Journal of Geoscience and Environment Protection, 2017, 5, 88-98
http://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Groundwater Quality Assessment Based on WQI and Its Vulnerability to Saltwater Intrusion in a Coastal City, Iran

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How to cite this paper: Tavassoli, S. and Mohammadi, F. (2017) Groundwater Quality Assessment Based on WQI and Its Vulnerability to Saltwater Intrusion in a Coastal City, Iran. *Journal of Geoscience and Environment Protection*, **5**, 88-98.
https://doi.org/10.4236/gep.2017.56010

Received: April 21, 2017
Accepted: June 11, 2017
Published: June 14, 2017

Abstract

The purpose of this paper was to assess the quality of groundwater in Behshahr (Iran) based on water quality index (WQI). Sixteen water samples from this coastal aquifer were collected and analyzed to study physico-chemical parameters such as pH, hardness, chloride (Cl), electrical conductivity (EC) and total dissolved solids (TDS). The results showed that the annual average of TDS value increased by 343 mg/l between 1999 and 2015 due to anthropogenic activities. According to WQI, it was concluded that the groundwater quality degraded over the last sixteen-year period so that the percentage of samples identified as "good water" decreased by 18.5% and on the other hand, alas, the percentage of "poor water" quality soared by nearly 12.5%. Correspondence of WQI distribution diagram with that of chloride-bicarbonate ratio attests to the significant contribution of saltwater intrusion to groundwater quality deterioration in this area.

Keywords

Groundwater Quality, Water Quality Index, Physico-Chemical Parameters, Saltwater Intrusion, Coastal Aquifers

1. Introduction

As demand for freshwater soars and its supplies dwindle, the world water crisis is becoming an enormous challenge. If remaining unsolved, this problem may have catastrophic consequences for humans and wildlife alike. Meanwhile, groundwater which plays a vital role in water supply in innumerable areas has been exploited during last decades. Groundwater pollution, thereupon, has become an acute problem that if thrust aside will escalate to a point of no return. A precise assessment of groundwater quality is required to devise a strategy to tackle the issue.

Processes governing groundwater quality are divided into two main categories: anthropogenic and natural factors each of which comprises their own distinctive effects. From anthropogenic perspective, fundamental causes of groundwater pollution are leaked sewage, seawater intrusion, industrial wastewater and fertilizer. Natural causes, on the other hand, encompass geology and geochemical processes, weathering, precipitation, temperature etc [1] [2] [3].

One of the most prevalent threats of groundwater quality deterioration in coastal aquifers is chloride contamination which for the most part occurs due to saltwater intrusion. Pumping from underground resources is the predominant cause of saltwater intrusion in coastal aquifers. It can reduce freshwater flow toward coastal discharge areas and cause saltwater to be drawn toward the freshwater zones of the aquifer. Saltwater intrusion decreases freshwater storage in the aquifers, and, in extreme cases, can result in the abandonment of supply wells [4]. Furthermore, high concentrations of chloride have adverse effects on human health, crops productivity, soil permeability, and durability of equipment used in water distribution systems [5].

It is noteworthy that retrieving the water quality is burdensome and costly once it is polluted especially by saltwater. Regular monitoring of the quality of groundwater, hence, appears to be essential [6].

The importance of groundwater monitoring and the complexity associated with numerous methods reveals the necessity of a simple yet accurate technique for evaluating groundwater quality. Traditional practices mostly include reports with a lot of details about variables and their compliance with official guidelines; however, in many cases, managers and the general public have no tendency to study accurate reports. Summarizing complex water quality data in an exoteric parameter is possible by means of Water quality index (WQI). WQI was first expressed by Horton and later developed in many papers on the water quality monitoring of all around the world [7] [8] [9] [10] [11]. This method has been recognized as a measure that indicates the complex effect of several variables on the overall water quality rating [12].

Since no study has been conducted in this area for groundwater resources, the main objective of this paper is to find the baseline groundwater quality of this region based on WQI and its relevancy to chloride contamination.

