International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Assessment of Groundwater Quality Resulting from Managed Aquifer Recharge of Treated Sewage Effluent, Wadi Fatimah, Saudi Arabia

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Abstract-*The disposal of treated sewage effluent (TSE) has acted as a recharge to the underlying shallow alluvial aquifer of Wadi Fatimah located in the western part of the Kingdom of Saudi Arabia. The aquifer recharge has significantly modified the groundwater chemistry of the aquifer. Thirteen groundwater samples were analyzed to assess the groundwater quality of the aquifer and to determine the irrigation potential of using the TSE mixed groundwater. The results show a significant reduction in the total ions as a result of mixing of TSE with groundwater thus improving the agricultural potential of groundwater of Wadi Fatimah.*

Keywords— *Agriculture, groundwater, irrigation, recharge.*

I. INTRODUCTION

An intentional banking and treatment of water in aquifer is termed as management of aquifer recharge or MAR (Dillon, 2005). It has been used to describe the emplacement of water within an aquifer under controlled conditions with the primary goal of increasing the water levels (Maliva et al., 2011). Quite often, MAR has been considered as a powerful management tool for meeting groundwater resources (Sheng and Zhao, 2015).

Tuinhoff and Heederik (2003) describe the types of MAR that uses techniques such as water injection wells and surface infiltration. Injection wells are commonly used for aquifer storage and recovery (ASR), and aquifer storage transfer and recovery (ASTR). They are ideal for urban setting because of minimal surface, no evaporation loss, algae or mosquitoes (Bekele et al., 2011). On the other hand, surface infiltration techniques uses ponds, basins, tanks, shallow buried trenches and can effectively be used for recharging near-surface aquifers (Maliva et al., 2011). MAR has the potential to convert aquifers that are currently saline and/or polluted to useful water supply aquifers by displacing or flushing the original water (Dillon, 2005).

Treated sewage effluent (TSE), also referred as the reclaimed or wastewater, is now widely appreciated as a valuable resource rather than simply being considered a disposal problem. In 2010, from the total 6.67 million m^3/day of municipal wastewater generated in Kingdom of Saudi Arabia (Al-Saud, 2010), 67% was either discharge via septic tanks/cesspools or was not treated at all because of the capacity issues with the wastewater treatment plants (WWTP). The remaining 33% was treated by WWTP and the TSE was disposed to tidal water in coastal areas, artificial lakes, or nearby *wadis* (Missimer et al., 2012).

Wadis (valleys) are elongate, ephemeral streams underlain by near-surface alluvial aquifers. According to an estimate, the Kingdom of Saudi Arabia (KSA) stores a volume of 64,000 x 10^6 m^3 of fresh water mostly in alluvial aquifers and the annual natural recharge is only 1200 x 10^6 m^3 (Dabbagh and Abderrahman, 1997). Over-abstracting the wadi aquifers for water supply and irrigation practices has lowered down the water levels and contaminating the aquifers (Elhadj, 2004).

As wadis are preferential locations for human habitations in the KSA and the only sources of fresh water, the geology, geomorphology, hydrogeology, and the groundwater quality of wadi aquifer systems have been studied for many years. Despite this large dataset of wadi aquifers, investigations focusing on the change in the groundwater quality of the wadi aquifers as a result of TSE disposal have never been carried out. Although Missimer et al. (2012) are in favour of restoring wadi aquifers by treated sewage effluent but their recommendation for wadi aquifers is primarily based upon the favourable hydraulic properties of the distal and middle segments of the wadis. A proper restoration of wadi aquifer by TSE would require an assessment of the groundwater quality after the disposal to decide if the groundwater after disposal is safe for the desired uses such as water supply or irrigation, etc.

Wadi Fatimah is one of the most important wadis in the western part of Saudi Arabia. Wadi Fatimah is important because it represents a primary source of water supply for these areas such as Al-Jamum, Haddah and Bahrah. It is an unconfined alluvial aquifer.

The rapid and fast growth of the industrial and human activity might have impacted the groundwater quality so Wadi Fatimah became an important area for several studies conducted in the past. Al-Kulibi (1994) and Bokhari (1998) studied the groundwater chemical quality and found that the electrical conductivity of the lower catchment is much higher than the upper catchment of the Wadi. Based on the water quality data from groundwater samples, Al-Yamani (2004) concluded that highly saline water in some parts of the Wadi Fatimah Aquifer might be attributed to the presence of semi isolated basins as s result of faulting. Subyani and Sharaf (2011) made an assessment of groundwater contamination related to toxic elements found in groundwater sample taken in winter 2004. Since then, no comprehensive groundwater quality data exists in the literature.

