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Suitability Assessment of Groundwater for Irrigation in Rabigh, Saudi Arabia: A Case Study of Combined Influence of Landfills and Saltwater Intrusion

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ABSTRACT

This research assessed the combined influence of permitted landfills and unlicensed dumps coupled with salt water intrusion on the suitability of groundwater in Rabigh, Saudi Arabia for irrigation purposes. Fourteen water samples were analyzed for physiochemical parameters, major ions and heavy metals. Quality assessment of groundwater for irrigation purposes was conducted on basis of sodium percentage (Na %), sodium adsorption ratio (SAR), magnesium hazard (MH), permeability index (PI), total hardness (TH), Kelley's ratio (KR), and soluble sodium percentage (SSP), Wilcox and the Food and Agriculture Organization of the United Nations (FAO) standard limits. Results showed that the domination of ions is in the order Na>Ca>Mg>K and Cl>SO4>HCO3 for cations and anions, respectively. Elevated concentration of Na and Cl coupled with very strong relationships between Na and Cl ($r = 0.994$), Na and EC ($r = 0.995$) and between Cl and EC ($r = 0.999$) indicates a strong influence of Red Sea saltwater intrusion. According to Wilcox and the FAO classifications of salinity (Electrical conductivity (EC)) in irrigation water, it can be concluded that the groundwater in the investigated area of Rabigh is undesirable for irrigation purposes. Based on Freeze and Cherry classification of total dissolved solids (TDS), the groundwater samples fall in the brackish to saline categories. However, saline water was recognized in the majority of the samples (64%). Concerning the FAO classification, 86% of the samples can be classified in the severe restriction category. According to the categorization of irrigation water based on sodium percentage, two-thirds of the water samples can be classified in the doubtful to unsuitable categories. The very high electrical conductivity values obtained in the groundwater samples near the landfill sites are an indication of the combined effect of leachate and Red Sea saltwater intrusion. Severe restriction is associated to 65% of groundwater samples according to the FAO classification of SAR. Nearly two-thirds of the groundwater samples fall in the medium to high sodium hazard categories. According to Kelley's ratio and soluble sodium percent, the majority of the groundwater samples (86%) show that the groundwater is undesirable for irrigation purposes. The analytical results of SSP conclude that the majority of groundwater samples (86%) are undesirable for irrigated agriculture. Samples of some groundwater wells show that the concentration of some heavy metals such as Aluminum (Al), Cobalt (Co), Copper (Cu), Chromium (Cr), Nickel (Ni), Vanadium (V), and Zinc (Zn), are higher than the corresponding FAO permissible limits.

Key Words: Groundwater quality; Landfill; Sea water intrusion; Saudi Arabia; Irrigation; Contamination

1. Introduction

The imbalance between available water resources and ever-increasing demands for the public and irrigation sectors, has become a great concern to water managers as they attempt to sustainably manage limited water resources, especially in arid and semi-arid regions (Al-Faraj and Scholz, 2014). Rapid population growth and socio-economic advancement coupled with climate change have exacerbated stress on water resources (Al-Faraj and Al-Dabbagh, 2015). In arid and semi-arid climate areas where precipitation is low and evapotranspiration rates are high, groundwater becomes a leading source of water to serve domestic, industrial, commercial, and irrigation sectors, especially in areas where perennial rivers are absent such as Saudi Arabia (Al-Hasawi and Hussein, 2012; Bhat et al., 2018).

Excessive abstraction of groundwater in many arid and semi-arid areas, has several undesirable consequences such as lowering groundwater levels, degradation of quality of groundwater and saltwater intrusion in coastal areas. Alfarrah and Walraevens (2018) stated that heavy withdrawal of groundwater has increasingly become a crucial concern in recent decades, particularly in coastal arid and semi-arid regions. Intrusion of salty marine water may degrade water quality to levels exceeding permissible drinking and irrigation water standard limits, which can jeopardise future abstraction and availability of groundwater (Prasanth et al., 2012). A continuing rise of Sea levels due to global warming puts additional pressure and concern on future suitability and utilisation of coastal aquifers, due to increased threat of saltwater intrusion.

Understanding effects of anthropogenic activities on groundwater quantity and quality is of paramount importance to the sustainable management of groundwater resources. Over-exploitation and reduced quality of groundwater influenced by sanitary landfilling, unlicensed dumping of solid waste and disposal of waste waters coupled with saltwater intrusion and rising of Sea levels, have become a growing concern and received special attention during the last two decades (Mukherjee et al., 2005; Al-Hasawi and Hussein, 2012; Shah and Mistry, 2013; Venkateswaran and Vediappan, 2013; Al-Faraj and Scholz, 2014; Singh et al., 2015; Al-Faraj and Al-Dabbagh, 2015; Alfarrah and Walraevens, 2018; Bhat et al., 2018; General Authority of Meteorology and Environmental Protection (GAMEP), 2018).

Sanitary landfills are common environmental facilities and practices for waste management worldwide. However, in some parts of the world, particularly in areas where absence of sanitary landfills is a critical issue, residents have been left with unlicensed indiscriminate use of open dump sites and disposal of waste waters (Oyiboka, 2014). Groundwater resources in areas adjacent to sanitary landfill sites and/or unauthorised open dump sites and coastal areas, are vulnerable to considerable contamination by leachates, unauthorised dumping and invasion of Seawater (Bougioukou et al., 2005; Fami and Oluwole, 2013; Department for Environment, Food and Rural Affairs and Environment Agency, 2016; GAMEP, 2018).

Considerable attention over the last two decades has been also given to assess the quality of groundwater in close proximity areas to landfills. Extensive research work has been carried out to examine the suitability of groundwater for agricultural irrigation near landfill sites (Mukherjee et al., 2005; Butt et al., 2008; Singh et al., 2015; Shah and Mistry, 2013; Venkateswaran and Vediappan, 2013; GAMEP, 2018).