2. Material and Method

Behshahr is a coastal city in the east of Mazandaran province, Iran. This city is Located on the south coast of the Gorgan gulf (Caspian Sea) at the foot of the Alborz Mountain. The average elevation of the city is about 20 m above mean sea level also its area is approximately 940 km^2 and has a population of 31,875.

In order to assess groundwater quality, 16 groundwater samples were collected in this study area. For each sample, quality parameters such as pH, TDS, EC, Total hardness, major cations and major anions were measured through the APHA standard methods. The analytical results in 1999 and 2015 are represented in Table 1 and Table 2 respectively. The location of sampling wells which are recorded in the Universal Transverse Mercator (UTM) coordinate system is shown in Figure 1 as well.

Being a convenient method to appraise and present water quality for drinking, WQI method was applied to combine and summarize different parameters measured for each sample. This method considers the effect of various water quality parameters on human health. Following four simple steps describe the calculation of WQI [13] [14]:

1) Assigning weight (w_i):

In the first step, weights are assigned to each parameter on a sliding scale of 5 to 1 based on their contribution to water quality from most important, 5, to the least, 1. Table 3 shows weights relating to each parameter [14].

2) Relative weight (W_i):

Relative weight is calculated using the following Equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

where the w_i is the weight of each parameter and n is the number of parameters (Table 3).

3) Quality rating scale (q_i):

Table 1. Physico-chemical parameters for selected water sample in the Behshar basin (1999).

Sampling Well	Geographical Coordinate (UTM Zone: 39S)		pH	EC (μS/cm)	TDS (mg/l)	TH (mg/l as $CaCO_3$)	Cations (meq/l)				Anions (meq/l)				WQI	Description
	X(m)	Y(m)					Ca	K	Na	Mg	HCO_3	CO_3	Cl	SO_4		
W1	709300	4061450	8.9	1224	796	350	3.60	0.06	6.50	3.40	4.00	2.40	5.60	1.31	95.75	good
W2	716600	4060600	8.1	584	410	265	2.50	0.02	1.32	2.80	4.60	0.00	1.65	0.60	56.88	good
W3	718100	4066050	8.3	970	670	230	1.00	0.05	6.14	3.60	3.40	1.80	5.00	0.45	75.5	good
W4	718650	4062150	8.2	894	583	340	2.80	0.03	3.00	4.00	5.50	0.00	3.95	0.60	77	good
W5	722760	4062800	7.8	508	330	285	3.90	0.01	0.29	1.80	4.90	0.00	0.45	0.74	52.66	good
W6	724150	4065500	8	1196	756	405	2.30	0.03	5.72	5.80	7.30	0.00	5.50	0.82	97.52	good
W7	725500	4067950	7.9	2054	1274	743	2.90	0.09	13.38	11.9	7.10	0.00	14.30	6.20	185.63	poor
W8	731500	4062000	8.2	588	392	290	3.00	0.05	0.87	2.80	4.45	0.00	0.50	1.54	58.5	good
W9	732400	4065100	8.3	725	474	360	3.20	0.02	1.12	4.00	5.55	0.60	0.50	1.48	68.32	good
W10	736250	4066500	8.1	555	375	265	2.90	0.03	0.82	2.40	4.50	0.00	0.70	0.87	54	good
W11	741900	4069400	8.1	565	383	320	4.10	0.01	0.47	2.30	5.50	0.00	0.50	0.42	57.71	good
W12	742550	4063560	8.1	508	314	265	3.15	0.02	0.72	2.15	5.05	0.00	0.45	0.61	92.2	good
W13	747250	4068900	8	970	685	470	3.60	0.04	2.16	5.80	6.80	0.00	2.15	2.27	51.42	good
W14	750510	4071500	8.4	1017	739	185	1.40	0.14	7.87	2.30	4.95	1.30	3.25	2.33	82.2	good
W15	751650	4067600	8	1224	789	370	4.10	0.06	6.12	3.30	5.20	0.00	6.50	2.27	100.47	poor
W16	752500	4071150	8.9	772	508	90	1.10	0.06	7.18	0.70	4.85	1.20	2.30	0.48	58.07	good

Table 2. Physico-chemical parameters for selected water sample in the Behshar basin (2015).

