Iraqi Journal of Science, 2018, Vol. 59, No.1C, pp: 534-551
DOI:10.24996/ijs.2018.59.1C.10

ISSN: 0067-2904

Determination of Lateral Hydraulic Connection of the Regional Aquifers in the Western Desert-Iraq using Hydrochemical and Hydrogeological data

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Abstract

In this study, lateral groundwater inflow was examined, according to the phenomena of groundwater mixing, groundwater flow and groundwater chemistry. The study region is composed of different aquifer systems; including karst-fracture media (Rattga-Jeed carbonates aquifer), fissure–porous media (Mullusi, Mullusi-Ubaid, Hartha-Rutba, and Digma-Tayarat aquifers) and porous media (Permo-carboniferous clastics rocks of Ga’ra aquifer).The aquifers are vertically super-imposed or of lateral contacts make open hydraulic connection between aquifers system. There is a severe shortage of water resources in the region because of rare precipitation and strong evapotranspiration. These conditions have hampered eco-environmental improvement. The aquifers should be considered as important water reserves for industrial use in mineral exploration and exploitation, as well agricultural purposes. The monitoring of groundwater quality network consist chemical variables (major ions concentration) and groundwater levels in sixty four water wells. The study describes the phenomena of lateral groundwater inflow (hydraulic connection) among aquifers systems using hydrogeologic phenomena compiled with the application of hydrochemical characterization on Piper Trilinear Plot. The results are supported and also benefit in studying the rational development of groundwater resources, which will significantly interpret the difference between supply and demand of groundwater, where the lateral groundwater recharge is a key factor in water balance studies, especially in semi-arid areas. Four mixing phenomena detected by Piper Trilinear Plot proved the existence of four trends of lateral groundwater flow interconnections within the hydrogeologic system. Accordingly, Al-Hamad complex hydrogeologic system can be classified into four subsystems, Mullusi-Ga’ra and Digma-Tayarat subsystem, Mullusi-Jeed and Rattga-Jeed subsystem, Mullusi-Rutba and Muhaywir-Ubaid subsystem, Mullusi and Mullusi-Ubaid subsystem.

Keywords: hydraulic connection, groundwater chemistry, lateral recharge, aquifer boundaries, groundwater mixing.

الاتصال الهيدروليكي الجانبي بين الخزانات الجوفية الإقليمية المتجاورة غرب العراق باستخدام المعطيات الهيدروجيولوجية والهيدروكيميائية

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الخلاصة

في هذه الدراسة، تم تحديد تغذية المياه الجوفية الجانبية وفقا لظاهرة الخلط، وكيمياء المياه الجوفية وجريانها. النظام الهيدروجيولوجي لمنطقة الدراسة يشتمل على نظم متعددة للخزن وسلوك الجريان؛ ومنها نظام الجريان الكارستي والخزن في كسور الطبقات الخازنة (Fracture media) (خزان الرطگة-الجيد الجيري)، ونظام الجريان في الوسط المسامي وكسور صخور الطبقات الحاملة للمياه (خزان ملصي، ملصي-عبيد، هارثة-رطبة و دگمة-طيارات)، اضافة الى نظام الجريان في الوسط المسامي(Porous media) (خزان الگعرة-صخور البيرمو -الكربونية). تخضع الخزانات الجوفية لظروف التطبق الافقي (غير متجانسة عموديا) وتتغير حدودها الجيولوجية الى ظروف التماس الجانبي(بسبب التطبق اللاتوافقي المائل)، والتي انشأت ظروف موقعية خدمت الاتصال الهيدروليكي الجانبي بين انظمة الخزانات الجوفية الاقليمية عند حدود تماسها. لأهمية تحديد واقع تغذية الخزانات الجوفية ولكونها تمثل احتياطيات مائية هامة وبسبب النقص الحاد في الموارد المائية السطحية لمنطقة الدراسة، استلزم رصد اتجاهات حركة المياه الجوفية وتحديد علاقتها بنوعية المياه، اذ تم رصد المتغيرات كيميائية (تركيز الأيونات الرئيسية) ومستويات المياه الجوفية في أربعة وستين بئرا للمياه. حددت الدراسة ظواهر تدفق المياه الجوفية الجانبية (الاتصال الهيدروليكي) بين أنظمة الخزانات الجوفية باستخدام المعطيات الهيدروجيولوجية مع نتائج تطبيق الخصائص الهيدروكيميائية (مخطط بايبر الثلاثي). اكدت الدراسة على وجود ظاهرة التغذية الجوفية الجانبية والتي تعد عاملا رئيسيا في دراسات الموازنة المائية الجوفية وخاصة في المناطق شبه القاحلة. أثبتت الدراسة وجود أربع ظواهر خلط وامتزاج تم تأكيدها بنتائج مخطط بايبر الهيدروكيميائي متطابقة مع أربعة اتجاهات لتدفق المياه الجوفية الجانبية داخل النظام الهيدروجيولوجي. وبناءا على ذلك، يمكن تصنيف النظام الهيدروجيولوجي المعقد في مقاطعة الحماد إلى أربعة أنظمة هيدروجيولوجية فرعية هي، نظام ملصي- گعرة- دگمة-طيارات الجوفي، ونظام ملصي-جيد-الرطگة الجوفي، ونظام ملصي- الرطبة- محيور-عبيد الجوفي، ونظام ملصي-عبيد الجوفي.

1. Introduction

The groundwater flow system was governed by natural rates of recharge and discharge. To evaluate the groundwater flow system prior to development, it must be determining the effects of aquifers against each other. Groundwater of aquifer system is generally or laterally interconnected with the groundwater of adjacent aquifers. The aquifer system existed in the marginal area of basins, has less or more yielding capacity than other parts, where the local groundwater system occurs. Wherever, precipitation is the major recharge source, the groundwater is recharged by infiltration of direct rainwater and/or intermittent runoff water and indirectly invaded as lateral flow towards adjacent aquifers. The groundwater flow is vigorously controlled by topographic karst stepped depression and plateaus (drainage system) and moves in the direction of basin trend [1]. In some situations, flow across a part of the geologic boundaries change in response to changes in head within the aquifer adjacent to the boundary. The flux in these situations is a specified function of that head and varies as the head varies. The regional groundwater flow and circulation have an effect on the attributes of local groundwater resource evaluation and eco-environmental protection.

1.1 Previous studies and Aims:

In the western plateau of Iraq, the groundwater is the main source of water supply because of the insufficient surface water, where the natural resources within the region such as minerals are available and expecting petroleum, too. Lateral groundwater recharge (inflow), defined as water that laterally moves between saturated zones of different aquifers. Lateral recharge is the step toward predicting the rate of solute transport to the aquifer [2, 3, 4 and 5].

Hydraulic characteristics and groundwater flow were assessed for aquifers, then and depending on the occurrence of groundwater within the geological Formations, eight districts of groundwater are identified in the study area [6]. Study of Hussien [7] indicated that the available groundwater resources in an Al Hamad zone are originated to old source.

The recharge is mainly happening during the southern pluvial period (late Pleistocene age) of high frequency precipitation dated back to (10000-30000) Years BP. Also Araim [8]; Jassim and Goff [9] studies confirmed a practical occurrence of recharge and water replenishment renewed aquifers by rain

and runoff waters penetrated throughout rock exposures within the valleys Hauran, Ghadaf, Alwalaj, Swab, and Rattga.
According to theory of groundwater systems [10], the water bearing with the same media and has a close to semi close hydraulic connection is often considered as an aquifer system, therefore the western region divided into seven aquifers within eight districts.

The aim of the study is to determine the lateral hydraulic connection and the groundwater interrelationship of eight aquifers system within the western desert of Iraq, using the plotting of Hydrochemical constituent's percentile on the Piper Trilinear diagram and comparing with the groundwater flow.

1.2 Study area

The study area which obtained 64 water wells is located within Hamad and Upper wedian zones to the west of longitude 40°40′ (west Iraq). It is bounded by Syria, Jordan and Arabia Saudia borders as shown in Figure-1, covering an area of about (39,000) km^2 with an altitude ranged from 175 to 900 m asl. The climate in the western desert is considered as arid to semi-arid with low impact of the Mediterranean Sea climate [6]. The mean annual value of air temperature, relative humidity, speed of winds, rainfall, and evaporation which was recorded at Rutba meteorological station during the period between 1941 and 2016 are 20.12°C, 45.6%, 3.12 m/sec, 106.9 mm/year, and 1686.1 mm/year, respectively. In semi-arid and arid environments, the recharge flux which represents renewability of aquifers is often heterogeneous, where the arid climate is potentially more variable in space and time.
The morphological features that influenced by Pleistocene rainy periods are multi drainage patterns within the hydrologic basins of Hauran, Rattga, Akash, Swab, Alwalaj, Kharja, Elattra, Elmerbagh and the tributaries of Ubayidh and Ghadaf valleys Figure- 1. The land surface represented by a plateau having undulant step reliefs gradually rises from north east towards south west.
The drainage of the main valleys is of parallel and dendritic patterns controlled by rock type and heterogeneity of sediments. Systems of blind central dendritic valleys are existed in Elmerbagh-Kharja basin and Breem valley within Alwalaj basin, which ends in a plain filled with friable sediments. Structurally, the study area is a part of Rutba subzone within the western zone of the stable shelf related to Arabic-African plate within Rutba subzone [9]. The depth of rock basement ranged between 6 to10 Km, [11].

