HYDROGEOLOGY OF THE HIGH FOLDED ZONE

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ABSTRACT

The Hydrogeology of the High Folded Zone, in Iraq is reviewed. This zone is characterized by rugged topography, and presence of deep canyons and narrow valleys with well defined mountainous topography. The oldest exposed rocks are Early Triassic in age, whereas the youngest are of Pliocene – Pleistocene age, which belong to the Bai Hassan Formation, in addition to Quaternary Sediments.

The High Folded Zone can be divided into five major hydrogeological basins, which are: Zakho, NW Barzany, Central Harir, Central Dokan and Sharazoor Basins. And these basins are subdivided into ten sub-basins. Two main groups of carbonate aquifers are described based on geological and hydrogeological characteristics; these are: Bekhme Karst Aquifers (Qamchuqa, Dokan and Kometan formations) and Pila Spi Fractured Karst Aquifers (Sinjar, Khurmala and Avanah formations). In addition to these important carbonate aquifer complexes, some clastic units, such as Quaternary Sediments, Bai Hassan, Mukdadiya, Injana, Fatha, Kolosh and Tanjero formations are sufficiently permeable to form local aquifers.

The source of recharge water within the High Folded Zone is mainly from direct precipitation and snow melt during summer at the highest elevated areas of the zone, and from the Suture and Thrust Zone at the northeast. The Low Folded Zone represents the discharge zone to the area, beside wells and springs. The general trend of the groundwater movement at this area is mainly from north and northeast towards south and southwest, with local different directions due to topographic and structural characteristics of the area. There is a hydraulic continuity between water bearing formations within this zone, depending on the piezometric relations of the water-bearing layers throughout the area.

The depth of the groundwater increases at the high lands and at the flanks of the synclines, and decreases at the central parts of the basins and at the discharge areas. The transmissivity of aquifers often increases at the central parts of the synclines and along river courses, and within the alluvial fans, as more permeable sediments are available.

The salinity of the groundwater is characterized by low values; with the prevailing type of fresh water being Ca (Mg)-HCO_3, with increasing magnesium content in dolomites. This salinity and chemical composition of groundwater changes in the presence of gypsum, anhydrite and halite in the Fatha Formation, which is sometimes present in the S and SW parts of the Zone. The hydraulic conditions and chemistry of aquifers within the High Folded Zone are closely linked to the stratigraphic, lithologic, structural and topographic characteristics of the water bearing formations. According to the hydrogeological evaluation of the High Folded Zone, it can be considered as promising zone for groundwater development in Iraq.

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هيدروجيولوجية نطاق الطيات العالية

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المستخلص

تمت مراجعة هيدروجيولوجية نطاق الطيات العالية في العراق الذي يمتاز بطوبوغرافيته الوعرة ووجود الوديان العميقة والضيقة وجباله العالية. إن أقدم الصخور المتكشفة تعود الى عصر الترياسي المبكر الى عصر البلايوسين – البلايستوسين المتمثلة بتكوين باي حسن، إضافة الى الترسبات الحديثة.

تم تقسيم نطاق الطيات العالية الى خمسة أحواض هيدروجيولوجية رئيسية وهي: زاخو، شمال غرب برزاني، مركز حرير، مركز دوكان وحوض شاره زور. قسمت تلك الأحواض الى عشر أحواض هيدروجيولوجية ثانوية. بالاعتماد على الخواص الجيولوجية والهيدروجيولوجية تم وصف مجموعتين من الخزانات الكاربوناتية وهي: خزانات بخمة الكارستية (تكوينات قمچوقة، دوكان وكوميتان) وخزانات البيلاسبي الكارستية المتكسرة (تكوينات سنجار، خورمالة وأقانة). إضافة الى هذه الخزانات المهمة تتواجد بعض الترسبات الفتاتية المكونة لخزانات جوفية موقعية مثل: الترسبات الحديثة، وترسبات تكوينات باي حسن، إنجانة، الفتحة، كولوش وتانجيرو.

إن مصدر التغذية للمياه الجوفية في نطاق الطيات العالية يتمثل بالأمطار الساقطة إضافة الى ذوبان الثلوج في المناطق المرتفعة ومناطق نطاق دسر - زاگروس المتراكب، بينما تتمثل مناطق الطيات الواطئة والآبار والعيون مناطق تصريف لمياه هذا النطاق. الاتجاه العام لحركة جريان المياه الجوفية يكون من الشمال والشمال الشرقي نحو الجنوب والجنوب الغربي، مع وجود اتجاهات موقعية مختلفة نتيجة الوضع الطوبوغرافي والتركيبي للمنطقة. كما يمتاز النطاق بوجود اتصال هيدروليكي واستمرارية لمستوى المياه الجوفية ضمن التكوينات الحاملة للمياه فيه، والذي يعتمد على الوضع البيزومتري للتكوينات الحاملة للمياه.