Sampling Well	Geographical Coordinate (UTM Zone: 39S)		pH	EC (μS/cm)	TDS (mg/l)	TH (mg/l as $CaCO_3$)	Cations (meq/l)				Anions (meq/l)				WQI	Description
	X (m)	Y (m)					Ca	K	Na	Mg	HCO_3	CO_3	Cl	SO_4		
W1	709300	4061450	8	1366	874	355	4.40	0.08	6.10	2.70	7.20	0.00	5.70	0.60	98.82	Good
W2	716600	4060600	7.8	823	549	330	4.50	0.06	1.60	2.10	6.70	0.00	0.90	0.70	69.37	Good
W3	718100	4066050	7.6	1610	945	335	3.10	0.09	8.90	3.60	7.80	0.00	5.10	2.80	108.83	Poor
W4	718650	4062150	7.9	819	550	325	3.40	0.05	1.70	3.10	6.50	0.00	0.90	0.80	68.80	Good
W5	722760	4062800	7.8	514	356	180	2.00	0.02	1.60	1.60	4.00	0.00	0.50	0.70	45.48	Excellent
W6	724150	4065500	7.7	850	566	330	4.50	0.05	1.90	2.10	6.10	0.00	1.40	0.90	70.73	Good
W7	725500	4067950	7.7	7120	4557	565	6.20	0.22	59.40	5.10	7.80	0.00	58.20	4.20	428.07	Unsuitable
W8	731500	4062000	7.5	1210	760	280	2.60	0.09	5.90	3.00	5.60	0.00	4.10	1.80	86.10	Good
W9	732400	4065100	8	1250	780	450	5.50	0.08	3.10	3.50	7.70	0.00	2.20	2.10	97.04	Good
W10	736250	4066500	7.7	950	625	345	4.90	0.05	2.60	2.00	6.90	0.00	1.40	1.20	76.85	Good
W11	741900	4069400	7.6	807	541	255	2.10	0.05	3.10	3.00	6.10	0.00	0.90	1.20	64.97	Good
W12	742550	4063560	7.9	512	357	180	2.10	0.07	1.50	1.50	4.00	0.00	0.50	0.60	46.20	Excellent
W13	747250	4068900	7.4	1192	760	440	5.90	0.05	2.70	2.90	8.40	0.00	1.30	1.80	92.22	Good
W14	750510	4071500	7.7	1450	875	465	6.40	0.09	4.70	2.90	7.00	0.00	3.90	3.10	108.87	Poor
W15	751650	4067600	7.7	1590	940	290	2.90	0.08	9.50	2.90	4.70	0.00	7.60	3.00	107.06	Poor
W16	752500	4071150	7.8	1550	930	460	6.10	0.07	5.90	3.10	8.20	0.00	4.10	2.80	112.88	Poor

