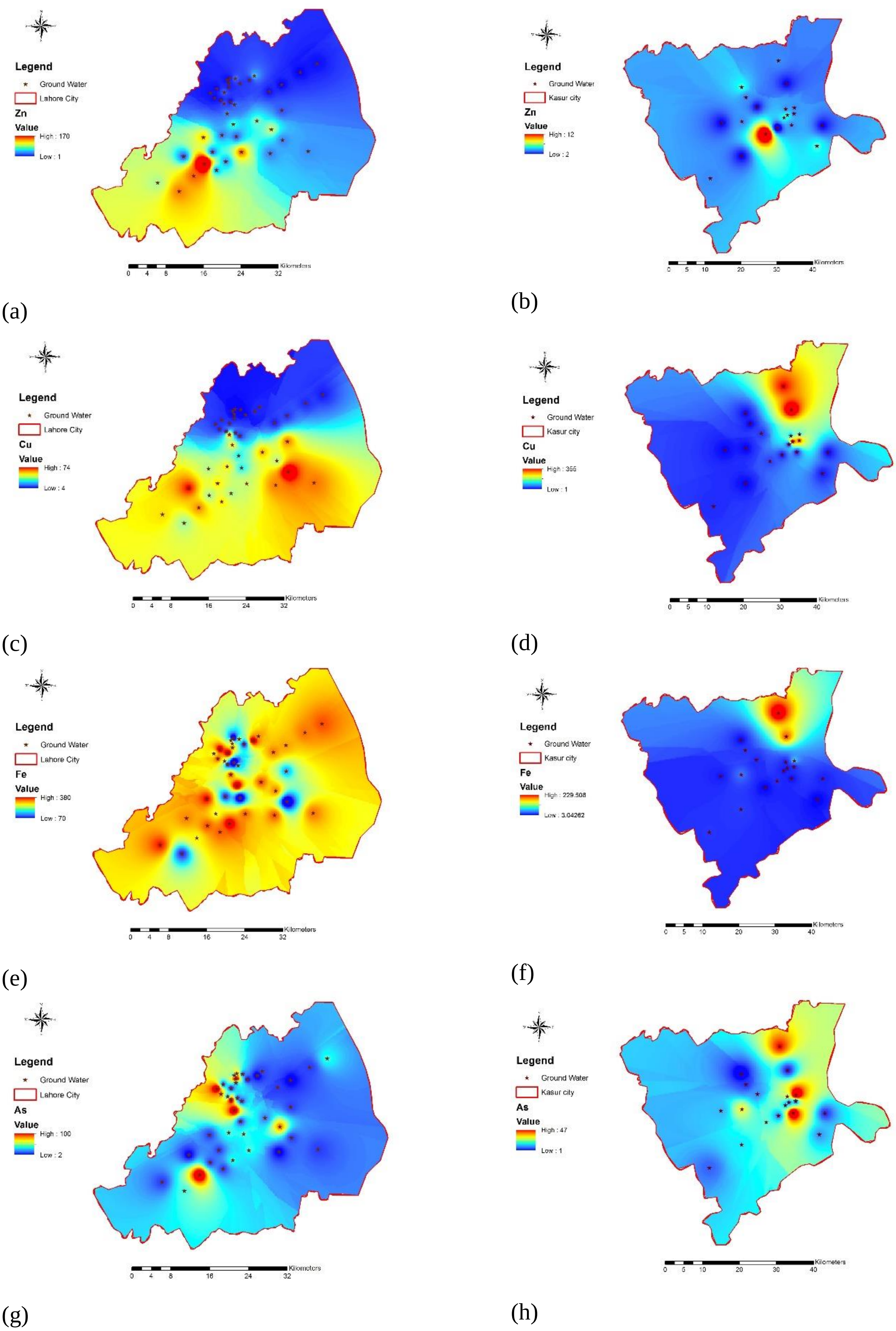
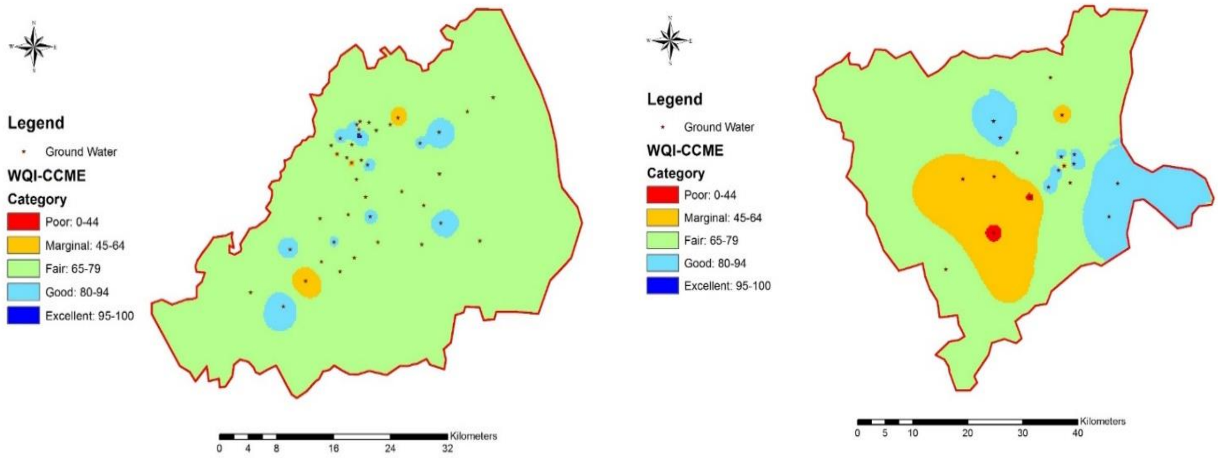