The water bearing horizons in the Iraqi western desert influenced by Hauran fold (anticlinorium) (Fig. 1a)with beds dipping from 1.0° to 2.0° in a direction of ESE and from 2.0° to 6.0° in a direction of WSW, NWN and NEN [12, 6 and 13]. The zone of fold axis forms regional groundwater divide [14] which controls the groundwater recharge and movement by deviating water towards South East (Nukhaib Depression), North (Ga'ra depression), and North West (Traybil-Tinf karstic replenished zone). The study area is highly irregular surfaces plateau, which descends towards the NE and E. The region composed of different kinds of rocks from Paleozoic to Cenozoic consisting of multiple aquifers system is dominantly a large-scale buried anticlinorium structure with NE-SW axis. In the study area the Cretaceous sediments lie unconformable on Jurassic, Triassic and Paleozoic sediments. According to the erosion surface which marks the base of the Cretaceous sediments, the region is morphologically irregular with an elevation difference of about 4m/km.

The highest slop of unconformity is found in the NE part towards Ana Graben, reaches 10m/km, while the slope is gentler in the western part (south of Rutba) not exceeds 4m/km [9]. The cretaceous stratigraphic units are underlined by Devonian-carboniferous units as detected in Swab well No.1/Syria followed by Early carboniferous in Akas Oil well No.1/Iraq followed by Permo-carboniferous sediments in Ga'ra depression, Swab catchment area, and Tinf well No.1/Syria.

Late Triassic Sediments units are represented by Mullusi and Zor Hauran Formations. Those units were found underlying the Cretaceous units in subsurface sections south Rutba–Amman highway extends to Rish oil wells in Jordan [15]. The Jurassic stratigraphic units cover the pre-cretaceous unconformity surface in the south eastern part of Ga'ra depression Figure- 2. They are found in the exposed and subsurface sections having a general NE-SW strike trend dipping towards SE. These formations are Ubaid, Hussayniyat, Amij, and Muhaywir Formation.

The unconformity surface is overlain by early Cretaceous sediments in the area east of Rutba city, exposed by two clastics-carbonate units (Naher Umer-Maudod and Rutba–Msad Formations). In the W, NW, and NE parts, the overlying units are of late Cretaceous age or of Paleogene including Hartha, Tayarat–Digma, Rattga and Ghar, Nefile and Zahra Formations [14]. The Quaternary sediments in most extension areas are covered by a thin veneer of residual soil with a thickness ranges between 0.3 and 0.5 meters. The considerable thick deposits are accumulated in the main depression and valleys. The main differential sediments are residual soil, valley, and depression fills, terraces, calcrete, eolian sand, and slope sediment.

The hydrogeologic regime is classified and screened into various aquifers, including Ga′ra, Mullusi, Ubaid-Mullusi, Hartha-Rutba, Digma-Tayarat (Geed), Muhaywir-Ubaid and Rattga aquifer. The aquifers are segregated within eight hydrogeologic districts [6] including District of Ga'ra aquifer (D1), District of Mullusi aquifer (D2), District of Hartha-Rutba aquifer (D3), District of Digma-Tayarat aquifer (D4), District of Muhaywir-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 available hydrologic information about the aquifers within districts such as permeability, storage and transmissivity coefficients, and groundwater depths, specific capacity of wells, pH, and total

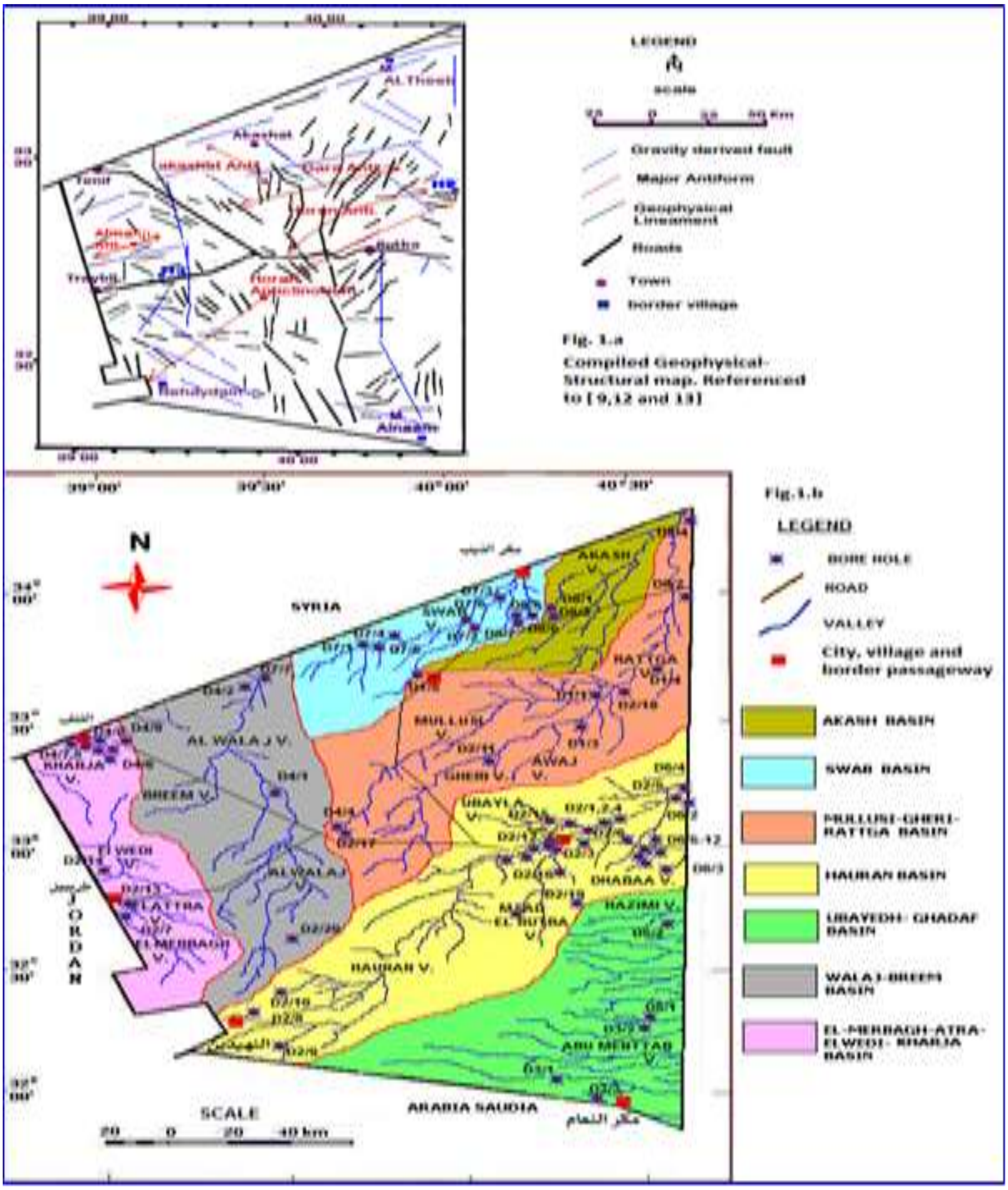

Figure 1(a)-Compiled Geophysical-structural map. (b) Location map of the study region.

dissolve solids are examined in a statistical prediction study, [16] and summarized as a probability of succeeding chance percent to 90% Table-1.

