



Hydrogeochemistry and Microbiology of Wadi Al Bih Limestone Aquifer in Northern United Arab Emirates

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ABSTRACT: This study investigated the hydrogeochemical characteristics and microbiological pollution of groundwater in Wadi Al Bih limestone aquifer, Ras Al Khaimah area, northern United Arab Emirates (UAE). Results indicate that the decrease of groundwater exploitation in Wadi Al Bih basin from 58 million cubic meter (MCM) during the period 1991-1995 to 22 MCM during the period 2011-2015, has increased groundwater storage, raised hydraulic heads by 1 m in Al Burayrat area and 16 m near Wadi Al Bih main dam, and decreased the average groundwater salinity by 30% in Wadi Al Bih well field and 45% in Al Burayrat well field. Results of chemical analyses showed noticeable fluctuations in groundwater temperature, EC, and TDS contents, rather than concentrations of all ions. The November 2014 and June 2015 isosalinity contour maps indicate that the groundwater salinity increases from east to west, in the direction of groundwater flow. The groundwater in the eastern part of Wadi Al Bih is good for domestic purposes and irrigation. However, the water hardness is high because the aquifer is predominantly composed of limestone. Wadi Al Bih limestone aquifer is highly sensitive to urban and agricultural activities, and several wells were recorded to have Coliform bacteria in Wadi Al Bih and Al Burayrat areas.

Keywords: Hydrogeochemistry, Microbiology, Ras Al Khaimah area, United Arab Emirates, Wadi Al Bih limestone aquifer

I. INTRODUCTION

Wadi Al Bih area is bounded by Latitudes 25°46' and 25°48' North, and Longitudes 56°00' to 56°05' East, which corresponds to 2850 and 2854 North, and 402 to 408 East, on the Universal Transverse Mercator (UTM) grid system (Fig. 1). The area includes Wadi Al Bih well field, which is located between the main dam in the east and an earthen dam at the entrance of the Wadi. The study area also includes Al Burayrat well field, which is located within the alluvial fan of Wadi Al Bih. These water-well fields belong to the Federal Electricity and Water Authority (FEWA) and represent the main source of the domestic water supply for Ras Al Khaimah city. Wadi Al Bih field includes 38 wells, with a depth ranging from 100 to 200 m, which supply groundwater to Al Burayrat desalination plant (Photo 1).

Several studies were conducted to investigate the hydrogeology and hydrogeochemistry of Wadi Al Bih. In the present, the basin is under the continuous supervision of the Ministry of Climate Change and Environment (MOCCAE), which has developed a database for climatologic and hydrologic data for Wadi Al Bih basin. The first detailed hydrogeologic survey of the study area was a part of Wadi Al Bih dam project [1]. The study assessed the hydrogeologic conditions as the follows "the area is characterized by a thin soil layer and scarce vegetation cover, good runoff potential and negligible storage capacity. These conditions favour flash floods and provide limited groundwater recharge". During the period 1984-1992, the International Atomic Energy Agency (IAEA), in cooperation with the Ministry of Energy and Water in the UAE, collected water samples from Wadi Al Bih basin for isotope hydrology investigations. Analysis of water resources in Wadi Al Bih alluvial fan area and their role in agricultural development was also studied [2]. This study used the climatic parameters to establish a water budget for Wadi Al Bih basin and estimate flood volumes under different climatic conditions. Several water resources studies were carried out on northern UAE, including Wadi Al Bih basin [3, 4, 5, 6, 7, 8].

II. MATERIALS AND METHODS

1. Field Work

Field work for the present study was conducted in November 2014 and June 2015. On November 22nd 2014, thirty four (34) water wells in Wadi al Bih and Burayrat areas were sampled, and on June 15th 2015, thirty three (33) water samples were collected from the same wells. In November 2014, four wells (WB22, WB27, Bu23 and Bu26) were under maintenance and were not sampled (Fig. 1; Table 1). In June 2015 Wells (WB14, Bu28, Bu11, Bu Dam and Main Dam) were not sampled because wells were under maintenance, and dam reservoirs were not sampled because they were dry.

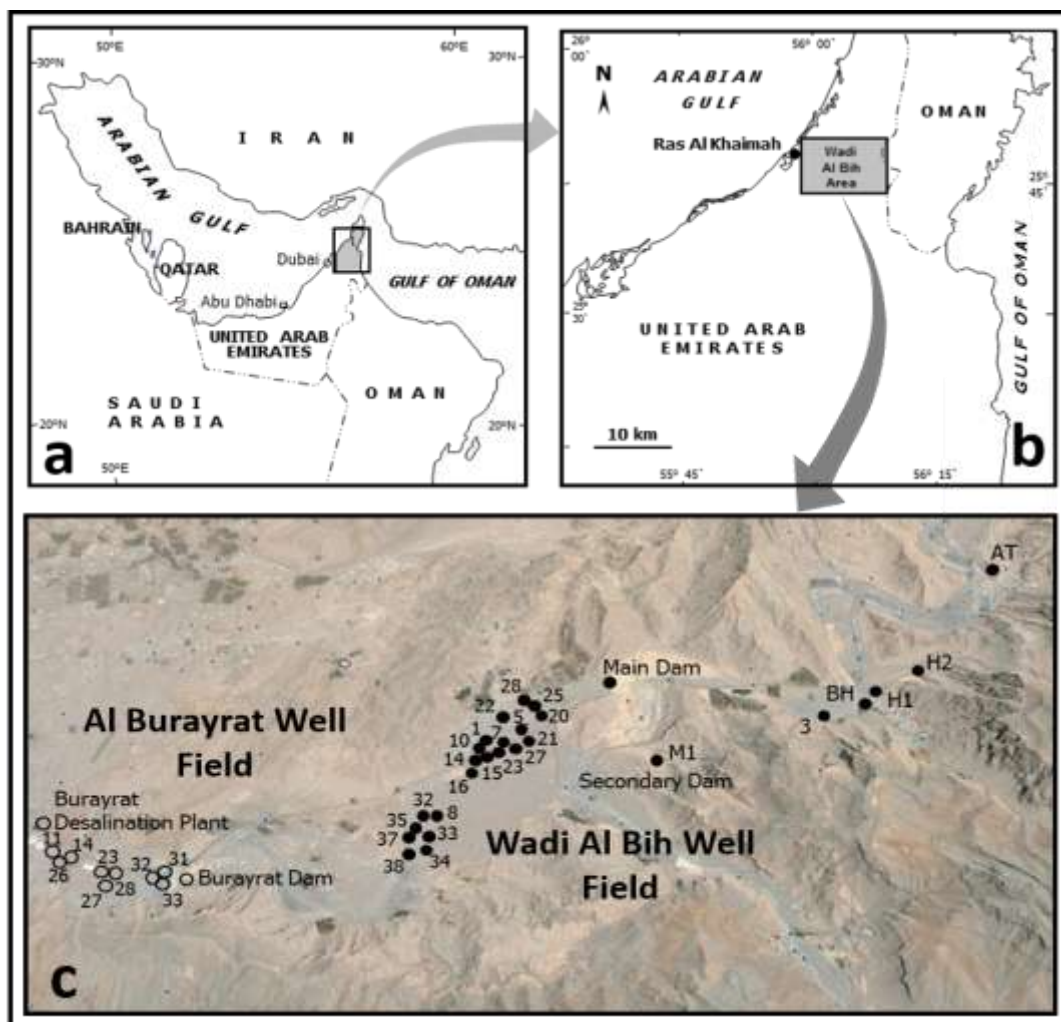


Figure 1. Location maps of the United Arab Emirates (a), Wadi Al Bih area (b), and sampling locations (c). Black and open circles on Figure 1c represent sampled sites during November 2014 and June 2015.

