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Natural and Anthropogenic Sources of Groundwater Salinization in Parts of Karachi, Pakistan

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Abstract: This study is aimed to evaluate the groundwater quality of Gulshan-e-Iqbal and Liaquatabad towns in Karachi. Thirty (n=30) groundwater samples were randomly collected from different locations by electrically pumped wells at various depths (14-91m). All the water samples were analyzed to determine their suitability for drinking purpose based on various physicochemical parameters. Data reveal that high concentration of TDS and hardness have deteriorated the groundwater quality of study area. The main phenomenon responsible for groundwater pollution is the seawater intrusion due to the proximity of study area to the Arabian sea. Large scale unplanned urbanization, poor waste management and other anthropogenic activities have also triggered the deterioration of groundwater quality. Study showed that local geology plays vital role in the distribution of major cations and anions. Data suggested that ground water of this study area is highly contaminated by seawater intrusion and considered not fit for drinking purpose.

Keywords: Groundwater quality, Karachi, sewerage contamination, drinking purpose, seawater intrusion.

Introduction

In arid and semi-arid regions of the world, groundwater is one of the most important natural resources necessary for human consumption, domestic services, agriculture, industry, manufacturing and other sectors (Papaioannou et al., 2010; Chae et al., 2004). Safe drinking water is the primary need of every human being. However rapid increase in world's population, supply of safe drinking water has become a great concern. In Pakistan, groundwater is considered as the major source of drinking water and 60% population of Pakistan depends on ground water for drinking and domestic purposes (Khattak et al., 2013). In Sindh province of Pakistan, 44% of the population lack access to safe drinking water (PCRWR, 2010; Alamgir et al., 2016). Due to inappropriate management, unlined sanitation, agricultural activities, seawater intrusion, over pumping and water logging, groundwater quality of Sindh has been continuously deteriorating. As a result, the local population is directly exposed to waterborne diseases (PCRWR, 2012; Bano et al., 2016; Bhowmik et al., 2015; Abbasi et al., 2015).

Karachi is one of the biggest metropolitan cities of Pakistan, with a population of over 16 million (KSDP, 2007). Municipal water for domestic use in Karachi is supplied from Keenjhar and Hub lakes for only a few hours per week through a faulty and leaky distribution system. Karachi Bulk Water Supply Scheme was designed in 1953, which is comprised of open canals, covered conduits, a tunnel, siphons, pumping stations, and water supply mains. Leakages in water supply mains, infiltration of sewerage water from adjacent broken sewerage lines during non-supply hours, installation of un-authorized suction pumps on water mains and sub-standard construction of household water storage tanks have resulted in highly polluted municipal supply water.

In Karachi, rapid increase in population and industrial activities have resulted in the shortage of water, which forced people to meet their requirements from ground water sources. Therefore, a large population in Karachi consumes groundwater for drinking purpose without any treatment. In addition, over extraction of groundwater and scarcity of seasonal rainfall triggers the lowering of groundwater table. As a result, groundwater resources in Karachi are depleting rapidly. Other factors such as seepage from sewerage line (JICA, 2007), unchecked dumping of liquid and solid waste and sea water intrusion are also responsible for groundwater quality degradation (Zaigham, 2004).

Geochemical evaluation of groundwater better identifies factors responsible for variations in water quality and determining its suitability for drinking purpose. Aquifers in the coastal areas need particular focus, where several geochemical and anthropogenic processes like seawater intrusion, cation exchange, high evaporation rate, climate change, water rock interaction, over extraction, landfills and mixing of sewage and groundwater can lead to high salinization. Preliminarily work (Naseem et al., 2003; Alamgir et al., 2016; Khan et al., 2018; Mashiatullah et al., 2002) suggested that groundwater resources in Karachi have been worsening due to improper waste management, seepage from industrial and domestic effluent and unplanned urbanization etc. However, these studies lack geochemical explanation of various constituents in the groundwater. Therefore, current study focuses on the geochemical evaluation of groundwater quality in densely populated Gulshan-e-Iqbal and Liaquatabad towns of Karachi. These areas are and have been facing worst shortage of municipally supplied water and people rely on groundwater to meet their daily requirements.