Analysis and appropriate understanding of quality of ground water is crucial in determining its usability for public water supply and irrigation. Literature exhibited that extensive work has been conducted in this area (Mukherjee et al., 2005; Shah and Mistry, 2013; Venkateswaran and Vediappan, 2013; Singh et al., 2015; Narayanamurthi, 2018). In Saudi Arabia, the assessment of groundwater suitability for irrigation has been well received by a number of researchers (Al-Harbi, 2009; FAO, 2009; El-Hames, 2010; Khashogji and Maghraby, 2012; Al-Hasawi and Hussein, 2012). AlAhmadi (2012) stated that there is growing demands for groundwater usage due to increased anthropogenic activities associated with population growth.

The aim of this study is to assess the quality of groundwater influenced by adjacent sanitary landfill and unlicensed dump sites, and saltwater intrusion of the Red Sea, for irrigation purposes. This, supports the establishment of a consistent long-term monitoring network and management programme and plan, to successfully manage the groundwater in a sustainable manner.

2. Materials and Methods

2.1 Study area and the climate setting

Rabigh is situated in Makkah, Saudi Arabia at latitude of 22°47′54″ N and longitude of 39°02′05″ E. Rabigh is located on the east coast of the Red Sea. It is characterized by intensive industrial activities (e.g. Arabian Cement Factory, Electric Power Plant, Water Supply Plant, Aramco Company Refinery, and Aramco Residential Area) and agricultural activities, and is considered to be one of the important industrial cities in Saudi Arabia. Its location will become more important and contribute to the economic development after the completion of King Abdullah Economic City, which is currently under construction about 40 km from Rabigh. The total area of Rabigh is 6,679 sq.km and the population based on the most recent census is 104,621 (GAMEP, 2018). Figure 1 shows the location of Rabigh and the study area.

A set of seven landfills is located in Al Jehfa in the south-east of Rabigh city about 16 km from Rabigh and 12 km from the coast of the Red Sea (Figure 1). Existing landfills in Rabigh receive waste from different sources such as households, fish farms, poultry farms, slaughter premises, industries and small farms (GAMEP, 2018). Maximum monthly temperatures range from 28.2 ℃ to 39.8 ℃ and minimums between 17.7 ℃ and 29.9 ℃. Average monthly temperatures range between 22.9 ℃ and 34.9 ℃. Monthly rainfall records between 2013 and 2017 show that rainfall ranges between nil and 10.25 mm with a total annual precipitation of 26.4mm (GAMEP, 2018). Average monthly relative humidity ranges from 46.5% to 60% with an annual mean of 52.3%.

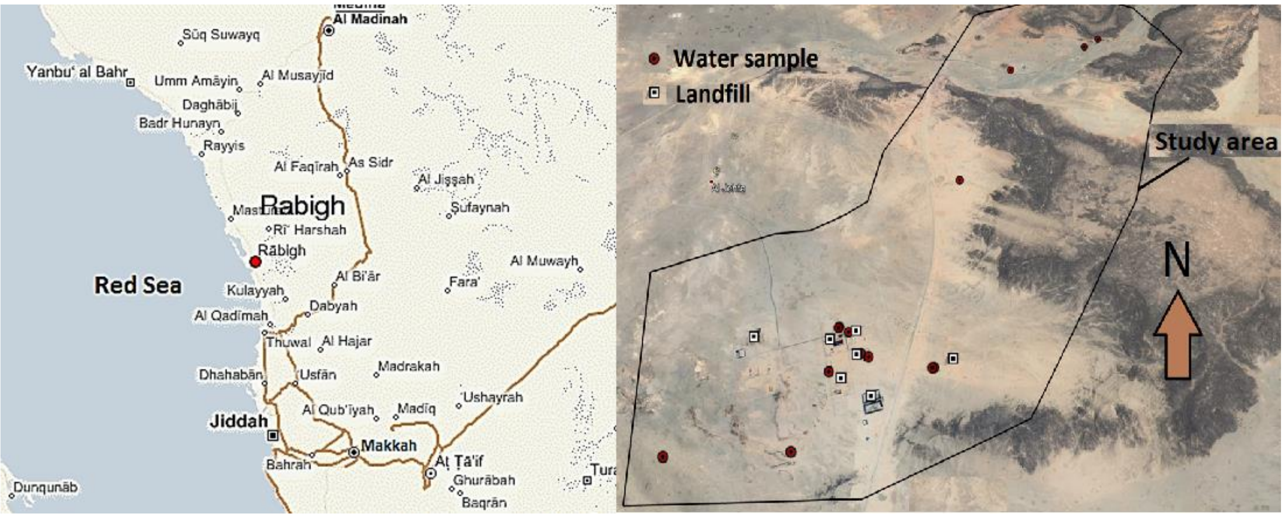

Figure 1 Location of the study area (Rabigh) in Saudi Arabia.

2.2 Data and Methods of Analysis

This study investigates the suitability of groundwater in Rabigh for agricultural irrigation. Fourteen water samples including groundwater wells, farms and disposal of waste water, were made available by GAMEP. The parameters are: Electrical conductivity (EC), Bicarbonate as CaCO3, Total Dissolved Solids (TDS), Sodium (Na), Calcium (Ca), Magnesium (Mg), Potassium (K), Chloride (Cl) and Sulphate (SO4). Data of heavy metal elements: Aluminium (Al), Arsenic (As), Cadmium (Cd), Cobalt (Co), Copper (Cu), Chromium (Cr), Nickle (Ni), Selenium (Se), Vanadium (V), and Zinc (Zn) were also made available by GAMEP. The water samples were collected between September and October 2018.

Information about the geographical coordinates of the location of water samples and the seven landfill sites were also provided. The location of the seven landfills and the water samples is shown in Figure 1. Distances between the seven landfills and the location of the water samples were determined using Google Earth. An array (7, 14) is prepared to examine the impact of the distance between the landfill site (point source) and the location of the water sample (receptor) on the quality of groundwater.