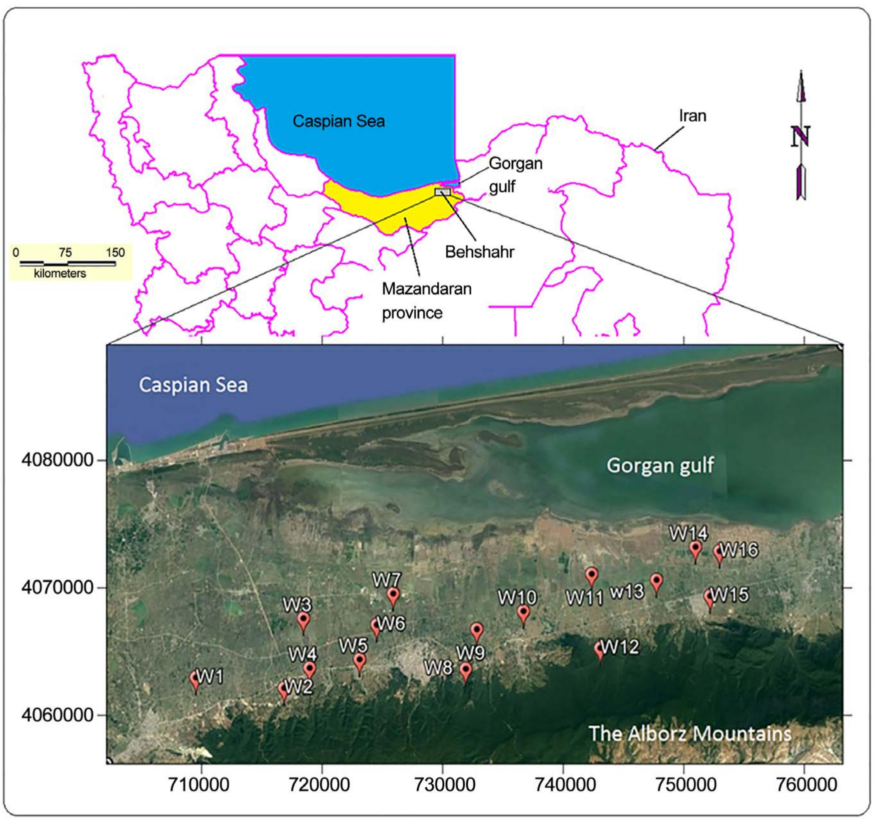

Figure 1. Google image of study area with sampling locations.

Table 3. Relative weight of physico-chemical parameters and the WHO standard for drinking purpose.

Chemical parameters	Weights (wi)	Relative weight (Wi)	WHO Drinking Standards (Si)
pH	3	0.09	6.5-8.5
CO_3 + HCO_3 (mg/l)	1	0.03	120
TDS (mg/l)	5	0.15	500
Ca (mg/l)	3	0.09	75
Mg (mg/l)	3	0.09	50
TH (mg/l)	2	0.06	180*
Cl (mg/l)	5	0.15	250
Na (mg/l)	4	0.12	200
K (mg/l)	2	0.06	12
SO_4 (mg/l)	5	0.15	250
Total	33	1.00	–

* USGS allowable limits [16].

The quality rating scale q_i for each parameter in each sample is determined by dividing the concentration of each parameter by its respective standard (S_i) given by WHO multiplied by 100 [15].

$$q_i = \frac{C_i}{S_i} * 100 \tag{2}$$

where the C_i is the concentration of each parameter which is reported in mg/l except for pH which is dimensionless and the S_i is maximum allowable limit for each parameter in mg/l (**Table 3**).

4) Sub-index (SI_i) and Water WQI:

To determine the sub-index and the WQI following Equations are applied respectively:

$$SI_i = q_i * W_i \tag{3}$$

$$WQI = \sum_{i=1}^{n} SI_i \tag{4}$$

where (SI_i) is the sub index of each parameter, q_i is the quality rating scale of each parameter and n is the number of parameters.

3. Result and Discussion

3.1. Water Quality

The water quality analysis of Behshahr showed that pH values were in the range of 7.4 - 8 in all the sixteen sampling wells. Total hardness, moreover, varied between 180 to 565 mg/l as $CaCO_3$ indicating a high rate of hardness in the study area.

Variation of TDS and EC were in the range of 356 to 4557 mg/l and 512 to 7120 μS/cm respectively. As anticipated, by approaching downstream total dissolved solid noticed to be higher in samples. The annual average of TDS has been soared from 592.4 mg/l to 935.3 mg/l in a 16-year period of 1999 to 2015. Currently, this value is disturbingly close to maximum allowable limits of drinking water proposed by WHO (Figure 2). It is mainly caused by anthropogenic activities such as infiltration of agricultural runoff and domestic wastewater or saltwater intrusion. The comparison between the percentage of water quality parameters in the most polluted sample (W7) and of those in seawater, represents significant similarities. These similarities are most noticeable in sodium and chloride concentrations (Figure 3). This could be the result of salt water intrusion into this aquifer which is highly probable since the area is located in the vicinity of Caspian Sea.

The chloride-bicarbonate ratio is a well-known and decent index to identify saltwater intrusion in coastal areas [17]. According to Raghunath, the ratio of $Cl/HCO_3 = 2.8$ is assumed to be the threshold of saltwater intrusion. The distribution of the mentioned ratio in this study area between 1999 and 2015 indicates that not only W7 is already contaminated by saltwater intrusion but also the threshold of saltwater intrusion has significantly moved landward during these years (Figure 4).