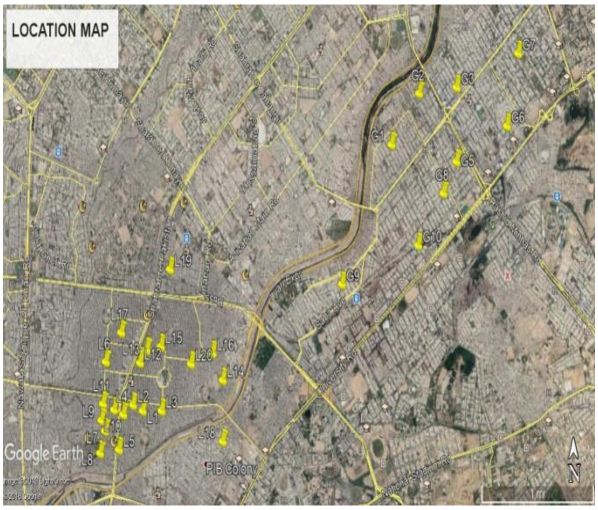

Fig. 1 Location map, showing groundwater sampling points.

Materials and Methods

Thirty groundwater samples were taken for their physicochemical characteristics. Twenty samples from different locations of Liaquatabad and 10 samples from Gulshan-e-Iqbal were randomly collected. Global Positioning System (GPS) was used to determine location of each well (Fig. 1). The well depth ranges from 14-91m which was noted from the record obtained from the well owner. Each sample was collected in two bottles of 1-liter and 100 ml capacities respectively. Sample bottles were properly washed and rinsed thoroughly with distilled water and then with groundwater at sampling site. Further, 1 ml boric acid was added in 100 ml bottle to preserve the sample for nitrate analysis while 1-liter bottle was used for further physicochemical analysis. Highly variable parameters including pH, electrical conductivity and temperature were determined just after the collection of samples at sampling site. Electrical conductivity and pH were measured by using EC meter (AD 330) and pH meter (AD 111) respectively. Whereas, other chemical parameters were estimated in laboratory. Sodium and potassium were determined by using flame photometer (JENWAY EFP7). Calcium and magnesium contents were measured by adopting EDTA titration standard method (1992). Chloride concentration of each sample was determined by argentometric titration method. Sulphate was analyzed by using gravimetric method and standard titration method (1992) was also adopted for bicarbonate determination.

Study Area Description

Gulshan-e-Iqbal and Liaquatabad are two adjacent towns of Karachi approximately 19 km away from the coast line of Arabian Sea. Gulshan-e-Iqbal town lies in the east of Karachi at 24.865N-24.963 N latitude, 67.084 E-67.113 E longitude and covers an area of approximately 65 sq.km. Whereas, Liaquatabad town is located in the middle of Karachi at 24.8880°-24.9223° N latitude, 67.0177°-67.0644° E longitude with an average area of 11 sq. km (Fig. 2).

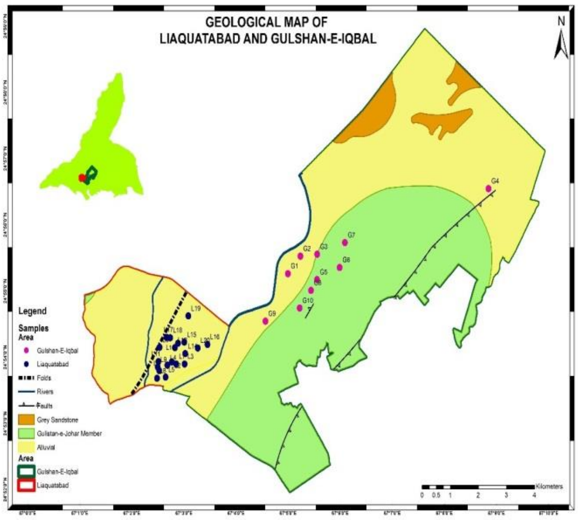

Fig. 2 Geological map of the study area.

