Environmental Nanotechnology, Monitoring & Management 14 (2020) 100334

Contents lists available at ScienceDirect

Environmental Nanotechnology, Monitoring & Management

journal homepage: www.elsevier.com/locate/enmm

Estimation of corrosion and encrustation from groundwater chemistry of the aquifers: A case study of Al Hammad zone

Bayan Muhie Hussien[a], Muwafaq Ayesh Rabeea[b,*], Husam Naji Mukhlif[c]

[a] *Department of Environmental Sciences, College of Applied Sciences, University Of Anbar. Hit, Anbar 31007, Iraq*
[b] *Department of Applied Chemistry, College of Applied Sciences, University Of Anbar. Hit, Anbar 31007, Iraq*
[c] *Center of Desert Studies, University Of Anbar, Iraq*

ARTICLE INFO

Keywords:
Groundwater
Ryznar index
Langelier index
Corrosion
Salt incrustation

ABSTRACT

This work propose new method to predict corrosion and encrustation from groundwater chemistry of the aquifers. The tendency of groundwater to react with minerals forming systems by corrosion mechanism and/or incrustation in water pumps, pipes, storage tanks, irrigation systems, and their accessories is examed. The chemical properties of the groundwater within the aquifers of eight hydrogeologic districts in the western portion of Iraq were used in the calculation of Ryznar Stability and Langelier saturation indices supported by Phreeqe software. The monitoring network of groundwater quality consisting of twelve physiochemical variables in 64 water wells has determined according to the water point inventory using a GPS apparatus. The hadrochemical data and corrosion indices have been presented in spatial distribution maps. The results have also correlated with Ryznar and Langelier classifications to determine the corrosion and incrustation potential, which is crucial for groundwater development and exploitation. The results show that the groundwater of all aquifers has a potential of incrustation with a majority percent of 95.4, while 4.2 % of the groundwater is continued to corrosion ability. A spatial variation in the ability of salts incrustation and/or corrosion mechanisms has observed between aquifers.

1. Introduction

The study area is located within the physiographic provinces of upper valleys and Hamad, crossed by a highway link between Rutba city and the border with Jordan and Syria by international highway road. The study involved a selected area to the west of longitude (40°40′) within the borders of Iraq with a long area of 39,000 square kilometers and elevation ranges between 252 and 850 m above sea level (Fig. 1). The area is located in the southern part of the Northern temperate zone and in the eastern end of the land connected to the deserts of Syria and Saudia Arabia. The area characterized by dry desert climate with weak effects of the Mediterranean climate (warm dry summers, mild wet little rain in winter) (UNEP, 1991).

There are no direct referring for the prediction of corrosion and encrustation (rust formation and salt incrustation), resulted from groundwater chemistry of the aquifers, for the metallic equipment such as well systems, pumps, storages, and pipes. Thus, this paper is uniquely focused on the estimation of corrosion from groundwater chemistry of the aquifers by Langelier and Ryznar indices using the spatial distribution maps by considering Al Hammad Zone as a case study.

1.1. Geomorphologic and structural settings

The study area is characterized by undulating terrain the land surface rises gradually from the east and northeast at an altitude of 233 m above sea level (masl) to the west and southwest at an altitude of 940 m asl (Fig. 1). The slope of the land surface varies between 0.5 and 14 m/km at an average of the decline of 2.85 m/km and 3.57 m/km towards east and northeast, respectively. Several valleys of seasonal flow formed a number of plateaus with pediment deposits (Hamza, 1997). The valleys are defined as main landforms within the study area including Hauran, Walaj, Ghadf and their tributaries (Alhazimi), Alubayidh and its tributaries, Rattga (Gheri and Mullusi), Swab, Akash, Elmerbagh, Elwidy, and Kharja. These valleys form important drainage basins for groundwater replenishment. The valley and depression fill sediments are considered as important geomorphic units, which are classified within the scope of the territory suitable for agricultural activities and nature reserves. The deposits resulting from the erosion of rocks are basins vary in thickness in stream valleys as fine and coarse sediments. The depression fill sediment overlies plateaus of varying areas, ranging from a few square meters to kilometers. The depressions are originated

* Corresponding author.
E-mail address: muw88@uoanbar.edu.iq (M.A. Rabeea).

https://doi.org/10.1016/j.enmm.2020.100334
Received 30 January 2020; Received in revised form 2 June 2020; Accepted 15 June 2020

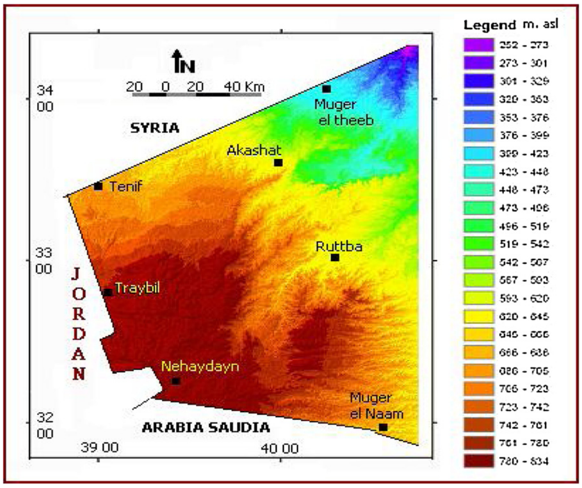

Fig. 1. Topographic map of the study area.

from the leaching of fractured dolomite and limestone rocks. Active winds and runoff are also sharing in filling the depressions with sand, mud and silt sediments. Structurally, the study area is located in the western part of the stable shelf (Jassim and Goff, 2006). The uplift contributed to the tectonic movements within successive geological periods affecting the stratigraphic and structural settings for Hauran anticlinorium of SW-NE direction, known as Rutba uplift.

Hydro-structural model based on geological data determined, by Rock Ware14 program (Fig. 2), indicates that the aquifers are influenced by Hauran anticlinorium, where the dip of fold flanks ranging between 1.0° to 2.0° ESE WSW and between 2.0° to 6.0° towards NWN and NEN. The model also shows the horizontal and vertical extension of geological formations within the geo-structural situation of the region.

Hauran anticlinorium (Rutba Uplift) extends to the east and northeast direction (Jassim and Goff, 2006) related to the movement of the base blocks within the Hail arch during the Paleozoic (Fig. 2). The zone of fold axis represents the groundwater divide which acts as a deviation of groundwater movement towards northwest and southeast. The dip of Permian, Triassic and Jurassic layers within Hauran fold are towards the south and southeast (Al-Bassam et al., 2000), while the dips of Cretaceous-Paleocene layers are towards the N and NE within Ana

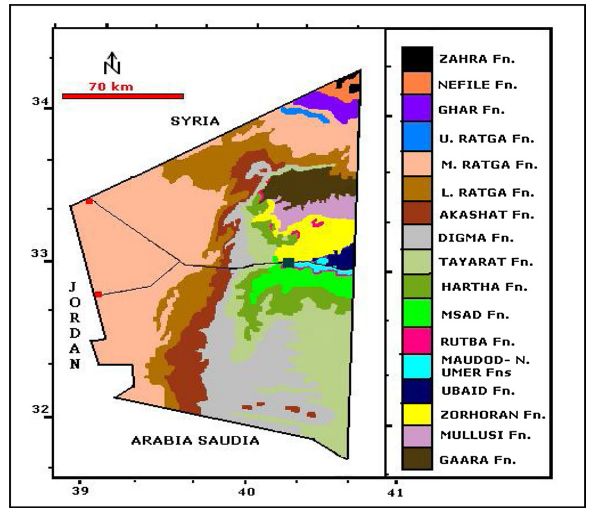

Fig. 3. Geologic map of the study area (Jassim and Goff, 2006).

block, and to the east and southeast in the eastern parts of the study area (AL-Mubarak, 1996).