Effective and immediate policies, consequently, entailing prevention of overexploitation of threatened wells along with injecting fresh water into these wells are highly recommended.

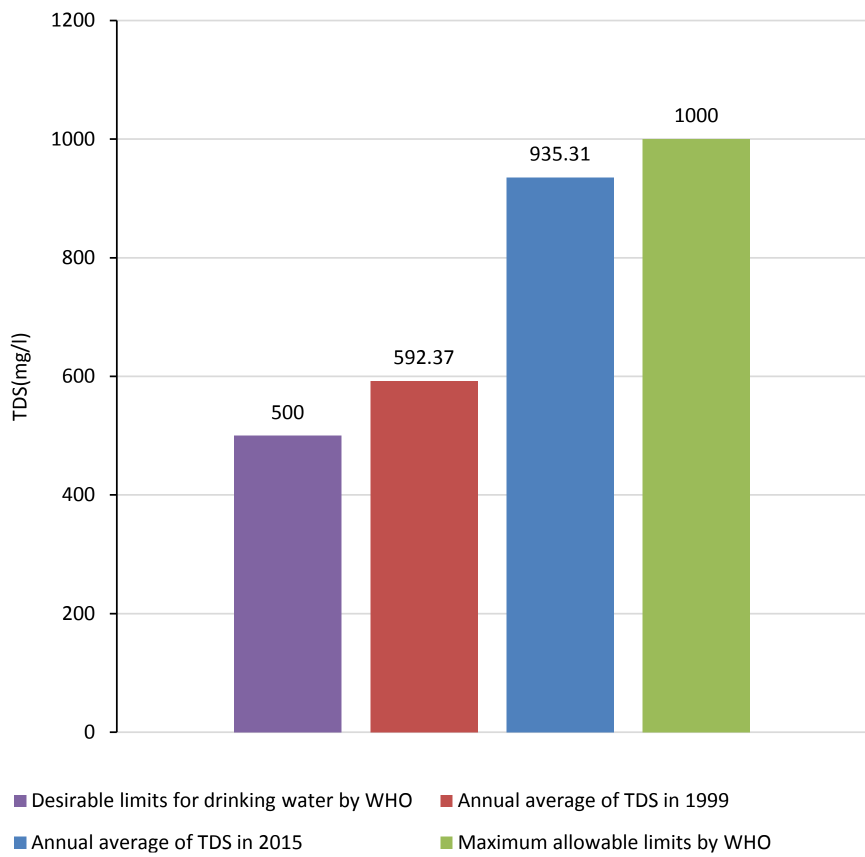

Figure 2. Annual average growth of TDS between 1999 and 2015.

