EFFECTS OF CESSPOOL SYSTEMS ON GROUNDWATER QUALITY OF SHALLOW BEDROCK AQUIFER IN THE RECHARGE AREA OF WADI FATIMAH, WESTERN ARABIAN SHIELD, SAUDI ARABIA

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Abstract:

An investigation of the potential contamination of groundwater from on-site domestic wastewater systems blasted in weathered and fractured bedrock in the upper reaches of Wadi Fatimah basin, west of Saudi Arabia, was conducted during April, 2005. Impacts of on-site systems on the shallow aquifer are evidenced by the elevated concentrations of NO_3^- and Cl. The chemical analyses results of the groundwater samples, collected from private domestic wells in a residential site, show that the NO_3^- concentration in the groundwater exceeded the maximum contaminant level (MCL) of 45 mg/l. It ranges from 151 to 556 mg/l with an average of about 235.9 mg/l which is greater than the average background (16.3 mg/l) of the NO_3^- concentration in the undeveloped region within the wadi basin. The high NO_3^- content is a widespread pollutant that possessing a serious threat to the public health. Nitrate contamination is generally observed in close proximity to potential point waste sources. The dominant groundwater movement in the area is the major factor enhanced the groundwater deterioration by nitrate that leached from on-site wastewater disposal systems. Chloride-nitrate relationship has been used to differentiate the potential sources of Cl^-. Non of Faecal coliforms were detected in the groundwater samples even in samples with the highest NO_3^- concentrations, suggesting that residence time in fractured and weathered bed rocks was sufficient for bacterial die-off.

Keywords: Shallow bedrock aquifer, Groundwater pollution , nitrate concentration

Introduction

The shallow aquifer in Wadi Fatimah basin in the western Arabian Shield is considered the principal source of water supplies to the towns and villages. During the past two decades a rapid growth of population and development in these areas has led to concern about potential water quality impacts, because the absence of municipal sewer services.

Disposal of sewage in the residential areas have been accomplished almost exclusively through the use of conventional on-site sewage systems. A traditional on-site sewage system consists of a cesspool (Fig.1) and a subsurface absorption system. The cesspool is a shallow pit with different lengths and widths, and average depth of about 2 meters. It is poorly designed and often built by bricks. Under ideal conditions, the effluent is assimilated and treated within the top soil as well as the weathered and fractured column immediately below and adjacent to the cesspool. No regulations are implemented for setback distance and lot sizes requirements and its design and/or installation, to ensure that the vertical separation between the bottom of the cesspool and the water table is large enough so that unsaturated conditions will be maintained even during wet seasons.

Several investigations in the literature discussed the fate and movement of chemical constituents of septic/cesspool effluent into shallow groundwater (e.g. Duda and Cromartie, 1982; Yates, 1985; Scandura and Sobsey 1997; Amade, 1999; Rose et al., 1999; Whitehead and Geary. 2000). Generally, most concern appears to be related to NO_3^- and bacterial contamination of aquifers because of possible health problems from NO_3^-. Recently, the investigations carried out in the Wadi Fatimah by Sharaf et al., (2004) and Saudi Geological Survey (2004) shown that many of the domestic water supply wells, particularly in the upper reaches of the wadi extract waters with high NO_3^- concentration (120 mg/l) which is greater than the acceptable maximum contamination level (MCL) of 45 mg/l (10 mg/l of nitrate-nitrogen) by the World Health Organization (1998, 2000). The high NO_3^- contents of the groundwater are commonly linked to the nitrogen-based fertilizers used, with no particular attention given to the possible groundwater pollution by on-site sewage disposal systems used in these regions.

In the present study, the upstream part of the Wadi Fatimah basin, where Alsail Alkabir town lies on shallow aquifer, was selected to identify any impacts arising from on-site wastewater disposal systems used in relation to groundwater quality.

Description of The study Area

During the last 15 years, Alsail Alkabir town has been grown rapidly; more than 2000 residents are living within the town. This town is located at the recharge area of the Wadi Fatimah drainage at altitude of about 1200 meters above the sea level (Fig. 2).

The rock types of the study area consists mainly of batholith of pink granite, surrounded by intrusive rocks that mainly of dioritic and grnodioritic composition. The