Microsoft Excel was used to determine some descriptive statistics such as minimum, maximum, mean and standard deviation. The suitability of groundwater for irrigation purposes in Rabigh was judged using seven indices that are commonly used worldwide. These indices are: (1) Sodium Percentage (Wilcox, 1955 cited in Jeyaseelan et al., 2013), (2) Sodium Adsorption Ratio (Ayers and Westcot 1976 cited in Jeyaseelan et al., 2013), (3) Magnesium Hazard (Szabolcs and Darab, 1964 cited in Bhat et al., 2018), (4) Permeability Index (Doneen, 1964 cited in Bhat et al., 2016), (5) Total Hardness (Sawyer and McCarty, 1967 cited in Bhat et al., 2018), (6) Kelley's Ratio (Kelly, 1940 cited in Shah and Mistry, 2013 and Bhat et al., 2018), and (7) Soluble Sodium Percentage (Shah and Mistry, 2013). Table 1 shows the standard limits corresponding to the seven water quality indices for irrigation. The Wilcox and the FAO standard limits for irrigation water are given in Table 2.

Regression analysis was conducted to explore and model the relationship between different water quality parameters. Correlation coefficients between all investigated parameters were determined using the statistical tools available in Microsoft Excel.

2.2.1 Sodium Percentage (Na %)

High concentrations of sodium are undesirable in water. The sodium percentage is one of the important indices, which is widely used for judging the quality of water for irrigation purposes (Bhat et al., 2018). The Na is computed as the percentage of sodium and potassium against all cationic concentration (Ibraheem and Khan, 2017). Irrigation water is classified into different classes from excellent (Na %) <20 to unsuitable (Na %)> 80 (Table 1). The Na% is computed using Equation 1. The calculated values are given in Table 3.

$$Sodium\ Percentage\ (Na\%) = \frac{Na+K}{Ca+Mg+Na+K}\ X\ 100 \text{-------------------------Equation 1}$$

Where Ca, Mg, Na, and K are measured in milliequivalents per liter

2.2.2 Sodium Adsorption Ratio (SAR)

Sodium adsorption ratio (SAR) is a universal indicator for assessing the degree of suitability of water for irrigated agriculture. The categorisation of suitability of groundwater for irrigation based on SAR is expressed in Table 1 (Joshi et al., 2009). SAR is calculated using Equation 2 and given in Table 3.

$$Sodium\ Adsportion\ Ratio\ (SAR) = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \text{----------------------------------Equation 2}$$

Where Ca, Mg, and Na are measured in milliequivalents per liter

2.2.3 Magnesium Hazard (MH %)

Magnesium hazard (MH) less than or equal to 50 is considered appropriate for irrigation whereas MH more than 50 indicates the unsuitability of water for irrigation (Szabolcs and Darab, 1964 cited in Bhat et al., 2018). With high concentration of MH, soils become more alkaline coupled with reduction in crops yield. Magnesium hazard is computed using the formula mentioned in Equation 3 (Bhat et al., 2018). The obtained values are given in Table 3.

$$Magnesium\ hazard\ (MH\%) = \frac{Mg}{Ca+Mg}\ X\ 100 \text{--------------------------------Equation 3}$$

Where Ca and Mg are measured in milliequivalents per liter

2.2.4 Doneen′s Permeability Index (PI%)

The prolonged use of irrigation water affects the permeability of soil as it is influenced by the presence of Na, Ca, Mg, and bicarbonate HCO3 contents. According to Doneen′s categorisation (1964, cited in Bhat et al., 2018), waters can be classified as class I (Excellent with PI>75%), Class II (Good with 25≤PI≤75) and Class III (Unsuitable for PI<25). Equation 4 is used to compute the permeability index. The computed values are given in Table 3.

$Doneen's\ Permeability\ Index\ (PI\%) = \frac{Na+\sqrt{HCO3}}{Ca+Mg+Na} \times 100$-------------------Equation 4

Where Na, Ca, HCO3 and Mg are measured in milligram per liter

2.2.5 Total Hardness (TH)

The total hardness (as CaCO3) of water samples can be estimated using Equation 5. Sawyer and McCarty (1967, cited in Bhat et al., 2018) proposed four classes to determine the suitability of water for irrigation (Table 1). Equation 5 is used to determine total hardness. Table 3 shows the computed values.

$Total\ Hardness\ (\text{as } CaCO_3) = 2.5(Ca) + 4.1(Mg)$--------------------------Equation 5

Where Ca and Mg are measured in milliequivalents per liter

2.2.6 Kelley's Ratio (KR)

Kelley's Ratio (KR) is a ratio of sodium ion concentration to the summation of Ca and Mg concentrations. Kelly's ratio of more than 1 indicates an excess level of Na in water. Water samples with Kelley's ratio less than 1 is considered suitable for irrigation whereas those with a ratio more than 3 is considered unsuitable for irrigation. The Kelly's ratio was computed using equation 6 (Kelly, 1963 cited in Shammi et al., 2016). The computed values are given in Table 3.

$Kelley's\ Ratio\ (KR) = \frac{Na}{Ca+Mg} \times 100$ --Equation 6

Where Ca, Mg, and Na are measured in milliequivalents per liter

2.2.7 Soluble Sodium Percentage (SSP)

Irrigation waters having SSP values more than 50 are considered unsuitable (Shah and Mistry, 2013). SSP is computed using Equation 7 shown below. The computed values are shown in Table 3.

$Soluable\ Sodium\ Percentage\ (SSP) = \frac{Na}{Ca+Mg+Na} \times 100$-------------------Equation 7

Where Ca, Mg, and Na are measured in milliequivalents per liter

Table 1. Range of the seven indices and the corresponding water quality categories for irrigation purposes.

Parameter	**Range**	**Category**	**Source**
Sodium Percentage (Na %)	Na<20	Excellent	(Wilcox, 1955 cited in Jeyaseelan et al., 2013)
	20≤Na≤40	Good	
	40<Na≤60	Permissible	
	60<Na≤80	Doubtful	
	Na>80	Unsuitable	
Sodium adsorption ratio (SAR)	SAR< 2	No hazards	(Venkateswaran and Vediappan, 2013)
	2≤SAR≤10	Low hazards	
	10<SAR≤18	Medium hazards	
	18<SAR≤26	High hazards	
	SAR>26	Very high hazards	
Magnesium hazard (MH) (%)	MH≤50	Suitable	(Szabolcs and Darab, 1964 cited in Bhat et al., 2018)
	MH>50	Unsuitable	
Doneen's Permeability index (PI) (%)	PI<25 (class III)	Unsuitable	(Doneen, 1964 cited in Bhat et al., 2018)
	25≤PI≤75 (class II)	Good	
	PI>75 (class I)	Excellent	
Total hardness (TH as $CaCO_3$)	TH<75	Soft	(Sawyer and McCarty ,1967 cited in Bhat et al., 2018)
	75≤TH≤150	Moderately hard	
	150<TH≤300	Hard	
	TH>300	Very hard	
Kelley's Ratio (KR)	KR≤1	Suitable	(Kelley et al., 1940 cited in Venkateswaran and Vediappan, 2013)
	KR>1	Unsuitable	
Soluable Sodium Percentage (SSP)	SSP≤50	Good	(Shah and Mistry, 2013)
	SSP>50	Unsuitable	

Table 2. Wilcox and the FAO Standard limits for irrigation water.