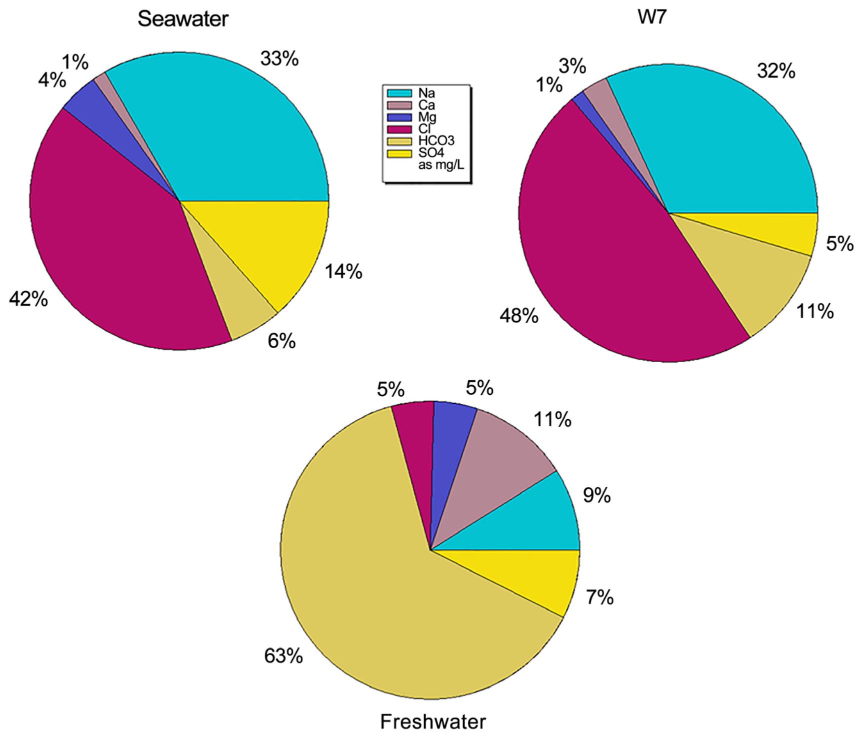

Figure 3. Comparison between percentages of water quality parameters in seawater with that of W7.

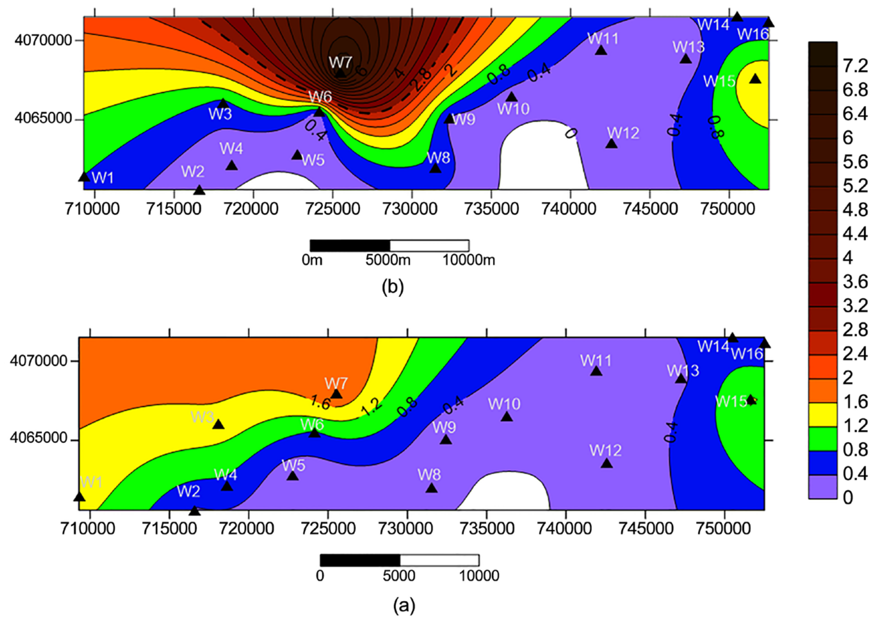

Figure 4. Distribution of Chloride-bicarbonate ratio between 1999(a) and 2015(b).

3.2. Water Quality Index

Calculation WQI can entail as many qualitative parameters as researchers desire. However, its outcome is a single dimensionless figure which represents water quality in each sample [12].

In this study eleven parameters including pH, TDS, TH, major cations and anions were considered to partake in WQI calculation. Taking into account the significance of each parameter on human health, weights were allocated to them. Results categorized samples into four different groups based on guidelines proposed by WHO and U.S. Geological Survey. Variation of WQI parameter was in the range of 45.48 to 428.07 in 2015 (Table 4). In order to achieve a general understanding of water quality in the area, distribution of WQI is shown in Figure 5.

According to Table 4 and Figure 5, it is found that in 2015 about 56.25% of the groundwater samples which covered a wide-range of this study area fitted into good category while in 1999 about 87.5% of samples fitted into this category. Since the water quality of those samples identified as "good water" is approximately close to natural condition, they are suitable for direct human consumption.

Table 4. Water quality index (WQI) legend.