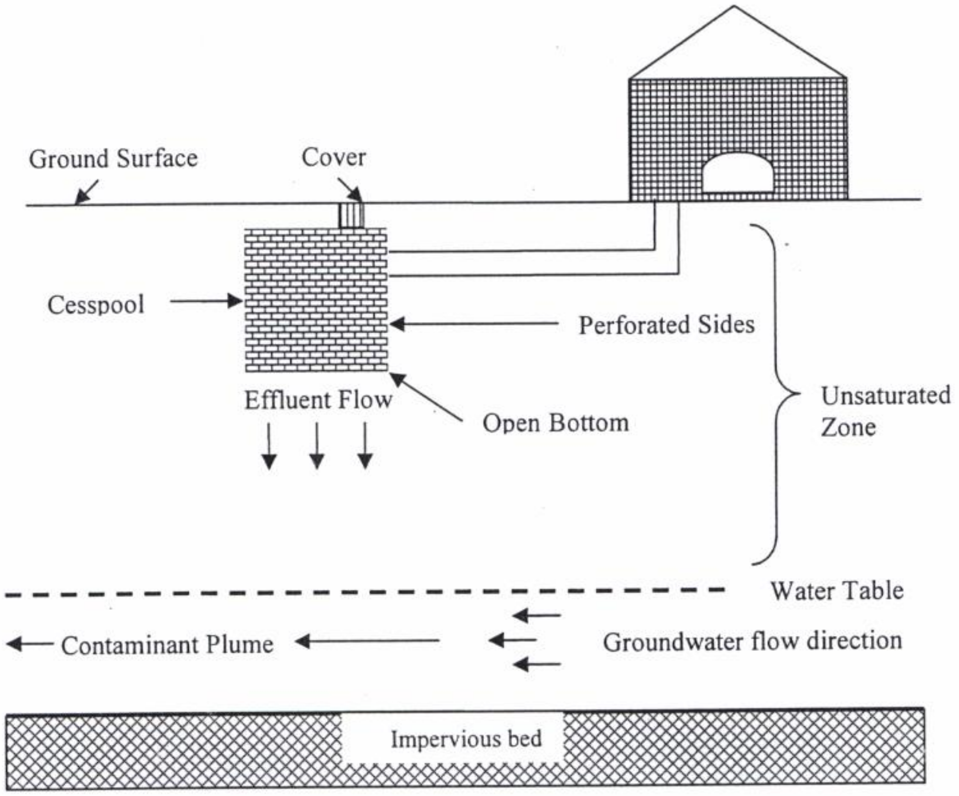


Figure 1. Traditional cesspool system used within the wadi basins.(not scale) .

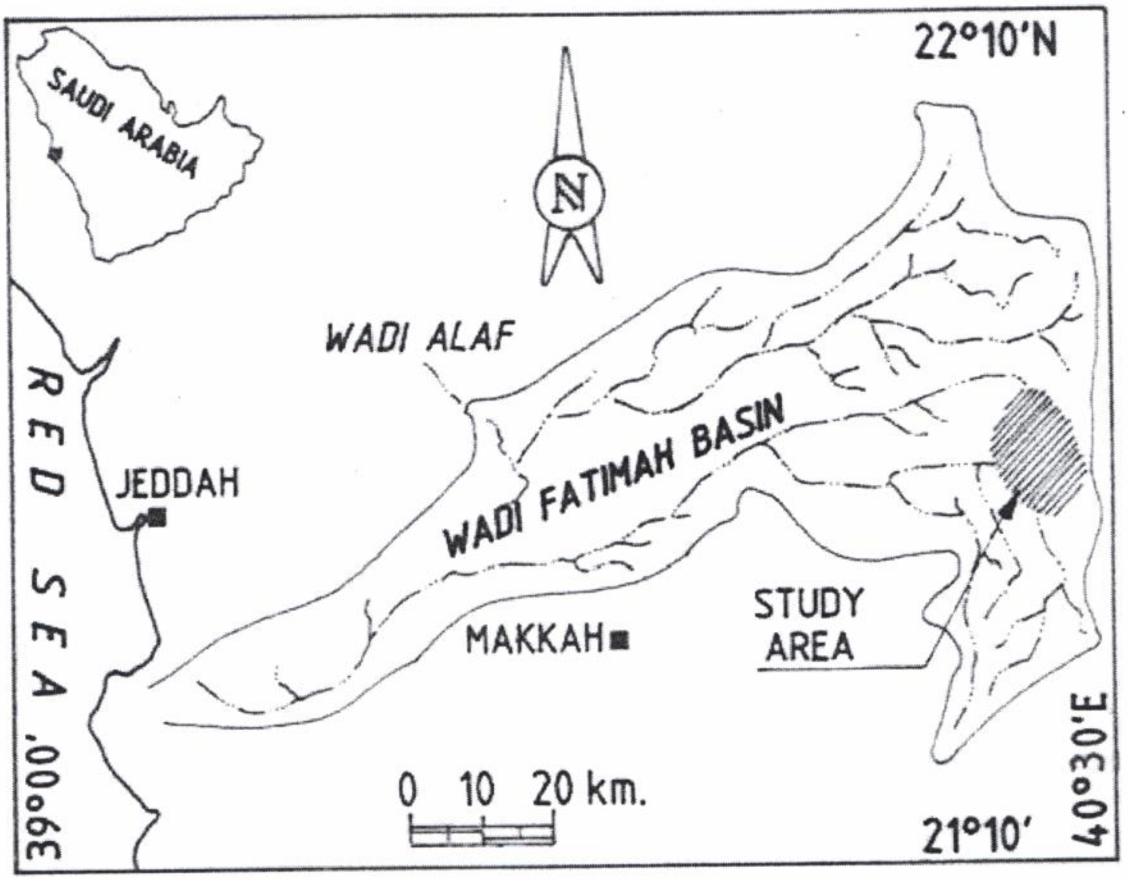


Figure 2. Location map of the study area.

batholith has a roughly circular outline about 7 km in diameter, and the contact of the pluton with its country rocks is sharp. The area has a gentle slope towards the west (Moore and Al-Rehaili, 1989). The Quaternary deposits almost found along the Wadi Harad that run from south to northeast direction (Fig. 3). These deposits range in size from course sand to pebble and gravel that serve as a permeable conduit for the percolation of surface water into the aquifers. In several places, the surface of the batholith is completely weathered down to 0.5 meter deep.