Electrical conductivity (EC) (Wilcox, 1955 cited in Jeyaseelan et al., 2013)	Excellent (100 - 250 µS/cm)
	Good (250 -750 µS /cm),
	Doubtful (750 - 2250 µS /cm)
	Unsuitable (>2250 µS /cm)
FAO (2009)	No restriction (EC<700 µS/cm)
	Slight to moderate restriction (700≤EC≤3000 µS/cm)
	Severe restriction (EC>3000 µS/cm)
	No restriction (TDS<450 mg/l)
	Slight to moderate restriction 450≤TDS≤2000 mg/l
	Severe restriction (TDS>2000 mg/l)
	No restriction (SAR<3 meq/l) surface irrigation
	Slight to moderate restriction 3≤SAR≤9 meq/l surface irrigation
	Severe restriction (SAR>9 meq/l) surface irrigation
Element	**FAO Standard limits for irrigation water (mg/l)**
Al	5.0
As	0.1
Cd	0.1
Cr	0.1
Co	0.05
Cu	0.2
Fe	5.0
Pb	5.0
Mn	0.2
Ni	0.2
Se	0.02
V	0.1
Zn	2.0

3. Results and Discussion

3.1 Irrigation Water Quality

3.1.1 Sodium Percentage (Na %)

The computed sodium percentage values using vary between 41.8% and 80.8%. Results (Table 3) show that approximately 36% of the water samples fall within the permissible levels for agricultural irrigation (40<Na≤60), nearly (7%) are considered inappropriate (Na>80) while the doubtful levels (60<Na≤80) are linked to the remaining (57%).

3.1.2 Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is an irrigation water quality index widely used to assess the sodium hazards to soil and crops. It is a measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in a water sample. The sodium in the irrigation water can displace the calcium and magnesium in the soil; if high SAR irrigation water is supplied over a long period of time, the soil infiltration rate and soil permeability will be reduced, leading to crops damage or reduce crops production. The SAR values of the water samples vary between 1.4 and 25.9. Results (Table 3) suggest that 50% of water samples are within the medium sodium hazard limits, nearly 22% linked to low sodium hazard range. Groundwater samples associated with no sodium hazard and high sodium hazard each came with approximately 14% of the water samples. Regarding the FAO standard limits, results exhibit that no restriction to use groundwater for irrigation is associated with 21%; 14% of the samples fall within the limits of slight to moderate restriction, while the remaining 65% are linked to sever restriction.

3.1.3 Magnesium Hazard (MH)

Venkateswaran and Vediappan (2013) stated that excess levels of magnesium in groundwater affects the quality of soils, which reduces crops yield. The computed magnesium hazard (MH) values range between 17.7% and 60.2%. Results (Table 3) recommend that almost (93%) of the water samples are suitable for irrigation, while the remaining (7%) are considered unsuitable.

3.1.4 Doneen′s Permeability index (PI)

Soil permeability is affected by a prolonged supply of irrigation water (Patel and Dhiman, 2017). The computed PI values of the water samples vary between 49.2% and 84.6%. Results (Table 3) reveal that approximately 14% of the water samples fall in class I (PI>75: Excellent), while the remaining (86%) are considered good for agricultural irrigation (class II: 25≤PI≤75).

3.1.5 Total Hardness (as CaCO3)

Results (Table 3) conclude that the total hardness of the water samples vary between approximately 27 and 1535 milliequivalents per liter. This suggests that soft hardness is linked to nearly 22% of the water samples, moderately hardness is associated with approximately 14%, about 7% falls within the hard class, while the remaining 57% fall within the very hard class.

3.1.6 Kelley's Ratio (KR)

In equation 6, the sodium level in ground water is measured against the calcium and magnesium. Kelley's ratio (KR) more than 1 suggests an excess level of sodium in water samples. Therefore, water samples with a KR less than 1 are considered suitable for irrigation, while those with a KR more than1 are unfit for irrigation. The computed KR values vary between 0.70 and 4.1. The minimum value associated with well 3CW1 while the maximum value linked to well 6AW1–Salih farm. Results (Table 3) reveal that approximately (14 %) of the water samples have good quality water for irrigation, while the unsuitable water quality for irrigation is associated with the remaining (86%).

3.1.7 Soluble Sodium Percent (SSP)

The computed values of SSP vary between 40.2 and 80.6 (Table 3). 14% of SSP values were found less than 50 indicating good quality water for irrigation, while the remaining 86 % are associated with unsuitable water quality for irrigation purposes.