Both Gulshan-e-Iqbal and Liaquatabad towns are densely populated and according to census 2017, have population about 644,362 and 448,484 respectively. The study area is bounded by Gadap town to the north, the Faisal and Malir cantonments to the east Liyari river to the south and Orangi drain to the west (Fig. 2). Geo-morphologically, Karachi comprises of mountainous highland, alluvial plain and coastal belt of Arabian sea. Elevation in the area ranges from 1.5 to 76 m. The climate of the study area is semi-arid to arid with low (174 mm) annual precipitation. In summer, temperature generally ranges from 30^{o}C to 36^{o}C, while in winter, average temperature falls between 10^{o} C to 21^{o} C (WMO 2014). The rock formations in the study area belong to Tertiary period and are overlain by deposits of Recent alluvium (Holocene) and sub Recent alluvium (Pleistocene). Alluvium overlies the Gaj Formation of Miocene age. The only exposed rocks in the area is Gaj Formation, which comprises of massive limestone, alternating with fine grained sandstone and conglomerate (Shah, 1977). While, rest of the area is covered by Recent to sub-Recent alluvium deposits, which mainly consist of sand, silt, and clay. The consistency of the sub Recent deposits is relatively more dense, compact and harder than top alluvium. The alluvium deposits are generally 2-25 m deep in Karachi (JICA 2013). Gaj Formation has approximately 50 m thickness and lies over the Nari Formation of Oligocene age (Shah 2009). Nari Formation consists of sandstone, shale, and subordinate limestone (Shah, 1977).

Table 1. Phsyico-Chemical parameters determined in groundwater of study area.

S. No.	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	Cl (ppm)	HCO3 (ppm)	SO_4 (ppm)	NO_3 (ppm)	pH	TDS (mg/L)
WHO Standard	75 (mg/L)	150 (mg/L)	200 (mg/L)	12(mg/L)	250 (mg/L)	300 (mg/L)	250 (mg/L)	10 (mg/L)	6.5-7.5	1000 mg/L
G1	147	70	535	7.6	1070	350	118	4.104	7.08	2380
G2	68	32	390	5.2	498	360	152	5.076	7.21	1664
G3	92	49	124	10.7	248	340	150	6.621	6.95	1106
G4	96	44	133	6.2	267	300	168	3.071	6.95	1106
G5	88	51	130	3.5	260	270	136	4.946	7.07	1022
G6	84	63	126	4.2	253	310	162	13.092	6.95	1131
G7	128	62	1860	15.2	3085	490	755	4.825	6.89	7475
G8	68	58	978	8.3	1099	450	405	14.04	7.31	3315
G9	152	66	190	37.6	371	490	285	14.315	6.73	1850
G10	88	75	175	2.4	341	440	171	25.06	6.75	1517
L1	55	40	38	38	58	320	142	11	7.5	695
L2	80	76	45	45	109	280	191	7.23	7.7	803
L3	92	68	42	42	178	350	52	7.996	7.39	862
L4	100	121	28	28	145	600	109	14.7	7.6	1138
L5	52	65	16	16	91	300	71	8.72	7.5	651
L6	44	68	85	85	198	400	55	7.29	8.02	875
L7	28	64	72	72	149	385	46	6.81	7.4	797
L8	98	76	105	105	231	423	52	8.1	7.2	1045
L9	56	78	34	34	157	303	51	8.77	7.8	720
L10	61.5	31	21	21	104	230	91	0.5	7.5	555
L11	89	28	98	98	106	402	164	7.96	7.5	910
L12	108	96	24	24	109	690	101	8.66	7.1	1219
L13	124	86	24	24	142	610	66	6.69	7.32	1180
L14	68	130	49	49	63	730	98	7.21	7.6	1208
L15	125	16	116	116	210	310	110	8.29	7.13	1080
L16	62	111	33	33	93	510	143	7.74	7.5	986
L17	52	36	90	90	132	310	142	9.21	7.6	793
L18	41	157	32	32	104	750	102	8.38	7.1	1156
L19	32	71	37	37	135	278	57	6.71	7.7	680
L20	37	65	61	61	114	550	32	7.29	7.4	900
Min	28	16	16	2.4	58	230	32	0.5	6.73	555
Max	152	157	1860	116	3085	750	755	25.06	8.02	7475
Mean	80.52	68.43	189.70	38.36	337.33	417.70	145.90	8.48	7.32	1360.63