The groundwater temperature ($^{\circ}\text{C}$), electrical conductivity (EC) in microsiemens per centimeters ($\mu\text{S}/\text{cm}$), hydrogen ion concentration (pH), total dissolved solids (TDS) in milligrams per liter (mg/L) and total hardness (TH in mg/L) were directly measured in the field because they change after sample collection [9].

2. Laboratory Analyses

2.1 Chemical analysis

The chemical analysis of the collected water samples was conducted in the Food and Environment Laboratories of Ajman Municipality and Planning Department (AMPD). Standard analytical techniques described in [10, 11, 12, 13, 14] were applied.



Photo 1. General view of storage tanks of Al Burayrat Reverse Osmosis (RO) Desalination plant in Wadi Al Bih area, Emirate of Ras Al Khaimah, United Arab Emirates.

Table 1. Number of groundwater samples collected from Wadi Al Bih limestone aquifer in November 2014 and June 2015.

Location	Number of groundwater Samples		
	November 2014	June 2015	Total
Wadi Al Bih	20	21	41
Burayrat	5	4	9
Inside Burayrat Plant	2	3	5
Atmar	1	1	2
Hujailah	2	2	4
Bih Main Dam	1	-	1
Burayrat Earth Dam	1	-	1
Bani Hamdan	1	1	2
Mukhelfah	1	1	2
Total	34	33	67

Chemical analyses of major, minor and trace chemical constituents were performed using titration methods, ion chromatography [15], atomic absorption spectrophotometry (AAS) [16], and inductively coupled plasma-atomic emission spectrometry (ICP-AES) [17]. For measurement of TDS, a 100 mL of well-mixed water sample was filtered through a standard glass fiber. The filtrate was evaporated to dryness in a weighed dish and dried to a constant weight at 180°C. The increase in dish weight represented the total dissolved solid [13]. For determination of alkalinity, soluble carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) anions were measured by titration of 50 mL water sample against 0.02 N HCl solution using phenolphthalein and methyl orange indicators [14]. Total hardness was measured by addition of 2 mL of the buffer solution pH-10 and 3 to 4 drops of Erichrome Black T indicator to 10 mL water sample, and titration with standard 0.01 M EDTA solution. Ion chromatograph, model Dionex-2020i, was used for the analysis of the anions; chloride (Cl^-), nitrate (NO_3^-), and sulphate (SO_4^{2-}). The Dionex-2020i ion chromatograph is a dual-channel, high-performance chromatographic system featuring two precision analytical pumps, a dual-channel advanced chromatography module with optional column heater and two conductivity detectors. The operating conditions were 10-40°C temperature range and 1,900 psi (129 atm.) maximum pressure. A calibration curve was prepared for each anion using aliquots anion concentrations higher than detection limits. The detection limits in mg/L of Cl^- , NO_3^- and SO_4^{2-} were 0.03, 0.13 and 0.03, respectively. Prior to the determination of total metal concentrations by AAS or ICP-AES, each water sample was acidified with nitric acid (8 mL/L Analar grade), boiled for 4-5 minutes to ensure complete solubility of metal ions [14], and then filtered. Filtrate was used for both AAS and ICP-AES

measurements. Atomic absorption spectrophotometry (AAS) was used for the determination of the cations; calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) by measuring their absorbance at the maximum wavelengths, against reagent blank [16]. Measurements were carried out using the AAS (GBC 906), equipped with autosampler and background corrector. ICP-AES was used for determination of trace elements chromium (Cr) and zinc (Zn), while the remaining trace elements, lead (Pb), cadmium (Cd), manganese (Mn), copper (Cu) and nickel (Ni) were below their detection limits.

2.2 Microbiological Analysis

For microbiological analysis, strong, thick-walled, glass sampling bottles, with a capacity of 1000 mL, were provided by Ajman Municipality Laboratory. Groundwater samples collected for microbiological analysis were obtained from existing wells tapping Wadi Al Bih limestone aquifer in Wadi Al Bih and Al Burayrat well fields (Fig. 1). In order to obtain actual groundwater samples and avoid sampling water resident in the system's piping, water were left to flow for several minutes before sampling until it has reached constant temperature and EC. Resident water are usually contaminated by piping material and does not represent aquifer's water. The water was allowed to flow into the bottle for sufficient time to displace the contents of the bottle at least three times. Care was taken to ensure that no air bubbles are introduced to the sample while the bottle is being filled, since this could alter the concentration of dissolved oxygen. The filled bottles were stored in icebox (4°C) and kept in darkness inside the car. Samples were kept in refrigerator the night of sampling day and were delivered to the Microbiology Department of the Food and Environment Laboratory of Ajman Municipality and Planning Department, Ajman. The Defined Substrate Technology (DST) method was used to detect the presence or absence of *Escherichia Coli* (*E.coli*), Total Coliform (*T. coliform*) and *Enterococcus faecalis* (*E. faecalis*) in collected groundwater samples [18].

III. RESULTS AND DISCUSSION

The following discussion is based on the results of field-measured groundwater temperature ($^{\circ}\text{C}$) and salinity (mg/L), chemical analyses of major and minor ions, trace elements (mg/L), and calculated water-dissolved salts (%) and sodium adsorption ration (SAR), in addition to microbiological analyses.

1. Hydrogeochemistry

1.1 Temperature

The temperature of groundwater samples collected in November 2014 ranged from 30.8°C in Well WBH2 to 37.4°C in Well WB34 and averaged 35.5°C . The average groundwater temperature dropped from 35.5°C in November 2014 to 33°C in June 2015, but temperature measurement of groundwater in 2015 were generally unreliable. Figure 2 shows the areal distribution of groundwater temperatures measured in November 2014. Generally, the low-temperature groundwater is located in the north and northeastern parts of the study area, while the temperature increases to south and southwest, in the direction of groundwater flow. High groundwater temperatures were also measured in wells where heavy groundwater pumping is taking place. The relatively lower groundwater temperatures in June 2015 indicate recharge of groundwater with low-temperature rainwater falling on mountains peaks surrounding Wadi Al Bih basin. In 1996, temperature of the groundwater samples collected from Wadi Al Bih aquifer varied between 32.8°C and 43.3°C , with averages of 36.1°C during April and 36.3°C during September [6]. The groundwater temperature decreased from 36.5 and 36.4°C during April to 36.4 and 35.8°C during summer in Wadi Al Bih and Al Burayrat well fields, respectively. The spatial and temporal distribution of temperature is given in Figure 3.

1.2 Total Dissolved Solids

The TDS of groundwater samples collected in November 2014 increased from 237 mg/L in Well WBH1 to 3,276 mg/L in Well WB28. The TDS of groundwater samples collected in November 2014 increased from 209 mg/L in Well WBH2 to 2,800 mg/L in Well WB28 (Fig. 1). The average TDS of groundwater decreased from 1624 mg/L in November 2014 to 1380 mg/L in June 2015. Figure 4 shows the areal distribution of groundwater salinity in Wadi Al Bih basin in 2014 and 2015. The Groundwater in the study area varies from fresh water (TDS $<1,000$ mg/L in Wells WB21 and WB 22 in the east) to brackish (TDS $>1,000$ to $<10,000$ mg/L in the majority of the study area). The increase of groundwater salinity from east to west occurs in the direction of groundwater flow towards the discharge area in the Arabian Gulf.