Fig. 6- Spatial distribution of heavy metals in the study area of Lahore and Kasur city



(a) (b)

Fig. 7- (a) Spatial distribution of WQI-CCME in Lahore city, (b) Spatial distribution of WQI-CCME in Kasur city

Table 3- Percentage of ground water samples with water category (WQI-CCME)

Category	**WQI-CCME**	**Sampling sites**		**%**
Excellent	95-100	*Lahore*	L6	2.5
		Kasur	none	-
Good	80-94	*Lahore*	L5, L10, L14, L18, L19, L23, L28, L32, L34, L39	25
		Kasur	K1, K2, K5, K8, K9, K12, K13, K17, K18	47.5
Fair	65-79	*Lahore*	L1, L2, L3, L4, L7, L9, L11, L12, L15, L16, L20, L21, L22, L24, L25, L26, L27, L29, L31, L33, L35, L36, L37, L38, L40	62.5
		Kasur	K4, K7, K10, K11	21
Marginal	45-64	*Lahore*	L8, L13, L17, L30	10
		Kasur	K3, K6, K14, K16	21
Poor	0-44	*Lahore*	none	-
		Kasur	K15, K19	10.5

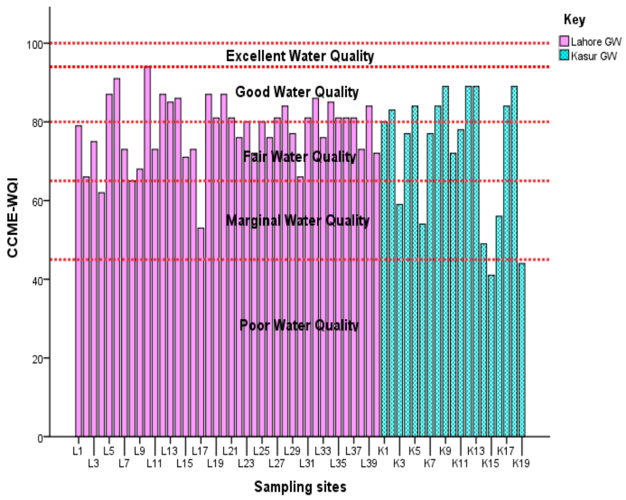


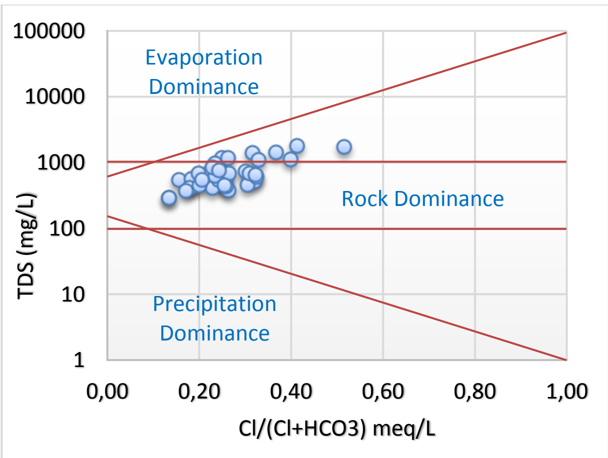
Fig. 8- Showing five categories of WQI-CCME model with ground water samples