WQI Range	Percentage of samples (2015)	Percentage of samples (1999)	Quality
50<	12.5	0	Excellent
50 - 100	56.25	87.5	Good
100 - 200	25	12.5	Poor
200 - 300	0	0	Very poor
>300	6.25	0	Unsuitable for drinking

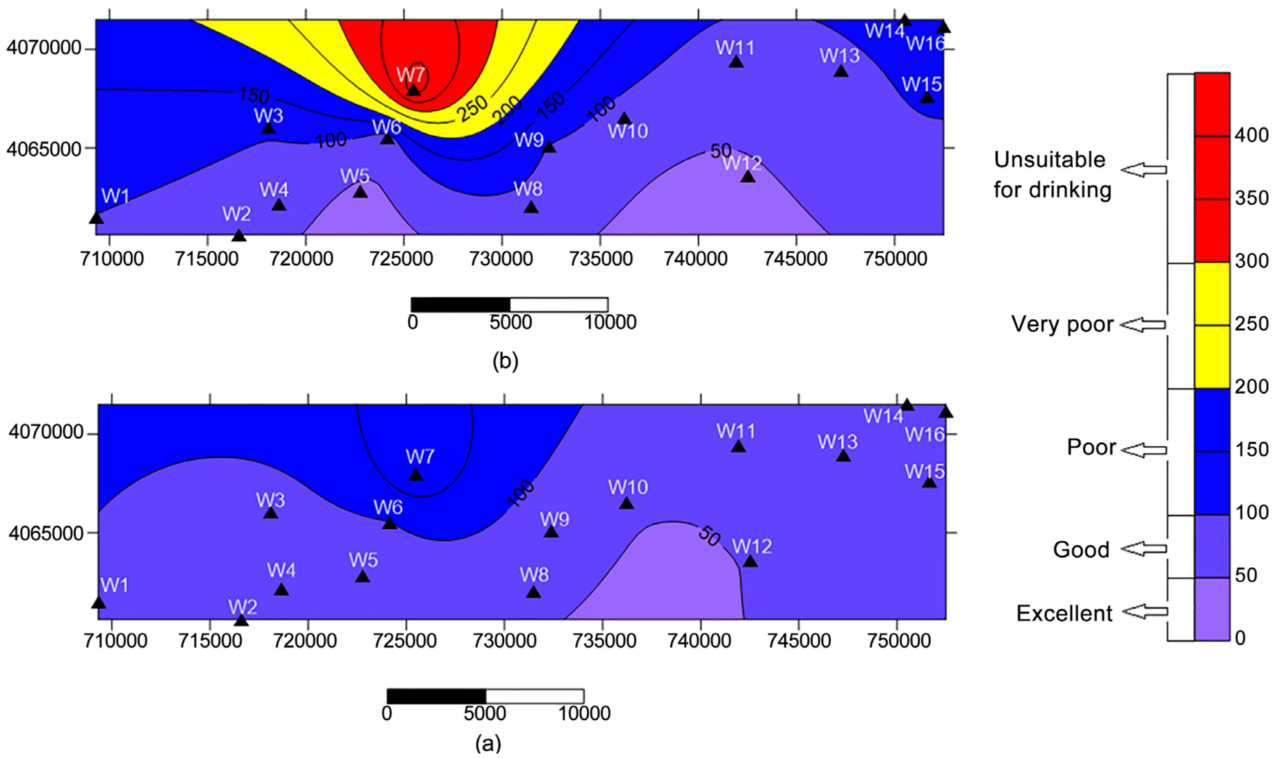

Figure 5. WQI distribution of sampling wells between 1999(a) and 2015(b).