1.2. Geologic and hydrogeologic settings

Based on geological studies (Buday and Hack, 1980; Al-Mubarak and Amin, 1983; Jassim et al., 1984; Al-Naqib et al., 1986; Al-Azzawi and Dawood, 1996; Sissakian and Mohamed, 2007), the study area was characterized by geological formations and sediments as distributed in the map given in Fig. 3, and illustrated by vertical extensions as shown in the geological model in Fig. 4. Depending on the occurrence of groundwater within the geological formations (Hussien and Fayadh, 2014) eight districts of groundwater are identified (Fig. 5), including District of Gaara aquifer(D1), District of Mullusi aquifer(D2), District of Hartha aquifer(D3), District of Digma-Tayarat aquifer (D4), District of Muhaywir and Ubaid aquifer(D5), District of Ubaid-Mullusi aquifer (D6), District of Rattga and Digma-Tayarat aquifers(D7) and District of Digma-Tayarat aquifer(D8).

The boundary conditions of the aquifers are summarized as follows:

1- Ga'ra Aquifer: The aquifer is recharged from the scope of Rutba

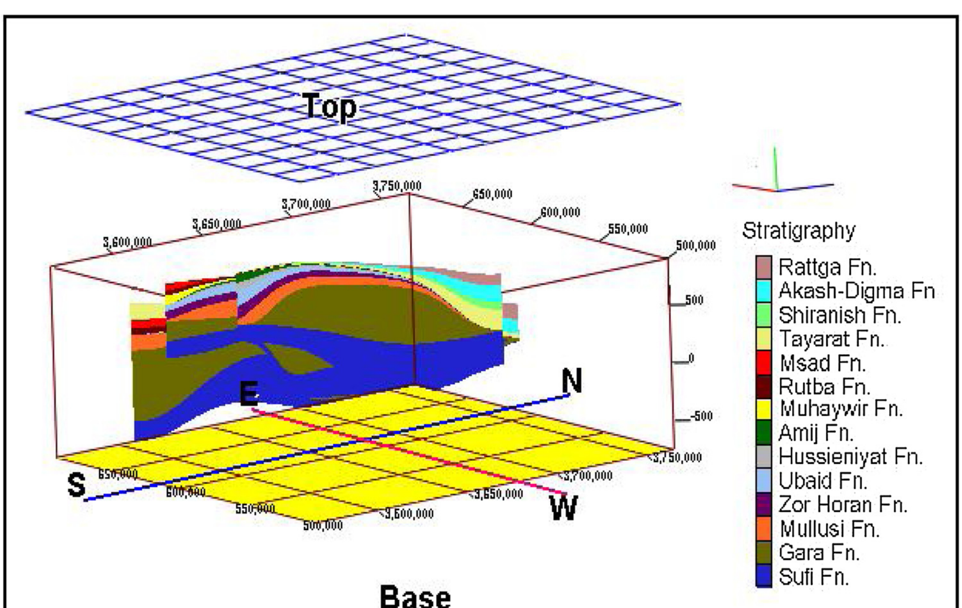

Fig. 2. Geo-structural model of the study area.

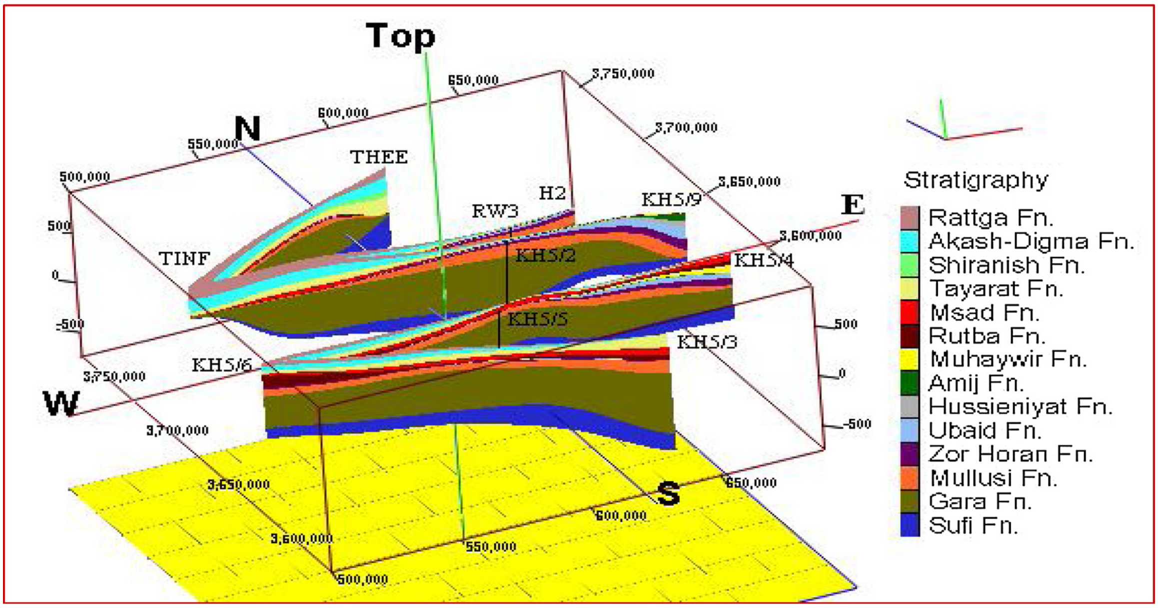

Fig. 4. 3D geologic model within the study area.

Uplift lands along Rattga Valley and from lateral leakage of waters passing from adjacent aquifers having a hydraulic head more than 470 m ASL, especially from the western parts (Hussien, 2013). Ga'ra aquifer is characterized by large extensions and Fig. 4 explains the model of Ga'ra Aquifer extension in three dimensions.

2- Mullusi Aquifer: Mullusi aquifer of the semi-confined condition is recharged from the scope of Rutba Uplift lands along Hauran Valley (Hussien, 2012). Mullusi aquifer characterized by large extensions and its thickness reaches 100 m in the south definitely in Abu Menttar and 130 m in Amij and northerly wedge out in Ga'ra depression at 30 m thick. Fig. 4 explains the model of the Mullusi Aquifer extension in three dimensions.