يزداد عمق المياه الجوفية ضمن المناطق العالية وأجنحة الطيات المقعرة، ويقل ضمن الأجزاء الوسطى للأحواض ومناطق التصريف. يزداد معامل الناقلية للخزانات الجوفية على العموم ضمن الأجزاء الوسطى من الأحواض وعلى طول مجاري الأنهار والمراوح الفيضية، حيث تتواجد الرسوبيات عالية النفاذية.

تمتاز ملوحة المياه الجوفية بانخفاضها، مع سيادة النوعية كالسيوم (مغنيسيوم) – بيكاربونات وضمن مياهها الكارستية. إن ملوحة المياه الجوفية وتركيبها الكيميائي يتغير بوجود الجبس والانهايدرايت ضمن صخور تكوين الفتحة والمتواجد أحيانا في المناطق الجنوبية والجنوبية الغربية من هذا النطاق.

إن الخصائص الهيدروليكية والكيميائية للخزانات الجوفية ضمن نطاق الطيات العالية تكون مرتبطة أو متأثرة بالخصائص الطباقية والصخارية والتركيبية والطوبوغرافية للتكوينات الحاملة للمياه. استنادا الى الخصائص الهيدروجيولوجية التي يمتاز بها نطاق الطيات العالية فأنه من الممكن اعتبار هذا النطاق من المناطق الواعدة لغرض استثمار وتطوير المياه الجوفية للأغراض المختلفة في العراق.

INTRODUCTION

The High Folded Zone extends in the northern and northeastern parts of Iraq. It has almost an oblong shape, and elongated from northwest to southeast. It is bounded by the Iraqi borders with Iran, from the southeast, while the Suture and Thrust Zone forms its northern and northeastern boundary. The Low Folded Zone forms its southern and southwestern boundary. The High Folded Zone covers small part of the Iraqi territory. It covers an area of about 15 000 Km². Topographically, the High Folded Zone is characterized by: **The elevated parts** (mountainous), which consist of rocky surface dissected by streams and valleys, and **the flat parts**, which are covered by clastics formations, and form small plains. From the regional tectonic point of view, the High Folded Zone forms the Outer Platform (Fouad, 2012), whereas (Al-Kadhimi *et al*., 1996, and Jassim and Buday in Jassim and Goff, 2006) considered it within Unstable Shelf of the Arabian Platform. The complex structural geology and variations in rock type in the High Folded Zone have created localized small scale aquifer systems, which together with the old rocks are often separated by synclines of Tertiary and Quaternary clastics which form isolated to semi-isolated aquifer systems.

▪ **Aim**

The main aim of this study is to express the general hydrogeological conditions of the groundwater in the High Folded Zone, including nature of aquifers, their extents, groundwater level, flow direction, recharge and discharge areas, type and salinity of the groundwater, in order to evaluate the quality and quantity and suitability of the groundwater for different purposes, and detect the most promising areas within the zone.

▪ **Previous Studies**

The hydrogeological and hydrological studies were carried out on different parts of the High Folded Zone by different researchers (Parsons, 1955 and 1957; Ingra, 1967; Araim, 1990; Al-Shami, 1993; UNICEF, 2000a, b and c; Al-Manmi, 2002 and 2008; Chnaray, 2003; Stevanovic and Iurkiewicz, 2004; Stevanovic and Markovic, 2004; Krasny *et al*., 2006; Ali, 2007; Al-Basrawi, 2007; Al-Jiburi, 2010a and 2010b, Sa'ood and Mohammad, 2010; Hama Amin, 2011 and Al-Jiburi and Al-Basrawi, 2013). These studies reflect the conditions of groundwater system in terms of groundwater flow direction, groundwater monitoring, classification of aquifers type, salinity and chemical type of water.

▪ **Materials Used**

In this study, the evaluation of hydrogeological and hydrochemical information is carried out for more than 450 drilled wells and springs, which are available in the hydrogeological data bank of the High Folded Zone, and it is updated recently by Stevanovic and Iurkiewicz (2004). Only representative wells are mentioned within the present study (Fig.1 and Table 1).

▪ **Climate**

The climate of this Zone is mainly semi arid, with clear effect of the Mediterranean climate on all parts. It is characterized by dry and hot summer, and cold with moderate rain in winter. According to the meteorological information supplied by the Iraqi General Organization for Meteorological Information (2000) for the years (1981 – 2000), the annual mean rainfall ranges from (400 – 950) mm. The annual relative humidity is within the range of (48 – 50) %, the annual evaporation is about 2000 mm. The annual mean temperature ranges from (18 – 22) °C and the annual mean wind speed ranges from (2.0 – 3.0) m/sec. Water balance in N and NE Iraq is influenced by snow that generally falls above 800 m a.s.l. The mean snow line occurs at 1160 m a.s.l. in March and at 1380 m a.s.l. in April (Stevanovic and Markovic, 2004). This Zone has the most favorable water balance in Iraq with the highest total precipitation (total rain and snow). Many important rivers with tributaries originate there; Khabour, Greater Zab, Lesser Zab and Diyala (Sirwan) rivers.