3.4 Mechanism controlling the quality of groundwater - Gibbs Plot/Diagram

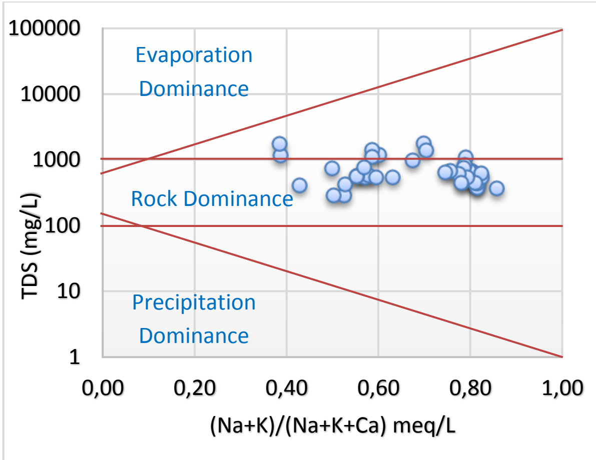
Gibbs plot is generally used to determine the hydro-geochemistry of an area. It is generally applied to determine the chemical link of water composition and its geological formation [39].

$$\text{For Anions} = {}^{Cl}\!/_{(Cl + HCO3)} \qquad \text{Gibbs I}$$

$$\text{For Cations} = {}^{(Na + K)}\!/_{(Na + K + Ca)} \qquad \text{Gibbs II}$$



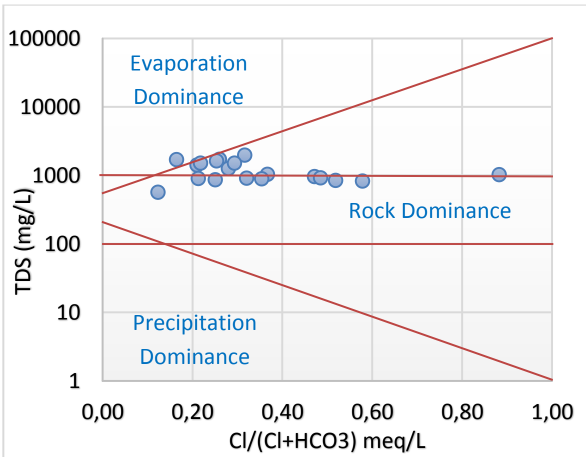
(a) Gibbs I



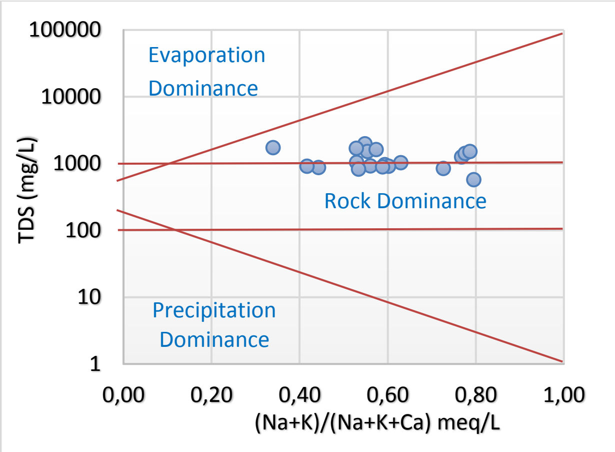
(b) Gibbs II

Fig. 9(a)(b) - Gibbs plot explaining Hydro-geochemistry of Lahore city.

Where all ions are expressed in milli-equivalent per litre (meq/L). Cations (Gibbs-I) and anions (Gibbs-II) are numerically manipulated with TDS to identify three distinct categories of groundwater controlling mechanism i.e rock-water interaction, evaporation and precipitation influence. Most of the groundwater samples of Lahore and Kasur exists in rock-water interface and evaporation dominance category as shown in (Fig. 9a-b) and (Fig. 10a-b). This clearly indicates the subsurface geochemistry of percolated water aquifers. Anthropogenic sources also add up and affect the groundwater quality by increasing Na and Cl element in the groundwater. Magesh *et al.*, (2013) determined similar patterns of silicate and carbonate mineral weathering in Dindigul district of India.



(a) Gibbs I



(b) Gibbs II

Fig. 10(a)(b) - Gibbs plot explaining Hydro-geochemistry of Kasur city

4 Conclusion

The current study reveals that the use of water quality index and GIS techniques could deliver a useful information for water quality evaluation. A thorough analysis and calculations were performed to classify and determine the hydrochemistry accountable for water quality deterioration. The groundwater exists in evaporation and rock-water interface. The pH of groundwater samples was slightly alkaline in nature which may possibly be due to the existence of HCO3 ions. The WQI-CCME revealed that the major portion of the study area falls under good to the fair category. The poor category is totally absent in Lahore city due to the installation of new tube wells at certain places. But in Kasur city, excellent water category was totally absent due to the dumping of untreated domestic and industrial waste. The curtailment of anthropogenic pollution load and pre-treatment procedure on sewage before draining into adjoining surface water channels are the right solutions to further improve and preserve the groundwater quality of Lahore and Kasur city.