A project for wastewater treatment of Makkah Region has started in 2011. As part of that, treated wastewater has been discharged through a 3m diameter inlet pipe into the Wadi

Fatimah near Haddah area with capacity of 80,000 to 125,000 m³/day which might have affected the groundwater quality. This study assesses the groundwater quality of Wadi Fatimah resulting from continuously disposing treated sewage effluent (TSE) and uses various parameters to determine the suitability of TSE mixed groundwater for irrigation purposes.

II. Materials and Methods

A. Study Area

Wadi Fatimah originates about 100 kms, to the north of Makkah and flows to Red Sea, crossing the Jeddah-Makkah highway near Bahrah. Most of the industrial development and the increase in population have taken place in the lower catchment comprising the towns of Haddah and Bahrah. Wastewater Treatment Plant (WWTP) is located near Haddah. The study area trends northeast along the wadi channel for a distance of about 15 km. the southwest end of the study area is near to the Jeddah-Makkah dual carriageway and WWTP drain marks the northeast boundary of the area. The study area is shown in Figure 1.

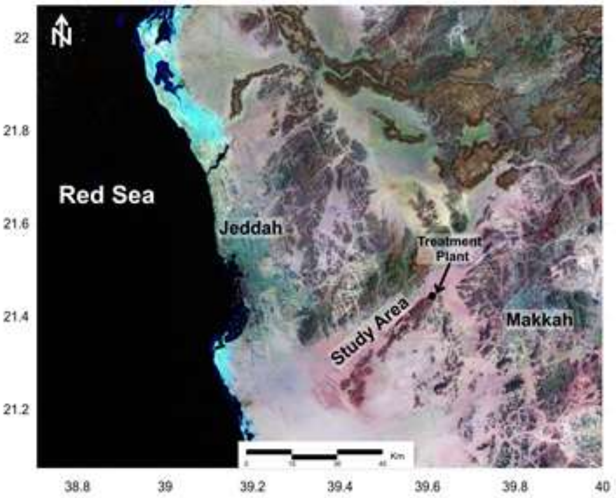

Fig. 1. Location of the study area.

B. Geology

From the geologic point of view, the study area comprises of Precambrian-Cambrian basement complex, Cretaceous-Tertiary sedimentary succession, the Tertiary-Quaternary basaltic lava flows, and the Quaternary-Recent alluvial deposits.

The Precambrian rock units in the study area consist of Late-Proterozoic basaltic to rhyolitic volcanic and volcanoclastic and epiclastics of primitive island-arc type, these rocks have been deformed and metamorphosed and injected by intrusive bodies of different ages and compositions.

The rock units are divided into Zibarah, Samran, and Fatimah groups (sedimentary rocks). Plutonic rock units are gabbro, diorite, tonalite and granodiorite to monzonite of probably early Cambrian ages (Figure 2).

Basalt lava flows from dis-continuous caps overlying the upper levels of both the basement complex and the sedimentary rocks. The lavas are either rest on penplain or infilled ancient valleys. They are preserved in three north – northwest trending, asymmetric depositional troughs which are the Sham, Suqah and Shumaysi troughs. These troughs are bounded in the north by faults downthrown to the west and in the west by an unconformity at the base of the easterly dipping strata.

Quaternary deposits cover large parts of the study area. The principle units of the Quaternary rocks are the terrace gravel, alluvial fan deposits, tallus deposits, alluvial sand and gravel of valley beds and some eolian edifices. The thickness of these deposits varies widely from one place to another.

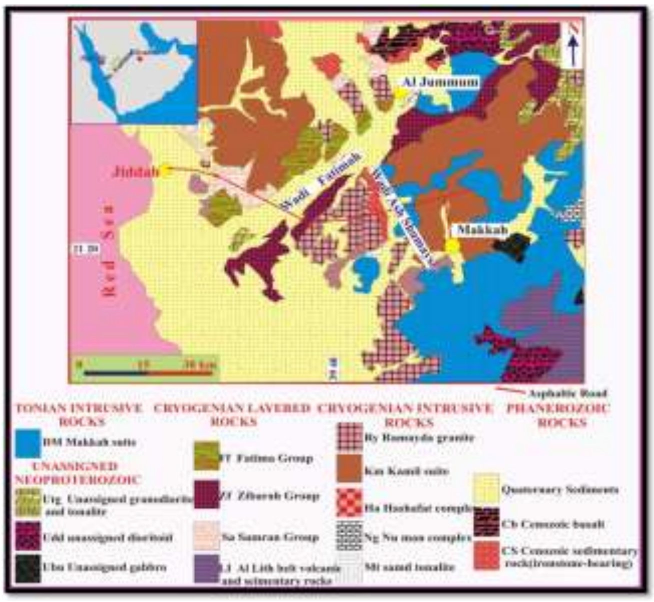

Fig. 2. Geology of the study area (Johnson, 2006).