Rainfall, seawater intrusion, and non-perennial Lyari and Malir rivers and their tributaries are major sources of aquifer recharge in Karachi city. Shallow wells (<14 m is installed in Holocene aquifers, while most of the groundwater is extracted from the aquifers of Gaj Formation at average depth of 40 m. There are few deeper wells (>50m) tap aquifers of Nari Formation.

Results and Discussion

The physicochemical parameters in groundwater samples (n=30) collected from both towns were studied for color, pH and turbidity. Most of all the samples were colorless and only three samples were found slightly yellow in color. In the analyzed samples, pH of all samples is within the circumneutral range and varies from 6.73-8.02 with the mean of 7.31 (Table 1). Concentration of Total Dissolved Solids in water samples is much higher than the prescribed limit of WHO guideline (<1000 mg/L). Gulshan-e-Iqbal town has much higher TDS concentration (Mean=2256 mg/L) than Liaquatabad town (Mean=912 mg/L). Total hardness ranges between 205-1590 mg/L with an average of 536 mg/L and around 74% of the samples are above the prescribed WHO limit (500mg/L). All the samples having hardness (>180mg/L) fall in the category of very hard water. Calcium concentration varies between 28-152mg/L with a mean of 81 mg/L.

About 36% of the total samples have calcium concentration within the WHO limit (75mg/L). Magnesium concentration ranges from 16 to 157 mg/L with an average of 68 mg/L. All the samples fall within the WHO guideline (150 mg/L). Data reveal that the normal trend of relative high concentration of calcium over magnesium depends on the solubility of ions (Ca>Mg). It is likely that Ca and Mg in the groundwater could be associated with calcareous soil and limestone in subsurface (Naseem et al., 2003). Majority of samples (n=20) have the Ca/Mg ratio (>1), also indicating the dominance of calcite over dolomite dissolution in the aquifer (Mayo et al., 1995). While in the rest of the samples, adsorption of calcium on clay lattices and release of magnesium to groundwater can lead to an increase in Mg content in groundwater.

Sodium content is highly variable in the study area and ranges between 16-1860 mg/L. Except very few samples (n=4), all the samples lie within the desirable limit of WHO (200 mg/L). In addition, chloride concentration varies from 58 to 3085 mg/L and 33% of samples exceed the permissible limit of WHO (250 mg/L). Evaporite dissolution, subsurface salt domes, and intrusion of brackish or seawater could be the source of high Cl content (Lorenzen et al., 2012; Appelo and Willemsen, 1987). Elevated Na and Cl concentrations may be due to proximity of study area to the Arabian sea and active and ancient seawater intrusion may increase the Na content in the groundwater. Chloride behaves conservatively and could be helpful to identify different water types and their sources, mobility of solutes and contaminants in subsurface (Giambastiani et al., 2012). Low Na/Cl molar ratio (<0.86) and high Ca/Mg ratio are indication of seawater intrusion. The Na/Cl (<1.0) ratio of all water samples (n=30) is < 0.89, suggesting that groundwater of study area is affected by sea water intrusion (Table 2).

Table 2. Relation between groundwater parameters.