HYDROGEOLOGICAL CONDITIONS OF THE HIGH FOLDED ZONE

The hydrogeological conditions within High Folded Zone are controlled by the structural setting and lithology of rocks. The deformed rock layers often dip very steeply or vertically especially on the S and SW flanks of anticlines. Thus hydrogeological bodies have very variable geometry, extent and thickness. Regional faults and local fractures systems control the direction of valleys and the predominant pathways of groundwater flow. Hydrogeologically, the most important units are the Cretaceous carbonates, which form the majority of the terrain of the High Folded Zone. Two main groups of carbonate aquifers were described by Stevanovic and Iurkiewicz (2004), based on geological and hydrogeological characteristics, these are mentioned hereinafter.

- **Bekhme Karst Aquifer**

This aquifer includes carbonates of Qamchuqa, Dokan and Kometan formations. It covers large areas within the northern and central parts of the zone, and represents a typical heterogeneous anisotropic aquifer, fractured, karstified with many karst features such as channels and caves. The base of fractured and karstified features is generally deeper than 100 m, enabling large quantities of groundwater to accumulate in the deeper parts of the aquifer.

Depth of the wells is mainly between (100 – 150) m with yields of up to 50 l/s. The transmissivity ranges between (9 – 8000) m^2/day (Stevanovic and Iurkiewicz, 2004, Krasny *et al*., 2006). This aquifer can store large quantities of groundwater. The effective recharge is estimated to be > 50% of the total rainfall. These relatively high estimates of groundwater resources are supported by the occurrence of highly fractured and karstified rocks, high precipitation during the wet season, reduced evaporation and absence of vegetation (almost no transpiration), and poorly developed hydrograph (Krasny *et al*., 2006).

The available information from the Hydrogeological Data Base reflect that the total depth of wells, within the Bekhme karst aquifer, ranges between (15.5 – 550) m; depth of water ranges between (0 – 168) below ground surface; static water level ranges between (0 – 61) m below ground surface; coefficient of transmissivity range between (3 – 864) m^2/day; coefficient of permeability ranges between (0.1 – 18) m/day; discharge of wells ranges between (30 – 1980) m^3/day; salinity of water is mainly less than 500 mg/l and exceptionally reaches 1000 mg/l or more due to contamination with evaporates in other formations. The type of groundwater is mainly bicarbonate (Table 1).

- **Pila Spi Fractured Karst Aquifer**

This aquifer includes carbonates of Sinjar, Khurmala and Avanah formations. It occupies mainly the central and southern parts of the zone. It is heterogeneous and anisotropic, up to 200 m thick, fractured and well karstified. The base of the karstification is at a depth of > 80 m. The depth of the drilled wells ranges mainly between (119 – 150) m, with yields of up to 40 l/s. The transmissivity ranges between (3.5 – 42000) m^2/day. This aquifer can store large amounts of groundwater. The effective recharge is estimated to be > (30 – 40) % of the total rainfall (Stevanovic and Iurkiewicz, 2004, Krasny *et al*., 2006).

The available information from the Hydrogeological Data Base reflect that the total depth of wells, within the Pila Spi fractured karst aquifer, ranges between (22 – 300) m, depth of water ranges between (1.2 – 140) below ground surface, static water level ranges between (0.5 – 118.2) m below ground surface, coefficient of transmissivity range between (3 – 2800) m^2/day, coefficient of permeability ranges between (0.1 – 23.9) m/day, discharge of wells ranges between (32 – 2689) m^3/day, salinity of water is mainly less than 500 mg/l and exceptionally reaches 1000 mg/l or more due to contamination with evaporates in other formations, like Gercus Formation. The type of groundwater is mainly bicarbonate (Table 1), (Krasny *et al*., 2006).

In addition to these important carbonate aquifer complexes, some clastic units, such as Kolosh and Tanjero formations are sufficiently permeable to form local fractured aquifers. Tertiary and Quaternary sediments are often hydraulically connected to the carbonate rocks forming a joint aquifer system.