C. Groundwater Sampling

A groundwater well survey was conducted downstream to the point of discharge of TSE to collect the hydrogeological field parameters and to identify the groundwater wells for collecting groundwater samples for geochemical analysis. Thirteen groundwater wells were selected (Figure 3).

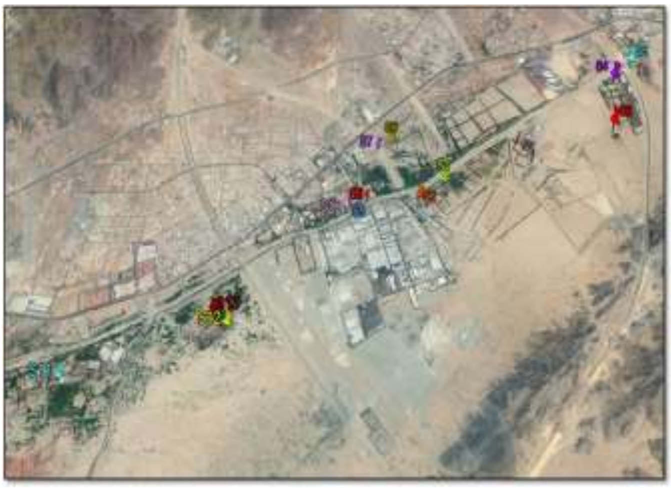

Fig. 3. Sampling location map of the study area.

Top of casing, depth to water level, electrical conductivity (EC), salinity, temperature and pH was measured at each well by using standard Solinst probe. Groundwater samples were collected from all the thirteen wells. The samples were collected in one-litre polyethylene bottles.

D. Agricultural Potential Calculations

Three parameters are commonly used to assess the suitability of water for agriculture. They are the sodium adsorption ratio, salinity index and sodium percentage analysis.

The sodium adsorption ratio (SAR) is an index of the potential of given irrigation water to induce sodic soil conditions. It is determined from the concentrations of the main alkaline and earth alkaline cations present in the water. It is also a standard diagnostic parameter for the sodicity hazard of a soil.

The formula for calculating the sodium adsorption ratio (SAR) is:

$$SAR = Na/ \{(Ca + Mg)/2\}^{1/2}$$

where sodium, calcium, and magnesium concentrations are expressed in milliequivalents/litre.

SAR allows to assess the state of flocculation or of dispersion of clay aggregates in a soil. Sodium and potassium ions facilitate the dispersion of clay particles while calcium and magnesium promote their flocculation. The behaviour of clay aggregates influences the soil structure and affects the permeability of the soil. In general, the higher the sodium adsorption ratio, the less suitable the water is for irrigation.

The salinity index or salinity hazard can be calculated from the electrical conductivity data and determines the amount of salts present in the irrigated water. The salts are generally originated from the high saline water table or dissolved minerals in groundwater. Any water used for irrigation (groundwater, TSE, etc.) having electrical conductivity less than 700 uS/cm is considered as good (Narany et al., 2014)

Ever since Wilcox (1955) used the sodium percentage analysis, this parameter has become a useful method for determining the suitability of water for irrigation purposes. The following equation can be used to calculate the sodium percentage:

$$Na\% = \{(Na + K)*100\}/(Ca + Mg + Na + K)$$

Irrigation water having less than 20 Na% is considered to be of excellent quality.

III. Results and Discussion

A. Water Quality

Table I summarizes water quality data obtained after performing chemical analysis on thirteen groundwater samples collected from the study area.

When compared with the drinking water standards of Saudi Arabia, the average values of all the cations and anions are found to be much higher than the standards. For example, drinking water standards are set at 200 mg/L for Na and Ca while average values of 576.9 mg/L and 253.6 mg/L were found for Na and Ca, respectively. Similarly, 966.1 mg/L of Cl and 441.0 mg/L of SO_4 was found as averages for Cl and SO_4 as compared to much lower values set in the drinking water standards for these anions.

TABLE I. Water quality data of groundwater samples.