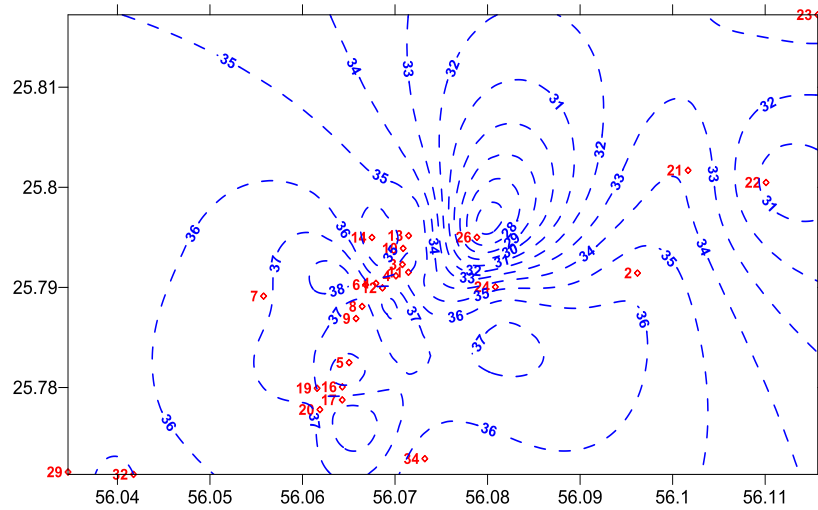


Figure 2. Iso-temperature ($^{\circ}\text{C}$) contour map for groundwater in Wadi Al Bih limestone aquifer, on November 22nd, 2014.

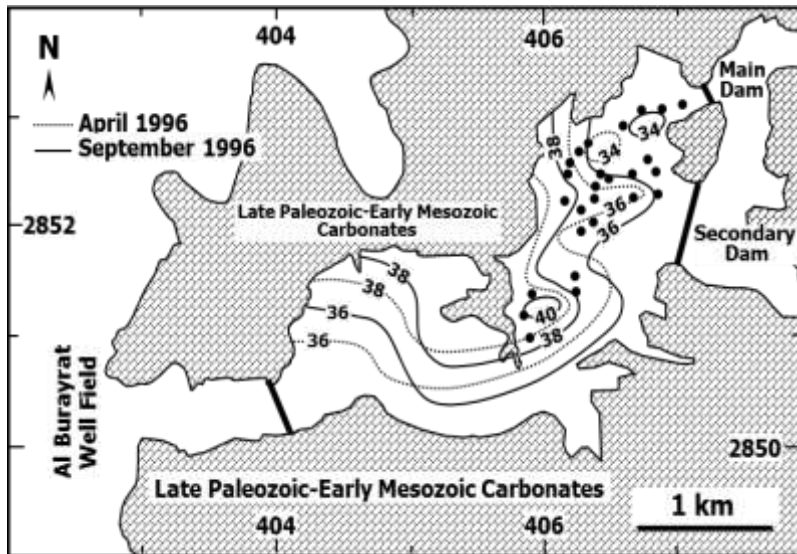


Figure 3. Iso-temperature ($^{\circ}\text{C}$) contour map for groundwater in Wadi Al Bih limestone aquifer in April 1996 (dashed lines) and September 1996 [6].

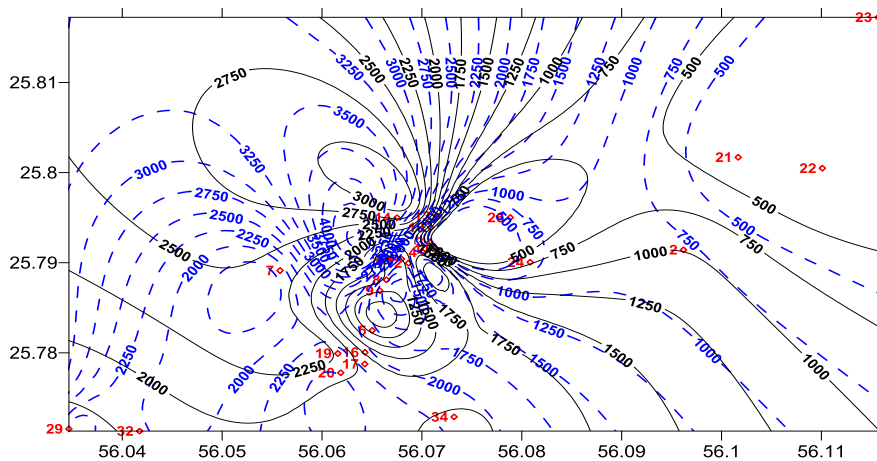


Figure 4. Isosalinity contour map of groundwater in Wadi Al Bih limestone aquifer in (mg/L), in November 2014 (dashed blue lines) and June 2015 (solid black lines).

1.3 Major Ions

The sequence of cations dominance in groundwater of Wadi Al Bih Limestone aquifer within the study area has the order: $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$. This sequence reflects the hydrogeologic conditions in Wadi Al Bih basin. The dominance of Na^+ points out to overexploitation of the aquifer within the study area. The second dominant cation is Ca^{2+} , which is a major rock-forming mineral in aquifer, dominating the study area. The presence of Wadi Al Bih basin within Ru'us Al Jibal Mountains explains the relatively high concentrations of Mg^{2+} and Ca^{2+} in groundwater of Wadi Al Bih basin. The dissolution of carbonate minerals and carbonate cement yields Ca^{2+} and Mg^{2+} to groundwater. The decrease in average concentrations of Ca^{2+} , Mg^{2+} and K^+ from (115, 54, and 21 mg/L, respectively) in 2014 to (87, 35 and 15 mg/L, respectively) in 2015, parallel to the decrease of average groundwater salinity (from 1624 mg/L in 2014 to 1380 mg/L in 2015), indicates dilution of cations by low-salinity recharge water entered Wadi Al Bih limestone aquifer during June 2015.

The sequence of anions dominance in groundwater of Wadi Al Bih limestone aquifer has the order: $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-} > \text{CO}_3^{2-}$. The dominance of Cl^- reflects overpumping, scarcity of rainfall the prevalence of arid condition. However, relatively high concentration of HCO_3^- , as the second anion in the aquifer, indicates the limited recharge the aquifer receives from the surrounding mountain peaks during short rainy seasons. The SO_4^{2-} is the third-dominant anion in Wadi Al Bih basin and may indicate upconing of SO_4^{2-} -rich high-salinity brines from deeper horizons in the aquifer [6]. The concentration of Cl^- generally increases from east to west, in the direction of groundwater flow. The low of Cl^- levels in the northeastern part of the study area, near wells WB02, WB21, WB22, WB24 and WB26, are associated with low groundwater salinity as a result of aquifer recharge from Wadi Al Bih main dam. The average concentrations of Cl^- decreased from 795 mg/L in 2014 to 661 mg/L in 2015, while HCO_3^- concentration increased from 159 mg/L in 2014 to 172 mg/L in 2015, supporting the hypothesis of dilution of groundwater-dissolved ions by low-salinity recharge water entered Wadi Al Bih limestone aquifer during June 2015. The increase of SO_4^{2-} from 102 mg/L in 2014 to 154 mg/L in 2015, opposite to all cations and anions, and similar to HCO_3^- , needs further investigation in the future.