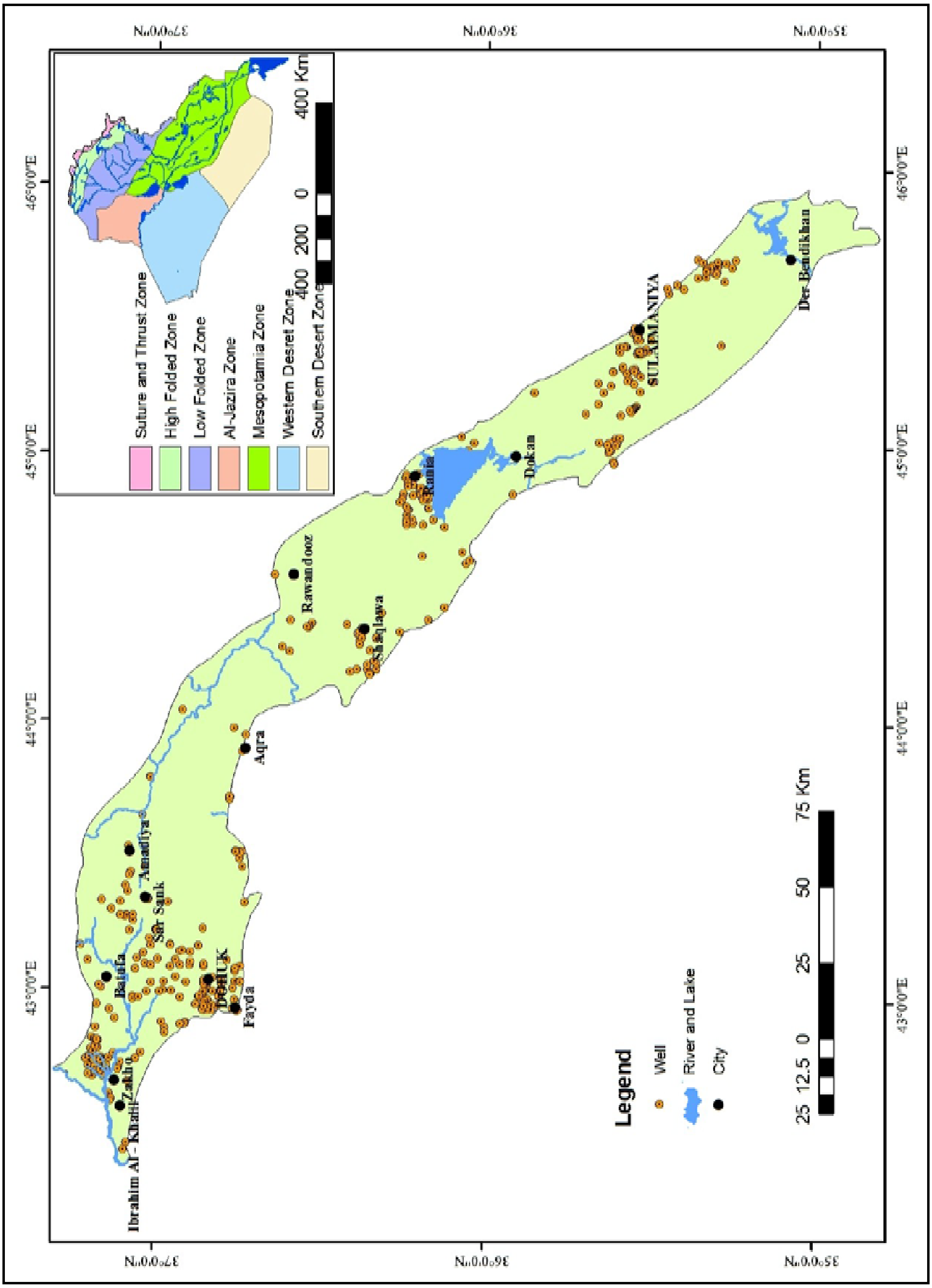

Fig.1: Location map of the available wells in the High Folded Zone

Table 1: Hydrogeological parameters and hydrochemistry of the groundwater in selected wells within the High Folded Zone