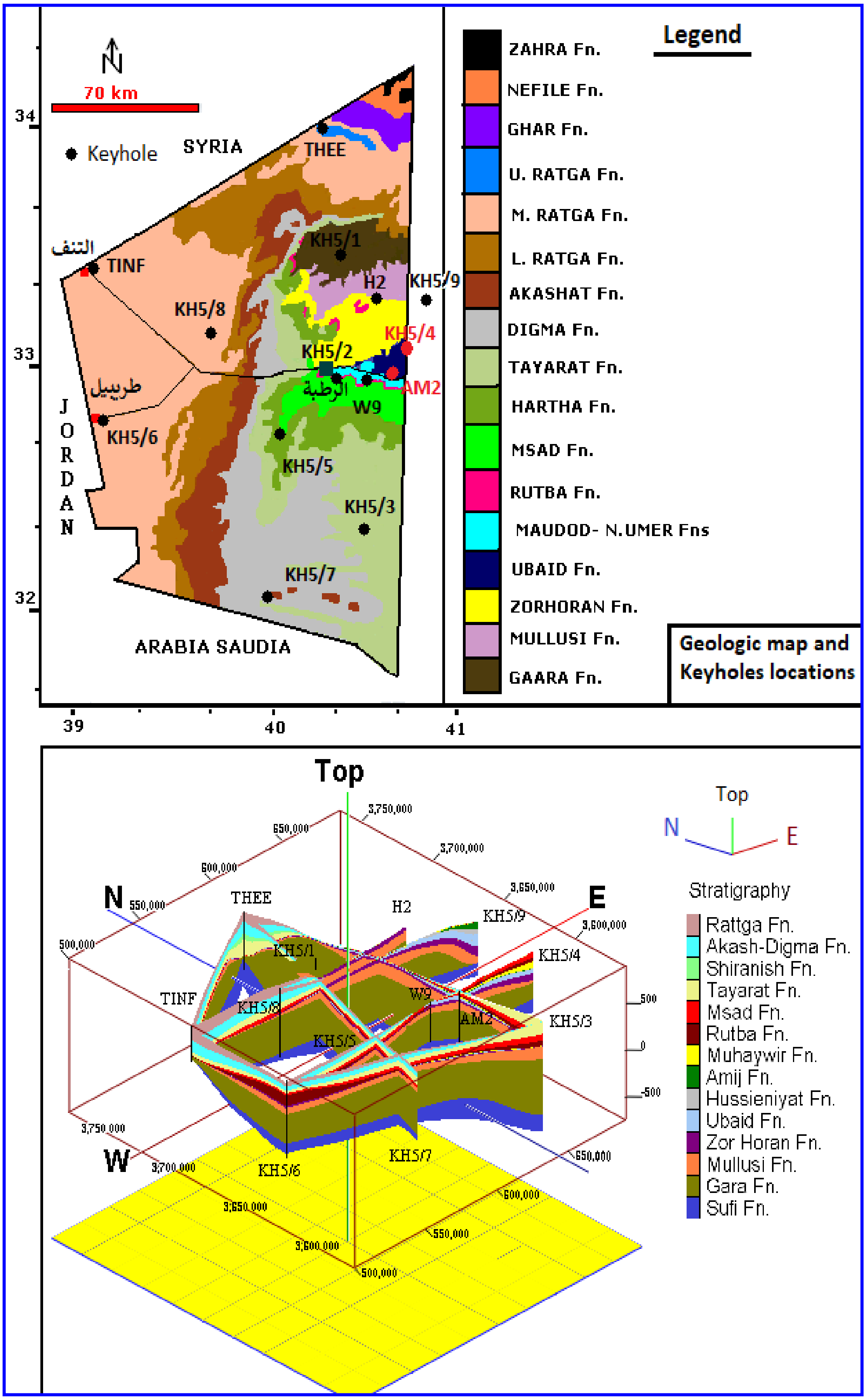

Figure 2-Geologic map and generalized 3D model of the geologic Formations.

Table 1-Hydraulic and Hydrochemical information of the aquifers within Hamad Districts.

Variable	D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8
Permeability (m/d)	≥ 0.0045	≥ 0.03	≥ 0.012	≥ 0.1	≥ 0.6	≥ 0.074	≥ 0.09	≥ 0.17
Transmissivity (m^2/d)	≥ 6.3	≥ 2.4	≥ 0.08	≥ 14	≥ 30	≥ 0.6	≥ 5	≥ 2.8
Storativity	≥ 0.0078	≥0.0003	≥0.0085	≥ 0.0048	≥ 0.007	≥ 0.008	≥ 0.003	≥ 0.008
Specific capacity (m^3/d/m)	≥ 50	≥ 3.8	≥ 1	≥ 21	≥ 6.5	≥ 4.9	≥ 4	≥ 40
Ground water level (m)	≥ 58	≥ 45	≥ 36	≥ 200	≥ 80	≥ 36	≥ 60	≥ 58
Acidity (pH)	≥7.0	≥ 7.2	≥ 7.0	≥ 7.1	≥ 6.9	≥ 7.3	≥ 7.1	≥ 6.9
TDS (ppm)	≥ 280	≥ 460	≥ 250	≥ 1000	≥320	≥ 400	≥ 400	≥ 650

Ga'ra Aquifer of static water levels ranged between 420 m asl and 470 m asl [17] is recharged from the scope of Rutba Uplift lands along Rattga Valley and from lateral leakage of waters passing from adjacent aquifers(mainly Akash-Digma aquifer, secondarily Rutba and Mullusi aquifers) having a hydraulic head more than 470 m asl, especially from the western parts. The aquifer influenced by structural setting resulted from Rutba uplift process, which gives an unconfined to semi confined conditions for shallow aquifer and confined conditions for the deep water bearing horizons. The aquifer characterized by large extensions and Figure-2 explains the model of Ga'ra Aquifer extension in three dimensions.

Mullusi aquifer is recharged from the scope of Rutba Uplift lands along Hauran Valley and its tributaries. The aquifer is of semi-confined conditions [18], characterized by large extensions and its thickness reaches 100 m in the south definitely in Abu Menttar, 130 meters in Amij and northerly wedge out in Ga'ra depression at 30 meters thick.

Ubaid Aquifer is recharged from the drainage basins of Horan and Hussayniyat Valleys in which Ubaid layers were exposed, creating the boundaries of unconfined to semi-confined conditions. The thickness of Ubaid water bearing horizons is influenced by paleo stratigraphic and structural settings, where Ubaid carbonate layers formed part of the geologic sequences in the Rutba Uplift zone. The thickness of the Ubaid carbonates aquifer and its extension in the 6th district ranged between 44 and 80 meters Figure-2.

Muhaywir Aquifer is recharged from its exposure zone within the Amij catchment area. The aquifer is characterized by a semi confined storage condition in the 5th district, which gradually changes to confined aquifer in the south eastern parts. The thickness of aquifer, including sandstone and carbonate beds ranges from 40 m to 96m. The extension of the aquifer is shown in Figure-2.

Hartha-Rutba Aquifer was fed by water from of Ghadaf catchment area, including Hazimi tributary and from lateral leakage of waters passing from Mullusi aquifer in the western parts. The aquifer characterized by semi confined to confined storage condition with a thickness of about 130 meters [14] in the east part of the 3rd district.

Digma-Tayarat is an unconfined aquifer of wide extension in Tenif and Swab sites (4th and 7th districts) with a thickness of the carbonate aquifer ranged between 140m and 180m intra-regional of Tenif and Swab. This aquifer characterized by a confined storage condition in a thickness ranged from 36 to 122 m within Muger Elthib site (8th district). Rattga Aquifer is of perched unconfined condition in the interior area of the Swab drainage basin within the 7th district. The thickness of Rattga aquifer ranged from 100 m to 138 meters.

2. Methods and Materials

The study was carried out based on the groundwater monitoring program in 64 wells within the scope of Iraqi Hamad wells system measured during March 2013. The groundwater levels measured by sensor electrical sounder and rely on procedures in scientific references [19, 20, 21 and 22]. The processes of taking samples from wells were achieved according to the field procedures explained in the studies [23 and 24]. All tools and bottles were washed with distilled water and then rinsed with sample water before packing to ensure the elimination of pollutants [25 and 26]. The reliability of the chemical composition results were checked using the charge balance method [4]. Groundwater samples were analyzed in Soil and Water Laboratory (Centre of the desert studies).

The chemical analyses of anions, cations, total dissolved solids (TDS) and groundwater levels are scheduled in Table-2. The interpretations of hydrochemical phenomena are statistically treated by a Trilinear Diagram [27] based on the Piper plot (using Rockwork14 program) and spatial analysis map (using Groundwater Contour software). On the basis of available litho logs of sixteen key bore holes [16 and 28] using RW-14 software, a 3D hydrogeologic models were performed to identify the distribution of the hydrogeologic system and their hosted geologic formations in X, Y and Z directions. This research describes the hydrogeologic framework and presents an analysis of groundwater preferential lateral flow within aquifers system, including a compilation in the graphical Trilinear format of the hydrochemical data compared with the transient groundwater flow direction.

3. Results and Discussion

The groundwater circulation patterns within the study region divided into shallow active circulation subsystem which involved with the Mullusi, Mullusi-Ubaid, Hartha-Rutba, Rattga-Jeed, Muhaywir-Ubaid, Digma-Tayarat aquifers, and deep stagnant system of slow circulation velocity obtained Ga’ra aquifer. The lateral boundaries of the groundwater flow are coincident with the trends of intermittent valleys and represented as flow boundaries. The Extending of the lateral boundaries within aquifers system allows the groundwater divide to shift beyond Rutba area, where groundwater withdrawals are located at or near the basin boundary. The aquifers system pinches out towards anticlinorium axis of NE trending Figure-3, where the replenishment mechanisms through different drainage patterns of valleys conform to several local groundwater divides.