Table 3. Calculated values of the seven water quality indices

Sample	Na%	SAR	MH	PI	TH	KR	SSP
4BW1–Waste water disposal site	60.59	13.76	42.62	67.72	1050.79	1.51	60.22
AW1–Almustadama landfill	77.78	25.86	35.45	82.24	686.55	3.46	77.57
AW2–Almustadama landfill	65.84	17.17	43.54	72.64	1033.29	1.91	65.64
BW1–GEMS landfill	61.87	16.84	35.19	68.27	1339.78	1.61	61.69
BW2–GEMS landfill	64.88	17.75	35.62	71.07	1149.17	1.84	64.73
3BW1–Phil landfill	62.50	18.48	35.75	68.89	1534.76	1.65	62.31
3BW2–SEPCO landfill	62.99	16.52	35.98	69.35	1181.91	1.69	62.77
3CW1–Phil landfill	43.14	1.57	17.68	49.17	50.54	0.74	42.44
3CW2–Afaq landfill	56.26	13.11	36.39	63.11	1303.53	1.27	56.04
4BW2–Nabe ́a Farm	65.23	2.61	47.65	75.18	26.49	1.83	64.68
5AW1–Rashid Farm	58.81	5.56	28.65	65.26	181.00	1.42	58.70
6AW1–Salih Farm	80.78	11.80	28.93	84.59	96.09	4.14	80.55
6BW1–Jama ́an Farm	57.77	4.46	25.81	63.59	128.19	1.34	57.33
6CW1–Kuleya Village	41.83	1.39	60.25	53.76	54.89	0.70	41.16
Min	41.83	1.39	17.68	49.17	26.49	0.70	41.16
Max	80.78	25.86	60.25	84.59	1534.76	4.14	80.55
Mean	61.45	11.92	36.39	68.20	701.21	1.79	61.13
Dev.S*	10.59	7.60	10.25	9.49	581.20	0.94	10.72

* Standard deviation

3.1.8 Wilcox─FAO Standard Limits

The EC is a good indicator of salinity hazards to crops when groundwater is used for irrigation. According to Wilcox (1955), groundwater was classified into four categories: Excellent (100-250 µS/cm), Good (250-750 µS/cm), Doubtful (750-2250 µS/cm), and Unsuitable (>2250 µS/cm). Concerning the FAO classification there is no degree of restriction to the irrigation water when EC <700 µS/cm, slight to moderate restriction when (700 µS/cm ≤EC≤3000 µS/cm), and severe restriction when EC>3000 µS/cm. The EC values (Table 4) of water samples range between 2310 µS/cm and 116000 µS/cm with a mean value of 56678.6 µS/cm and a standard deviation of 44644.2 µS/cm. This suggests the unsuitability of water for irrigation. The maximum value was associated with well 3BW1–Phil landfill followed by 99900 µS/cm and 96500 µS/cm, which are linked to well BW1–GEMS landfill and well AW1–Almustadama landfill, respectively. The minimum value was associated with well 4BW2–Nabe'a farm. The large value of the standard deviation (44644.2 µS/cm) indicates that EC values vary widely between the examined water samples.

Results (Table 4) revealed that the dominance of cations is in the order Na>Ca>Mg>K. The corresponding concentrations range between 255 and 19000 mg/l, 85 and 6420 mg/l, 39 and 2170 mg/l; and 12 and 369 mg/l, respectively. The corresponding means and standard deviations are 9225.4 and 7461.5 mg/l, 2859.8 and 2366.5mg/l, 1018.6 and 854.6mg/l, and 152.6and 121.3 mg/l, respectively. The concentrations of anions declined in the order Cl>SO4. The corresponding minimum, maximum, mean and standard deviation values are 483, 44900, 21457.7, and 17641.8 mg/l, and 258, 3200, 1559.6, and 920.5mg/l, respectively. The most abundant cation (Na) and anion (Cl) are linked to well 3BW1–Phil landfill.

The normal range of pH for agricultural irrigation is from 6.5 to 8.4 (FAO, n.d.). The pH values of ground water samples vary between 4.58 and 8.08 (Table 4). This suggests that the pH values in all surveyed wells except the well (3CW2–Afaq landfill: pH=4.58) are well within the standard limits prescribed by the FAO. An abnormal value observed in well 3CW2–Afaq landfill is a warning that the water quality needs further investigation.

The concentrations of bicarbonate (HCO3) in all examined groundwater wells (Table 4) vary between 38 and 206 mg/l, which are within the permitted limits of FAO (Gameh et al., 2014) for irrigation (610 mg/l).

Freeze and Cherry (1979) classified water into four categories depending on the TDS value: Fresh water (TDS: 0-1000 mg/l); Brackish water (TDS: 1000-10,000 mg/l); Saline water (TDS: 10,000-100,000 mg/l); and Brine water (TDS>100,000 mg/l). As far as TDS values are concerned (Table 4), the maximum value of 80300 mg/l is associated with well 3BW1–Phil landfill followed by 70500 mg/l linked to well BW1–GEMS landfill. The minimum, maximum, mean and standard deviation are 1490, 80300, 38458.6, and 30855.5 mg/l, respectively. Results conclude that 36% of the groundwater samples are classified as brackish water, while the remaining 64% as saline water. Concerning the FAO standard limits, results demonstrate that slight to moderate restriction is associated with 14% of the samples, while sever restriction is linked to the remaining 86%.

The concentrations of the heavy metals (Table 5) were compared with the FAO maximum allowable limits (Table 2). Al, Co, Cu, Cr, Ni, and V were detected in 4BW1–Waste water disposal site and 3BW2–SEPCO landfill at levels higher than the permissible concentration limits. The corresponding values are 681mg/l and 235mg/l, 0.64mg/l and 0.16mg/l, 1.16mg/l and 0.261mg/l, 2.96mg/l and 0.792mg/l, 3.73mg/l and 0.734mg/l and 3.0mg/l and 0.65mg/l, respectively. Selenium was found in well 5AW1–Rashi farm at concentration of (0.03mg/l), which is slightly above the FAO standard limit of 0.02mg/l. Zinc was distinguished in three wells, 4BW1–Waste water disposal site (8.62mg/l), BW2–GEMS landfill and 3BW1–Phil landfill of 3.44 mg/l at level exceeding the permissible limit of 2.0mg/l. As and Cd values (Table 5) are less than the FAO standard limits.

Aluminium was seen in the water samples of 3BW2–GEMS landfill and 4BW1–Waste water disposal site at levels exceeded the permissible limit. The corresponding concentrations are 235mg/l and 681mg/l, respectively. As and Cd values (Table 5) are less than the FAO permissible limits. However, Iron and Manganese were found in 4BW1–Waste water disposal site at levels higher than permissible limits. The corresponding concentrations are 1170 mg/l and 16.2mg/l, respectively. The FAO maximum recommended values of Iron and Manganese in irrigation are 5.0 and 0.5mg/l, respectively (FAO, n.d.).