Well No.	Latitude	Longitude	Elev. a.s.l. (m)	Total Depth (m)	S.W.L. b.g.l. (m)	D.W.L. b.g.l. (m)	Discharge (m^3/day)	K (m/day)	T (m^2/day)	Salinity (mg/l)	Hardness (mg/l)	Water Type
1	36.40944	44.19528	901	67	6	9.1	222	1.3	71	590	375.59	Bicarbonate
2	36.35	44.19444	789	124	29	39	1386	2.2	161	366	239.79	Bicarbonate
3	36.55722	44.34778	712	41	16	20	881	7.5	187	218	86.42	Bicarbonate
4	36.55528	44.35028	717	41	18	21	873	14.9	321	204	179.4	Bicarbonate
5	36.07833	44.58333	667	134	14.2	19.4	940	2.3	197	291	224.21	Sulphatic
6	36.75	43.09444	839	170	49.8	91.8	432	0.1	13	1193	969.59	Sulphatic
7	36.75	43.46167	472	196	26	44	518	0.2	36	273	144.87	Bicarbonate
8	36.77	43.52167	511	151	30	80	297	0.1	8	212	106.07	Bicarbonate
9	36.8075	43.03583	580	145	118.2	140.2	58	0.2	3	332	218.62	Bicarbonate
10	36.85833	42.93611	501	185	21	47	881	0.3	45	470	206.87	Bicarbonate
11	37.16028	42.71833	469	100	8	60	455	0.2	12	320	211.55	Bicarbonate
12	37.19806	42.82111	638	106	30	48	324	0.3	22	224	201	Bicarbonate
13	36.76389	42.945	442	145	22	30	1555	2	239	486	381.42	Sulphatic
14	37.02222	43.16667	1089	102	15	48	518	0.3	21	326	249.22	Bicarbonate
15	36.96472	43.17083	870	100	5	25	1037	0.8	67	300	189.85	Bicarbonate
16	36.76167	42.93861	446	101	22	25	1166	5.6	436	489	379.06	Sulphatic
17	36.93417	43.14583	853	182	18	75	330	0.1	6	187	164.84	Bicarbonate
18	37.17694	42.80917	617	140	11	78	528	0.1	11	323	295	Bicarbonate
19	37.23722	43.16333	770	71	11	27	660	1	53	267	254.73	Bicarbonate
20	36.91611	42.87917	604	116	12	15	1584	5.1	502	167	138.39	Bicarbonate
21	36.93417	43.09444	966	160	7	72	231	0.1	3	289	144.73	Bicarbonate
22	36.86111	42.97778	529	140	20	54	346	0.1	13	363	255.65	Bicarbonate
23	36.86111	42.93056	502	150	14	72	346	0.1	6	506	422.67	Sulphatic
24	37.18083	42.80722	570	157	18	28	1210	1.4	134	505	425.13	Sulphatic
25	37.15694	42.71139	458	120	22	58	518	0.2	20	247	225.37	Bicarbonate
26	36.87472	42.98028	615	175	72	81	536	0.7	71	350	292.69	Bicarbonate
27	36.97778	42.86111	1097	195	23	35	1037	0.7	107	339	281.54	Bicarbonate
28	36.97778	42.84444	987	195	29	39	950	0.7	112	361	268	Bicarbonate
29	36.76667	43.075	582	155	4.5	48	1164	1.5	36	1122	783.9	Sulphatic
30	36.87917	43.16667	1085	115	32	50	389	0.4	24	280	221.85	Bicarbonate
32	36.92778	43.15	785	164	1.5	11	1848	1.9	220	258	224.21	Bicarbonate
33	37.11667	43.27778	1235	160	12	72	397	0.1	7	295	292.69	Bicarbonate
34	36.86667	43.23333	628	175	108	119	346	0.6	38	338	216.26	Bicarbonate
35	37.04722	42.76806	824	89	20	48.8	320	0.3	14	567	413.7	Sulphatic
36	36.80972	43	545	185	71	110	346	0.1	12	294	225.97	Bicarbonate
37	36.84667	42.94028	475	182	21	44	1080	0.9	57	357	280.62	Bicarbonate
38	36.84917	42.92861	474	176	19	52	1166	0.4	48	367	281.5	Sulphatic
39	36.85833	43	550	165	35	60	778	0.4	42	568	476.38	Sulphatic
40	36.86111	43	559	235	90	100	259	0.3	30	301	241.87	Bicarbonate
41	36.85444	42.9447	497	180	12	65	259	0.1	5	388	241.27	Bicarbonate
42	36.85833	43.03333	661	156	13	19	1987	5.1	375	318	255.97	Bicarbonate
43	36.75472	42.93278	396	80	6	17.5	132	0.2	11	481	399.68	Bicarbonate
44	36.855	42.94139	497	200	11	56	467	0.1	9	401	330.32	Sulphatic
45	37.18222	42.81278	580	140	9	33	990	0.5	46	226	183.94	Bicarbonate
46	37.15778	42.67417	439	80	11	35	396	0.4	21	226	183.94	Bicarbonate
47	35.5125	45.24722	813	62	18	42	277	0.5	15	535	318.96	Bicarbonate
48	36.19583	44.82167	522	58.8	8.4	12.9	257	1.3	65	252	313.78	Bicarbonate
49	36.21917	44.91639	528	18	6.9	13.5	353	8.2	90	341	163.64	Bicarbonate
50	35.59167	45.27917	767	46.5	10	30	419	1	26	225	190.41	Bicarbonate
51	35.55667	45.40667	771	182	16	25	241	0.2	30	180	270.03	Bicarbonate
52	35.55278	45.34861	732	110	11	59	818	0.3	25	380	196.42	Bicarbonate
53	35.51667	45.4	733	51	6	9.5	667	4.6	207	300	187.59	Bicarbonate
54	35.61111	45.375	871	100	5	65	392	0.2	9	306	212.14	Bicarbonate
55	35.56111	45.27778	735	39	11	22	458	2.7	24	189	175.39	Bicarbonate
56	35.61944	45.025	904	67	6	12	778	6.2	148	281	216.4	Bicarbonate
57	35.55028	45.35944	743	38	10.5	35	194	0.6	10	253	219.22	Bicarbonate
58	36.17944	44.74556	520	98	20	28	990	1.9	148	340	299.68	Bicarbonate
59	35.62222	45.02889	888	90	11	52	421	0.4	8	271	140.47	Bicarbonate
60	35.62583	45.03889	891	80	7	48.6	389	0.4	6	245	148.7	Bicarbonate
61	35.62222	45.02194	903	102	10	73	259	0.3	5	445	278.54	Bicarbonate
62	35.62722	45.01528	902	37.5	19	25	858	13.7	171	363	230.96	Bicarbonate
63	35.56667	45.29444	740	67	15	35	778	1.9	50	211	190.41	Bicarbonate
64	35.57222	45.425	838	98	30.5	67	130	0.2	5	529	319.66	Sulphatic