Sample No	Na+K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO_3 (mg/L)	Cl (mg/L)	SO_4 (mg/L)
S1	942.7	380.7	119.17	305	1295.9	926
S2	447.8	116.2	44.9	274.4	479.4	336.2
S3	1540.1	865.7	211.6	183	3958	514
S4	94.43	24.05	29.2	306	177.5	41.3
S5	300.58	74.15	42.6	350.7	197.03	336.2
S6	1092.4	633.2	158.1	259.25	2218.7	960.6
S7	1142.7	741.4	177.54	201.3	2165.54	1563.4
S8	74.66	40.08	14.6	256.2	124.5	85
S9	197.3	56.11	19.5	228.75	213	105.7
S10	448.13	140.28	36.5	442.3	408.3	297.8
S11	502.6	64.13	29.2	274.6	550.2	144
S12	467.87	134.7	47.2	414.8	550.25	244.95
S13	248.82	26.05	8.5	335.5	221.8	177.7
Min	74.66	24.05	8.5	183	124.5	41.3
Max	1540.1	865.73	211.6	442.3	3958	1563.4
Average	576.9	253.6	72.2	294.7	966.1	441.0

TABLE II. Maximum acceptable concentration of various ions in the wastewater reuse for agricultural purposes (Environment, 2011; WHO, 2006).

Ions	Wastewater Reuse for Agriculture (KSA) (mg/L)	Average of ions present in wadi Fatimah (mg/L)
Calcium	230	253.6
Magnesium	-	72.2
Sodium	-	574.9
Sulfate	600.0	441
Chloride	100.0	966.2
TDS	2000	2666.4

When looked at the minimum and maximum values of common ions, an interesting scenario emerges. Minimum values, in general, were found to be originating from wells located in close proximity to the main wadi course carrying treated sewage effluent. On a similar note, S3 is farthest away from the main wadi course and the highest values of 1540.1 mg/L for Na+K and 3958 mg/L for Cl were found at this location. The groundwater chemical composition at S8 located at a distance of less than 150 m away from the wadi showed 74.6 mg/L for Na+K and 85.0 mg/L for Cl. When compared with the treated sewage effluent (Na=59.5 mg/L, Cl=62.4 mg/L), the chemical composition of S8 was found to be much closer compared to other samples. Because of the permeable nature of the alluvial deposits near the main wadi course, the recharge of treated sewage effluent has taken place resulting in the change in the groundwater quality.

In order to assess the change in the groundwater quality as a result of mixing of treated sewage effluent (TSE) with the groundwater, the present data were compared with the historic data of Wadi Fatimah prior to sewage disposal. This pre-TSE data was obtained from Al-Yamani (2004) who collected groundwater samples from the upstream as well as downstream reaches of Wadi Fatimah. As the thickness of Wadi Fatimah Aquifer is fault-controlled (deeper aquifer bottom in the upstream vs shallow downstream), only the downstream groundwater chemistry data were considered for this study. This area corresponds to the area subjected to the

TSE recharge. Figure 4 is a plot of average concentration of common ions of Wadi Fatimah before and after the TSE disposal. A significant downward trend in all the concentrations is quite visible. This plot represents the change in groundwater quality that has taken place as a result of TSE disposal over a period of three years (2011-2014). As the mixing would spread away from the main wadi course with the passage to time, a significant overall improvement of the groundwater quality of Wadi Fatimah is warranted.

B. Agricultural Potential

Table III classifies water quality on the basis of sodium absorption ratio. 61.5% of water samples falls in the category of excellent water quality while all the remainder samples are classified as "good." Therefore the risk of converting the Wadi Fatimah soil into alkaline soil as a consequence of using TSE as irrigation water does not arise. However, average concentration of most common ions present in in Wadi Fatimah Aquifer is somewhat higher than the wastewater reuse standards for agriculture in KSA (Table II). Average concentration of SO_4 is much lower than 600 mg/L standard set for wastewater reuse. Average TDS concentration was also found to be a bit higher than the standards.