3.1 Hydraulic Interrelationships of Aquifers

Groundwater levels in the aquifers system are influenced by conditions such as climatic changes that ultimately control the rate and amount of recharge to the aquifer and pumping stresses that remove ground water from the aquifer. Groundwater levels were recorded at 59 wells (point measurements) within the study area. Observation wells that were unaffected by human derived recharge or withdrawals were selected to measure water levels wherever possible.

A compiled water table map as shown in Figure-4 illustrates the elevations of groundwater levels in the study area, which are derived primarily from water level data Table-2 measured during March 2013. The water table reflects the effect of topography, the highest water table elevations extend along Hauran valley that roughly parallels the structural boundary (anticlinorium axis of NE trending). This area of the main replenishment zone represents the major groundwater divide that drains groundwater to the NW and ESE. The shallow groundwater table occurs along the main valley of Rattga basin at the NE portion; coincide with the topographic lowest in the study area. The groundwater depths in the aquifers within district-1, 2, 3, 4, 5, 6, 7 and 8 are ranged from 58 to 197 meters, 26 to 399 meters, 104 to 246 meters, 194 to 309 meters, 85 to 295 m, 15 to 295 meters, 36 to 216 meters and from 70 to 86 meters, respectively. The recharge of the aquifers were varied according to the rates determined from water budgets study [6], and ranged from7.15x10^6 m^3/year to 72.57x10^6 m^3/year, totaling to 204.36 x10^6 m^3/year.

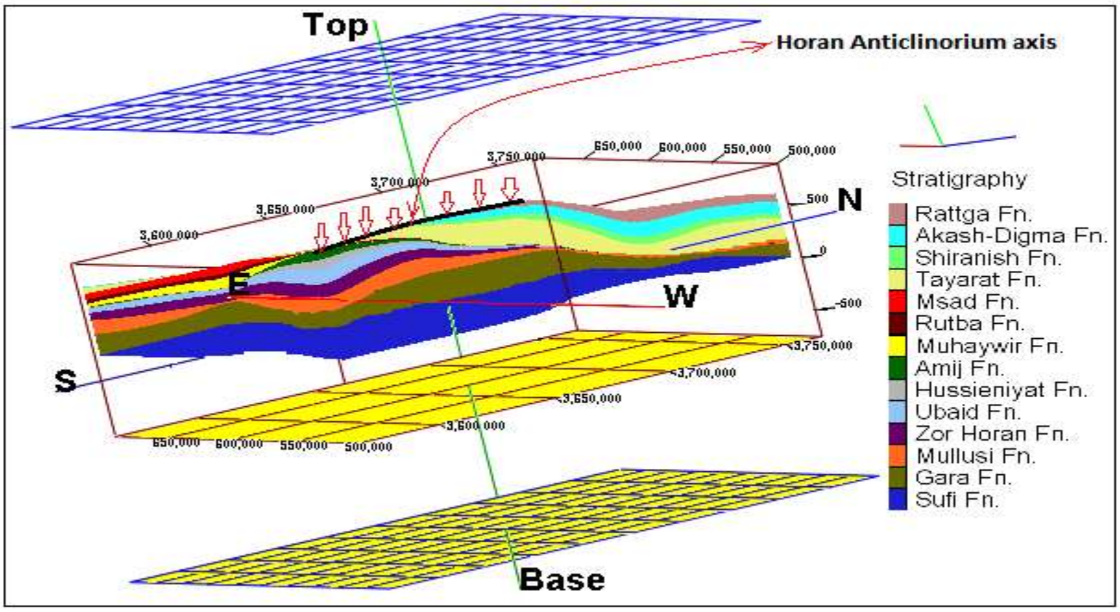

Figure-3-Generalized 3D model showing the pinches out of the geologic Formations towards anticlinorium axis of NE trending.

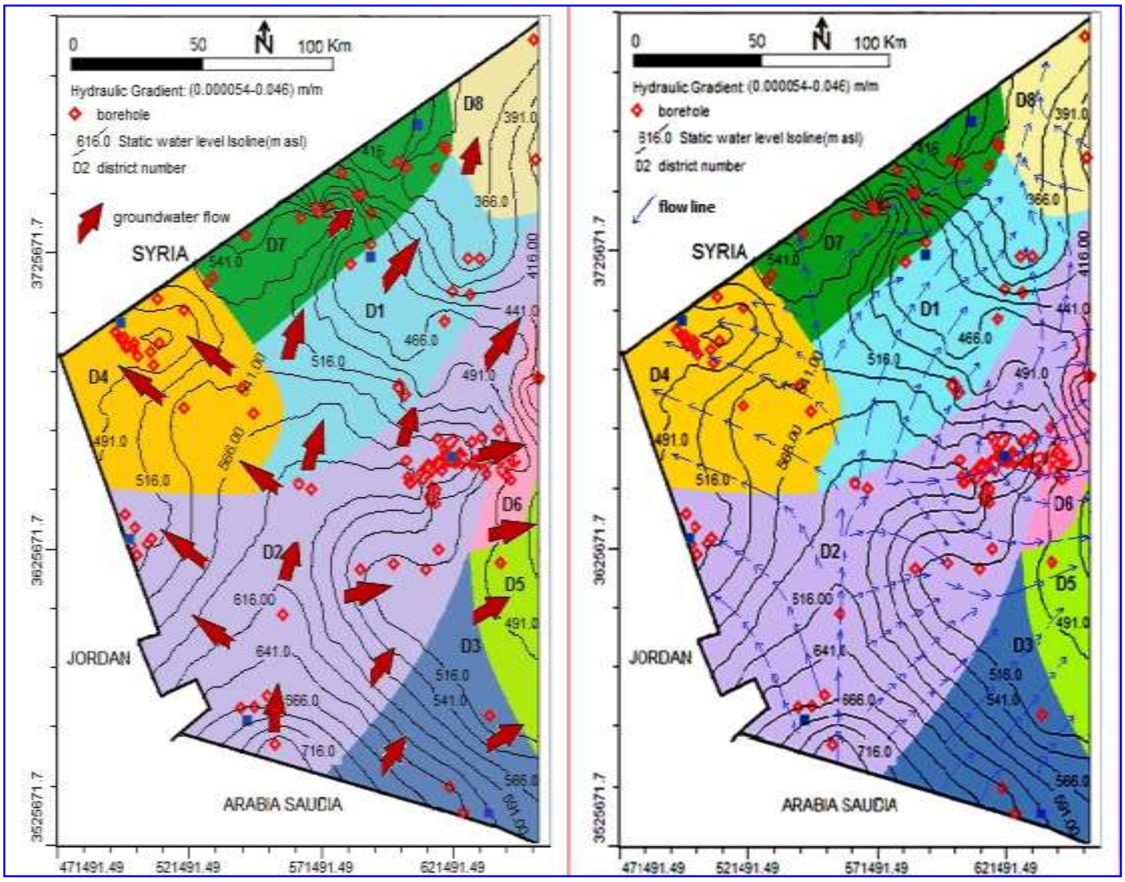

Figure 4-Groundwater flow within aquifers system.

Table 2- Static water level measurements and Chemical analyses of the groundwater.