Over the study area, the rainfall is irregular and has torrential nature. The annual average rainfall is about 180 mm. The rainfall season is from December to May. December and January receive nearly about 70% of the annual rainfall. During the rest of the year, rainfall is limited to isolated events. The general recharge source of the aquifer has been commonly attributed to infrequent runoff events, which infiltrate to the water table promptly by a process much enhanced through the zone of aeration. During the recharge processes, the thin alluvial deposits overlying the bedrock become partly saturated. Throughout a short period of time, the water level considerably declines owing to the combined effects of evaporation processes and subsurface infiltration. The water table is generally shallow, resulting a recent recharge occurred. It almost varies between 4..4 to 6.8 m from the wadi floor. The wadi channel is topographically lower than the surrounding areas by nearly 1.5 m. Most of the existing wells have been dug into the bed rock and almost entirely penetrate the weathered and fractured zones. The major groundwater pumping from these zones, whereas supplies from the surficial deposits overlying the bed rock are commonly temporary and may deplete completely during the dry period (Alyamani and Hussein, 1995). Most of the drilled wells are placed along the main course of Wadi Harad. The most common type of well construction is the large diameter well, with an average diameter of 3 meters. The thickness of the fractured and weathered zones of about 12 m.

The groundwater is under unconfined condition and the groundwater flow (Fig.3) is from southeast to northwest. Due to the presence of fault-filling dike on the northern side, which acts as water barrier, the groundwater flow has been modified towards the west throughout Wadi Alyamaniyyah (Alyamani, in press).

Methodology and Sampling Collection

During April, 2005, a total of 23 groundwater samples were collected from private domestic water supply wells of the Wadi Harad (Fig.3). For comparison purpose, the background of groundwater chemistry was determined in 9 samples (Table 1) that were

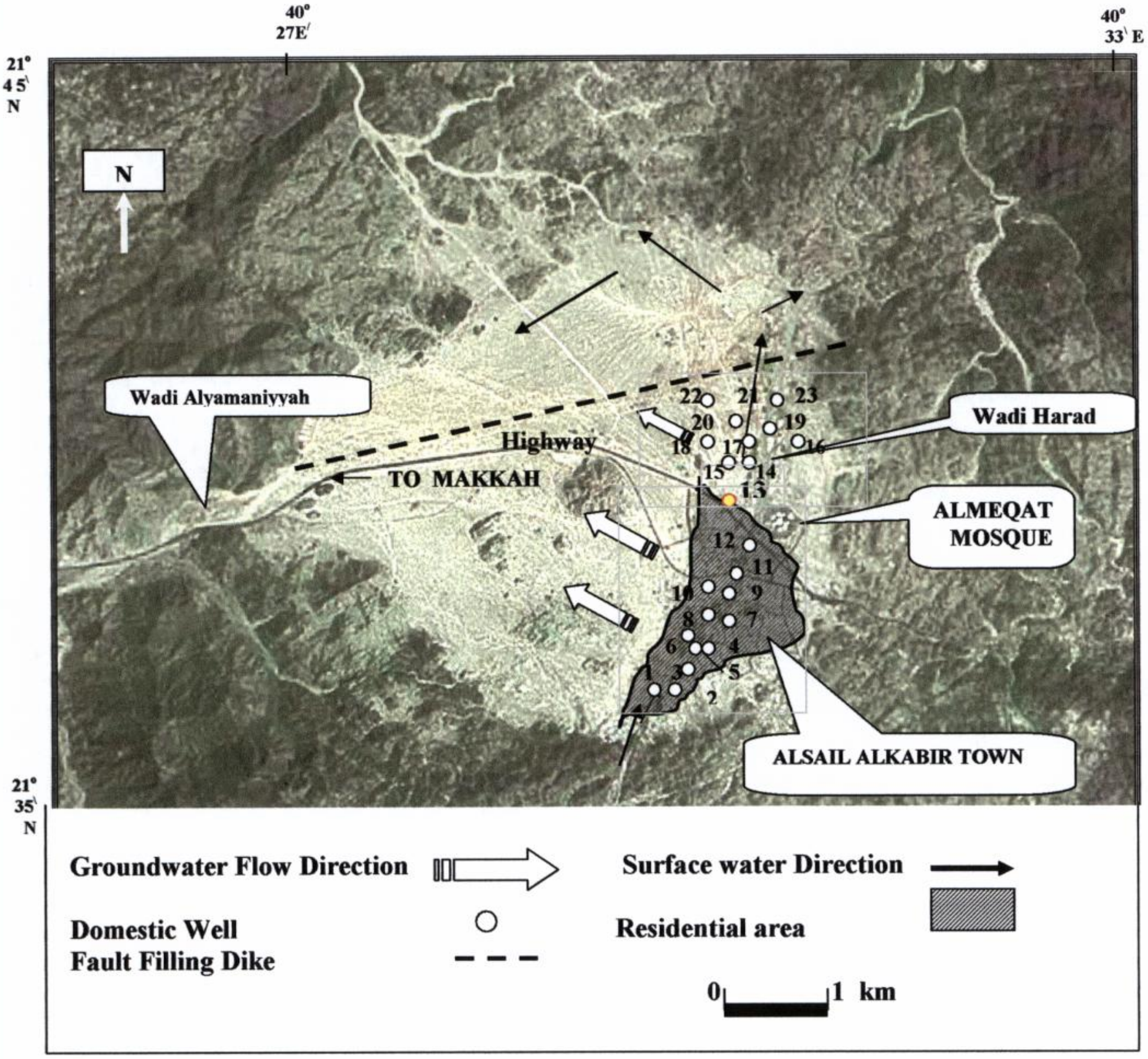


Figure 3. Well location map and groundwater flow direction.