References

[1] Azizullah, A., Khattak, M. N. K., Richter, P., & Häder, D.P., Water pollution in Pakistan and its impact on public health—a review, *Environment International*, Vol. 37, No. 2, 2011, pp. 479-497.

[2] Balan, I.N., Shivakumar, M., Kumar, P.M., An assessment of groundwater quality using water quality index in Chennai, Tamil Nadu, India, *Chronicles of young scientists*, Vol. 3, No. 2, 2012, pp. 146.

[3] Liu, H., Li, W., Dissolved trace elements and heavy metals from the shallow lakes in the middle and lower reaches of the Yangtze River region, China, *Environmental Earth Sciences*, Vol. 62, No. 7, 2011, pp. 1503-1511.

[4] Magesh, N., Krishnakumar, S., Chandrasekar, N., Soundranayagam, J.P., Groundwater quality assessment using WQI and GIS techniques, Dindigul district, Tamil Nadu, India, *Arabian Journal of Geosciences* Vol. 6, No. 11, 2013, pp. 4179-4189.

[5] Pei-Yue, L., Hui, Q., Jian-Hua, W., Groundwater quality assessment based on improved water quality index in Pengyang County, Ningxia, Northwest China, *Journal of Chemistry*, Vol. 7, No. S1, 2010, pp. S209-S216.

[6] Ramakrishnaiah, C., Sadashivaiah, C., Ranganna, G., Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India, *Journal of Chemistry*, Vol. 6, No. 2, 2009, pp. 523-530.

[7] Semiromi, F.B., Hassani, A., Torabian, A., Karbassi, A., Lotfi, F.H., Water quality index development using fuzzy logic: A case study of the Karoon River of Iran, *African Journal of Biotechnology*, Vol. 10, No. 50, 2011, pp. 10125-10133.

[8] Logeshkumaran, A., Magesh, N., Godson, P.S., Chandrasekar, N., Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India, *Applied Water Science*, Vol. 5, No. 4, 2015, pp. 335-343.

[9] Falkenmark, M., Rockström, J., *Balancing water for humans and nature: the new approach in ecohydrology*, Earthscan, 2004.

[10] Akram, A.A., Olmstead, S.M., The value of household water service quality in Lahore, Pakistan, *Environmental and Resource Economics*, Vol. 49, No. 2, 2011, pp. 173-198.

[11] Qadir, M., Wichelns, D., Raschid-Sally, L., Minhas, P.S., Drechsel, P., Bahri, A., McCornick, P.G., Abaidoo, R., Attia, F., El-Guindy, S., Agricultural use of marginal-

quality water: opportunities and challenges, 2007.

[12] WWF, Hudaira Drain Pollution Control: A Prefeasibility Study. In. Lahore, (2007).

[13] Khattak, M.A., Ahmed, N., Qazi, M.A., Izhar, A., Ilyas, S., Chaudhary, M., Khan, M., Iqbal, N., Waheed, T., Evaluation of ground water quality for irrigation and drinking purposes of the areas adjacent to Hudiara industrial drain, Lahore, Pakistan, *Pak J Agri Sci*, Vol. 49, No. 4, 2012, pp. 549-556.

[14] Rana, I.A., Bhatti, S.S., Lahore, Pakistan–Urbanization challenges and opportunities, *Cities*, 2017.

[15] Shirazi, S.A., Kazmi, S.J.H., Analysis of population growth and urban development in Lahore-Pakistan using geospatial techniques: Suggesting some future options, *South Asian Studies*, Vol. 29, No. 1, 2014, pp. 269.

[16] WASA, Presentation on the Initiative Taken in WASA Lahore Regarding Benchmarking of UWSS, Water and Sanitation Agency, 2007.

[17] Afzal, M., Shabir, G., Iqbal, S., Mustafa, T., Khan, Q.M., Khalid, Z.M., Assessment of heavy metal contamination in soil and groundwater at leather industrial area of Kasur, Pakistan, *CLEAN–Soil, Air, Water*, Vol. 42, No. 8, 2014, pp. 1133-1139.