3- Ubaid Aquifer: The aquifer recharged from the drainage basins of Hauran and Hussayniyat Valleys in which Ubaid layers were exposed, creating boundaries of unconfined to semi-confined conditions (Hussien, 2010a). The thickness of Ubaid carbonates aquifer within its

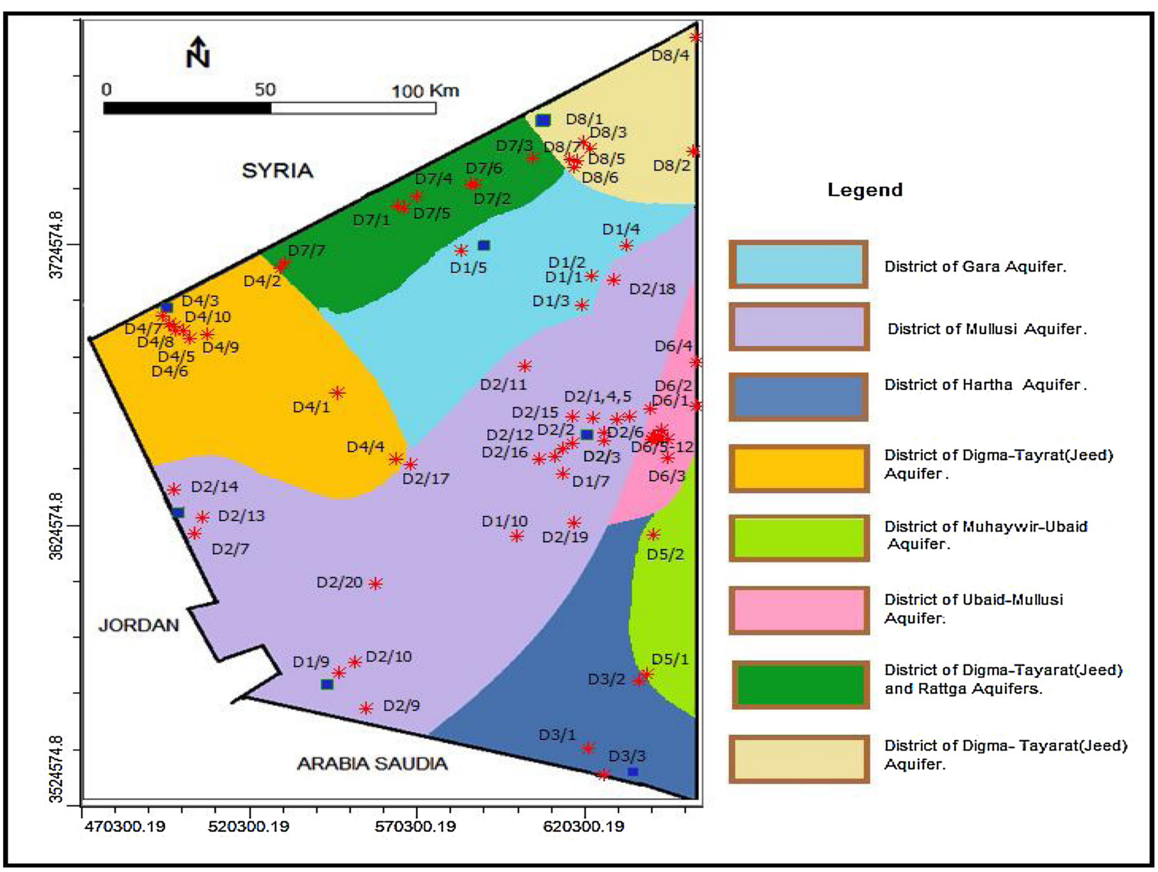

Fig. 5. Spatial distribution map of aquifers within the study area.

Table 1
Chemical analyses of the groundwater within the study area (Hussien, 2018).

Well No.	Temp °C	pH	TDSmg/L	H_T mg/L	K^+mg/L	Na^+mg/L	Ca^{++}mg/L	Mg^{++}mg/L	Cl^-mg/L	$SO_4^=$mg/L	HCO_3^-mg/L
D1/1	22.5	7.3	514	330.12	6.26	25.3	48.9	50.7	82.4	151.2	171.4
D1/2	21	7.3	2208	915.23	12.9	336.7	193.4	105.3	581.5	501.6	488.6
D1/3	22	7.3	1800	740.84	10.56	272.8	124.3	104.9	437.7	499.7	284.3
D1/4	23	7.5	3150	1125.5	36.75	423.2	283.8	166.4	733.4	944.6	540.5
D1/5	22	7.6	2200	1119.6	19.94	253.7	238.1	127.9	540.3	631.2	295.2
D2/1	22	7.2	720	382.9	4.3	69.5	99.4	32.8	153.4	152.6	235.5
D2/2	23	7.3	1844	665.8	20.33	282.2	151.7	69.9	332	264	771.7
D2/3	26	7.5	688	351.1	7.82	64.4	82.4	35.4	78.5	101.3	378.8
D2/4	25	7.4	904	419.4	5.47	87.2	103	39.5	187.1	191.5	304.4
D2/5	24	7	576	290.7	7.04	65.1	68.9	28.9	87	144	222
D2/6	25	7.1	545	298.8	3.13	37	67.7	31.6	57.2	61.9	314.2
D2/7	23	7.3	2100	927.6	12.51	289.3	217.4	93.7	517.6	588.5	383.7
D2/8	25	7.05	760	422.5	8.99	63	109.8	36.1	77	277.9	250.7
D2/9	25	7.4	1598	586.48	18.77	270	115.2	72.8	367.1	533	231.2
D2/10	26	7.3	1044	320.2	5.87	211.1	77.9	30.6	128.5	388.3	290.4
D2/11	24	7.4	559	237.6	3.13	78.2	63.9	19	108.6	103.7	176.9
D2/13	26	7.7	2373	1456	9.38	190.4	320	160.1	316.7	715.2	814.4
D2/14	25.5	7.8	1830	954.7	10.56	178	220.2	98.6	273.7	621.1	482.5
D2/15	25	7.8	1814	956.5	24.24	176	229.9	93.1	240	615.8	464.2
D2/16	25	7.3	790	410.9	6.26	71.3	130.9	20.4	124.3	160.8	345.9
D2/17	26	7.3	1197	707.1	10.17	63.3	155.1	77.9	97.3	317.3	534.4
D2/18	24	7.5	1086	431.9	12.51	168.8	120.8	31.7	249.6	279.8	261.1
D2/19	25	7.4	988	333.6	11.73	181	71.3	37.9	237.9	284.6	180.6
D2/20	23	7.2	784	452.4	4.69	59.3	106	45.7	162.6	160.3	271.5
D3/1	23	7.4	756	332.5	4.69	112.7	67.9	39.7	160.8	154.6	254.4
D3/2	24	7.3	1350	526.3	23.85	209.3	145.9	39.4	309.9	337.4	337.9
D3/3	24	7.4	1180	579.6	7.04	139.6	132.3	60.7	268.7	381.1	180
D4/1	22	7.4	1912	1022.4	22.68	112.7	179.2	140.1	284.7	616.3	521
D4/2	23	7.4	1453	582.2	8.21	120.1	188.2	93.1	143.1	401.8	641.1
D4/3	22	7.6	1923	926.8	20.72	226.1	188.2	111.3	433.8	291.4	735.1
D4/4	23	7.6	1776	1068.2	16.42	133.4	201.8	137.5	298.2	547.2	496.5
D4/5	24	7.5	1968	927.9	11.73	244	200.8	103.9	396.9	275.5	861.9
D4/6	22.5	7.3	2438	1021.5	37.53	285.9	222.8	113.3	491.3	369.6	840
D4/7	24.5	7.5	1690	723.8	14.86	250.9	151.1	84.4	358.9	344.6	567.9
D4/8	24	7.5	1470	791.8	8.21	136.9	184.4	80.7	161.2	406.6	621
D4/9	23	7.4	1050	562.3	6.26	99.4	104.9	73.2	148.4	347	314.2
D4/10	23	7.4	2450	1223.7	14.86	294.6	279.4	128.1	535	649.4	613.1
D5/1	22	7.3	1056	411	12.51	167.2	76.2	53.8	193.8	347	206.2
D5/2	21	7.25	1190	633.1	6.65	103.7	139.1	69.6	65	473.8	400.8
D6/1	24	7.5	726	429.2	4.3	50.1	82.8	54.2	105.8	148.3	328.2
D6/2	25	7.3	1744	1135.6	20.33	66	261.7	117.4	268.7	687.4	344
D6/3	24.3	7.4	706	430.9	1.95	49.9	82	55.1	153	169.9	183
D6/4	23	7.7	1480	687.5	5.87	59.1	145.3	79.1	87.3	353.8	439.8
D6/5	23.5	7.5	860	418.6	5.87	101	100.2	41	165.1	227.5	256.2
D6/6	22	7.45	911	479.2	3.13	91.1	112	48.6	142	54.7	438.6
D6/7	21	7.9	874	454.5	5.08	99	101.6	48.9	122.1	109.9	477.6
D6/8	23	7.41	1003	519	23.85	94.8	112	58.3	142	203	447.7
D6/11	24	7.29	997	459.2	17.2	91.3	104	48.6	156.2	105.6	414.2
D6/12	23	7.46	1010	598.5	19.55	91.1	111.8	77.8	148.7	149.8	439.2
D7/1	25	7.8	700	340.1	5.87	92	76.2	36.5	127.4	141.1	274.5
D7/2	24	8.1	688	346.1	8.99	69.9	57.9	49.1	114	168	232.4
D7/3	23	7.7	578	329.4	1.56	33.6	67.3	39.3	45.8	110.4	300.7
D7/4	22	7.4	673	329.7	2.35	78.9	87.6	27	124.6	189.6	164.7
D7/5	24	7.7	658	269.9	14.08	94.1	71.9	22	134.9	118.6	250.1
D7/6	23	7.6	1120	657.7	8.99	77.1	118.6	88.1	119.3	267.4	533.1
D7/7	24	7.4	845	421.8	5.08	76.82	95.6	44.6	113.2	79.7	469.1
D8/1	21	7.55	757	326.6	4.3	107.6	83.4	28.8	141.3	142.6	303.8
D8/2	24	7.4	1072	379.1	10.17	191.6	85.9	40.1	285.8	159.4	336.7
D8/3	25	7.5	2338	727.57	25.42	466.7	126.7	100.2	675.9	419	526.4
D8/4	26	7.6	672	290.3	5.08	94.8	78.1	23.2	129.2	135.4	256.2
D8/5	23	7.16	989	390	25.81	190.7	82.2	45	284	121	340.4
D8/6	24	7.45	1089	400.1	25.02	183.8	88.2	43.8	213	120.5	463.6