collected from wells in Wadi Alaf, which least likely to be impacted by human activity (Fig.2). Groundwater temperature and pH were measured in situ. All the groundwater samples were analyzed for some major ions including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-), inorganic nutrients involved (nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_4^+) as nitrogen and phosphorus (PO_4^{3-}), and trace elements including lead (Pb), boron (B), manganese (Mn), zinc (Zn), and iron (Fe). Each well was pumped for at least 5 minutes prior to sampling. These analyses were carried out in the Faculty of Earth Sciences Laboratories, King Abdulaziz University. These elements were analyzed using the standard methods (APH/AWWA/WPCF, 1989) and ICP- Optical Emission Spectrometer, Optima 2000 DV. In the laboratory, the groundwater samples were biologically analyzed for total coliform, fecal coliform and fecal streptococci, dissolved oxygen (DO) and biological oxygen demand (BOD). The results of these chemical analyses are given in Table (2).

Results and Discussion

A comparison of the values in Table 2 with background concentrations (Table 1) indicates that the total dissolved solids (TDS) are generally elevated by an order of magnitude above the average background concentrations (Table 1), with nitrate and chloride concentrations being significantly elevated (Table 2). The Cl concentrations range from 103 to 289 mg/l, with an average of about 161.9 mg/l which is higher than the average reference of undeveloped area by an order of magnitude (71 mg/l). The NO_3^- concentrations increased from 151 to 556 mg/l with an average of about 235.9 mg/l, which is 15 times higher than the average background concentrations (16.3 mg/l). The concentration of SO_4^{2-} in water varies from 77.9 to 185 mg/l with an average of about 133.5 mg/l. The high concentrations of SO_4^{2-} probably due to the oxidation of pyrite (FeS_2), which is a very common accessory mineral in the country rocks (Moore and Al-Rehili, 1989)). The other major constituents such as Na^+ , Ca^{2+} and Mg^{2+} and HCO_3^- are slightly above the background concentrations. Concentrations of NH_4 are rather low and varied from 0.001 to 0.403 mg/l, whereas the NO_2 concentrations ranged between 0.003 to 0.092 mg/l with an average of 0.044 mg/l. On the other hand, there were significant differences in the concentrations of PO_4^+ and B where both elements are higher than the average background. The average concentration of PO_4^+ is 0.721, while it ranges between 0.065 and 4.16 mg/l and only 14 of 23 samples exceeded 0.70 mg/l.

Table1. Background concentrations (mg/l) of the groundwater and rain water.

Variable	**Average background groundwater chemistry Wadi Alaf) (9)**			**† Rain water chemistry (5)**
	Max	Min	Average	Average
Na^{+}	74.3	45.0	62.6	2.8
Ca^{2+}	168.0	77.4	108.5	3.5
Mg^{2+}	29.7	13.1	21.2	1.2
HCO_3^{-}	190.6	139.4	167.6	14.0
SO_4^{2-}	73.6	56.4	66.8	4.1
Cl^{-}	89.4	56.9	71.2	5.9
NO_3^{-}	28.7	2.04	16.3	-
NH_4^{+}	0.017	0.010	0.0122	-
PO_4^{3-}	0.10	0.046	0.063	-
Fe	0.13	0.005	0.0485	-
Mn	0.008	0.004	0.0064	-
Zn	0.079	0.008	0.0293	-
Pb	0.0049	0.0015	0.0037	-
B	1.26	0.37	0.653	-
TDS	572.1	433.4	515.4	-
DO	1.51	1.04	0.32	-
BOD (5-day)	-	-	-	-
Water temp. (°C)	30.4	33.9	30.6	-
pH	7.44	7.56	7.11	7.3

( ) in the brackets, the number of groundwater samples.

† After Alyamani and Hussein (1995).

Table 2. Chemical analyses results of the groundwater in (mg/l) of the study area.