1.4 Minor Ions

The World Health Organization (WHO) permissible limit for nitrate concentration in drinking water is 10 mg/L of nitrate as nitrogen [19], or 45 mg/L as nitrate [20]. In 2014, concentration of NO_3^- varied between 5.0 mg/L in the middle and 14 mg/L in the north and averaged 7.0 mg/L. In 2015, NO_3^- increased from 0.3 mg/L in the middle to 3.0 mg/L in the north and averaged 1.0 mg/L. The decrease in average concentration of NO_3^- in 2015 relative to 2014 coincides with decreasing salinity and concentrations of major ions, except HCO_3^- and SO_4^{2-} , and supports the dilution of groundwater-dissolved ions in May 2015.

1.5 Trace Elements

Trace elements were analyzed in groundwater samples collected from the limestone aquifer in Wadi Al Bih basin during November 2014 and June 2015. Detected concentrations of zinc (Zn) and chromium (Cr) were measured, but concentrations of copper (Cu), lead (Pb), manganese (Mn), nickel (Ni) and cadmium (Cd) were below their detection limits. The WHO limit for Zn in drinking water is 3 mg/L [19]. The standard in the USA, Canada and Russia is 5 mg/L, and in the UAE is 0.03 mg/L [21]. Zn concentrations were below detection limit (< 1 mg/L) in most groundwater samples collected from the study area in 2014 and 2015. Measureable concentrations of Zn in November 2014 varied between 0.05 mg/L in 13 wells in Wadi Al Bih and Al Burayrat areas and 1.20 mg/L in Well WB08. In 2015, Zn was between ≤ 0.05 mg/L in 14 wells within the study area and 1.10 mg/L in Well WB08. Zn in groundwater samples measured in 2014 varied between 0.05 mg/L or below and 1.20 mg/L in WB08, and in 2015 varied between 0.05 mg/L or below and 1.10 mg/L in WB08. The average Zn concentrations in the study area were 0.29 mg/L in 2014 and 0.31 mg/L in 2015, which are below the WHO and international standards, but higher than the UAE standard. The natural Cr concentration in groundwater varies between 0.006 and 0.400 mg/L [21]. Because of the carcinogenic properties of some Cr compounds, a risk-based drinking water standard of 0.050 mg/L has been established by the WHO for Cr in drinking water. The UAE, Europe, Canada and Russia have the same standard as the WHO, while the USA has set the standard at 0.1 mg/L. The Cr concentrations in all groundwater samples collected from the study area during 2014 (34 samples) and 2015 (33 samples) were below detection limit of 0.05 mg/L. The concentrations of other trace metals, Cd, Cu, Mn and Pb, were below their detection limits in all groundwater samples collected from the limestone aquifer in Wadi Al Bih basin in November 2014 and June 2015.

1.6 Water-Dissolved Salts

In 2014, the percentage of $\text{Ca}(\text{HCO}_3)_2$ salt was generally low throughout the study area, ranging from 1% in Wells WB10 in the Wadi Al Bih well field, 28% in Well WB21 in the east and averaging 8%. In 2015, the minimum percentage of $\text{Ca}(\text{HCO}_3)_2$ was 1% in Well WB32 in the western side of Wadi Al Bih basin, 47% in Well WBH1 in the northwest, and averaging 13%. The areal distribution of $\text{Ca}(\text{HCO}_3)_2$ increased from 15%

in the western part of the study area to 30% in the northeast (Fig. 5). High $\text{Ca}(\text{HCO}_3)_2$ percentages were calculated in 2015 in the northeastern part of the study area (Fig. 1). The percent of $\text{Ca}(\text{SO}_4)$ is low in the west, and increases to the north, east and around Wadi Al Bih well field. The increase of percentages of $\text{Ca}(\text{SO}_4)$ around Wadi Al Bih well field is possibly attributed to upconing of sulphate-rich brine from deeper zones in the aquifer [6]. In 2014, the percentage of $\text{Ca}(\text{SO}_4)$ increased from 1% in Wells WB35 in the west to 21% in Well WB03 in the middle. In June 2015, the percentage of $\text{Ca}(\text{SO}_4)$ increased from 1% in Wells WB05 and Bu32 in the middle and west, respectively, to 21% in Well WB22 in the middle. The average $\text{Ca}(\text{SO}_4)$ percentage was 7% in 2014 and 8% in 2015. In 2014, the percentage of the CaCl_2 increased from 13% in Well Bu28 in the west to 28% in Well WBH2 in the east, and the average was 11%. In 2015 the percentage of CaCl_2 increased from 9% in Well WB38 to 23% in Well WB25, and the average was 5%. Figure 6 shows the areal distribution of the CaCl_2 salt in the limestone aquifer within the study area in November 2014 and June 2015.

The MgSO_4 is the second dominant water-dissolved salt within the study area. In 2014, the percentage of this salt increases from 1% in Wells WB37 and WB38 to 43% in Well WBM1 in the middle. In 2015, the percentage of MgSO_4 increases from 1% in Well WB34 in the middle to 26% of the total water-dissolved salts in Well WBM1 in the middle. The average MgSO_4 percentage was 4% in 2014 and 7% in 2015. The highest percentages MgSO_4 are concentrated in the Wadi Al Bih well field in Wadi Al Bih basin (Fig. 7). The 2014 MgCl_2 percentages ranged from 4% in Well WB07 in the middle to 73% in Well WB25 in the middle, and averaged 16%. The 2015 MgCl_2 percentages varied between 3% in Wells WB08 and WBAT and 26% in Well Bu31 in the west, and averaged 11%. The areal distribution of MgCl_2 salt is high in the middle central part of the study area, reflecting the impact of human activities on dissolved-salts concentration in this area.

NaCl is the most dominant water-dissolved salt in Wadi Al Bih limestone aquifer within the study area. The NaCl salt percentage and distribution reflects the influence of increasing groundwater salinity in the middle and western parts of Wadi Al Bih basin, and westwards in the direction of groundwater flow (Fig. 8). In 2014, NaCl percentage increased from 3% in Well WB25 in the middle to 77% in Well WB07 in the middle, and averaged 55%. In 2015, NaCl salt percent jumped from 7% in Well WBH2 in the middle to 79% in Well WB38 in the northwest, and averaged 54%.

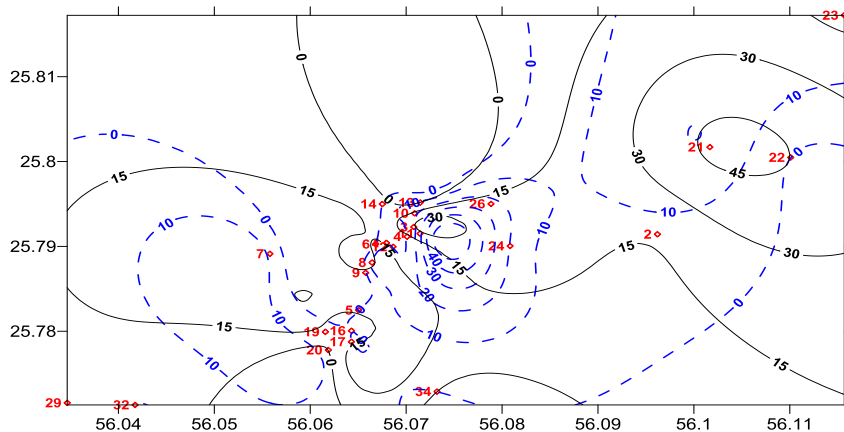


Figure 5. Percentage distribution of the hypothetical salt $\text{Ca}(\text{HCO}_3)_2$ in Wadi Al Bih limestone aquifer, in November 2014 (dashed blue lines) and June 2015 (solid black lines).