extension in the district (D6) ranges between 44 and 80 m.

4- Muhaywir Aquifer: The aquifer is recharged from its exposure zone within Amij catchment area, characterized by a semi-confined storage condition within the district (D5), which changes to confined aquifer in the southeastern part. The thickness of aquifer including sandstone and carbonate beds is ranged from 40 to 96 m. The extension of the aquifer is shown in (Fig. 4).

5- Hartha Aquifer: The aquifer is fed by water from Ghadaf catchment area including Hazimi tributary and from lateral leakage of waters passing from Tayarat-Digma aquifer. The aquifer is characterized by semi-confined to confined conditions with a thickness of about 130 m in the east part of the district (D3).

6- Tayarat–Digma Aquifer: Tayarat–Digma is an unconfined aquifer of wide extension in Tenif and Swab sites (D4 and D7 district), with a thickness of carbonate aquifer ranged between 140 and 180 m intra-regional of Tenif and Swab. This aquifer is characterized by confined

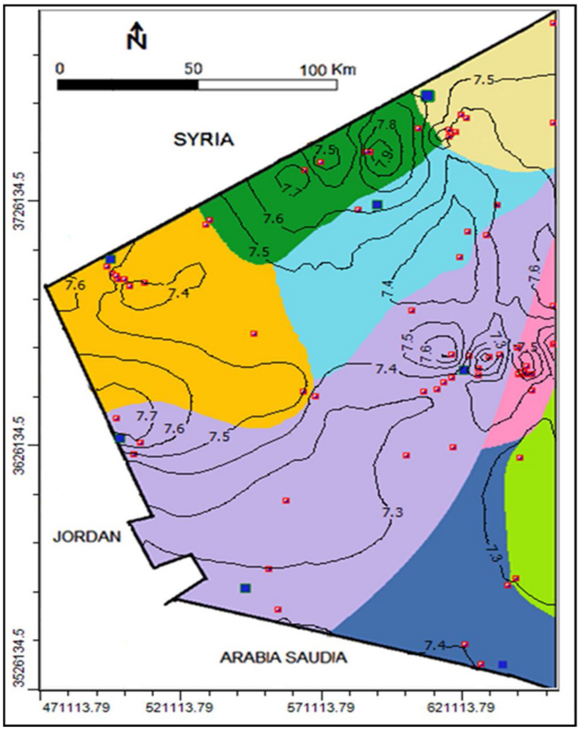

Fig. 6. Spatial distribution map of pH.

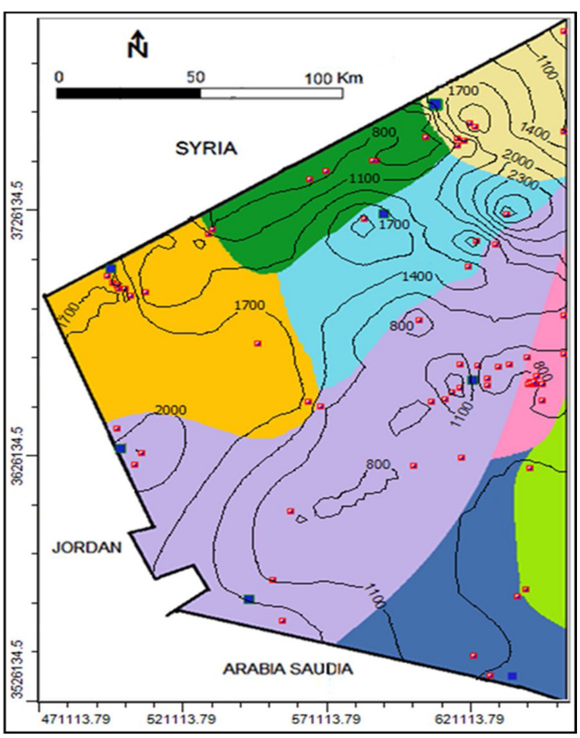

Fig. 7. Spatial distribution map of TDS(Hussien, 2018).

storage conditions in a thickness ranging from 36 to 122 m within Muger Elthib Site.

7- Rattga Aquifer: The aquifer is of a perched unconfined condition in the interiors area of Swab drainage basin within the district (D7). The thickness of Rattga aquifer is ranged from 100 to 138 m.

The available groundwater resources in Al Hamad zone are originated as same as the old source. The recharge mainly occurs during the southern pluvial period (late Pleistocene age) of high-frequency precipitation dated back to more than 30,000 years before present (BP) and followed by a northern pluvial period (early Holocene) that continued during 15,000 and 22,000 Years BP. Then the third pluvial period continued between 6000–14000 Years BP. Finally, the fourth-lowest pluvial period (Neolithic period) is < 5000 Years BP. These results are confirmed through the analysis of isotopes elements (^{14}C,^{3}H,^{13}C and ^{18}O) (Hussien, 2010b). Al Hamad physiographic zone is considered as a main recharge zone of the aquifers within study area, (Araim, 1990; Jassim and Goff, 2006; Hussien, 2010a), just as these studies confirmed a practical occurrence of recharge and water replenishment renewing aquifers by rain and runoff waters penetrated throughout rocks exposure within the valleys, Hauran, Ghadaf, Alwalaj, Swab and Rattga. The amount of infiltration to all aquifers that penetrated to the groundwater in the study area is equal to 204.36 × 10^6 m^3/year. The recharge inflow is also, done as a result of hydraulic connection between aquifers.