Sample No.	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	NO_2	NH_4^+	PO_4^{3-}	Pb	Zn	Mn	B	Fe	pH	DO	BOD	Temp. (°C)	TDS
1	67	185.2	45.8	197.7	104	161	151	0.054	0.013	0.896	0.033	0.009	0.001	2.67	0.011	7.33	1.79	0.34	29.8	1055.7
2	46	165.5	44.6	132.2	156	109	244	0.072	0.021	0.945	0.0027	0.004	0.001	2.21	0.02	7.12	1.8	0.96	29.7	900.2
3	109	198.3	46.2	200.1	139	197	274	0.058	0.005	0.792	0.03	0.0082	0.001	2.02	0.015	7.44	1.69	0.56	30.1	1164.2
4	48	144.2	32.9	187.0	87	133	294	0.064	0.029	0.859	0.039	0.0085	0.001	2.2	0.018	7.22	1.77	1.1	30.5	783.9
5	66	185.2	50.6	188.2	97	199	153	0.005	0.014	0.654	0.033	0.007	0.011	4.16	0.018	7.45	1.98	0	30.3	1173.8
6	33	165.4	39.9	187.0	107	163	271	0.085	0.013	0.965	0.02	0.0085	0.014	3.29	0.016	7.2	1.1	0.8	30.1	967.4
7	82	195.4	45.9	234.7	77.9	157	232	0.049	0.005	0.802	0.032	0.013	0.015	2.73	0.022	7.44	1.91	0.67	29.7	1025.8
8	45	193.6	52.0	226.3	143	144	197	0.005	0.004	0.843	0.01	0.015	0.02	3.08	0.024	7.34	1.43	0	30.4	1001.3
9	55	177.2	41.3	194.2	119	121	177	0.071	0.025	4.16	0.021	0.031	0.04	0.93	0.32	7.44	1.44	0	30.3	888.8
10	39	178.8	55.1	172.7	161	103	387	0.055	0.022	1.30	0.005	0.017	0.018	2.94	0.022	7.38	0.9	1.03	31.2	863.2
11	49	408.5	54.8	148.7	152	158	163	0.003	0.004	1.02	0.009	0.028	0.012	8.54	0.025	7.15	1.45	0.9	30.6	1134.6
12	68	175.1	40.4	262.1	102	174	381	0.056	0.016	0.829	0.024	0.009	0.018	3.09	0.018	7.15	1.85	0.4	29.9	1203.5
13	82	113.4	59.8	207.3	108	289	556	0.092	0.403	0.95	0.008	0.015	0.015	4.06	0.02	7.23	2.45	1.22	29.3	1416.6
14	66	187.2	35.6	115.5	185	151	188	0.045	0.005	0.078	0.007	0.071	0.051	0.80	0.15	7.22	1.41	0	31.2	928.5
15	78	191.1	37.0	128.6	112	175	167	0.003	0.061	0.087	0.0062	0.001	0.004	0.90	0.011	7.1	1.52	0.34	30.8	889.0
16	67	191.1	36.7	123.9	133	133	201	0.006	0.038	0.093	0.0057	0.001	0.006	1.19	0.02	7.43	0.9	0.51	30.3	886.0
17	71	177.5	38.8	139.2	173	143	156	0.07	0.074	0.090	0.004	0.001	0.008	1.05	0.015	7.35	1.48	0	30.5	898.9

Table 2. Continue

Sample No.	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	NO_2^-	NH_4^+	PO_4^{3-}	Pb	Zn	Mn	B	Fe	pH	DO	BOD	Temp. (°C)	TDS
18	84	175.2	35.7	186.4	156	154	188	0.042	0.013	0.082	0.0022	0.001	0.004	0.98	0.015	7.52	1.66	0	30.4	979.0
19	97	210.9	37.1	132.2	106	168	218	0.063	0.053	0.067	0.0026	0.0093	0.005	1.59	0.019	7.22	0.8	0	30.8	969.5
20	77	175.1	35.3	168.1	177	163	191	0.022	0.001	0.84	0.033	0.0093	0.061	1.03	0.046	7.1	1.26	0.52	31.3	987.5
21	86	175.5	35.1	154.8	174.5	187	186	0.046	0.001	0.065	0.0029	0.009	0.009	0.9	0.018	7.45	0.94	0.32	30.6	999.2
22	81	128.4	38.5	190.6	117	198	266	0.043	0.001	0.065	0.013	0.339	0.008	1.15	0.022	7.24	1.44	0.41	30.3	1019.6
23	67	164.3	36.5	220.7	183	145	184	0.005	0.023	0.097	0.0065	0.363	0.002	1.05	0.021	7.2	1.54	0.29	31.2	1001.1
Max	**109**	**408.5**	**59.8**	**262.1**	**185**	**289**	**556**	**0.092**	**0.403**	**4.16**	**0.039**	**0.363**	**0.061**	**8.54**	**0.32**	**7.52**	**2.45**	**1.22**	**31.3**	**1416.6**
Min	**33**	**113**	**32.9**	**115.5**	**77.9**	**103**	**151**	**0.003**	**0.001**	**0.065**	**0.0022**	**0.001**	**0.001**	**0.80**	**0.011**	**7.1**	**0.8**	**0**	**29.3**	**783.9**
Average	**67.9**	**185.2**	**42.5**	**178.2**	**133.5**	**161.9**	**235.9**	**0.0443**	**0.0367**	**0.721**	**0.0152**	**0.0425**	**0.0141**	**2.29**	**0.0385**	**7.29**	**1.50**	**0.451**	**30.4**	**1006.0**

On the other hand, boron concentrations varied from 0.8 to 8.54 mg/l and the average reaches upto 2.29 mg/l. The Pb concentrations range between 0.0022 and 0.039 mg/l, with an average of 0.0152 mg/l. From the 23 samples, only 7 samples are greater the drinking water standard (0.01mg/l). The groundwater was oxygenated where the dissolved oxygen (DO) ranged between 0.8 and.2.45 mg/l, with an average of about 1.50 mg/l. Oxygen enters groundwater through recharge of oxygen-enriched water that percolates down through the aerated zone. The biological oxygen demands (BOD) varies from zero to 1.22 mg/l and average of about 0.451 mg/l