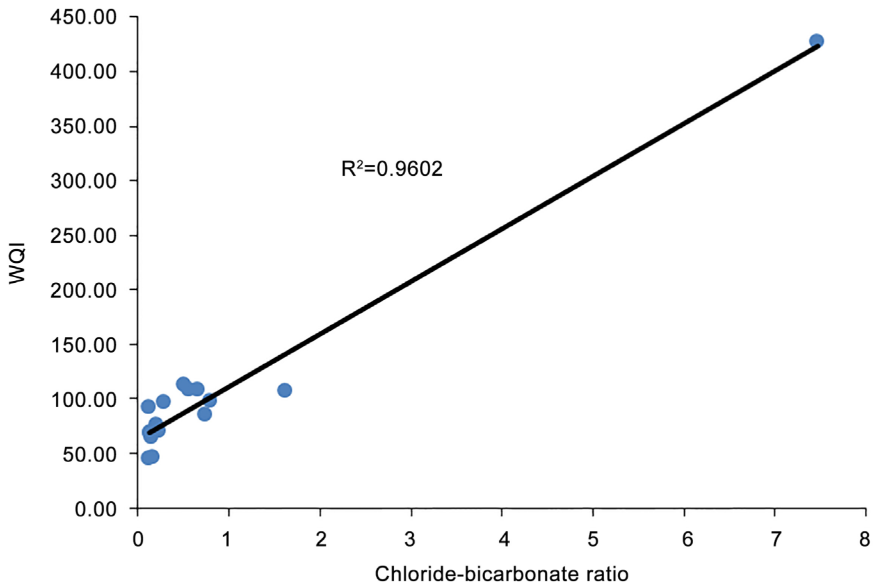

Figure 6. Correlation coefficient between WQI and chloride-bicarbonate ratio.

Regarding the excellent category, although an increase of 12.5% can be observed between 1999 and 2015, the improvements in the water quality occurring in W5 was fairly insignificant and probably reflect natural events, furthermore, the improvement in W12 might have occurred as a result of being located in the recharge area which could make it quite sensitive to the raw water quality.

As can be seen in Table 4 in 2015 nearly 25% of samples fitted into poor category. Comparing to 12.5% of those in this category in 1999, it showed a twofold increase. The quality of water in these samples mostly located in northern and western part of this basin are occasionally threatened or impaired. Consequently, they can be only used for irrigation, bathing and swimming, though for drinking, industrial or laundry purposes conventional treatment is highly recommended.

Since the water quality of those samples fitted into poor category occasionally depart from natural state, it is suggested that the mentioned category be considered as the threshold of unnatural activities. This consideration helps policy makers to make optimized decisions based on priority and importance of each quality zones to prevent groundwater contamination.

Through approaching northern parts of the basin, water quality perceived to be impaired. This is especially pronounced in W7 which fitted into "Unsuitable for drinking" category in 2015 whereas in 1999 it was located in the zone that was just in progress to be impaired. Water quality in W7 has been drastically affected by high concentration of TDS and sodium chloride during this period of time.

The parallelism between distribution diagrams of WQI and chloride-bicarbonate reveals the fact that threshold of saltwater intrusion fairly corresponds with the very poor quality zone. Assigning a high weight to chloride in WQI calculation is a contributing factor to this similarity. This makes the results highly sensitive to drastic changes in chloride concentration. In addition, the correlation coefficient between chloride-bicarbonate ratio and WQI confirms that saltwater intrusion plays leading role in water quality deterioration in this study area (**Figure 6**).

4. Conclusions

In this study area annual average of TDS increased nearly 343 mg/l and reached to 935 mg/l in 2015 due to anthropogenic activity. The WQI rating represented various water quality categories in this study area. In 1999 about 87.5% of groundwater samples were suitable for drinking purpose whereas in 2015 the number of potable samples decreases to 69% of all groundwater samples. In a related vein, number of samples belonging to poor category increased about 12.5% over this period of time. This means extracted water from these wells and that in the immediate vicinity is only to be used for irrigation, bathing or swimming unless conventional treatment is conducted.

The comparison between Percentage of seawater quality parameters and those of in W7 represented significant similarities especially in sodium-chloride concentration. Furthermore, comparing the chloride-bicarbonate distribution diagram in the last 16-year period indicated that saltwater/freshwater interface has significantly moved landward.

The correspondence between WQI distribution and chloride-bicarbonate ratio shows that the main reason of very poor water quality zone is chloride contamination and also the correlation coefficient between aforementioned parameters confirms that saltwater intrusion is the most possible consequence of anthropogenic activities in this coastal area.

Accordingly, to gain a true understanding of water quality in an area WQI is highly recommended. This simple yet precise method presents a comprehensive interpretation of water quality in a basin. Its sensitivity to chloride that has high weight makes it a good measure for seeking out the threshold of saltwater intrusion in this study area. Relying on this method's results a basin can be divided into different zones with different water usages. Policy makers would achieve a great benefit utilizing this method.

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