1.3. Hydraulic characteristics and groundwater flow within aquifers

Hydraulic characteristics and flow regime were assessed for aquifers based on the available information on the hydrogeological studies (Hussien and Fayyadh, 2014). The permeability of aquifers within district D-1, 2, 3, 4, 5, 6, 7 and 8 ranged from 0.0078 to 2.01 m/day, 0.0078–3.01 m/day, 0.1–1.3 m/day, 0.2–1.51 m/day, 0.5–1.01 m/day, 0.1–3.51 m/day, 0.51 to 4.51 m/day and from 0.2–4.1 m/day respectively. Those aquifers are classified as aquifers of low permeability compared with Laboutka classification (Laboutka, 1974). The transmissivity coefficient of aquifers within district D-1, 2, 3, 4, 5, 6, 7 and 8 varies from 60 to 240.8 m^2/day, 0.8 to 632 m^2/day, 4 to 200 m^2/day, 5 to 250 m^2/day, 60 to 180 m^2/day, 5 to 60.8 m^2/day, 60 to 120.8 m^2/day and from 60.4–360.8 m^2/day, respectively. The aquifers within the Districts D-1, 5, 7 and 8 are classified as aquifers of middle to high transmissivity comparing with Laboutka classification, while the aquifers within Districts D-2, 3, 4 and 6 are of low to high class. The groundwater of aquifers within district-D-1, 3, 5, 6, and 8 are controlled by unconfined to semi-confined conditions, where the average of storativity is 8.8 × 10^{-3},1.15 × 10^{-2}, 1.8 × 10^{-2}, 1.46 × 10^{-2} and 9.2 × 10^{-3} respectively. While the groundwater of aquifers within districts D-2, 4 and 7 is controlled by semi-confined to confined conditions, with a storativity of 5 × 10^{-3}, 6.4 × 10^{-3} and 4.4 × 10^{-3} respectively. The specific capacity of the water wells penetrated aquifers within district D-1, 2, 3, 4, 5, 6, 7 and 8 ranged between 32.2 and 107.2 m^3/day/m, between 2.9 and 92.2 m^3/day/m, between 17 and 44 m^3/day/m, between 22 and 51.2 m^3/day/m, between 11.2 and 24.6 m^3/day/m, between 6.6 and 62.1 m^3/day/m, between 4.96 and 77.9 m^3/day/m and from 48 to158.4 m^3/day/m, respectively.

2. Materials and methods

The study was conducted based on the groundwater monitoring program in 64 wells within the scope of Hamad well systems during 2013. The coordinates set by hand GPS. The groundwater levels were measured by sensor electrode and rely on scientific procedures and references (Barcelona et al., 1985; USEPA, 1989; Plazak, 1994; Nielsen, 2006), while the adopted procedures in the hydrogeological studies (Shelton, 1994; USEPA, 2000) were used in the process of taking samples from wells. All tools and bottles were washed with distilled water and then rinsed by sample water (Hem, 1990; Shafer et al., 1997), before packing to ensure the elimination of pollutants. Field measurements of water temperature, pH and TDS using EC-pH meters after calibration were conducted, while the chemical analyses included the anions and cations were analyzed in the soil and water laboratory (Centre of the Desert Studies). Test results and field measurements are shown in Table 1. The groundwater of the aquifers was classified based on corrosion and salt incrustation Indices. The spatial analysis map of Indices results was plotted using a Groundwater Contour program,

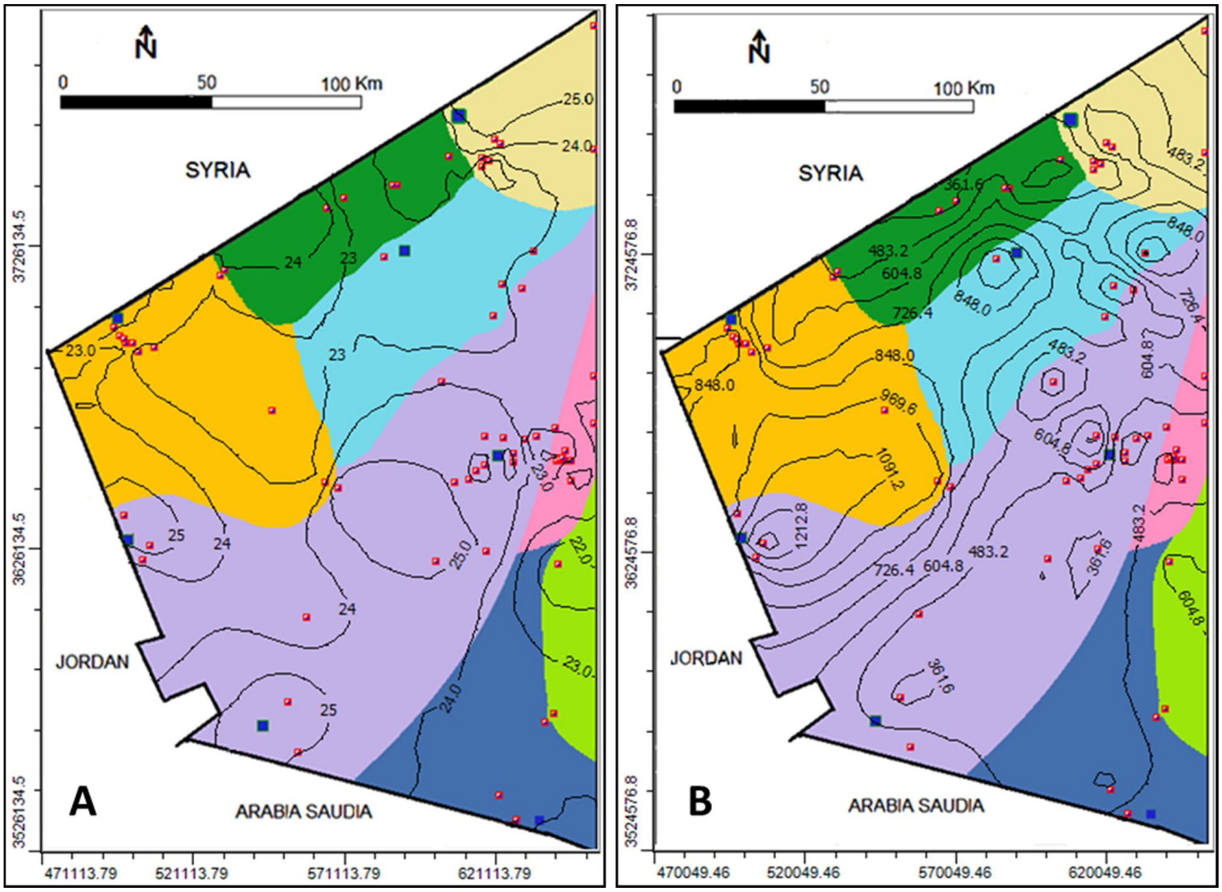

Fig. 8. **(A)** Spatial map of the groundwater Temperature, **(B)** Spatial map of the total Hardness within aquifers.

while Rock work14 was used for geo-structural and hydrogeological models. The corrosion and incrustation mechanisms of the groundwater were determined by calculating the coefficients of Langelier and Ryznar Indices according to the equations below (Carrier, 1965, Moody et al., 1988, ASHRAE, 1995, Rafferty, 1999). Using PhreeqC software program.