[18] Ashraf, M.A., Maah, M.J., Yusoff, I., Mehmood, K., Effects of polluted water irrigation on environment and health of people in Jamber, District Kasur, Pakistan, *International Journal of Basic & Applied Sciences*, Vol. 10, No. 3, 2010, pp. 37-57.

[19] Rashid, H., Takemura, J., Farooqi, A., Soil Explorations and Groundwater Monitoring to Evaluate Subsurface Contamination Due to Chromium in District Kasur, Pakistan, *Journal of Environmental Science and Engineering*, Vol. 5, No. 7, 2011.

[20] APHA/AWWA/WEF, Standard Methods for the Examination of Water and Wastewater, American Public Health Association Washinton D.C., USA, 2006.

[21] Lenntech, B.V., Water treatment solutions: water hardness calculator, 2012.

[22] WHO, Guidelines for drinking-water quality. Geneva: World Health Organization, 2011.

[23] ESRI, ArcGIS 10.1., Environmental Systems Research Institute Redlands, USA, 2012.

[24] Keskin, M., Dogru, A.O., Balcik, F.B., Goksel, C., Ulugtekin, N., Sozen, S., *Energy Systems and Management*, Springer, 2015.

[25] Rühaak, W., A Java application for quality weighted 3-d interpolation, *Computers & geosciences*, Vol. 32, No. 1, 2006, pp. 43-51.

[26] Shepard, D., *A two-dimensional interpolation function for irregularly-spaced data.* Proceedings of the 1968 23rd ACM national conference, January, pp. 517-524, 1968.

[27] CCME, Canadian Water Quality Guidelines for the Protection of Aquatic Life: Canadian Council of Ministers of the Environment Water Quality Index. Winnipeg, 2001.

[28] Azeez, P., Nadarajan, N., Mittal, D., The impact of a monsoonal wetland on ground water chemistry, *Pollution Research*, Vol. 19, No. 2, 2000, pp. 249-255.

[29] Copes, R., Hrudey, S.E., Payment, P., Act, D.W., Turbidity and microbial risk in drinking water, Prepared for The Minister of Health, Province of British Columbia, pursuant to Section 5, 2008.

[30] Damo, R., Icka, P., Evaluation of water quality index for drinking water, *Polish Journal of Environmental Studies*, Vol. 22, No. 4, 2013, pp. 1045-1051.

[31] Venkatramanan, S., Chung, S., Ramkumar, T., Rajesh, R., Gnanachandrasamy, G., Assessment of groundwater quality using GIS and CCME WQI techniques: a case study of Thiruthuraipoondi city in Cauvery deltaic region, Tamil Nadu, India, *Desalination and Water Treatment*, Vol. 57, No. 26, 2016, pp. 12058-12073.

[32] Magesh, N., Chandrasekar, N., Evaluation of spatial variations in groundwater quality by WQI and GIS technique: a case study of Virudunagar District, Tamil Nadu, India, *Arabian journal of Geosciences*, Vol. 6, No. 6, 2013, pp. 1883-1898.

[33] Selvam, S., Manimaran, G., Sivasubramanian, P., Balasubramanian, N., Seshunarayana, T., GIS-based evaluation of water quality index of groundwater resources around Tuticorin coastal city,

South India, *Environmental earth sciences*, Vol. 71, No. 6, 2014, pp. 2847-2867.

[34] WHO, Potassium in drinking-water: background document for development of WHO guidelines for drinking-water quality, 2009.

[35] Stumm, W., Morgan, J.J., *Aquatic chemistry: chemical equilibria and rates in natural waters*, John Wiley & Sons, 2012.

[36] Farooqi, A., Masuda, H., Firdous, N., Toxic fluoride and arsenic contaminated groundwater in the Lahore and Kasur districts, Punjab, Pakistan and possible contaminant sources, *Environmental Pollution*, Vol. 145, No. 3, 2007, pp. 839-849.

[37] Muhammad, S., Shah, M.T., Khan, S., Arsenic health risk assessment in drinking water and source apportionment using multivariate statistical techniques in Kohistan region, northern Pakistan, *Food and Chemical Toxicology*, Vol. 48, No. 10, 2010, pp. 2855-2864.

[38] Lumb, A., Halliwell, D., Sharma, T., Application of CCME Water Quality Index to monitor water quality: A case study of the Mackenzie River basin, Canada, *Environmental Monitoring and Assessment*, Vol. 113, 2006, pp. 411-429.

[39] Gibbs, R.J., Mechanisms controlling world water chemistry, *Science*, Vol. 170, No. 3962, 1970, pp. 1088-1090.