The studied area represents the recharge zone of the Wadi Fatimah basin. It receives a yearly recharge rate greater than 180 mm/yr. One would expect that the prevalent chemical composition of the groundwater is relatively close to that observed either in rain water or at least to that in the undeveloped area (Table 1). Nevertheless, it rather reflects that in all respects, some of its elements concentrations particularly NO_3^-, Cl^- are much higher than those in the background chemistries of both rain water and groundwater in undeveloped area.. It has also observed that the NO_3^- concentrations are randomly distributed. The variations in NO_3^- contents and the other constituents along the main course of Wadi Harad might be attributed to the changes of local flow in fractured media and might have affected the enrichment of NO_3^- from off-site sources. However, such disparity may indicate that the groundwater has been affected by on-site sewage disposal systems used in the study area.. In unsewered residential area and shallow groundwater, both NO_3^- and Cl are the most significant contaminants associated with domestic wastewater (EPA, 2004). Chloride (Cl^-) is a good indicator parameter of sewage impacts because it is not subject to adsorption, ion exchange, or oxidation-reduction "redox" reactions. To differentiate the potential sources of Cl^- and NO_3^- in the groundwater of the study area; the plots of NO_3^- vs Cl^-, Na^+ vs Cl^-, Cl^- vs $NO_3^- + Na^+$ and NO_3^- vs dissolved oxygen (DO) are shown in Figures 4 and 5. The relationship between NO_3^- and Cl^- in an area of known cesspool system contamination is shown in Figure 4a. It appears that Cl almost increases linearly with increasing NO_3^- with correlation coefficient (r^2) of about 0.61. On the other hand, the relationship between Na and Cl ions was given (Fig. 4b), which might be practically utilized to identify the concentration due to evaporation processes (Eugster and Jones, 1979). Figure 4b shows a weak correlation with ($r^2 = 0.30$). The data also indicate that the points are randomly distributed and lie far from the halite dissolution line (1:1), indicating that halite salt resulted from the evaporation processes is not the potential source for Cl^- ion. The observed deviation of the data points from the dissolution line might be resulted from an excess of Cl^- ions. It is more likely that the Cl ions entered the groundwater by wastewater discharged from on-site systems that used in the area to groundwater. Figure 5a demonstrates that neither Na^+ nor NO_3^- is by themselves sufficient to account for the Cl^-

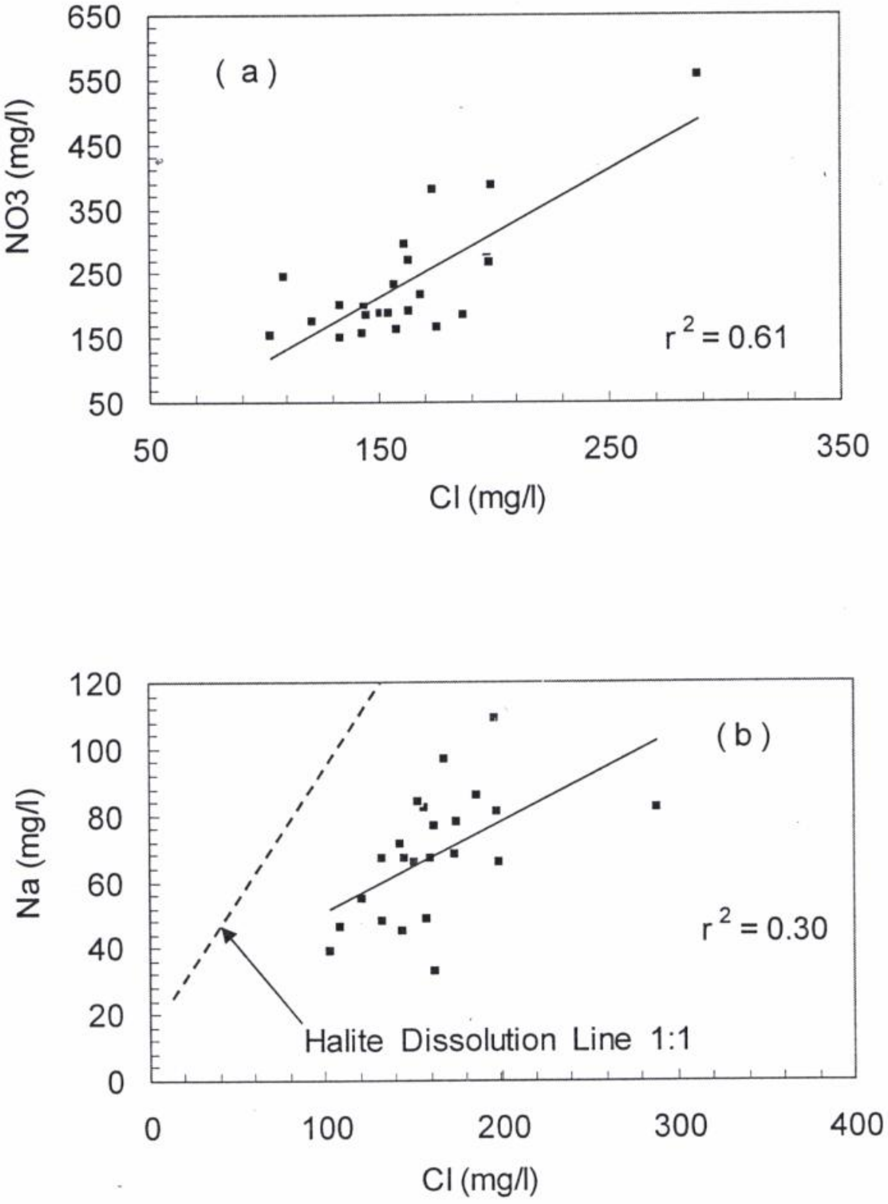
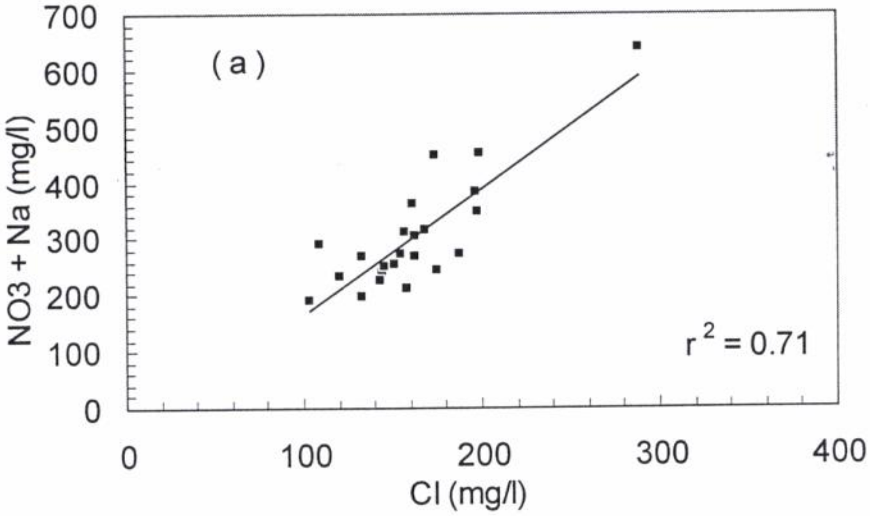