Langelier Saturation Index (LSI) = pH – pHs

Ryznar Stability Index (RI) = 2 pHs- pH, where

pH; groundwater acidity (pH field measurement).

pHs = -log{K_2* γ_{Ca}*[Ca]*γ_{HCO3}*[HCO_3]/ K_{sp}}, where,

pHs = pH of the water in equilibrium with solid $CaCO_3$

γ_{Ca}: Activity coefficient for Ca,

γ_{HCO3}: Activity coefficient for HCO_3,

K_2: Carbonate equilibrium constant = [H][CO_3]/HCO_3,

K_{sp}: Solubility product for $CaCO_3$ derived from phreeqc program results.

3. Results and discussion

3.1. Hydrochemical characteristics

The groundwater acidity (pH) of the aquifers within district-1, 2, 3, 4, 5, 6, 7 and 8 are ranged from 7.3–7.6, 7.0–7.8, 7.3–7.4, 7.3–7.6, 7.25–7.3, 7.29–7.9, 7.4–8.1 and from 7.16 to 7.69, respectively. The distribution map of the groundwater acidity (Fig. 6) indicated that there is a low spatial variation of (pH) ranged between 0.00000005 and 0.0009 pH/meter within all aquifers.

The total dissolved solids within district-1, 2, 3, 4, 5, 6, 7 and 8 are ranged from 514 to 3150 mg/l, 500–2373 mg/l, 756–1350 mg/l, 1050–2450 mg/l, 1056–1160 mg/l, 706–1744 mg/l, 538–1120 mg/l and from 672 to 2338 mg/l, respectively. The groundwater was classified as fresh to slightly saline water according to TDS classification in (Collin's, 1975; Matthess, 1982; Hem, 1990; Todd and Mays, 2005).

Distribution map of TDS (Fig. 7), showed increase of concentration in an enrichment grade of 0.0002 to 0.188 mg/ liter/m to the northwest portion (within district-6 and western part of district-2) and to the northeast direction corresponding with the flow direction, while TDS values decreased in the catchment area of Swab and Hauran valleys which represented the zone of infiltration and source of groundwater replenishment.

The groundwater temperature within district-1, 2, 3, 4, 5, 6, 7 and 8 were ranged from 21 to23 °C, 22–26 °C, 23–24 °C, 22–24.5 °C, 21–22 °C, 21–25 °C, 22–25 °C and from 21 to 26 °C, respectively, which were classified as warm water (Laboutka, 1970, Matthess, 1982; Todd and Mays, 2005). The distribution map of the groundwater temperature (Fig. 8-A), showed an increase of temperature as heat flow grade ranging between 0.0000007 and 0.0005 °C/meter towards the H3, Traybil provinces and northeast of Bir Al Rah village with the direction of groundwater flow.

The total hardness of the groundwater within district-1, 2, 3, 4, 5, 6, 7 and 8 were ranged from 330.12–1125.5 mg/l, 237.6–956.5 mg/l, 332.5–579.6 mg/l, 562.3–1223.7 mg/l, 411–633.1 mg/l, 418.6–1135.6 mg/l, 269.9–657.7 mg/l and from 279.9–727.5 mg/l, respectively. The groundwater was classified as very hard water according to total hardness classification in (Todd and Mays, 2005; Hem, 1990), where the temporary hardness formed 57 % from the total hardness, meaning the groundwater might be unsuitable for direct industrial purposes (needs treatment before use).

The variation in total hardness values within the aquifers was due to fluctuation in calcium and magnesium concentrations according to the process of dissolution and ion exchange, especially, the minerals forming rocks of aquifers are (calcite and dolomite). Fig. 8-B illustrates

Table 2
Langelier and Ryznar Indices of the groundwater within the study area.