Cont. Table 1:

Well No.	Latitude	Longitude	Elev. a.s.l. (m)	Total Depth (m)	S.W.L. b.g.l. (m)	D.W.L. b.g.l. (m)	Discharge (m^3/day)	K (m/day)	T (m^2/day)	Salinity (mg/l)	Hardness (mg/l)	Water Type
65	35.66111	45.20833	823	60	15.2	21.3	389	2	74	174	150.74	Bicarbonate
66	35.61111	45.12639	830	82	21.5	30.5	356	0.8	48	279	138.39	Bicarbonate
67	35.52639	45.35861	699	67	3.5	13	156	0.3	19	415	212.14	Bicarbonate
68	36.19167	44.7875	518	85	17	22.5	1296	5.1	290	196	178.35	Bicarbonate
69	35.56167	45.41611	812	175	42	75	544	0.4	19	219	119.3	Bicarbonate
70	35.56278	45.41917	820	65	13	43	347	0.4	15	398	316.78	Bicarbonate
71	35.37417	45.62389	563	82	26	36	320	0.7	38	185	120.18	Bicarbonate
72	35.57	45.24028	791	60	8	36	369	0.6	18	181	106.95	Bicarbonate
73	35.31222	45.67167	563	110	8	28	713	0.5	45	265	242.99	Bicarbonate
74	35.57444	45.29194	748	49	10.5	36	449	0.9	23	203	122.53	Bicarbonate
75	35.56833	45.285	743	60	11	35	356	0.5	19	153	106.07	Bicarbonate
76	36.05556	45.02778	566	120	8	42	778	0.3	30	292	178.35	Bicarbonate
77	35.31278	45.665	591	130	12	20	759	1	92	260	147.22	Bicarbonate
78	35.55556	45.44444	848	200	30	43	324	0.2	34	198	97.84	Bicarbonate
79	36.24167	44.88167	560	100	26	33	907	2.4	168	196	149.26	Bicarbonate
80	35.32889	45.65639	552	94	24	40	462	0.9	35	324	178.94	Bicarbonate
81	36.27778	44.8125	672	103	31	43	594	0.9	59	261	210.39	Bicarbonate
82	35.27083	45.65833	654	76	24	40	528	0.9	40	220	175.71	Bicarbonate
83	35.325	45.65333	556	115	24	36	660	1.2	66	354	229.48	Bicarbonate
84	36.26111	44.76111	566	220	60	80	594	0.2	38	253	188.93	Bicarbonate
85	35.32472	45.65417	556	75	26	38	50	0.1	5	242	207.15	Bicarbonate
86	35.32833	45.65833	551	94	21.5	36	454	0.6	40	194	138.25	Bicarbonate
87	36.22083	44.85417	532	110	14	44	726	0.4	31	220	160.73	Bicarbonate
88	35.28889	45.675	596	115	33	40	858	1.8	132	202	150.46	Bicarbonate
89	35.25833	45.6875	626	105	25	41	594	0.6	45	203	144.87	Bicarbonate
90	35.54167	45.35333	723	157	30	36	1056	3.4	201	185	106.67	Bicarbonate
91	36.20833	44.83333	531	112	8	14	1296	18	276	201	199.2	Bicarbonate
92	35.64333	45	913	52	16	19	924	9.8	333	184	162.2	Bicarbonate
93	35.61111	45.355	827	85	7	25	792	2.2	55	235	161.01	Bicarbonate
94	35.675	45.025	884	70.5	18	23	924	4.4	221	259	210.39	Bicarbonate
95	36.2125	44.825	539	108	28	33	660	4.3	150	311	200.12	Bicarbonate
96	36.25417	44.78056	584	120	40.4	42	648	5.5	430	206	188.65	Bicarbonate
97	36.86111	43.04167	746	140	24	51	660	0.4	18	416	344.98	Bicarbonate
98	36.855	42.94861	495	153	18	37	99	0.1	4	309	264.48	Bicarbonate
99	36.85222	42.94139	491	182	20	36	1188	0.6	59	422	376.15	Bicarbonate
100	36.145	44.42333	747	98	15	42.9	594	0.4	26	511	341.99	Bicarbonate
101	36.06833	44.59667	605	90	0.7	15	1782	1.8	157	322	249.6	Bicarbonate
102	36.86111	43.02778	704	131	14	45	829	0.3	35	417	350.86	Bicarbonate
103	36.21167	44.61111	700	149	33	61	583	0.3	13	185	182.18	Bicarbonate
104	36.86111	43.02778	704	131	14	45	829	0.4	35	268	197.16	Bicarbonate
105	36.21667	44.83611	539	96	38	39.5	627	7.7	441	254	230.96	Bicarbonate
106	35.63333	45.02778	869	99	5.5	14.2	1620	8.2	237	354	261.52	Bicarbonate
107	35.5125	45.24722	813	61.7	17.6	28.2	292	0.8	35	408	295.68	Bicarbonate
108	35.3575	45.67944	540	96	48.6	54.2	389	1.7	75	253	200.96	Bicarbonate
109	35.6125	45.04167	885	122	9	46	1056	0.4	41	286	164.84	Bicarbonate
110	35.56667	45.44444	882	195	44	51	1382	1.6	239	299	230.4	Bicarbonate
111	36.28056	44.80833	872	100	15	19.5	1642	5.9	433	202	161.61	Bicarbonate
112	35.63056	44.95	860	150	3	31	1642	0.7	74	308	200.4	Bicarbonate
113	36.21111	44.725	550	122	36	42	1166	2.9	239	207	118.7	Bicarbonate
114	36.21111	44.84167	532	103	16	20	1918	6.7	571	3324	3298.25	Sulphatic
115	36.25694	44.88056	577	120	27	58	648	0.4	27	207	146.34	Bicarbonate
116	36.19444	44.85556	509	100	16	20	1944	7.3	601	196	135.76	Bicarbonate
117	36.19944	44.83333	523	98	16	18	1555	10.8	864	220	149.86	Bicarbonate
118	35.3125	45.68056	548	120	19	30	778	1	88	209	178.66	Bicarbonate
119	36.24028	44.83333	564	123	42	44	648	4.4	351	262	238.59	Bicarbonate
120	37.15	42.7	454	120	40	46	648	1.6	122	3279	2237.78	Sulphatic
121	35.325	45.64167	565	71	17	35	648	1.1	45	268	109.31	Bicarbonate
122	35.31528	45.64444	568	90	30.2	33.5	778	4.5	259	310	201.6	Bicarbonate
123	35.33472	45.65417	548	106	14.5	16.5	778	4.5	409	380	161.64	Bicarbonate
124	35.56389	45.15833	794	110	6.8	46	648	0.7	21	186	146.34	Bicarbonate
125	36.24028	44.73194	643	126.5	43.1	45.5	950	5.2	430	210	129.28	Bicarbonate
126	35.56667	45.15333	791	90	7	48	449	0.2	16	232	163.68	Bicarbonate
127	35.56944	45.15	795	84	10	38	207	0.2	9	350	301.48	Bicarbonate
128	35.31806	45.6375	573	80	26.6	65.6	315	0.3	10	345	240.11	Bicarbonate