S. No.	Lattitude	Longitude	Cl/HCO_3	Na/Cl	Ca/Mg
G1	24.8983	67.0475	3.06	0.50	2.1
G2	24.8988	67.0461	1.38	0.78	2.13
G3	24.8983	67.0502	0.73	0.50	1.88
G4	24.898	67.0447	0.89	0.50	2.18
G5	24.8950	67.0441	0.96	0.50	1.73
G6	24.9025	67.0422	0.82	0.50	1.33
G7	24.8966	67.0421	6.30	0.60	2.06
G8	24.8947	67.0414	2.44	0.89	1.17
G9	24.8975	67.0416	0.76	0.51	2.30
G10	24.8984	67.0434	0.78	0.51	1.17
L1	24.8989	67.0418	0.66	0.18	1.38
L2	24.9024	67.0471	0.41	0.39	1.05
L3	24.9035	67.0481	0.24	0.51	1.35
L4	24.9009	67.0504	0.19	0.24	0.83
L5	24.9038	67.0501	0.18	0.30	0.80
L6	24.9032	67.0575	0.43	0.50	0.65
L7	24.9050	67.0444	0.48	0.39	0.44
L8	24.9049	67.0456	0.45	0.55	1.29
L9	24.9104	67.0514	0.22	0.52	0.72
L10	24.9023	67.0544	0.20	0.45	1.98
L11	24.92103	67.08325	0.92	0.26	3.18
L12	24.92544	67.08724	0.22	0.16	1.13
L13	24.92593	67.09263	0.17	0.23	1.44
L14	24.94245	67.14746	0.78	0.09	0.52
L15	24.91953	67.09256	0.55	0.68	7.81
L16	24.92258	67.09982	0.35	0.18	0.56
L17	24.92885	67.1015	0.68	0.43	1.44
L18	24.91683	67.09066	0.31	0.14	0.26
L19	24.90906	67.07606	0.27	0.49	0.45
L20	24.91237	67.08701	0.54	0.21	0.57

Similarly, Ca/Mg ratio ranges from 1.17 to 2.30 also indicate strong influence of seawater intrusion in the aquifers of study area. Seawater intrusion is also determined by using Cl/HCO_3 (El Moujabber et al., 2006). Apart from four, remaining samples have Cl/HCO_3 ratio <1, suggesting severe groundwater contamination by sea water (Toth, 1999). Rock mineralogy and weathering rate are other factors that could control aquifer hydrogeochemistry. Bicarbonate content varies widely between 230-750 mg/L with a mean of 418 mg/L. Apart from 6% of the samples, the rest of the samples exceed the limit (>300 mg/L). Strong correlation (r=0.76) between HCO_3 and Mg reflects that groundwater is interacting with the limestone units of aquifer matrix and results in calcite dissolution (Fig. 3). Low pH (<8) also plays a vital role in calcite dissolution. In the analyzed samples, pH is circumneutral (6.5-8.5), which means that it is supporting the dissolution process. Chloride shows strong positive correlation with Na and SO_4 (r=0.98 and r=0.89) respectively, suggesting that these ions were derived from the same source of seawater (Fig. 3).

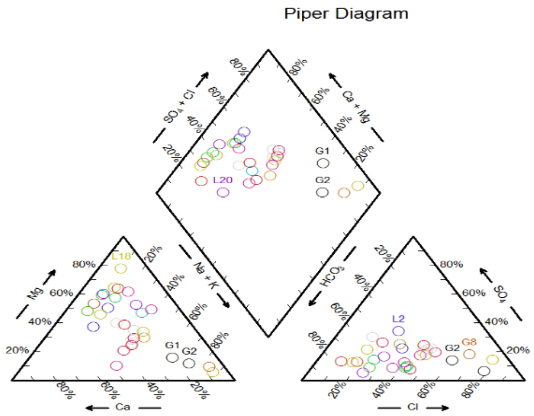

Fig. 3a Piper diagram showing main hydrofacies types.