Well No.	[Ca] moL/L	[HCO_3] moL/L	γ_{Ca}	γ_{HCO3}	K_2 moL/L	K_{sp} moL^2/L^2	pHs *	pH	Langelier saturation index LSI	Ryznar index RI
D1/1	0.00122	0.00281	0.654	0.899	6.72×10^{-11}	3.338×10^{-9}	7.391	7.3	−0.091	7.482
D1/2	0.00483	0.00801	0.496	0.839	8.468×10^{-11}	3.467×10^{-9}	6.405	7.3	0.895	5.51
D1/3	0.0031	0.00466	0.521	0.849	8.261×10^{-11}	3.467×10^{-9}	6.817	7.3	0.483	6.334
D1/4	0.00708	0.00886	0.454	0.820	9.631×10^{-11}	3.338×10^{-9}	6.171	7.5	1.329	4.842
D1/5	0.00594	0.00484	0.493	0.837	8.704×10^{-11}	3.467×10^{-9}	6.526	7.6	1.073	5.452
D2/1	0.00248	0.00386	0.623	0.889	6.95×10^{-11}	3.467×10^{-9}	6.97	7.2	0.23	6.74
D2/2	0.00378	0.01265	0.510	0.845	8.61×10^{-11}	3.388×10^{-9}	6.28	7.3	1.22	5.26
D2/3	0.00205	0.00621	0.633	0.893	7.45×10^{-11}	3.235×10^{-9}	6.78	7.5	0.72	6.06
D2/4	0.00257	0.00499	0.604	0.881	7.64×10^{-11}	3.235×10^{-9}	6.79	7.4	0.61	6.18
D2/5	0.00172	0.00364	0.648	0.897	7.00×10^{-11}	3.311×10^{-9}	7.11	7	−0.11	7.22
D2/6	0.00169	0.00515	0.662	0.901	7.09×10^{-11}	3.311×10^{-9}	6.95	7.1	0.15	6.8
D2/7	0.00542	0.00629	0.500	0.841	8.78×10^{-11}	3.388×10^{-9}	6.43	7.3	0.87	5.56
D2/8	0.00274	0.00411	0.608	0.883	7.60×10^{-11}	3.311×10^{-9}	6.86	7.05	0.19	6.67
D2/9	0.00288	0.00379	0.533	0.855	8.612×10^{-11}	3.311×10^{-9}	6.888	7.4	0.512	6.376
D2/10	0.00194	0.00476	0.583	0.875	8.06×10^{-11}	3.235×10^{-9}	6.93	7.3	0.37	6.56
D2/11	0.00159	0.0029	0.662	0.901	6.87×10^{-11}	3.388×10^{-9}	7.25	7.4	0.15	7.1
D2/13	0.00798	0.01335	0.479	0.831	9.71×10^{-11}	3.235×10^{-9}	5.89	7.7	1.81	4.08
D2/14	0.00549	0.00791	0.515	0.847	8.98×10^{-11}	3.311×10^{-9}	6.29	7.8	1.51	4.87
D2/15	0.00578	0.00761	0.516	0.847	8.86×10^{-11}	3.311×10^{-9}	6.28	7.8	1.52	4.76
D2/16	0.00376	0.00567	0.608	0.883	7.59×10^{-11}	3.311×10^{-9}	6.58	7.3	0.72	5.86
D2/17	0.00387	0.00876	0.566	0.867	8.29×10^{-11}	3.235×10^{-9}	6.37	7.3	0.93	5.44
D2/18	0.00301	0.00428	0.579	0.873	7.79×10^{-11}	3.388×10^{-9}	6.82	7.5	0.68	6.14
D2/19	0.00178	0.00296	0.591	0.877	7.80×10^{-11}	3.311×10^{-9}	7.19	7.4	0.21	6.98
D2/20	0.00264	0.00445	0.612	0.885	7.24×10^{-11}	3.388×10^{-9}	6.87	7.2	0.33	6.54
D3/1	0.00169	0.00417	0.621	0.887	7.14×10^{-11}	3.338×10^{-9}	7.08	7.4	0.32	6.76
D3/2	0.00364	0.00554	0.554	0.863	8.13×10^{-11}	3.338×10^{-9}	6.63	7.3	0.67	5.96
D3/3	0.0033	0.00295	0.566	0.867	7.98×10^{-11}	3.338×10^{-9}	6.94	7.4	0.46	6.84
D4/1	0.00447	0.00854	0.511	0.845	8.42×10^{-11}	3.467×10^{-9}	6.4	7.4	1.0	5.4
D4/2	0.00433	0.01051	0.542	0.857	8.13×10^{-11}	3.388×10^{-9}	6.29	7.4	1.11	5.18
D4/3	0.00469	0.01205	0.511	0.845	8.40×10^{-11}	3.467×10^{-9}	6.23	7.6	1.37	4.86
D4/4	0.00503	0.00814	0.514	0.847	8.54×10^{-11}	3.388×10^{-9}	6.35	7.6	1.25	5.1
D4/5	0.00501	0.001413	0.509	0.845	8.81×10^{-11}	3.388×10^{-9}	7.10	7.5	0.4	6.7
D4/6	0.00556	0.01377	0.494	0.837	8.79×10^{-11}	3.388×10^{-9}	6.08	7.3	1.22	4.86
D4/7	0.00377	0.00931	0.527	0.851	8.62×10^{-11}	3.311×10^{-9}	6.39	7.5	1.11	5.28
D4/8	0.0046	0.01018	0.54	0.857	8.32×10^{-11}	3.388×10^{-9}	6.27	7.5	1.23	5.04
D4/9	0.00261	0.00515	0.579	0.872	7.63×10^{-11}	3.388×10^{-9}	6.81	7.4	0.59	6.22
D5/1	0.0038	0.00338	0.533	0.855	8.09×10^{-11}	3.467×10^{-9}	6.86	7.3	0.44	6.42
D5/2	0.00694	0.00657	0.507	0.843	8.29×10^{-11}	3.467×10^{-9}	6.33	7.25	0.92	5.41
D6/1	0.00206	0.00538	0.622	0.887	7.29×10^{-11}	3.388×10^{-9}	6.88	7.5	0.62	6.26
D6/2	0.00653	0.00564	0.515	0.847	8.89×10^{-11}	3.311×10^{-9}	6.36	7.3	0.94	5.42
D6/3	0.00204	0.003	0.622	0.889	7.32×10^{-11}	3.311×10^{-9}	7.13	7.4	0.27	6.86
D6/4	0.00362	0.00721	0.572	0.871	7.71×10^{-11}	3.388×10^{-9}	7.4	7.7	0.3	7.1
D6/5	0.0025	0.0042	0.604	0.881	7.41×10^{-11}	3.388×10^{-9}	6.91	7.5	0.59	6.32
D6/6	0.00279	0.00719	0.606	0.883	7.15×10^{-11}	3.467×10^{-9}	6.65	7.45	0.8	5.85
D6/7	0.00253	0.00783	0.605	0.883	7.01×10^{-11}	3.467×10^{-9}	6.67	7.9	1.23	5.44
D6/8	0.00279	0.00734	0.587	0.875	7.53×10^{-11}	3.388×10^{-9}	6.63	7.41	0.78	5.85
D6/10	0.00209	0.0072	0.583	0.875	7.20×10^{-11}	3.467×10^{-9}	6.8	7.42	0.62	6.18
D6/11	0.00259	0.00679	0.602	0.881	7.50×10^{-11}	3.388×10^{-9}	6.68	7.29	0.61	6.07
D6/12	0.00279	0.0072	0.583	0.875	7.58×10^{-11}	3.388×10^{-9}	6.64	7.46	0.82	5.82
D7/1	0.0019	0.0045	0.628	0.889	7.38×10^{-11}	3.311×10^{-9}	6.97	7.8	0.83	6.14
D7/2	0.00144	0.00381	0.632	0.891	7.17×10^{-11}	3.388×10^{-9}	7.18	8.1	0.92	6.26
D7/3	0.00168	0.00493	0.654	0.899	6.79×10^{-11}	3.388×10^{-9}	7.01	7.7	0.69	6.32
D7/4	0.00218	0.0027	0.634	0.893	6.86×10^{-11}	3.467×10^{-9}	7.18	7.4	0.22	6.96
D7/5	0.00179	0.0041	0.64	0.895	7.09×10^{-11}	3.388×10^{-9}	7.05	7.7	0.65	6.4
D7/6	0.00296	0.00874	0.573	0.869	7.72×10^{-11}	3.388×10^{-9}	6.53	7.6	1.07	5.46
D7/7	0.00238	0.00769	0.615	0.885	7.36×10^{-11}	3.388×10^{-9}	6.66	7.4	0.74	5.92
D8/1	0.00208	0.00498	0.624	0.889	6.8×10^{-11}	3.467×10^{-9}	6.94	7.55	0.61	6.33
D8/2	0.00214	0.00552	0.586	0.875	7.71×10^{-11}	3.388×10^{-9}	6.86	7.4	0.54	6.32
D8/3	0.00316	0.00863	0.491	0.837	9.31×10^{-11}	3.311×10^{-9}	6.50	7.5	1.0	5.5
D8/4	0.00195	0.0042	0.635	0.893	7.44×10^{-11}	3.235×10^{-9}	6.97	7.6	0.63	6.34
D8/5	0.00205	0.00558	0.587	0.875	7.54×10^{-11}	3.388×10^{-9}	6.88	7.16	0.28	6.6
D8/6	0.0022	0.0076	0.587	0.875	7.69×10^{-11}	3.388×10^{-9}	6.71	7.45	0.74	5.97
D8/7	0.0016	0.0072	0.602	0.881	7.05×10^{-11}	3.467×10^{-9}	6.90	7.67	0.77	6.13

the phenomenon of spatial distribution model of total hardness within the aquifers.

3.2. Corrosion and salt incrustation

The ability of groundwater within hydrogeologic districts for corrosion and incrustations were determined and classified after calculating Ryznar Stability Index and Langelier Saturation Index. More details are found in (Stumm and Morgan, 1981; Loewenthal and Marais, 1982; Edstrom Industries, 1998; Moody et al., 1988; ASHRAE, 1995; Rafferty, 1999). The Indices were calculated using the following equations, supported by Phreeqc software, the results were scheduled in Table 2.

Langelier Saturation Index (LSI) = pH – pHs.