Station ID	X coordinat m	Y coordinate m	Elev. m asl	SWL m asl	pH	K^+ meq/L	Na^+ meq/L	Ca^{++} meq/L	Mg^{++} meq/L	Total Cations	Cl^- meq/L	$SO_4^=$ meq/L	HCO_3^- meq/L	Total Ani	Error Percent %	TDS mg/L
D1/1	622232.6739	3713038.972	495.5	437.7	7.3	0.16	1.1	2.44	4.17	7.87	2.32	3.15	2.81	8.28	2.54	514
meq %						2	14	31	53	100	28	38	34	100		
D1/2	622232.6739	3713038.972	495.5	412	7.3	0.33	14.64	9.65	8.66	33.28	16.38	10.45	8.01	34.84	2.29	2208
meq %						1	44	29	26	100	47	30	23	100		
D1/3	619263.6507	3702836.155	518	503	7.3	0.27	11.86	6.2	8.63	26.96	12.33	10.41	4.66	27.4	0.81	1800
meq %						1	44	23	32	100	45	38	17	100		
D1/4	632910.7522	3724271.096	453	255.1	7.5	0.94	18.4	14.16	13.69	47.19	20.66	19.68	8.86	49.2	2.08	3150
meq %						2	39	30	29	100	42	40	18	100		
D1/5	583647.1768	3722174.598	610	417	7.6	0.51	11.03	11.88	10.52	33.94	15.22	13.15	4.84	34.6	0.96	2200
meq %						1.5	32.5	35	31	100	44	38	18	100		
D2/1	633750.1859	3663286.77	584.6	543	7.2	0.11	3.02	4.96	2.7	10.79	4.32	3.18	3.86	11.36	2.57	720
meq %						1	28	46	25	100	38	28	34	100		
D2/2	616751.3575	3653828.621	622.1	597	7.3	0.52	12.27	7.57	5.75	26.11	9.35	5.5	12.65	27.5	2.59	1844
meq %						2	47	29	22	100	34	20	46	100		
D2/3	626084.259	3654560.083	621	564	7.5	0.2	2.8	4.11	2.91	10.02	2.21	2.11	6.21	10.53	2.48	688
meq %						2	28	41	29	100	21	20	59	100		
D2/4	622611.1985	3662524.842	610	573	7.4	0.14	3.79	5.14	3.25	13.52	5.27	3.99	4.99	14.25	2.62	904
meq %						1	38	37	24	100	37	28	35	100		
D2/5	629878.1175	3662002.465	596	/	7	0.18	2.83	3.44	2.38	8.83	2.45	3	3.64	9.09	1.45	576
D2/6	626048.649	3657331.915	619.3	580	7.1	0.08	1.61	3.38	2.6	7.67	1.61	1.29	5.15	8.05	2.41	545
meq %						1	21	44	34	100	20	16	64	100		
D2/7	503150.234	3618414.677	807	509.4	7.3	0.32	12.58	10.85	7.71	31.46	14.58	12.26	6.29	33.13	2.58	2100
meq %						1	40	34.5	24.5	100	44	37	19	100		
D2/8	655467.0825	3667304.593	561	507	7.05	0.23	2.74	5.48	2.97	11.42	2.17	5.79	4.11	12.07	2.76	760
meq %						2	24	48	26	100	18	48	34	100		
D2/9	554999.1939	3559058.736	840	769	7.4	0.98	29.02	11.09	7.81	48.91	12.42	27.31	11.79	51.52	2.59	1598
meq %						2	59.35	22.68	15.97	100	24.11	53	22.89	100		
D2/10	551771.1707	3575669.523	850	451	7.3	0.15	9.18	3.89	2.52	15.74	3.62	8.09	4.76	16.47	2.27	1044
meq %						1	58.3	24.7	16	100	22	49.1	28.9	100		
D2/11	602321.3803	3681265.209	670	435	7.4	0.08	3.4	3.19	1.56	8.23	3.06	2.16	2.9	8.12	0.67	559
D2/13	506242.6316	3627269.64	820	529	7.7	0.24	8.28	15.97	13.17	37.66	8.92	14.9	13.35	37.17	0.65	2373
meq %						0.64	22	42.4	34.96	100	23.98	40.1	35.92	100		
D2/14	497661.0048	3637245.085	780	499	7.8	0.27	7.74	10.99	8.11	27.11	7.71	12.94	7.91	28.56	2.6	1830
meq %						1	28.55	40.53	29.92	100	27	45.3	27.7	100		
D2/15	616641.3848	3663067.946	640	575	7.8	0.615	7.652	11.47	7.663	27.4	6.76	12.83	7.61	27.2	0.36	1814

meq %						2.24	27.93	41.86	27.97	100	24.85	47.17	27.98	100		
D2/16	606745.721	3648047.454	650	616	7.3	0.16	3.1	6.53	1.68	11.48	3.5	3.35	5.67	12.52	0.16	790
meq %						1.46	27	56.92	14.62	100	28	26.73	45.27	100		
D3/1	621178.0129	3544850.345	750	646	7.4	0.12	4.9	3.39	3.27	11.68	4.53	3.22	4.17	11.92	1.02	756
meq %						1	42	29	28	100	38	27	35	100		
D3/2	636593.3807	3569069.274	750	289	7.3	0.61	9.1	7.28	3.24	20.23	8.73	7.03	5.54	21.3	2.57	1350
meq %						3	45	36	16	100	41	33	26	100		
D3/3	626013.5278	3535669.577	731	/	7.4	0.18	6.07	6.6	4.99	17.84	7.57	7.94	2.95	18.46	1.71	1180
meq %						1	34	37	28	100	41	43	16	100		
D4/1	546611.0505	3671722.908	755.5	445.8	7.4	0.58	7.58	8.94	11.53	28.63	8.02	12.84	8.54	29.4	1.32	1912
meq %						2.03	26.47	31.22	40.28	100	27.27	43.67	29.06	100		
D4/2	529385.2798	3716003.286	688	455	7.4	0.21	5.22	8.66	7.66	21.75	4.03	8.37	10.51	22.91	2.6	1453
meq %						0.96	24	39.82	35.22	100	17.59	36.53	45.88	100		
D4/3	494241.3736	3698960.148	721	/	7.6	0.53	9.83	9.39	9.16	28.91	12.22	6.07	12.05	30.34	2.41	1923
meq %						1.82	34	32.49	31.69	100	40.27	20	39.73	100		
D4/4	563858.5001	3647798.836	807	735	7.6	0.42	5.8	10.07	11.31	27.6	8.4	11.4	8.14	27.94	0.61	1776
meq %						1.53	21	36.48	40.99	100	30	40.67	29.06	100		
D4/5	500774.8028	3693938.636	723	472	7.5	0.3	10.61	10.02	8.55	29.48	11.18	5.74	14.13	31.05	2.59	1968
meq %						1	36	34	29	100	36	18.5	45.5	100		
D4/6	502532.3506	3691167.267	726	489	7.3	0.96	12.43	11.12	9.32	34.53	13.84	7.7	13.77	35.31	1.11	2438
meq %						2.8	38	32.2	27	100	39.2	21.8	39	100		
D4/7	496435.3338	3696433.773	718	476	7.5	0.38	10.91	7.54	6.94	25.7	10.11	7.18	9.31	26.6	1.72	1690
meq %						1.5	42.5	29	27	100	38	27	35	100		
D4/8	498191.2445	3693969.57	730	487	7.5	0.21	5.95	9.2	6.64	22.02	4.54	8.47	10.18	23.19	2.58	1470
meq %						0.96	27.04	41.82	30.18	100	19.59	36.53	43.88	100		
D4/9	507544.8448	3692524.911	722	485	7.4	0.16	4.32	5.23	6.02	15.73	4.18	7.23	5.15	16.56	2.57	1050
meq %						1.03	27.47	33.22	38.28	100	25.27	43.67	31.06	100		
D4/10	497623.1797	3695263.142	722	476	7.4	0.38	12.81	13.94	10.54	37.67	15.07	13.53	10.05	38.65	1.28	2450
meq %						1	34	37	28	100	39	35	26	100		
D5/1	636593.3807	3569069.274	750	289	7.3	0.32	7.27	3.8	4.43	15.82	5.46	7.23	3.38	16.07	0.78	0.32
meq %						2	46	24	28	100	34	45	21	100		
D5/2	640576.3624	3620872.001	745	648	7.25	0.17	4.51	6.94	5.73	17.35	1.83	9.87	6.57	18.27	2.58	0.17
meq %						1	26	40	33	100	10	54	36	100		
D6/1	639983.8816	3666146.441	580	529	7.5	0.11	2.18	4.13	4.46	10.88	2.98	3.09	5.38	11.45	2.55	726
meq %						1	20	38	41	100	26	27	47	100		
D6/2	655467.0825	3667304.593	561	515	7.3	0.52	2.87	13.06	9.66	26.11	7.57	14.32	5.64	27.53	2.64	1744
meq %						2	11	50	37	100	27.5	52	20.5	100		
D6/3	644855.9594	3648657.964	600	521	7.4	0.05	2.17	4.09	4.53	10.84	4.31	3.54	3	11.25	1.85	706
meq						0.47	20	37.76	41.77	100	38.35	35	26.65	100		