Figure 4. Correlation diagrams showing the relationship between (a) NO_3 vs Cl; and (b) Na vs Cl.



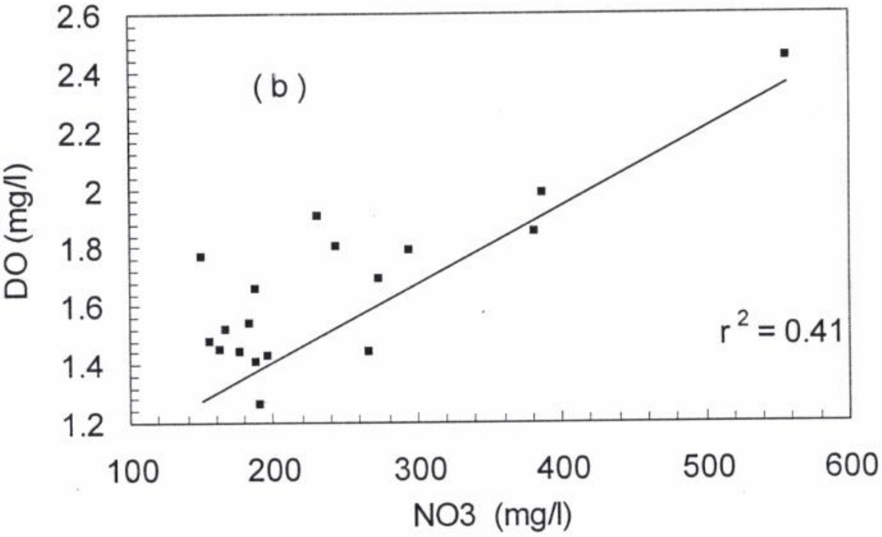


Figure 5. Correlation diagrams showing the relationship between (a) Na+NO_3 vs Cl; and (b) NO_3 vs dissolved oxygen (DO).

in the groundwater. But together these two elements do balance to some extent ($r^2 = 0.71$) the concentration trend of Cl^-. The contribution of NH_4^+ to the overall nitrate concentrations in the groundwater can be depicted from the positive relationship between NO_3^- and dissolved oxygen (DO) (Fig.5b). It demonstrates that the NH_4^+ concentrations in the groundwater may be lost due to microbial conversion to nitrate (nitrification process). However, in oxic conditions, the ammonia in sewage can be oxidized to nitrate that normally occurs in the unsaturated zone before effluent percolates to groundwater.

Coliform bacteria were not detected, even in samples with the highest NO_3^- concentrations, suggesting that substantial residence time of these waters in fractured and weathered rocks was sufficient for bacterial die-off (Geary and Whitehead, 2001).

Two significant factors may account for the movement of contaminants from on-site wastewater systems to the groundwater. Firstly, the local groundwater flow system (Fig.3) where the domestic wells are surrounded by areas where cesspools are present; the general flow direction of the groundwater, which is from southeast to northwest direction, seems to be passes through areas with cesspools before it gets to the domestic wells. Figure 6 represents a conceptual pollutant transport model in fractured media from the cesspool areas to the groundwater storage in the study area (not scale). Such effects of groundwater flow on the groundwater contamination can be traced from the maximum values of NO_3^- (556 mg/l) and Cl^- (289 mg/l) that recorded in well no. 13. This well is located in the vicinity of the "Almegat Mosque" (Fig.3), where is closely spaced from the wadi course. Almegat Mosque is a holy place annually visited by several thousands of pilgrims before starting the pilgrimage gurney to Makkah, the holy city. It is that expected a large amount of sewage water seeps through the weathered and fractured zones to the wadi. The volume of wastewater that derived from the mosque is unknown, but it seems to be quite large as evidenced by the high concentrations of NO_3^- and Cl observed; and secondly, when the number of homes are built in close proximity where their cesspool leaching field may together exceed the rock and sediment's absorption capacities.