Table 4. Concentrations of various parameters of the water samples.

Sample	**EC (µS/cm)**	**Na (mg/l)**	**Ca (mg/l)**	**Mg (mg/l)**	**K (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**	**pH**	**HCO3 (mg/l)**	**TDS (mg/l)**
4BW1—Waste water disposal site	73100	11500	3790	1710	299	26900	1940	6.88	134	48700
AW1—Almustadama landfill	96500	17800	2890	964	369	37200	2770	6.95	62	67100
AW2—Almustadama landfill	84200	14200	3650	1710	214	32100	2310	7.02	71	47400
BW1—GEMS landfill	99900	16200	5670	1870	216	38700	1760	6.98	68	70500
BW2—GEMS landfill	95500	15800	4820	1620	178	37000	2080	7.13	48	67400
3BW1—Phil landfill	116000	19000	6420	2170	253	44900	1940	6.81	38	80300
3BW2—SEPCO landfill	92100	14900	4920	1680	242	35700	1620	6.48	99	64100
3CW1—Phil landfill	3330	308	299	39	15	483	929	7.97	93	2170
3CW2—Afaq landfill	86500	12400	5380	1870	192	33800	1530	4.58	0.8	60200
4BW2—Nabe ́a Farm	2310	342	85	47	14	542	282	7.58	206	1490
5AW1—Rashid Farm	15200	2000	873	213	15	3280	320	7.12	192	9960
6AW1—Salih Farm	16300	3090	461	114	75	5320	886	7.03	108	10800
6BW1—Jama ́an Farm	9910	1360	653	138	42	3820	258	7.15	62	6560
6CW1—Kuleya Village	2650	255	126	116	12	663	329	8.08	148	1740
Min	2310	255	85	39	12	483	258	4.58	38	1490
Max	116000	19000	6420	2170	369	44900	2770	8.08	206	80300
Mean	56678.6	9225.4	2859.8	1018.6	152.6	21457.7	1353.8	7.00	102.2	38458.6
Dev.S	44644.2	7461.4	2366.5	854.65	121.35	17641.8	844.4	0.8	53.6	30855.5

Table 5. Concentrations of the heavy metals of the water samples.

Values marked in **Bold** are higher than the standard limits.

Sample	Mg/l									
	Al	**As**	**Cd**	**Co**	**Cu**	**Cr**	**Ni**	**Se**	**V**	**Zn**
4BW1-Wastewater disposal site	**681**	0.059	0.0014	**0.64**	**1.16**	**2.96**	**3.73**	<0.01	**3.00**	**3.17**
AW1-Almustadama landfill	1.06	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.010	<0.01	<0.01	0.171
AW2-Almustadama landfill	1.74	<0.001	<0.0001	<0.001	<0.001	<0.012	0.0110	<0.01	<0.01	0.100
BW1-GEMS landfill	0.55	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	**8.620**
BW2-GEMS landfill	<0.02	<0.002	<0.0002	<0.002	0.0020	<0.002	<0.002	<0.02	<0.02	**3.440**
3BW1-Phil landfill	4.75	<0.002	<0.0002	<0.002	0.0210	0.0260	<0.002	<0.02	<0.02	**3.440**
3BW2-SEPCO landfill	**235**	0.0320	<0.0002	**0.160**	**0.2610**	**0.7920**	**0.7340**	<0.02	**0.65**	0.555
3CW1-Phil landfill	0.45	<0.001	<0.0001	<0.001	<0.001	<0.001	0.0020	<0.01	0.01	0.052
3CW2-Afaq landfill	0.45	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	<0.005
4BW2-Nabe ́a Farm	<0.01	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.01	0.01	0.008
5AW1-Rashid Farm	<0.01	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	**0.03**	0.02	<0.005
6AW1-Salih Farm	<0.01	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	0.044
6BW1-Jama ́an Farm	<0.01	<0.001	<0.0001	<0.001	0.0030	<0.001	<0.001	<0.01	<0.01	<0.005
6CW1-Kuleya Village	<0.01	<0.001	<0.0001	<0.001	<0.001	0.003	0.002	<0.01	0.01	0.047

3.2 Distance between the location of water samples and existing landfills

Table 6 shows the distances between the location of the water samples and the existing landfills in Rabigh. Results show that the distances vary between few meters to 14.4 kilometres. The degree to which the landfill site poses a risk to the quality of groundwater depends on the linkage between the three elements (source, pathway, and receptor). A specific-site risk assessment and management based on real-time data monitoring network and system along with a consistent regulatory framework of regulations and legislation, facilitates early detection of potential risks associated with operation of sanitary landfills and unauthorised dumping and intrusion of sea water. One of the main issues and challenges to sustainably managing the groundwater resources in terms of quantity and quality is the lack of reliable and informative data that could lead to inadequate and fragile plan and policies (Ranjith, 2012; Miezah et al., 2015).

Table 6. Calculated distances (km) between water samples and landfills.