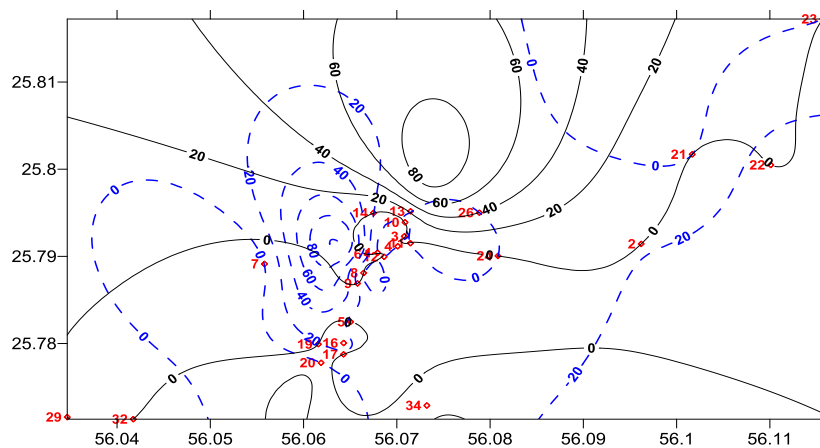


Figure 6. Percentage distribution of the hypothetical salt CaCl_2 in the Wadi Al Bih limestone aquifer, in November 2014 (dashed blue lines) and June 2015 (solid black lines).

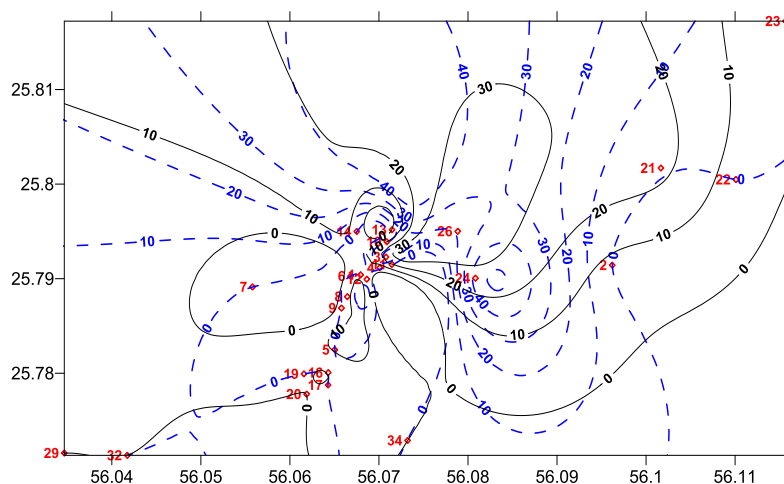


Figure 7. Percentage distribution of the hypothetical salt $\text{Mg}(\text{SO}_4)$ in Wadi Al Bih limestone aquifer in November 2014 (dashed blue lines) and June 2015 (solid black lines).

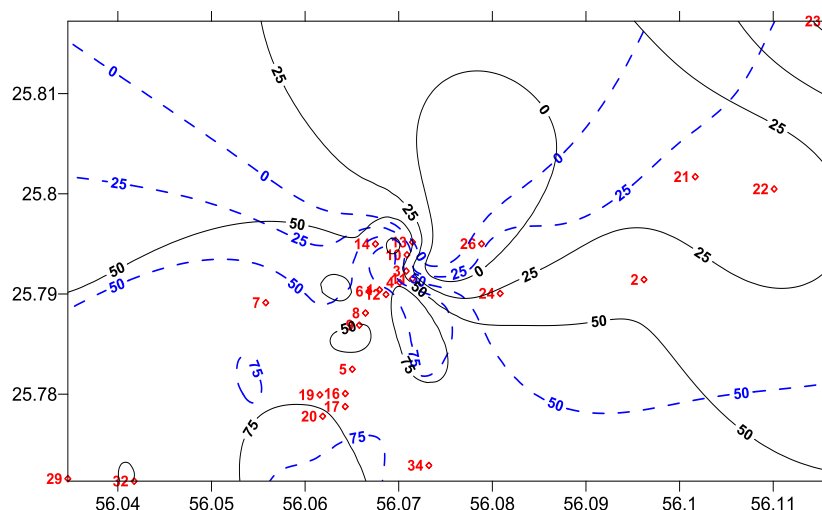


Figure 8. Percentage distribution of the hypothetical salt NaCl in Wadi Al Bih limestone aquifer in November 2014 (dashed blue lines) and June 2015 (solid black lines).

1.7 Hydrochemical Ratios

The Na/Cl ratio in sea water is less than unity (0.73), while groundwater has Na/Cl ratios greater than unity [22]. Therefore, the main source of increasing groundwater salinity in Wadi Al Bih limestone aquifer (0.46 in November 2014 and 0.38 in May 2015) is upconing of brine from deeper zones in absence of appreciable recharge [6], or halite solution (Table 2). Both sources of increasing groundwater salinity are possible because of the presence of evaporites in the stratigraphic sequence of Wadi Al Bih aquifer, in addition to the carbonate nature of the aquifer.

The $\text{Cl}/(\text{CO}_3+\text{HCO}_3)$ ratio is used to evaluate salt-water intrusion, either from neighboring areas or from underlying formations. The chloride ion (Cl^-) is a dominant anion in salt water and normally occurs in small amounts in groundwater. On the other hand, the bicarbonate ion (HCO_3^-) is the most abundant anion in groundwater. Figure 1 and Table 2 indicate brine upconing into relatively fresh groundwater in Wadi Al Bih limestone aquifer in the Ras al Khaimah area.

The TDS is >500 throughout the study area supporting brine upconing influence on groundwater salinity in Wadi Al Bih limestone aquifer. The $(\text{Cl}/\text{sum anions})$ ratio, varied between 0.59 in June 2015 and 0.66 in November 2015 (Table 2), indicates the influence of brine or evaporites on groundwater within the study area. Similarly, the $(\text{HCO}_3^-/\text{Sum Anions})$ ratio, ranged from 0.22 in November 2014 and 0.24 in June 2015

(Table 2), suggesting the influence of brine on groundwater in Wadi Al Bih limestone aquifer in Ras Al Khaimah area.

Table 2. Hydrochemical ratios used for identification of the possible chemical reactions in Wadi Al Bih limestone aquifer in November 2014 and May 2015, according to [22].

Hydrochemical Parameter	Attention value	Conclusion	Calculated value		Explanation for Wadi Al Bih
			Nov. 2014	May 2015	
Na/(Na+Cl)	>0.5	Sodium source other than halite - albite, ion exchange	0.46	0.38	Brine or halite solution
TDS	<500	Silicate weathering	1624	1380	Carbonate weathering or brine
Cl/Sum Anions	>0.8 and TDS>500	Seawater or brine or evaporites	0.66	0.59	Brine or evaporites
HCO ₃ ⁻ /Sum Anions	>0.8	Silicate or carbonate weathering	0.22	0.24	Brine

1.8 Total Hardness

Water is classified according its hardness into soft water (<60 mg/L), moderately hard water (61-120 mg/L), hard water (121-180 mg/L) and very hard water (>180 mg/L) [9]. According to this classification, groundwater in Wadi Al Bih limestone aquifer ranged from moderately hard to very hard in November 2014 and June 2015. The average TH was very hard, reaching 504 mg/L in November 2014 and 367 mg/L in June 2015. Groundwater in Wadi Al Bih limestone aquifer was moderately hard in Well WBAT (TH = 90 mg/L in 2015), hard in Well WBH2 (TH = 140 mg/L in 2015) and Well WBH1 (TH = 150 mg/L in 2015), and very hard in rest of the wells. TH of Wadi Al Bih limestone aquifer ranged between 230 and 1,200 mg/L in 2014, and between 90 and 750 mg/L in 2015. In 2015, all groundwater sampled from Wadi Al Bih basin were very hard (TH >180 mg/L). Figure 9 shows the areal distribution of groundwater hardness in Wadi Al Bih basin. The TH increases from east to west, in the direction of groundwater flow, with a decrease from November 2014 to June 2015.