On the other hand, under the prevailing groundwater flow and NO_3^- pollution of recharge zone, the NO_3^- is easy to move down further and follows the groundwater flow direction in this area. Therefore great concern should be paid to contaminants flow to other surrounding areas particularly Wadi Alyamaniyyah sub-basin in downgrdient flow, where the groundwater flowpath has been modified to the wadi sub-basin (Fig.3). Therefore, it may necessary to assess the groundwater quality and to identify any impacts arising from on-site wastewater disposal systems being utilized in the study area.

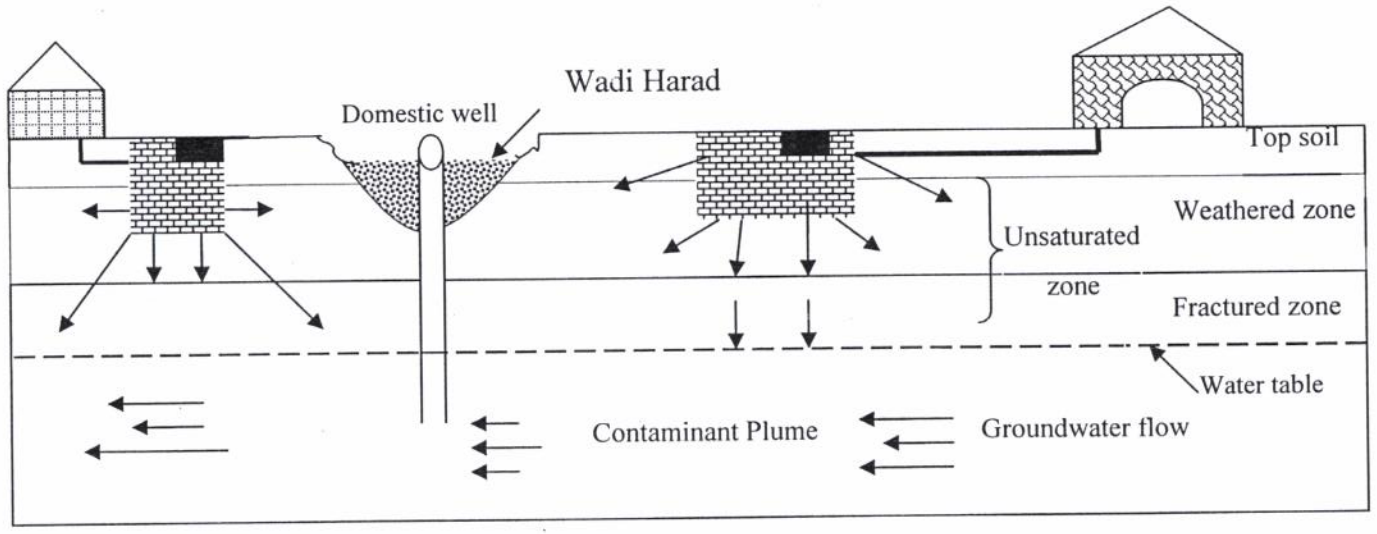


Figure 6. Conceptual model of contaminant flow from the cesspool to the groundwater body in the study area (not scale).

Questions must be posed as to the adequacy under the new (EPA, 2000) regulations of the minimum thicknesses requirement (between 0.9-1.2m) of soil to prevent bacteria and viruses from entering groundwater. It must be kept in mind that the EPA manual requires 1.2 m of unsaturated subsoil beneath the invert of the percolation trench. In many parts of the area studied, the water table is within 2.0 to 3.0 m of the surface particularly in the wet weather, where the thickness of unsaturated zone been decreased. This figure therefore must be taken into consideration with many other factors mentioned above and not used on its own.

It is beyond the objective of this paper to present a comprehensive assessment of cumulative and comparative risk for the study area. The average concentration of NO_3^- is about 235.9 mg/l. This is 5 times above the risk value of the drinking water level (45 mg/l; as 10 mg/l of nitrate-nitrogen). Increasing NO_3^- concentrations will continue as long as on-site systems contribute significantly to the risk value. Therefore, to deal with potentially degrading water quality from cesspool wastewater systems as well as to decrease exposure risk, regulations for cesspool systems that used in the area should be implemented.

Conclusions

In nominate area; nitrate represents the chemical of greatest concern in the groundwater under unsewered developments. The nitrate concentration in the groundwater ranges between 151 and 556, mg/l with an average of about 235.9 mg/l that exceeds the drinking water standard. Impacts from on-site systems on the shallow aquifer are highly witnessed as evidenced by the elevated concentrations of NO_3^- and Cl. Nitrate contamination is generally observed in close proximity to potential point waste sources. Coliform bacteria have not been detected in the groundwater samples, which may be due to that the substantial residence time of these waters in fractured and weathered rocks was sufficient for bacterial die-off. Lot-size and setback distances of the cesspool are critical factor in determining the amount of natural attenuation that occurs between the location where cesspool effluents enter the aquifer, and the nearest down-gradient point of groundwater withdrawal. Recommendations are provided for better source water protection.

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Acknowledgement

The author is grateful to Profs. Z. Hamimi and O. Hijab for their critically reading and constructive comments on the manuscript.