%																
D6/4	655216.7814	3683012.969	521	331	7.7	0.15	2.57	7.25	6.51	16.18	2.46	7.37	7.21	17.04	2.58	1480
meq %						0.94	14	44.82	40.24	100	14.43	43.28	42.29	100		
D6/5	643206.1755	3654948.94	610	520	7.5	0.15	4.39	5	3.37	12.9	4.65	4.74	4.2	13.59	2.6	860
meq %						1.17	34	38.74	26.09	100	34.28	34.85	30.87	100		
D6/6	640956.2682	3656210.2	590.3	492	7.45	0.08	3.96	5.59	4	13.63	4	1.14	7.19	12.33	5.0	911
D6/7	643103.06	3658459.288	580	498.3	7.9	0.13	4.3	5.07	4.02	13.52	3.44	2.29	7.83	13.56	0.15	874
meq %						0.96	31.81	37.5	29.73	100	25.37	16.89	57.74	100		
D6/8	642217.5614	3655119.4	593	/	7.41	0.61	4.12	5.59	4.8	15.12	4	4.23	7.34	15.57	1.46	1003
meq %						4.03	27.25	36.97	31.75	100	25.69	27.17	47.14	100		
D6/10	644914.9591	3655220.464	591.3	480	7.07	0.34	4.06	4.19	7.6	15.35	4	4	7.2	15.2	0.49	2497
meq %						2.2	26.45	27.3	44.05	100	26.31	26.32	47.37	100		
D6/11	640455.0544	3654970.802	595.3	512	7.42	0.44	3.97	5.19	4	13.6	4.4	2.2	6.79	13.39	0.77	1100
meq %						3.24	29.19	38.16	29.41	100	32.86	16.43	50.71	100		
D6/12	641381.105	3655538.593	598.3	489.4	7.29	0.5	3.96	5.58	6.4	15.54	4.19	3.12	7.2	14.51	3.42	997
meq %						3.22	25.48	35.12	36.18	100	28.88	21.5	49.62	100		
D7/1	564551.3628	3738197.231	608	443	7.8	0.15	4	3.8	3	10.95	3.59	2.94	4.5	11.03	0.36	700
meq %						1.37	36.53	34.7	27.4	100	32.56	26.61	40.83	100		
D7/2	587809.6617	3745806.431	437	345	8.1	0.23	3.04	2.89	4.04	10.2	3.21	3.5	3.81	10.52	1.54	688
meq %						2.26	29.85	28.37	39.52	100	30.56	33.24	36.2	100		
D7/3	604744.8976	3755342.489	470	316	7.7	0.04	1.46	3.36	3.23	8.09	1.29	2.3	4.93	8.52	2.58	578
D7/4	570440.4063	3741781.031	627	417	7.4	0.06	3.43	4.37	2.22	10.08	3.51	3.95	2.7	10.6	2.51	673
meq %						0.61	34	43.39	22	100	33.13	37.22	25.48	100		
D7/5	564551.3628	3738197.231	609	579	7.7	0.36	4.09	3.59	1.81	9.85	3.8	2.47	4.1	10.37	2.57	658
meq %						0.34	41.52	36.45	21.69	100	36.62	23.87	39.51	100		
D7/6	586343.7101	3745916.227	585	430.5	7.6	0.23	3.35	5.92	7.25	16.76	3.36	5.57	8.74	17.67	2.64	1120
meq %						1.4	20	35.34	43.26	100	19	31.5	49.5	100		
D7/7	531003.0633	3717917.84	678	569	7.4	0.13	3.34	4.77	3.67	11.91	3.19	1.66	7.69	12.54	2.57	845
meq %						1.1	28	40.07	30.83	100	25.42	13.28	61.31	100		
D8/1	615923.0117	3754671.552	464	369	7.55	0.11	4.68	4.16	2.37	11.32	3.98	2.97	4.98	11.93	0.3	757
meq %						0.98	41.3	36.76	20.96	100	33.36	24.93	41.71	100		
D8/2	654011.1478	3757863.281	497.6	427.9	7.4	0.26	8.33	4.29	3.3	16.18	8.05	3.32	5.52	16.89	2.14	1072
meq %						1.64	51.49	26.48	20.39	100	47.69	19.65	32.66	100		
D8/3	620079.256	3761069.525	412	326.1	7.5	0.65	20.29	6.32	8.24	35.5	19.04	8.73	8.63	36.4	1.25	2338
meq %						1.84	57.16	17.8	23.2	100	52.3	24	23.7	100		
D8/4	653347.2526	3798525.859	325	/	7.6	0.13	4.12	3.9	1.91	10.06	3.64	2.82	4.2	10.6	2.61	672
meq %						1.28	41	38.76	18.96	100	34.36	26.6	39.04	100		
D8/5	615897.7113	3754640.437	465	369	7.16	0.66	8.29	4.1	3.7	16.75	8	2.52	5.58	16.1	1.98	989
meq %						3.64	49.49	24.78	22.09	100	49.69	15.65	34.66	100		

D8/6	615896.9588	3754702.041	467	370	7.45	0.64	7.99	4.4	3.6	16.63	6	2.51	7.6	16.11	1.59	1089
meq %						3.85	48.04	26.46	21.65	100	37.24	15.58	47.18	100		
D8/7	615923.3881	3754640.751	466	368	7.67	0.42	8.47	3.2	2.4	14.49	6.1	2.42	7.2	15.72	4.07	1070
meq %						2.9	58.46	22.08	16.56	100	38.8	15.4	45.8	100		

The groundwater flux (Darcy velocity V) and groundwater pore velocity (U), (Table-3**)** within aquifer systems are calculated, using equations; V=KI [4], where I: hydraulic gradient, K: permeability.
U = V/s [4; 29], where V: groundwater Flux, s: specific yield or effective porosity.

The mean annual inflow and outflow rate to/from the aquifer systems are estimated, depending on map of groundwater flow and hydraulic parameters of aquifers, using Darcy equation; Q=TIL (Darcy equation in [4] where Q = Inflow or Outflow (m^3/day), T=Transmissivity (m^2/day), I= Hydraulic Gradient (dimensionless), L=Section length (meters).

Table 3-Hydraulic and hydrogeologic data of aquifers extracted from the flow map.

Aquifer	GW. Head (m.asl) from	GW. Head (m.asl) to	Flow direction towards	Hydraulic gradient (I)	Per.(K) m/day	Darcy velocity(V) m/day	Effective porosity	GW. Pore velocity m/day
Ga'ra aq. (D1)	591	366	NE	0.0018	0.20	0.00036	0.0085	0.042
Mullusi aq. (D2)	736	416	NNE	0.00128	0.695	0.00089	0.0055	0.161
Hartha-Rutba aq.(D3)	711	516	NW	0.0022	0.7	0.00154	0.011	0.134
Digma-Tayarat aq.(D4)	566	466	NW	0.001	0.58	0.00058	0.0065	0.089
Muhaywir-Ubaid aq. (D5)	491	466	E	0.00067	1.194	0.0008	0.018	0.044
Mullusi-Ubaid aq.(D6)	516	441	E & SE	0.003	1.1	0.0033	0.014	0.226
Rattga - Tayarat aq.(D7)	541	366	E &NE	0.0016	0.615	0.0026	0.041	0.634
Digma-Tayarat aq. (D8)	416	366	NNE	0.001	0.21	0.00021	0.009	0.023

The groundwater inflow and outflow rates (Q=TIL) for each aquifer are calculated on various equipotential lines representing the borders of aquifers. The groundwater balance which is determined by the rate difference of groundwater inflow and outflow (ΔQ) in Gar′a aquifer (D1), Mullusi aquifer (D2), Hartha-Rutba aquifer (D3), Digma-Tayarat aquifer (D4), Muhaywir-Ubaid aquifer (D5), Mullusi-Ubaid aquifer(D6), Rattga-Digma-Tayarat aquifer (D7) Digma-Tayarat aquifer (D8), is $0.300x10^6$, $-0.974x10^6$, $0.041x10^6$, $0.138x10^6$, $0.019\ x10^6$, $0.501x10^6$, $0.020\ x10^6$ and $0.248x10^6$ m^3/year, respectively.

The positive values of balance change between inflow and outflow Table-4 within aquifer systems may indicate the loss of the groundwater by deep percolation mechanism throughout pores, karst or/and fissure passages to the regional groundwater system as regional circulation**.**

While the negative value of balance change in Mullusi aquifer (D2) confirms the presence of ground-water replenishment along Hauran valley (Hauran anticlinorium axis) and its tributaries coincide with the trend of groundwater flow. Finally, the lateral outflow of $13.54x10^6$ m^3/year represents the total shallow active circulation from study region, which forms 6.63% of the total amount of infiltration ($204x10^6$ m^3/year), while the 93.37% of infiltration rate may change pattern passages to the deep regional circulation within study region.

Aquifer	T m^2/d	Hydraulic gradient	Width (m)		lateral inflow m^3/d	lateral outflow m^3/d	lateral outflow m^3/year	Balance change (ΔQ)	
			inflow	outflo w				m^3/d	m^3/year
Aquifer- D1	96	0.0018	51520	46760	8902.7	8080.1	$2.95x10^6$	822.6	$0.300x10^6$
Aquifer- D2	23	0.00128	76100	166700	2240.4	4907.7	$1.79x10^6$	-2667	$-0.974x10^6$
Aquifer- D3	51	0.0022	69000	68000	7741.8	7629.6	$2.78x10^6$	112.2	$0.041x10^6$
Aquifer- D4	65	0.001	71440	65610	4643.6	4264.6	$1.55x10^6$	379	$0.138x10^6$
Aquifer- D5	27	0.00067	70000	67000	1266.3	1212	$0.44x10^6$	54.3	$0.019\ x10^6$
Aquifer- D6	33	0.003	73340	59480	7260.7	5888.5	$2.15x10^6$	1372	$0.501x10^6$
Aquifer- D7	36	0.0016	41800	40830	2407.7	2351.8	$0.86x10^6$	55.9	$0.020\ x10^6$
Aquifer- D8	60	0.001	46760	35430	2805.6	2125.8	$1.02x10^6$	679.8	$0.248x10^6$

3.2 Aquifers and Hydrochemical Facies Interrelationships

The hydrochemical facies of the groundwaters in aquifers had been determined by the application of ions dominance order, which reflects the effect of hydrogeochemical processes occurring between minerals forming rocks and groundwater [30 and 31]. The groundwater facies in the eight aquifer systems reveal the majority of;

-Chloride group of 80% of groundwater samples as Na–chloride and Ca-chloride families within D-1.
-Both chloride and bicarbonate groups of 74% as Na-chloride and Ca-bicarbonate families within D-2.
-Chloride group of 66.6% as Na–chloride family within D-3.
-Bicarbonate, chloride and sulphate groups as Ca, Na-bicarbonate, Ca, Na-chloride, and Mg–sulphate families in D-4.
-Sulphate group (All groundwater samples) of Na and Ca–sulphate families within D-5.
-Both bicarbonate and sulphate groups of 90.5% as Ca, Mg-bicarbonate, Ca, and Mg–sulphate families within D-6.
-Bicarbonate group of 85.5% as Ca, Mg, Na-bicarbonate within district-7, whereas both bicarbonate and chloride groups (100% of groundwater samples) as Na-bicarbonate and Na-chloride families within D-8.