Sample	**Landfill**						
	Almustadama 22 °39'19.00"N 39 °12'46.23"E	Rabigh 22 °38'51.62"N 39 °11'43.75"E	Afaq 22 °39'4.39"N 39 °11'19.37"E	SEPCO 22 °39'40.79"N 39 °11'26.74"E	Phil 22 °39'22.28"N 39 °11'29.33"E	GEMS 22 °39'33.95"N 39 °11'6.27"E	Al-Baladiya 22 °39'35.79"N 39 °10'4.27"E
4BW1–Wastewater disposal site 22 °38'14.40"N 39 °10'49.9"E	3.8	1.9	Afaq	2.9	2.4	2.5	2.8
AW1–Almustadama landfill 22 °39'12.20"N 39 °12'31.50"E	Almustadama	1.5	2.0	2.0	1.8	2.5	4.3
AW2–Almustadama landfill 22 °39'12.00"N 39 °12'30.00"E	Almustadama	1.5	2.0	2.0	1.8	2.5	4.3
BW1–GEMS landfill 22 °39'43.00"N 39 °11'12.00"E	2.7	1.8	1.2	0.4	0.8	GEMS	2.0
BW2–GEMS landfill 22 °39'43.70"N 39 °11'12.60"E	2.7	1.8	1.2	0.4	0.8	GEMS	2.0
3BW1–Phil landfill 22 °39'22.80"N 39 °11'32.60"E	2.0	1.0	0.6	0.5	Phil	0.8	2.6
3BW2–SEPCO landfill 22 °39'39.40"N 39 °11'20.70"E	2.5	1.5	1.0	SEPCO	0.5	0.4	2.0
3CW1–Phil landfill 22 °39'20.10"N 39 °11'39.10"E	2.0	1.0	0.6	0.5	Phil	0.8	2.6
3CW2–Afaq landfill 22 °39'9.00"N 39 °11'9.10"E	2.7	1.0	Afaq	1.0	0.7	0.7	2.0
4BW2–Nabe ́a Farm 22 °45'24.40"N 39 °15'36.30"E	12.3	13.8	13.9	12.8	13.3	13.4	14.4
5AW1–Rashid Farm 22 °42'5.70"N 39 °12'51.10"E	5.0	6.0	6.0	5.0	5.5	5.5	6.6
6AW1–Salih Farm 22 °44'33.40"N 39 °13'48.90"E	9.9	11.2	11.0	9.9	10.4	10.4	11.2
6BW1–Jama ́an Farm 22 °45'11.20"N 39 °15'18.40"E	11.7	13.3	13.2	12.2	12.6	12.7	13.7
6CW1–Kuleya Village 22 °38'11.20"N 39 °9'18.40"E	6.2	4.3	3.8	4.6	4.3	3.9	2.9

3.3 Linear Regression Modelling

Results of the linear regression modelling show that the relationships between the investigated variables fall between a moderate to a very strong relationship. The correlations coefficients range between 0.524 and 0.999. The minimum correlation coefficient was found between K and the HCO3 (r = 0.524) whereas the maximum was observed between Cl and EC (r = 0.999). Table 7 shows the correlation coefficients. The best model developed between the Cl and the EC associated with the highest correlation coefficient of (r = 0.999) is demonstrated in Figure 2. A very strong correlation coefficient was also linked to other relationships such as the model between the Na and the Cl (Figure 3) and the Na and the EC (Figure 4). Figure 5 shows a moderate negative relationship between HCO3 and K.

Table 7. Correlation coefficient (r)***** of linear models of various parameters of water samples.

Element	Na	Ca	Mg	K	Cl	SO4	HCO3	TDS	EC
Na	1	0.922	0.915	0.916	0.994	0.917	0.639	0.988	0.995
Ca	0.922	1	0.979	0.772	0.956	0.748	0.660	0.958	0.955
Mg	0.916	0.979	1	0.804	0.947	0.786	0.613	0.935	0.948
K	0.916	0.773	0.804	1	0.893	0.927	0.524	0.888	0.994
Cl	0.994	0.956	0.947	0.894	1	0.887	0.672	0.995	0.999
SO4	0.961	0.758	0.786	0.928	0.888	1	0.600	0.869	0.891
HCO3	0.639	0.660	0.613	0.524	0.672	0.600	1	0.658	0.656
TDS	0.988	0.958	0.936	0.888	0.995	0.869	0.658	1	0.995
EC	0.995	0.956	0.948	0.898	0.999	0.891	0.656	0.995	1

*** Confidence level: 95%**

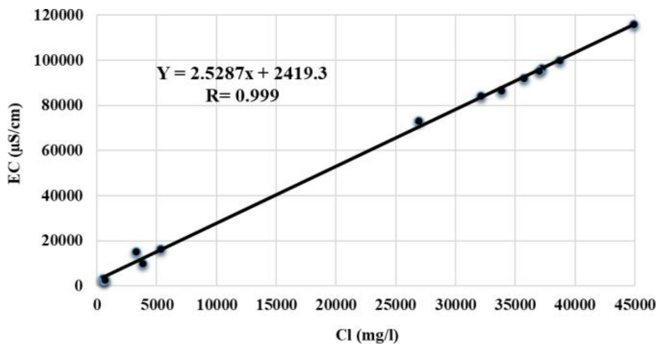

Figure 2 Linear regression model between the Chloride (Cl) and the Electrical Conductivity (EC).

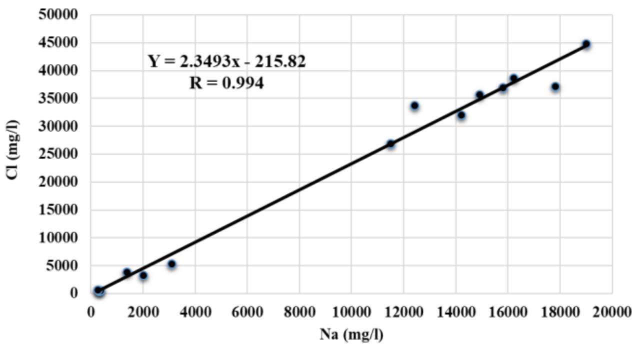

Figure 3 Linear regression model between the Sodium (Na) and the Chloride (Cl).

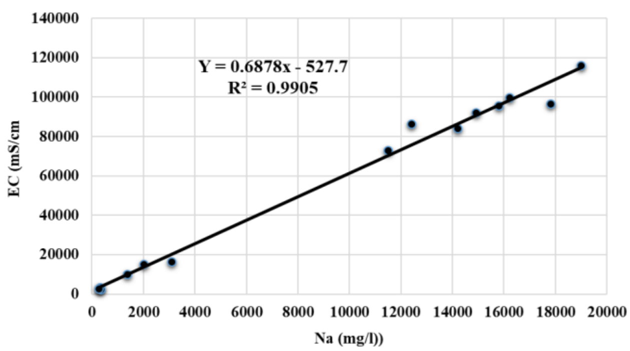

Figure 4 Linear regression model between the Sodium (Na) and the Electrical Conductivity (EC).