Index Value Indication (Carrier, 1965)

Scale forming but non corrosive

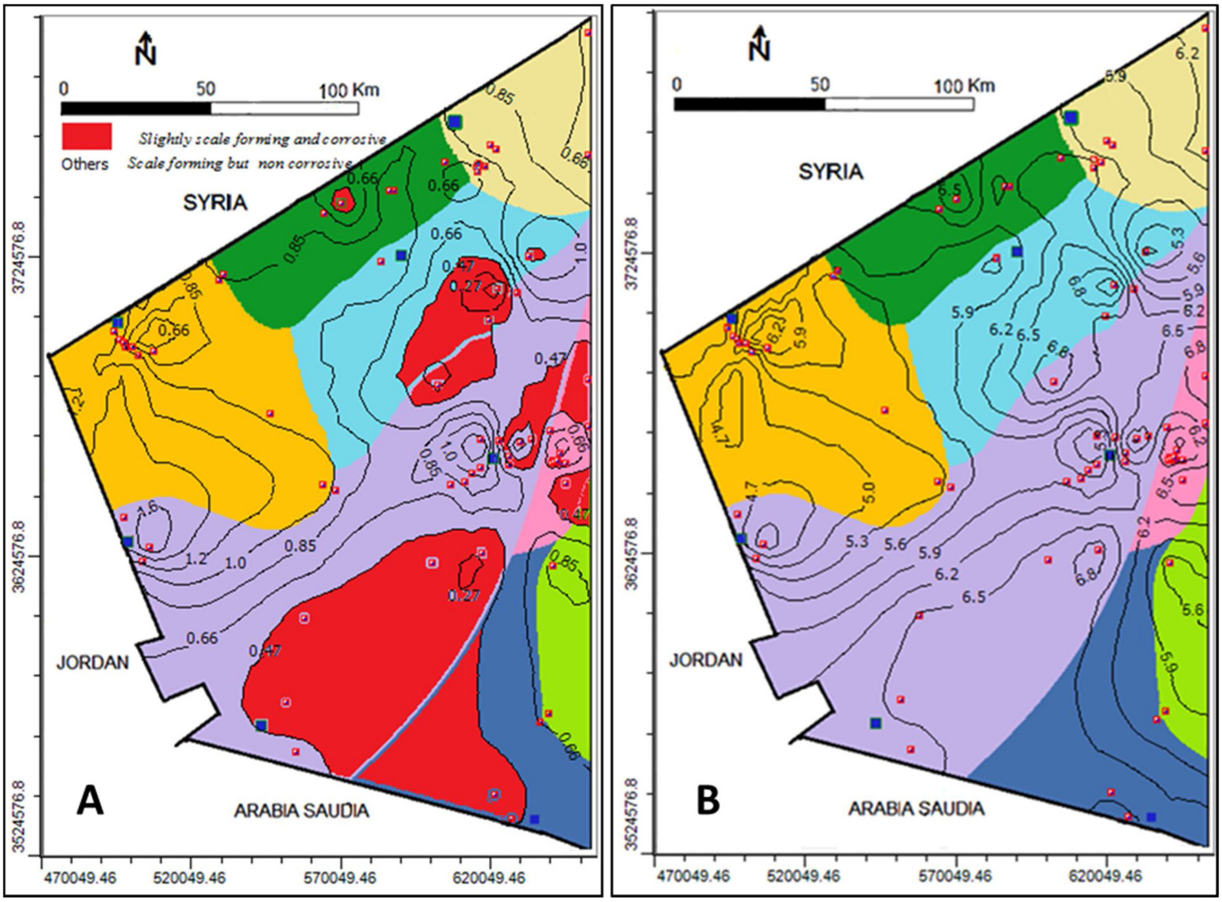

Fig. 9. (A) Spatial distribution map of LSI, **(B)** Spatial distribution map of RSI.

Slightly scale forming and corrosive
Balanced but pitting corrosion possible
-0.5 Slightly corrosive but non-scale forming
-2.0 Serious corrosion
Ryznar Stability Index (RI) = 2pHs-pH
Interpretation of the Ryznar Stability Index (Carrier Air Conditioning Com, 1965)
4.0–5.0 Heavy scale will form. If RI < 5.5 Heavy scale will form.
5.0–6.0 Light scale will form. If 5.5 < RI < 6.2 scale will form.
6.0–7.0 Scale or corrosion will form If 6.2 < RI < 6.8 scale and/or corrosion will form.
7.0–7.5 Corrosion significant If 6.8 < RI < 8.5 water is corrosive.
7.5-9.0 Heavy corrosion If RI > 8.5 water is very corrosive.
> 9.0 Corrosion intolerable
$pHs = -\log\{K_2 * \gamma_{Ca} * [Ca] * \gamma_{HCO3} * [HCO_3] / K_{sp}\}$.

The results of corrosion and scales according to Langelier Saturation Index, Table 2 indicated that:

- The groundwater of Ga'ra aquifer (D1) is mainly characterized by the ability of salt incrustation with low ability to do corrosion.
- The groundwater of Hartha aquifer (D3) classified mainly as water of slightly scale forming and corrosive, and secondly as water of scale forming but non-corrosive.
- The groundwater of Digma-Tayarat aquifer (D4) classified as water of scale forming without effective corrosion.
- The water of Muhaywir-Ubaid aquifer (D5) classified as water of scale forming but non-corrosive.
- The groundwater of Mullusi aquifer (D2), Ubaid-Mullusi aquifer (D6), Rattga and Digma-Tayarat aquifer (D7), Digma-Tayarat aquifer (D8) are classified as water has ability of salt incrustation and water of slightly scale forming and corrosive.

Fig. 9-A shows the spatial distribution model of Langelier Saturation Index for the groundwater of aquifers with an average variance of Langelier index ranges from 0.00000018 to 0.00014/ meter. The results of corrosion and scales according to Ryznar Stability Index, Table 2 confirmed that:

- The groundwater of Ga'ra aquifer (D1) classified as water forming heavy scales and water has ability to do corrosion.
- The groundwater of Mullusi aquifer (D2) classified between water forming light scale and water of significant corrosion.
- The groundwater of Hartha aquifer (D3) classified mainly as water of slightly scales forming.
- The groundwater of Digma-Tayarat aquifer (D4), Muhaywir-Ubaid aquifer (D5) classified as water forming slightly scales and/or corrosion.
- The groundwater of Ubaid-Mullusi aquifer (D6), Rattga and Digma-Tayarat aquifer (D7), Digma-Tayarat aquifer (D8) are classified as water forming slightly scales or corrosion.

Fig. 9-B shows the spatial distribution model of Ryznar Stability Index (RI) within the ground-water of aquifers. The average variance of Ryznar index ranges between 0.00000005 RI/meter and 0.0003 RI/ meter of distance in the groundwater of aquifers within the hydrogeologic provinces.

4. Conclusions

This paper investigate the groundwater ability for corrosion and salt encrustation within aquifers (west Iraq), based on Langelier and Ryznar Indices. The results have indicated a predominant distinction of encrustation and low ability of corrosion. Therefore, the study recommends treating the groundwater before used in industrial purposes (boilers, chillers and heat-exchange devices). The treatment requires removing the temporary hardness, which constituted about 57 % of the total hardness and may be clogging pipes carriers by forming salt crusts. On the other hand, it is necessary to use sheathed casing pipes and non-metallic filters in the linings of wells and transporting pipes. Also, the maintenance of pumps, replacing valves, regularly cleaning water tanks should take place periodically. The pumps, valves and accessories should be preferably made of alternative materials such as rubber and plastic.

Data availability statement

All data generated or analyzed during this study are included in this published article.

Funding

This research received no grant from any funding agency.

Ethical approval

Not required.

Declaration of Competing Interest

None declared.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.enmm.2020.100334.

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