All such bicarbonate types are the result of hydrochemical processes acting between water and aquifer matrix such as the dissolution of carbonate rocks, while the variation reflects the effectiveness of groundwater flow. Some water types characterize salty groundwater with Na–Cl dominant type probably derived from the dissolution of disseminated salt minerals in fine-grained sediments [32 and 33].

Water of Ca–Cl dominant type indicated marine fossil water origin with trap process. While water of Na–Mg; SO_4–Cl dominant type representing a mixed water type. Water–rock interaction can alter groundwater with high SO_4 concentrations associated with the dissolution of gypsum, which is commonly encountered within aquifer media. As mentioned in Item 3.1, the groundwater flow map (Fig. 4) shows a presence of lateral hydraulic connection of groundwater among aquifers subsystems as follows:

Groundwater of Mullusi aquifer (D-2) moves towards Groundwater of Gar′a aquifer (D-1).
Groundwater of Gar′a aquifer (D-1) moves towards Groundwater of Digma-Tayarat aquifer (D-8).
Groundwater of Mullusi aquifer (D-2) flows to Digma-Tayarat aquifer (D-4).
Groundwater of Digma-Tayarat aquifer (D-4) moves towards Rattga-Digma-Tayarat aquifer (D-7).
Groundwater of Mullusi aquifer (D-2) moves towards Groundwater of Hartha-Rutba aquifer (D-3).
Groundwater of Hartha-Rutba aquifer (D-3) flows to Muhaywir-Ubaid aquifer (D-5).
Groundwater of Mullusi aquifer (D-2) moves towards Groundwater of Mullusi-Ubaid aquifer (D-6).
To perform a hydrochemical comparison and confirmation the lateral hydraulic connection relations, the above mentioned relationships can be segregated and categorized into the following subsystems.

-Groundwater of Mullusi aquifer (D2), Gar′a aquifer (D1) and Digma-Tayarat aquifer (D-8) subsystem.
-Groundwater of Mullusi aquifer (D2), Digma-Tayarat aquifer (D4) and Rattga-Digma-Tayarat aquifer (D7) subsystem.
-Groundwater of Mullusi aquifer (D2), Hartha-Rutba aquifer (D3) and Muhaywir-Ubaid aquifer (D5) subsystem.
-Groundwater of Mullusi aquifer (D2) and Mullusi-Ubaid aquifer (D6) subsystem.

Hydrochemical data (meq%) in Table-2 was plotted in Piper plot [34] for the purpose of characterizing groundwater types within aquifers. Figure-5 which shows the plotted points of the groundwater samples of Mullusi aquifer (D2), Gar′a aquifer (D1) and Digma-Tayarat aquifer (D-8) is mainly indicating mixed waters of Ca+Mg; SO_4+Cl type, followed by Na+K; SO_4+Cl water type, then by ions of carbonate hardness represented by renewal and recharge waters of Ca+Mg; HCO_3 water type.

The percent of the groundwater samples have interrelated water type in Mullusi, Ga'ra, and Jeed aquifers as shown in the intersected zone of Figure-5 are 53%, 80%, and 87.5% respectively. There are practically found mixtures of multi-types of groundwater with variable concentrations of major ions, as might be expected from the chemistry of the lateral groundwater recharge.

The plotted points of the groundwater samples of Mullusi aquifer (D2), Digma-Tayarat aquifer (D4) and Rattga-Digma-Tayarat aquifer (D7) as shown in Figure-6, are mainly indicated mixed waters of Mg + Ca ; SO_4 + Cl type, followed by replenishing groundwater of Ca+Mg; HCO_3 water type, then by Na+K; SO_4+Cl water type. The percent of the groundwater samples nearly have same water type in Mullusi, Jeed, and Rattga-Jeed aquifers as shown in the intersected zone Figure-6 are 42%, 58%, and 71% respectively.

There are practically proved the mixing of multi-types of groundwater with variable concentrations of ions influenced by dissolution mechanism along the flow direction, as detected from the hydraulic connections between adjacent aquifers (lateral groundwater recharge).

The plotted points Figure-7 of the groundwater samples of Mullusi aquifer (D2), Hartha-Rutba aquifer (D3) and Muhaywir-Ubaid aquifer (D5), indicate mixing phenomenon represented by mixed waters of Mg + Ca ; SO_4 + Cl type, followed by Na+K; SO_4+Cl water type, then by replenishment waters of Ca+Mg; HCO_3 water type. The percent of the groundwater samples have interrelated water types in Mullusi, Hartha-Rutba, and Muhaywir-Ubaid aquifers as shown in the intersected zone in Figure-7 are 58%, 100%, and 100% respectively. A phenomenon of groundwater source and mixing waters is occurred along the flow direction within the adjacent southern aquifers, as might be expected from the hydraulic connections (groundwater flow map).

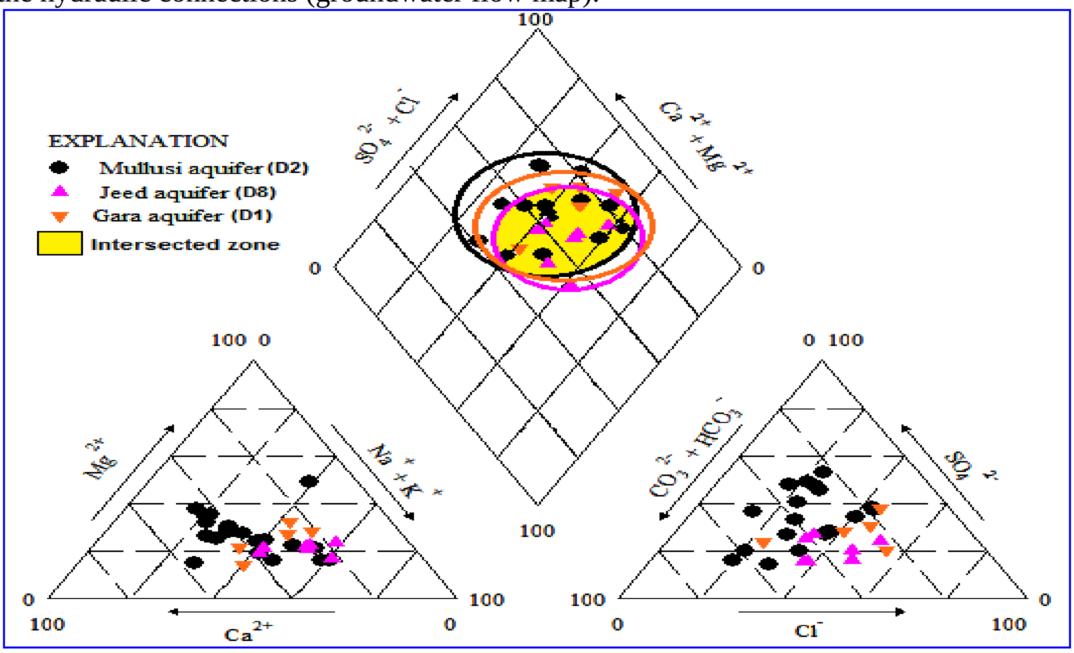

Figure 5-The Piper Diagram of Ground- water quality of Mullusi aquifer (D2), Gar′a aquifer (D1) and Jeed aquifer (D-8).