1.9 Sodium Adsorption Ratio

For evaluating the suitability of groundwater in the study area for agricultural uses, the SAR is used for classification of irrigation water because sodium reacts with soil and reduces its permeability, which adversely affects plants and soils. SAR values <12 has limited harmful effect on plants and soil, between 12 and 18, groundwater is moderately harmful to soil and plants, between contours 18 and 26 groundwater is highly harmful to soil and plants, and at SAR values >26 groundwater can be very harmful to soil and plants if this water were to be used for irrigation of traditional crops. The calculated SAR values for the limestone aquifer within Wadi Al Bih basin varied between 1 and 70, and averaged 38 in 2014. In 2015, the SAR ranged from 1 and 83 and averaged 34. Figure 10 displays the areal distribution SAR values for groundwater in Wadi Al Bih limestone aquifer. Except a small area in the southwestern parts of the basin, groundwater of Wadi Al Bih limestone aquifer is good for irrigation can cause a limited harmful effect to soil and plants when used for irrigation of conventional crops.

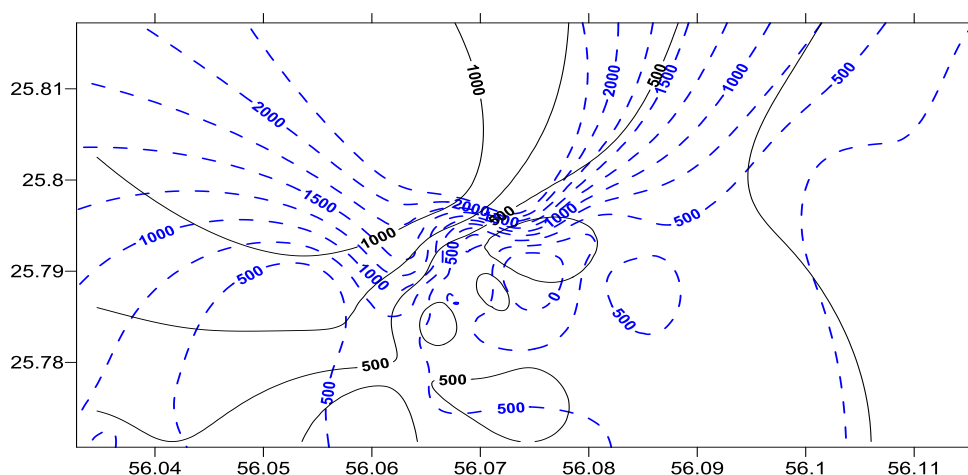


Figure 9. Iso-total hardness (TH) in (mg/L) for groundwater of Wadi Al Bih limestone aquifer in November 2014 (dashed blue lines) and June 2015 (solid black lines).

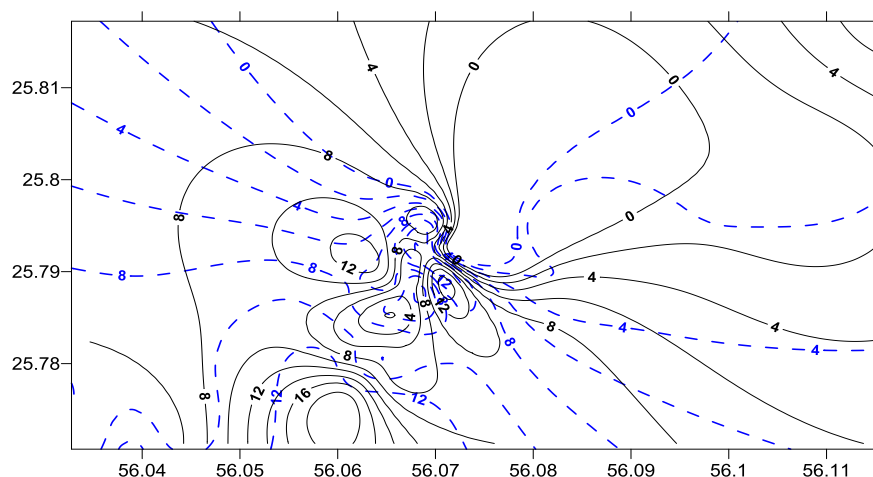


Figure 10. Iso-sodium adsorption ratio (SAR) contours calculated for groundwater samples collected from Wadi Al Bih limestone aquifer in November 2014 (dashed blue lines) and June 2015 (solid black lines).

II. MICROBIOLOGY

Pathogenic organisms may infiltrate through soil, sediment and rocks, contaminating groundwater [23]. Improper design of water wells may also lead surface pollutants to reach groundwater [24]. The increased use of agrochemicals [25], in addition to application of manure [26], on agricultural land contributes to biological pollution of aquifer systems. The usage of polluted water can cause serious health problems [27, 28]. But, fortunately there are indicator organisms their presence points out water pollution [29] which are easy to identify using standard culture methods [30].

The DST analytical method was used to detect the presence or absence of *E.coli*, *T. coliform* or *E. faecalis* in groundwater samples collected from Wadi Al Bih limestone aquifer in November 2014 and May 2015. After addition of reagent to culture groundwater, samples were incubated at 37°C for 24 hours in the Microbiology Laboratory of Ajman Municipality and Planning Department. The results were as follows: If the vessel were transparent the sample is negative for *T. coliforms* and *E. coli*, if the vessel were yellow-colored the sample is positive for *T. coliform*, and if the vessel had fluorescence color, using 365nm UV lamp the sample is positive for *E. coli*.

In 2014, the samples WBAT, WBSW, BuDam, Bu14, Bu27 and Bu28 were positive with respect of bacterial growth of *T. coliform*, *E.coli*, and *S. faecalis*, sample WB10 showed the presence of *S. faecalis* and *T. coliform*, and samples WB37, WBH1 witnessed the growth of *T. coliform*. The rest of groundwater sampling sites (25) indicated absence of *T. coliform* growth (Photo 2).

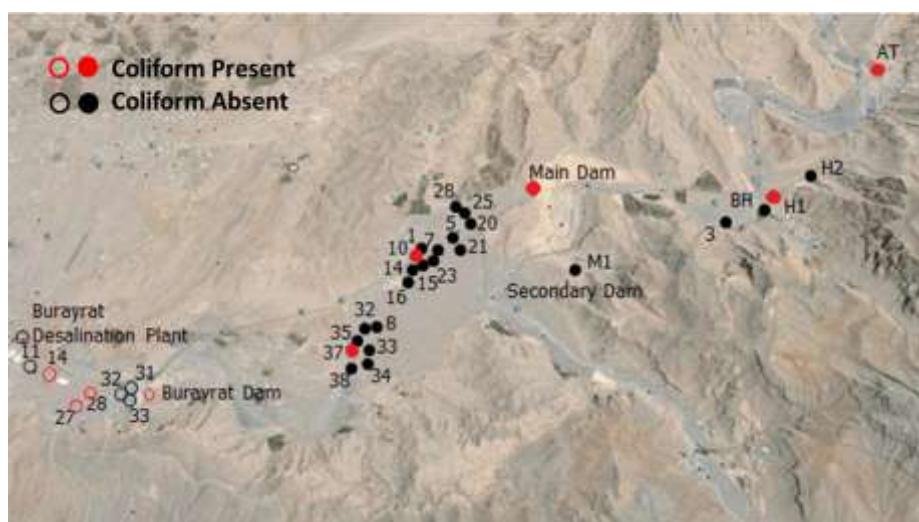


Photo 2. Locations of presence and absence of Coliform in water wells tapping Wadi Al Bih limestone aquifer in Al Burayrat area (open circles) and Wadi Al Bih basin (closed circles) in November 2014.