In coastal aquifers, seawater intrusion and ion exchange are important mechanisms of groundwater quality modification (Andersen et al, 2005; Appelo and Postma, 2010; Daniele et al., 2011). Clays and organic matter act as expected ion exchanger (Giambastiani et al., 2012). Thus in the study area, seawater intrusion and later on its interaction with aquifer material plays a vital role for an increasing groundwater salinity of study area.

Nitrate concentration in the study area ranges from 0.5-25.06 mg/L and only 13% of samples exceed the recommended value of WHO (<10 mg/L). While the rest of the samples have NO_3 concentration far below the recommended limit of WHO. This extremely low concentration of NO_3 could be associated with the presence of nitrate reducing bacteria in the subsurface or denitrification (Vazquez et al., 2005) as it is indicated by low concentration of NO_3 as compared to HCO_3 in the groundwater. Elevated NO_3 content in rest of the samples may be associated with sewerage contamination, because these samples were taken from shallow wells (<14m). Nitrate shows positive correlation (0.20) with HCO_3, while Ca and Mg confirms anthropogenic sources responsible for groundwater pollution (Devendra et al., 2016). The leakage from broken sewerage lines and percolation of liquid domestic waste in subsurface water and mixing with groundwater is quite common.

Potassium concentration varies between 2.5-116 mg/L and around 75% of the samples show elevated potassium concentration compared with WHO limit (12 mg/L). Main sources of K are the clayey units of Gaj Formation of Miocene age, which is widely distributed in the study area. The clay of upper Gaj member in the aquifer sediments is considered as a source of high potassium content in groundwater.

Table 3. Correlation between elements.

	TDS	Ca	Mg	Na	K	Cl	HCO_3	SO4	NO_3
TDS	1	0.42	-0.10	0.98	-0.27	0.98	0.18	0.92	-0.01
Ca		1.00	-0.10	0.33	-0.14	0.39	0.10	0.38	0.07
Mg			1.00	0.15	-0.17	-0.11	0.77	-0.13	0.20
Na				1.00	-0.26	0.98	0.04	0.91	-0.05
K					1.00	-0.27	0.00	-0.28	-0.08
Cl						1.00	0.04	0.89	-0.09
HCO_3							1.00	0.06	0.21
SO_4								1.00	0.08
NO_3									1

In the study area, sulphate varies between 32-755 mg/L with a mean of 146 mg/L. Except very few samples (n=3), the rest of the samples have sulfate content within the prescribed limit of WHO (250 mg/L). Weak positive correlation (0.43) is observed between Ca and SO_4, indicating that gypsum may be partly responsible for high SO_4 content in groundwater. Possibly SO_4 could be associated with marine sources, because SO_4 is the second abundant ion in seawater. Thus, sea water intrusion could be a contributing factor for the rise of SO_4 in the groundwater. There is no significant correlation between NO_3 and SO_4, which indicates that anthropogenic pollution is not responsible for increased SO_4 content in the aquifers. Correlation between TDS and pH is -0.40, which shows that the mineral dissolution is predominant in the area (Table 3). Gaj Formation (Miocene) consists of massive limestone with alternating dolomitic limestone, which could be the source of high Mg content in the aquifers of the study area. Thus, semi-arid climate, high evaporation rate and low precipitation, anthropogenic activities also contribute to increased salinity of groundwater of the study area.

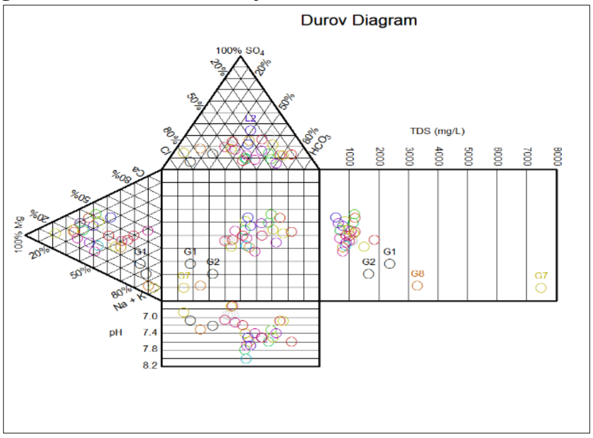

Fig. 3b Durov diagram showing groundwater major composition.