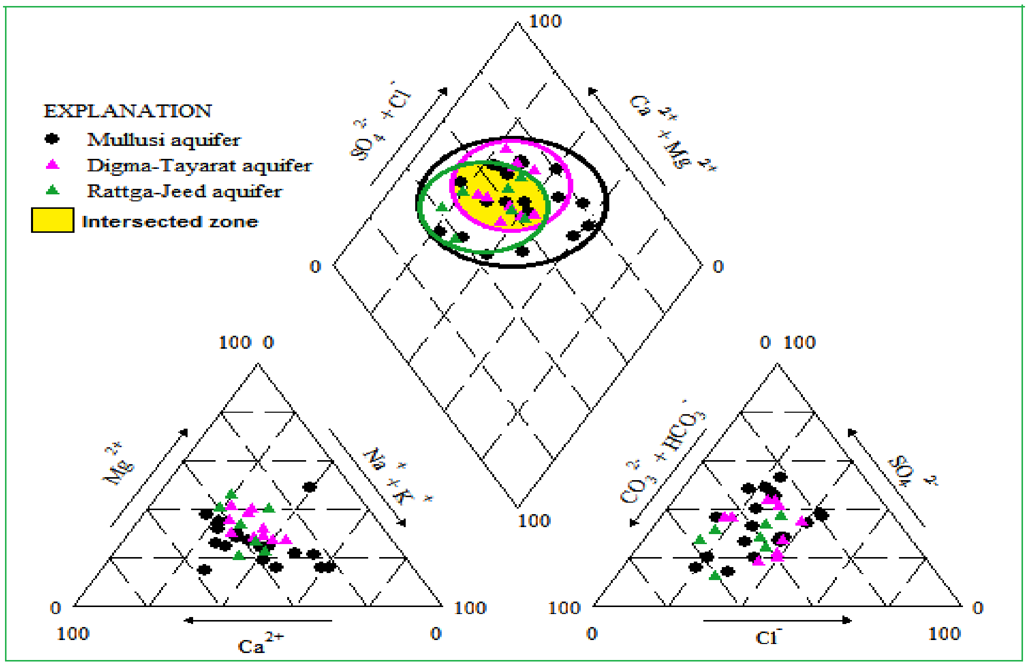

Figure 6-The Piper Diagram of Ground-water quality of Mullusi aquifer (D2), Jeed aquifer (D4) and Jeed aquifer (D-7).

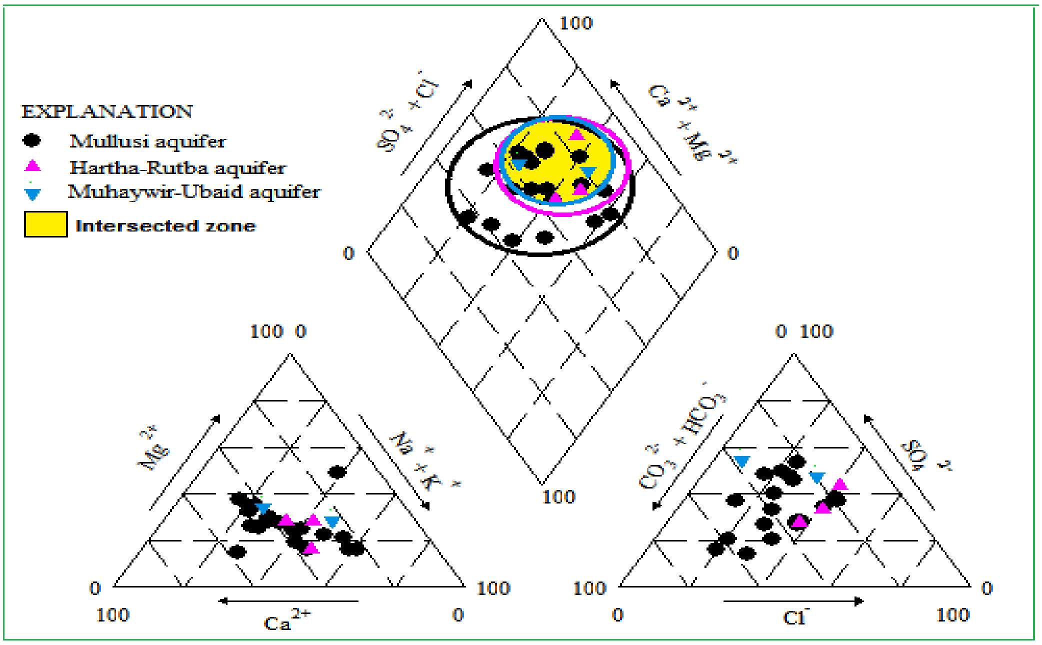

Figure 7-Groundwater quality of Mullusi (D2), Hartha-Rutba (D3) and Muhaywir-Ubaid aquifers.

The plotted points of the groundwater samples of Mullusi aquifer (D2) and Mullusi-Ubaid aquifer (D6) as shown in (Fig. 8**),** indicate a presence of mixed waters of Mg + Ca; SO_4 + Cl type, followed by replenished waters of Ca+Mg; HCO_3 water type through sinkholes and blind valleys, then by Na+K; SO_4+Cl water type. The percent of the groundwater samples have same water type in Mullusi, and Mullusi-Ubaid aquifers as shown in the intersected zone (Fig. 8) are 79%, and 81% respectively. Same phenomena of groundwater recharge and mixing waters is proved along the flow direction within the adjacent aquifers, as indicated by the results of groundwater flow map.

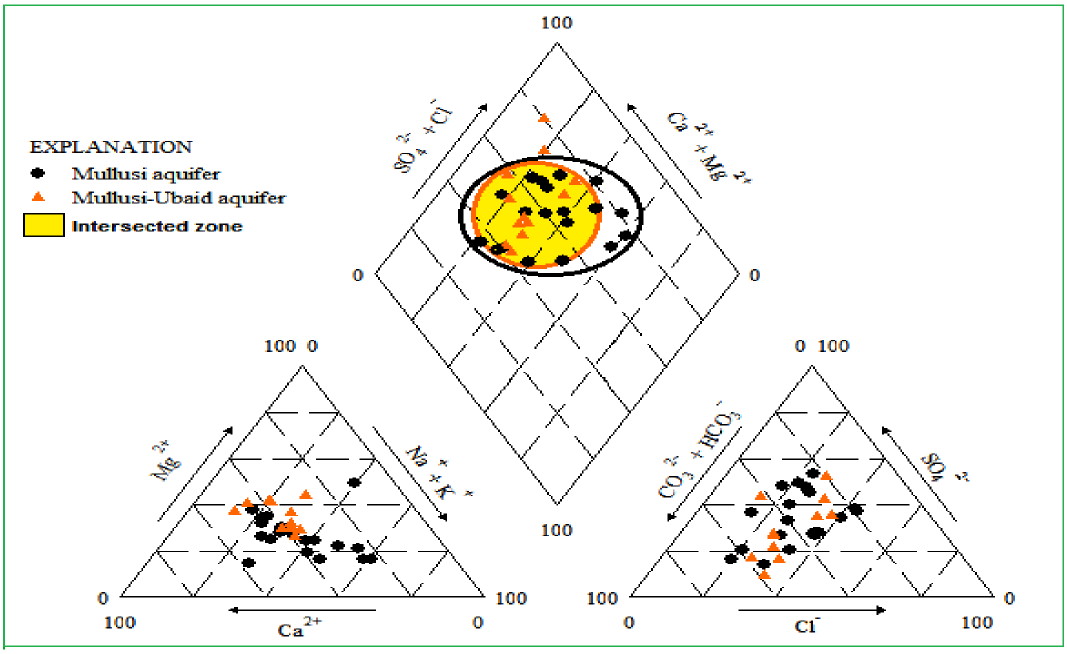

Figure 8-Groundwater quality of Mullusi aquifer (D2) and Mullusi-Ubaid aquifer (D6).

4. Conclusions

This research is concerned with the determination of groundwater recharge as lateral leakage of waters passing from adjacent aquifers having a high hydraulic head. The study examined the impact of replenishment mechanism on the groundwater of the aquifers within eight districts.

The area of the main replenishment zone represents the major groundwater divide that distribute groundwater to the NW and ESE, while the low groundwater level occur along the main valley of Rattga basin in the NE portion; coincide with the lowest topography in the study area. The water replenishment mechanisms through different drainage patterns of valleys conform to several local groundwater divides. The boundaries of the groundwater flow are coincident with the trends of the intermittent valleys which represents as flow boundaries. The lateral groundwater outflow which represents the shallow active circulation forms 6.63% of the total amount of infiltration, while the 93.37% of infiltration rate may change the paths of water passages to the deep regional circulation within study region.

The deduced results from the statistical Piper Diagram, using hydrochemical data from the groundwater samples of the aquifers within eight districts, showed that the plotted points are mainly indicated by ions of alkaline earths (Ca+Mg) exceeds alkalis (Na+K) and ions of strong acids (SO_4+Cl) exceeds ions of weak acids (CO_3+HCO_3) represented by mixed water of Ca+Mg; SO_4+Cl water type, followed by Na+K; Cl+SO_4 water type, then by replenished waters of Ca+Mg; HCO_3 water type.

A phenomena of groundwater chemistry and mixing waters are proved along the flow direction within the adjacent aquifers coincide with the phenomena of hydraulic connections as expected from the groundwater flow map. Four trends of groundwater flow within the hydrogeologic system are indicated by lateral groundwater connection supported by hydrochemical application, using Piper Plot. Then four aquifer subsystems are determined within the study region, including Mullusi-Ga'ra and Jeed (Digma-Tayarat) aquifers subsystem, Mullusi-Jeed and Rattga-Jeed subsystem aquifers, Mullusi-Hartha-Rutba and Muhaywir-Ubaid subsystem aquifers, Mullusi and Mullusi-Ubaid subsystem aquifers.

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