In 2015, the samples WB16, WB38 and Bu27 showed positive bacterial growth of *coliform*, *E.coli*, and *S. faecalis*. The wells WB08, WB20, WB22, WB25, WBH2, Bu23, Bu26 and Bu31 witnessed *T. coliform*

growth. The well WB05 showed the presence of *S. faecalis* and *coliform*, while the well WBBH indicated *E. coli* and *T. coliform* presence. The rest of groundwater samples (20) witnessed absence of *T. coliform* growth (Photo 3). The 2014 results indicated that most of the contaminated samples were collected from water wells near Al Burayrat desalination plant. The bacterial contamination of three wells (Bu14, Bu27 and Bu28) out of seven in Al Burayrat area is a result of the presence of relatively high urban and agricultural activities (Photo 4). Percolation of surface water from Al Burayrat dam reservoir into the aquifer can be an additional source of bacterial pollution to groundwater in this area (Photo 4). In contrast, only four out of 25 samples were bacterially contaminated in Wadi Al Bih basin (Table 3). The pollution of wells WBAT and WBH2 is a result of urban development, while the bacterial contamination of WB10 and WB37 is related to agriculture activities in nearby farms (Photo 5). The bacterial contamination was detected in 9 out of 34 wells in November 2014, while the bacterial growth was recorded in 13 out of 33 wells in June 2015.

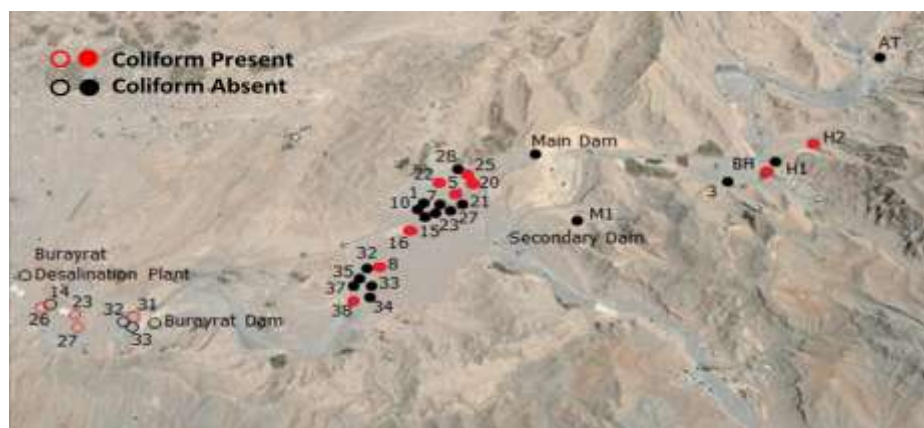


Photo 3. Locations of presence and absence of *T. coliform* in water wells tapping Wadi Al Bih limestone aquifer in Al Burayrat area (open circles) and Wadi Al Bih basin (closed circles) in June 2015.



Photo 4. Al Burayrat desalination plant and surrounding human activities may represent potential sources of groundwater pollution in the study area. Percolation of surface water from Al Burayrat dam reservoir can contribute to bacterial pollution of Wadi Al Bih limestone aquifer.

IV. CONCLUSIONS

Wadi Al Bih basin receives an average annual rainfall of 155 mm, which is higher than the UAE's annual average (119 mm). Annual rainfall in excess of 400 mm is common in the study area. The percentage of aquifer recharge from the total annual rainfall (74 million m³) was ≈9% (6.7 million m³), increased to 13% (17.6 million m³) after construction of Wadi Al Bih dam in 1982. The average annual groundwater production in Wadi Al Bih limestone aquifer decreased from 9.0 million m³ during the period 1991-1995 to 4.5 million m³ during the period 2011-2015. The decrease in groundwater pumping from the aquifer paralleled the construction of Al Burayrat, Al Humraniyah, Rafaq, Ghalilah and Al Nakheel desalination plants, with a total production capacity of 93 thousand m³ per day. These conditions have eased pressure on the aquifer, increased groundwater storage, raised hydraulic heads by 1 m in Al Burayrat area and 16 m near Wadi Al Bih main dam, and decreased the average groundwater salinity from 2,122 milligrams per liter (mg/L) and 3,901 mg/L in Wadi Al Bih and Al Burayrat well fields, respectively, during the period 1991-1995, to 1,497 and 2,145 mg/L in Wadi Al Bih and Al

Burayrat well fields, respectively, during the period 2010-2014. The decrease in groundwater salinity due to the aquifer recovery was 30% in Wadi Al Bih well field and 45% in Al Burayrat well field.

Table 3. Results of bacteriological analyses (P = presence and A = absence) of *T. coliform* in water wells tapping the limestone aquifer in Wadi Al Bih basin in November 2015 and May 2015.

2014	<i>E. coli</i>	<i>T. coliform</i>	<i>S. faecalis</i>	2015	<i>E. coli</i>	<i>T. coliform</i>	<i>S. faecalis</i>
WB1	A	A	A	WB1	A	A	A
WB3	A	A	A	WB3	A	A	A
WB5	A	A	A	WB5	A	P	P
WB7	A	A	A	WB7	A	A	A
WB8	A	A	A	WB8	A	p	A
WB10	A	P	P	WB10	A	A	A
WB14	A	A	A	WB15	A	A	A
WB15	A	A	A	WB16	P	P	P
WB16	A	A	A	WB20	A	p	A
WB20	A	A	A	WB21	A	A	A
WB21	A	A	A	WB22	A	p	A
WB23	A	A	A	WB23	A	A	A
WB25	A	A	A	WB25	A	p	A
WB28	A	A	A	WB27	A	A	A
WB32	A	A	A	WB28	A	A	A
WB33	A	A	A	WB32	A	A	A
WB34	A	A	A	WB33	A	A	A
WB35	A	A	A	WB34	A	A	A
WB37	A	P	A	WB35	A	A	A
WB38	A	A	A	WB37	A	A	A
WBH1	A	P	A	WB38	P	P	P
WBH2	A	A	A	WBH1	A	A	A
WBAT	P	P	P	WBH2	A	p	A
WBM1	A	A	A	WBAT	A	A	A
WBBH	A	A	A	WBM1	A	A	A
WBSW	P	P	P	WBBH	P	P	A
Bu11	A	A	A	Bu14	A	A	A
Bu14	P	P	P	Bu23	A	p	A
Bu27	P	P	P	BU26	A	p	A
Bu28	P	P	P	Bu27	P	P	P
Bu31	A	A	A	Bu31	A	p	A
Bu32	A	A	A	Bu32	A	A	A
Bu33	A	A	A	Bu33	A	A	A
BuDam	P	P	P				

The rocks forming the aquifer are stratified, solid, dense and impermeable, but characterized by a network of extensive, internal karstification mass, which increases secondary porosity and hydraulic conductivity (K varies between 32.65 and 67.30 m/d and averages 50 m/d). The structural setting of the study area affects aquifer recharge since most of the Wadi Al Bih tributaries are located along faults that allow surface water to move laterally or infiltrate into the subsurface.