Cont. Table 1:

Well No.	Latitude	Longitude	Elev. a.s.l. (m)	Total Depth (m)	S.W.L. b.g.l. (m)	D.W.L. b.g.l. (m)	Discharge (m^3/day)	K (m/day)	T (m^2/day)	Salinity(mg/l)	Hardness (mg/l)	Water Type
129	35.34667	45.65694	530	100	9	14	821	4.9	181	380	250.34	Bicarbonate
130	35.63194	45.28639	875	50	15.9	44.5	104	0.2	6	260	55.53	Bicarbonate
131	36.75	43.03889	523	107	40	50	389	0.7	44	534	340.87	Bicarbonate

Each formation in this zone is characterized as water bearing formation or aquitard, but in some cases the water bearing formation could be identified as dry formation, due to the influence of tectonics or its folding structure. UNICEF (2000a, b and c) arranged formations in this zone as the following system:

– Highly productive aquifers, includes; Mukdadiya, Bai Hassan formations and Alluvium.
– Moderately productive aquifers, includes; Qamchuqa, Kometan, Shiranish, Sinjar and Pila Spi formations.
– Regions without significant groundwater resources, includes; Tanjero, Kolosh, Gercus, Fatha and Injana formations.

The regional direction of the groundwater flow in High Folded Zone is generally to the southwest and south towards the Low Folded Zone, with other different directions towards the Upper Zab, Lower Zab, Khabour and Sirwan rivers, due to the complexity of the structure and topography of the zone. The available updated Hydrogeological information in the Hydrogeological Data Base indicates the presence of a water divide, within the area between Zakho and Sar Sank, with a general E – W trend, in addition to other water divides along different structures within the zone. These water divides cause the groundwater to flow into different opposite directions along their trends (Fig.2).