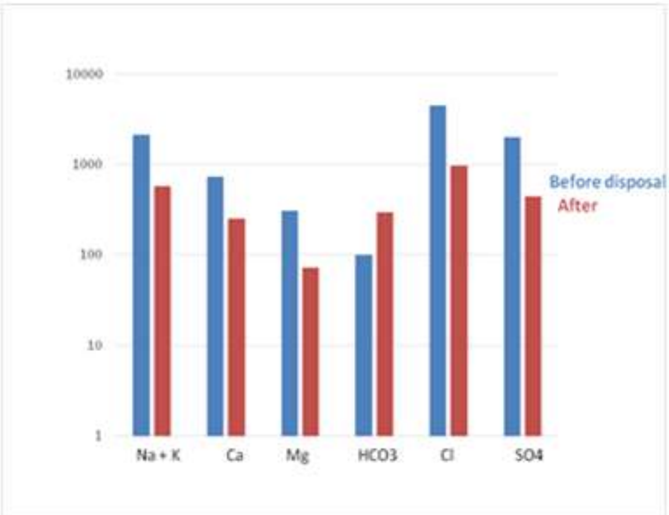

Fig. 4. Average concentration of most common ions (mg/L).

TABLE III. Classification of water quality on the basis of sodium absorption ratio (Narany et al., 2014; Todd, 1959).

Value of SAR	Water quality	Percentage
<10	Excellent	61.5%
10-18	Good	38.5%
19-26	Doubtful	-
>26	Unsuitable	-

Figure 5 plots the salinity index of groundwater samples. Again, S3 located far away from the main wadi course showed the highest EC (>16000 uS/cm) from all the thirteen groundwater samples. Although, few groundwater samples close to the main wadi course showed EC values much lower than S3, none of the water samples showed EC values in the "excellent" or "good" quality (<750 uS/cm).

TABLE IV. Classification of water quality on the basis of electrical conductivity (Handa, 1969; Narany et al., 2014).

EC (µs/cm)	Water salinity	Classification	%
0-250	Low (excellent quality)	Class I	-
251-750	Medium (good quality)	Class II	-
751-2,250	High (permissible quality)	Class III	31%
2,251-6,000	Very high	Class IV	38%
6,001-10,000	Extensively high	Class V	8%
10,001-20,000	Brines weak concentration	Class VI	23%
20,001-50,000	Brines moderate concentration	Class VII	-
50,001-100,000	Brines high concentration	Class VIII	-
>100,000	Brines extremely high concentration	Class IX	-

According to Table IV, 69% of groundwater samples can be classified as "high" or "very high" salinity while 23% are classified as brines with weak concentration. Out of all the IX classes suggested by Narany et al. (2014), majority of water samples falls in Class III or IV.

Lastly, groundwater of Wadi Fatimah Aquifer was classified on the basis of sodium percentage (Table V). None of the groundwater samples showed excellent or good water quality, however 46% of groundwater samples showed Na% of permissible quality. Equal number of water samples were classified as "doubtful." Na% for >90% water samples showed NA% less than 80. Water quality of only <10% was found to unsuitable. As the water quality classification for determining irrigation potential of groundwater are based on the chemical composition, a significant reduction in the total ions as a result of mixing of TSE with groundwater with time would result in improving the irrigation potential of groundwater of Wadi Fatimah.

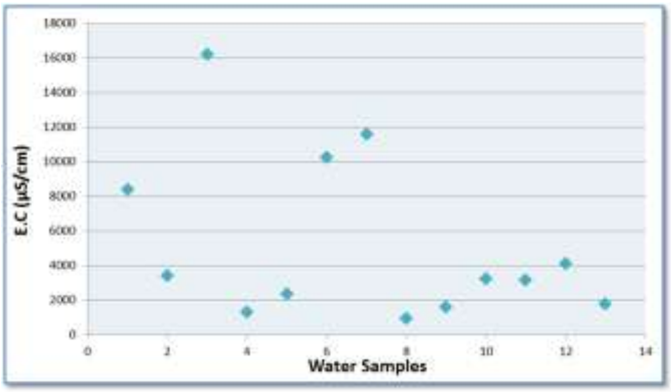

Fig. 5. Salinity index for groundwater samples for Wadi Fatimah area.

TABLE V. Classification of water quality on the basis of sodium percentage (Narany et al., 2014; Wilcox, 1955).

Sodium Percentage	Water Quality	Percentage
<20	Excellent	-
20-40	Good	-
40-60	Permissible	46%
60-80	Doubtful	46%
>80	Unsuitable	8%

IV. Conclusion

The assessment of groundwater quality of Wadi Fatimah as a result of treated sewage effluent (TSE) disposal has been made on the basis of hydrogeochemical analysis performed on groundwater samples. The results were compared with the pre-TSE mixed groundwater quality data. The results indicate that the discharge of TSE to Wadi Fatimah Aquifer has significantly lowered the concentration of most common ions and improved the groundwater agricultural potential of Wadi Fatimah.

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