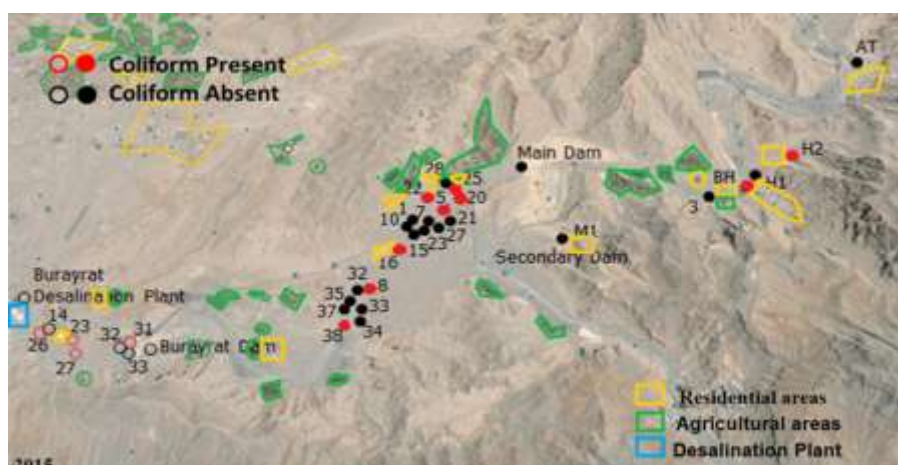


Photo 5. The pollution source of wells WBAT and WBH2 is a result of urban development, while the bacterial contamination of WB10 and WB37 is related to agriculture activities in nearby farms.

The temperature of the groundwater in Wadi Al Bih limestone aquifer varied between 32.8°C and 43.3°C, with averages of 36.1°C during winter and 36.3°C during summer. The average groundwater temperature decreases from 36.5 and 36.4°C during winter to 36.4 and 35.8°C during summer in Wadi Al Bih and Al Burayrat well fields, respectively. The decrease of groundwater temperature in the aquifer is associated with decreasing salinity and indicates aquifer recharge from rains falling on the mountain peaks surrounding the basin.

The average TDS of groundwater decreased from 1624 mg/L in November 2014 to 1380 mg/L in June 2015. The Groundwater in Wadi Al Bih limestone aquifer varies from fresh water (TDS <1,000 mg/L in Wells WB21 and WB 22 in the east) to brackish (TDS >1,000 to <10,000 mg/L in the majority of the study area). The increase of groundwater salinity from east to west occurs in the direction of groundwater flow towards the discharge area in the Arabian Gulf.

The decrease in average concentrations of Ca^{2+} , Mg^{2+} and K^+ from (115, 54, and 21 mg/L, respectively) in 2014 to (87, 35 and 15 mg/L, respectively) in 2015, parallel to the decrease of average groundwater salinity (from 1624 mg/L in 2014 to 1380 mg/L in 2015), indicates dilution of cations by low-salinity recharge water entered Wadi Al Bih limestone aquifer during June 2015. The average concentrations of Cl^- decreased from 795 mg/L in 2014 to 661 mg/L in 2015, while HCO_3^- concentration increased from 159 mg/L in 2014 to 172 mg/L in 2015, supporting the hypothesis of dilution of groundwater-dissolved ions by low-salinity recharge water entered Wadi Al Bih limestone aquifer during June 2015.

The average percentage $\text{Ca}(\text{HCO}_3)_2$ was generally low in 2014 (8%) and 2015 (13%) throughout the aquifer. The average percentage of $\text{Ca}(\text{SO}_4)$ was 7% in 2014 and 8% in 2015. The average percentage of CaCl_2 average in 2014 was 11% and 5% in 2015. The average percentage of KCl in 2014 and 2015 was the same (2%). MgSO_4 is the second dominant water-dissolved salt within the study area, and its percentage was 4% in 2014 and 7% in 2015. The highest percentage MgSO_4 was in Wadi Al Bih well field in the eastern part of Wadi Al Bih basin. NaCl is the most dominant water-dissolved salt in Wadi Al Bih limestone aquifer within the study area. The NaCl salt percentage and distribution reflects the influence of increasing groundwater salinity in the middle and western parts of Wadi Al Bih basin, and westwards in the direction of groundwater flow.

The hydrochemical ratio $\text{Na}/(\text{Na}+\text{Cl})$ in November 2014 (0.46) and June 2015 (0.38), indicate that main source of increasing groundwater salinity in Wadi Al Bih limestone aquifer is upconing of brine from deeper zones in the aquifer. The $\text{Cl}/(\text{CO}_3+\text{HCO}_3)$ ratio support the upconing of high- SO_4^{2-} brine form lower part of the aquifer. The high groundwater salinity (average TDS = 1,624 mg/L in 2014 and 1,380 mg/L in 2015) and the hydrochemical ratio ($\text{Cl}/\text{sum anions}$) of 0.59 in 2014 and 0.66 in 2015, indicate the influence of brine and evaporites on increasing groundwater salinity in Wadi Al Bih limestone aquifer.

The TH of Wadi Al Bih limestone aquifer ranged from 230 and 1,200 mg/L in 2014, to 90 and 750 mg/L in 2015. In 2015, all groundwater sampled from Wadi Al Bih basin were very hard (TH >180 mg/L). TH generally increased from east to west, in the direction of groundwater flow, but decreased from November 2014 to June 2015. The SAR values for the limestone aquifer varied between 1 and 70, and averaged 38 in 2014. In 2015, the SAR ranged from 1 and 83 and averaged 34. The areal distribution of SAR values in Wadi Al Bih limestone aquifer shows that, except a small area in the southwestern parts of the basin, groundwater of Wadi Al Bih limestone aquifer is good for irrigation can cause a limited harmful effect to soil and plants when used for irrigation of conventional crops.

In 2014, the samples WBAT, WBSW, BuDam, Bu14, Bu27 and Bu28 were positive with respect of bacterial growth of *T. coliform*, *E.coli*, and *S. faecalis*, sample WB10 showed the presence of *S. faecalis* and *T. coliform*, and samples WB37, WBH1 witnessed the growth of *T. coliform*. The rest of groundwater sampling sites (25) indicated absence of *T. coliform* growth. In 2015, the samples WB16, WB38 and Bu27 showed positive bacterial growth of *T. coliform*, *E.coli*, and *S. faecalis*. The wells WB08, WB20, WB22, WB25, WBH2, Bu23, Bu26 and Bu31 witnessed *T. coliform* growth. The well WB05 showed the presence of *S. faecalis* and *T. coliform*, while the well WBBH indicated *E.coli* and *T. coliform* presence. The rest of groundwater samples (20) witnessed absence of *T. coliform* growth. The bacterial contamination of three wells (Bu14, Bu27 and Bu28) out of seven in Al Burayrat area is a result of the presence of relatively high urban and agricultural activities, and percolation of surface water from Al Burayrat dam reservoir into the aquifer can be an additional source of bacterial pollution to groundwater in Wadi Al Bih limestone aquifer. The pollution of wells WBAT and WBH2 is a result of urban development, while the bacterial contamination of WB10 and WB37 is related to agriculture activities. The bacterial contamination was detected in 9 out of 34 wells in November 2014, while the bacterial growth was recorded in 13 out of 33 wells in June 2015.

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