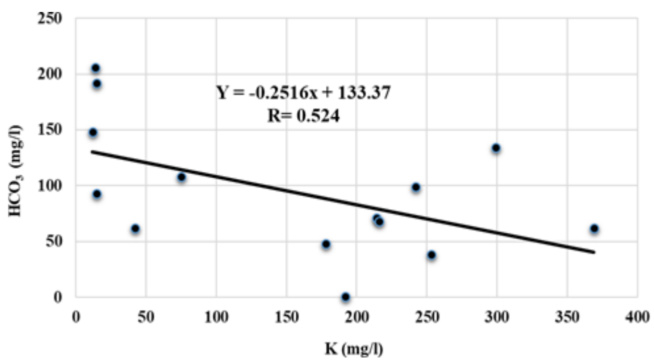

Figure 5 Linear regression model between the Bicarbonate (HCO3) and the Potassium (K).

4. Conclusions and Recommendations

4.1 Conclusions

This research aimed to examine the suitability of groundwater quality in Rabigh for irrigation using various water quality measures. Outcomes of this study supports water managers and decision makers in designing a robust plan and determining appropriate actions coupled with using integrated water resources management tools to sustainably use and protect groundwater from possible contamination sources, and to initiate a scheme of sustainable groundwater development and agriculture in the area.

Seven indices namely sodium percentage (Na%), Sodium Adsorption Ratio (SAR), Magnesium hazard (MH), Permeability index (PI), Total hardness (TH), Kelley´s ratio, and Soluble Sodium Percentage (SSP) were used to assess the suitability of groundwater in Rabigh for irrigation purpose. Wilcox and the FAO standard limits were also considered.

The domination of ions was in the order of Na>Ca>Mg>K and Cl>SO4>HCO3 for cations and anions, respectively. Elevated concentration of Na and Cl associated with a very strong relationships between Na and Cl (r = 0.994), Na and EC (r = 0.995) and between Cl and EC (r = 0.999) represents effects of Seawater intrusion and indicates the vulnerability of groundwater to Red Sea invasion. According to Wilcox and the FAO classifications of salinity (EC) in irrigation water, it can be concluded that the groundwater in the investigated area of Rabigh is undesirable for irrigation purposes.

A set of linear regression models associated with a moderate to a very strong correlation coefficients was established between various ions. Among the best models, the strength of correlation coefficient was in order Cl─EC>Na─EC=TDS─EC=TDS─Cl>Na─Cl=EC─K. The corresponding correlation coefficients are 0.999, 0.995, 0.995, 0.995, 0.994, and 0.994, respectively. A moderate negative relationship was seen between HCO3 and other parameters associated with a correlation coefficient falls between 0.524 and 0.672.

Based on Freeze and Cherry classification of TDS, the groundwater samples fall under the brackish to saline categories. However, saline water was recognised in the majority of the samples (64%). Concerning the FAO classification, 86% of the samples were classified under severe restriction for irrigation.

Concerning the categorisation of irrigation water based on sodium percentage, two-thirds of the water samples are in the doubtful to unsuitable categories. The very high electrical conductivity values obtained in the groundwater samples near the landfill sites are an indication of the combined effect of leachate and the Red Sea saltwater intrusion.

SAR serves as a universal measure to assess the suitability of irrigation water for agriculture. Severe restriction is associated to 65% of the groundwater samples according to FAO classification of SAR. Nearly two-thirds of the groundwater samples fall under the medium to high sodium hazard categories. According to Kelley’s ratio and soluble sodium percent, the majority of the groundwater samples (86%) show that groundwater is undesirable for irrigation purposes. The analytical results of SSP conclude that the majority of groundwater samples (86%) are undesirable for irrigated agriculture.

Analysis of total hardness reveal the 57% of the samples fall under the very hard category. However, about two-thirds of the samples are under hard to very hard categories, which would affect crop yields. The Mg ratios suggest that the majority of the samples (93%) fall under the suitable category.

The areas adjacent to landfill sites experience unauthorised dumping of solid wastes and disposal of waste waters. Results showed that samples taken from unauthorised waste water disposal site and some groundwater wells within the landfills area are contaminated by elevated concentrations of some heavy metals such as Aluminium (Al), Cobalt (Co), Copper (Cu), Chromium (Cr), Nickel (Ni), Vanadium (V), and Zinc (Zn), which are above permissible limits recommended by the FAO. The sample taken from the unlicensed site of waste waters disposal shows also high concentrations of Iron and Manganese that exceeded the corresponding permissible limits. This suggest that the indiscriminate dumping of solid waste and disposal of waste waters have a direct impact on groundwater quality and should be discouraged. These wastes generate pollutants that pose significant risks to public health and environment if not adequately monitored and managed. The elevated concentrations of some heavy metals in the groundwater wells that are located within and in close proximity of the landfill sites imply that the proximity to open dump site, waste water disposal site or landfill site is crucial to the groundwater contamination.

The effect of distance from permitted landfill site, unlicensed dump site, unlicensed waste water disposal site, and Sea water on groundwater contamination needs further investigations by drilling a set of observation wells at various distances to establish a proper correlation between distance and contamination. The overall conclusion indicates that the groundwater quality in the study area is not suitable for irrigation.

4.2 Recommendations

The main environmental concern in this study is the combined effect of landfills leachate and salt water intrusion of the Red Sea on groundwater quality and its suitability for irrigation purposes. The results support recommendations that are not limited to the current situation but could be considered of value to closed or unlicensed dump sites and/or unlicensed waste waters disposal as well as new landfills that require continuous monitoring as part of environmental risks assessments. The key recommendations are:

1. Design and establish a site-specific real-time data monitoring network based on the source-pathway-receptor linkage taking into account that groundwater plays the role of both pathway and receptor. The monitoring network of water quality and water level sensors and associated management programme should comply with regulatory standards of groundwater quality and landfill permission plan and implementation.
2. The vulnerability of groundwater should be evaluated against the potential hazards posed by a source (i.e. landfill leachate and salt water intrusion of the Red Sea) and whether or not there are any migration pathways which can allow contaminants to migrate from the source to the receptor.
3. Monitoring should be considered as a central part of a long-term risk assessment programme.
4. Observation wells should be drilled at various distances to properly monitor contaminant levels. The location of the observation wells should provide a full image about the spatial and temporal contamination with distance.
5. Further research work needs to be carried out considering a larger sample size of groundwater associated with analysis of soil and leachate samples.

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