Several geochemical criteria can be used to decipher the seawater intrusion and origin of high salinity of aquifers. Graph plots of (Ca+Mg) vs (HCO_3+SO_4) are used as an indicator of groundwater mineralization (Datta and Tyagi, 1996) Data points fall above the 1:1 equiline which is due to carbonate weathering, while points below the equiline are associated with the silicate weathering in aquifers. Approximately, all the samples are above the 1:1 equiline, representing that carbonate weathering is a dominant phenomenon in the aquifer of study area (Fig. 4). Elevated concentration of Ca+Mg over HCO_3+SO_4 reflects the reverse ion exchange process in groundwater as a result of seawater intrusion (Wanda et al., 2011; Nasher et al., 2013). Cation exchange phenomenon under the influence of seawater intrusion is also evidenced by negative correlation (-0.4) among (Ca+Mg)-(SO_4+HCO_3) and (Na+K)-Cl.

The subsurface hydrogeochemical processes of rock-water interaction, evaporation and precipitation are better explained by the Gibbs diagram, which is plotted among TDS vs Na/(Na+Ca) and TDS vs Cl/(Cl+HCO_3) for cations and anions respectively. Gibbs plot reveals that groundwater of study area is highly influenced by rock water interaction and evaporation, as all the samples lie above the line of rock-water interaction in the zone of evaporation (Fig 3a, Fig 3b).

Hydrochemical Facies

Lithology, residence time and regional flow pattern of groundwater play important role in the evolution of hydrofacies (Jamshidzadeh and Mirbagheri, 2011). To evaluate the dominant groundwater types in the study area, piper and Durov diagrams were used. Analyzed groundwater quality data were plotted on the Piper diagram (Fig. 3a) which shows the relative concentrations of major cations and anions (Piper, 1944) and provides better explanation regarding groundwater interaction with aquifer matrix. On the basis of piper classification, all the samples of Gulshan-e-Iqbal town belong to Na-Cl water type. As Na-Cl facies is an indicator of seawater intrusion and ion exchange phenomenon in aquifer. In the study area, clay is widespread in subsurface as part of Gaj Formation. Thus, when seawater passes through these clayey layers, ion exchange phenomenon may take place, which results in Na-Cl hydrofacies (Al Farrah et al., 2011). In Liaquatabad town almost 70% of samples show dominance of Mg-HCO_3 facies, which shows the leading edge of seawater intrusion in shallow unconfined aquifers (Younger, 2009). While rest of the samples (30%) represent mixed water type. Moreover, the mixed type of hydrofacies in Liaquatabad town is also supported by Durov diagram (Fig. 3b). This mixed water type of hydrofacies might be due to recent recharge of groundwater, which exhibit simple mixing with no major dominant ion (Ravikumar et al., 2015).

Conclusion

- High salinity in the groundwater of Gulshan-e-Iqbal and Liaquatabad towns make this water unsatisfactory for drinking purpose.
- Multivariate statistical analyses show that groundwater of study area has high concentration of TDS, hardness, sodium and chloride, which seem to be originated from marine sources.
- Groundwater quality in most of aquifers is deteriorating by seawater intrusion, high evaporation and low annual precipitation rate.

- Shallow wells (>14m) are contaminated by seepage from sewerage lines, as indicated by high nitrate concentration in few water samples.
- Anthropogenic activities such as over pumping, insufficient sewerage management and dumping of waste are also responsible for poor groundwater quality.
- In the study area, semi arid climate, high evaporation rate, low groundwater recharge due to drought and seawater intrusion seem to be active and dominant along with anthropogenic activities to raise the salinity of Karachi groundwater.

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