HYDROGEOLOGICAL BASINS

The High Folded Zone can be divided into five major hydrogeological basins and subdivided into ten sub-basins (Fig.3) (Stevanovic and Iurkiewicz, 2004; Krasny *et al*., 2006). The extension of each sub-basin should be recognized with the help of the wells, flow direction and tectonics. These aquifers represent the total resource of the groundwater and the available water reservoir is variable and depends on different parameters such as storage coefficient, transmissivity, thickness of the aquifer and the water table condition.

The sub-basins are described hereinafter:

- **Zakho Basin**

The Zakho Basin coverage area is about 1400 Km². It's an almost closed E-W trending intermountain basin filled by clastic sediments of Injana, Mukdadiya and Bai Hassan formations and Quaternary Sediments. The groundwater flow direction is towards the Khabour River and its tributaries. The eastern extension of the Zakho Basin passes into the NW Barzany Basin, particularly with Amadia – Barsan Sub-basin, which is in the catchment area of the upper reaches of the Greater Zab River. The Zakho Basin is located within the High Folded Zone, but its Hydrogeological character is similar to the aquifers of the Low Folded Zone. The performed pumping tests of wells discharging from this basin showed that the transmissivity of the aquifers ranges between (3 – 654) m^2/day, permeability ranges between (0.1 – 2.5) m/day, discharge of wells ranges between (46 – 1760) m^3/day and the static water level ranges between (1 – 25) m below ground surface. Flow direction net is to Khabour River from east, north and south direction. The available updated Hydrogeological information in the Hydrogeological Data Base indicates the presence of a water divide, within the area between Zakho to Sar Sank, with a general E – W trend. The aquifers are of confined and unconfined type according to the hydrogeological conditions within the basin. The groundwater is mainly fresh water of salinity ranges from (300 – 900) mg/l and with bicarbonate and sulphatic water type in general (Figs.2, 3, 4 and 5).

- **NW Barzany Basin**

The NW Barzany Basin is subdivided into two sub-basins, these are described hereinafter.

— **Amadia – Barzan Sub-Basin:** The Amadia – Barzan Sub-basin coverage area is about 300 Km². It's characterized by the prevalence of karstic and karstic – fissured aquifers, with small basins mostly filled with impervious rocks. The results of pumping tests performed in wells discharging from this sub-basin showed that, the transmissivity of the aquifers ranges between (3 – 134) m^2/day, permeability ranges between (0.1 – 5) m/day, discharge of wells ranges between (19 – 1555) m^3/day and the static water level ranges between (8 – 24) m below ground surface. There are confined and unconfined aquifers are present in the sub-basin. The groundwater is mainly fresh water with salinity ranges from (300 – 900) mg/l and with bicarbonate and sulphatic water type in general (Figs.2, 3, 4 and 5).

— **Atrush – Dinarta Sub-Basin:** The Atrush – Dinarta Sub-basin coverage area is about 1950 Km². It's also characterized by the prevalence of karstic and karstic – fissured aquifers, with small basins filled with impervious rocks. The performed pumping tests of wells discharging from this sub-basin showed that, the transmissivity of the aquifers ranges between (3 – 2800) m^2/day, permeability ranges between (0.1 – 23.9) m/day, discharge of wells ranges between (32 – 2689) m^3/day and the static water level ranges between (6 – 32) m below ground surface. The aquifers are confined and unconfined. The groundwater is mainly fresh water with salinity ranges from (300 – 800) mg/l and of bicarbonate and sulphatic water type in general (Figs.2, 3, 4 and 5).

- **Central Harir Basin**

The Central Harir Basin is subdivided into two sub-basins, they are described hereinafter.

— **Diana – Merga Soor Sub-Basin:** The Diana – Merga Soor Sub-basin coverage area is about 625 Km². It's characterized by the presence of karstic and karstic – fissured aquifers, prevalence at the edges, the sub-basin often filled with impervious rocks. The results of pumping tests performed in wells discharging from the sub-basin showed that, the transmissivity of aquifers ranges between (6 – 662) m^2/day, permeability ranges between (0.1 – 14.6) m/day, discharge of wells ranges between (20 – 2070) m^3/day and static water level ranges between (1.2 – 60) m below ground surface. The aquifers are confined and unconfined. The groundwater is mainly fresh water with salinity ranges from (300 – 600) mg/l and of bicarbonate water type in general (Figs.2, 3, 4 and 5).

— **Harir – Shaqlawa Sub-Basin:** The Harir – Shaqlawa Sub-basin coverage area is about 1535 Km². It's also characterized by the presence of karstic and karstic – fissured aquifers, the sub-basin is often filled with impervious rocks. The performed pumping tests of wells discharging from this sub-basin showed that, the transmissivity of the aquifers ranges between (3 – 611) m^2/day, permeability ranges between (0.1 – 19.1) m/day, discharge of wells ranges between (37 – 2310) m^3/day and static water level ranges between (4 – 60) m below ground surface. The aquifers are confined and unconfined. The groundwater is mainly fresh water with salinity ranges from (300 – 700) mg/l and of bicarbonate water in general (Figs.2, 3, 4 and 5).

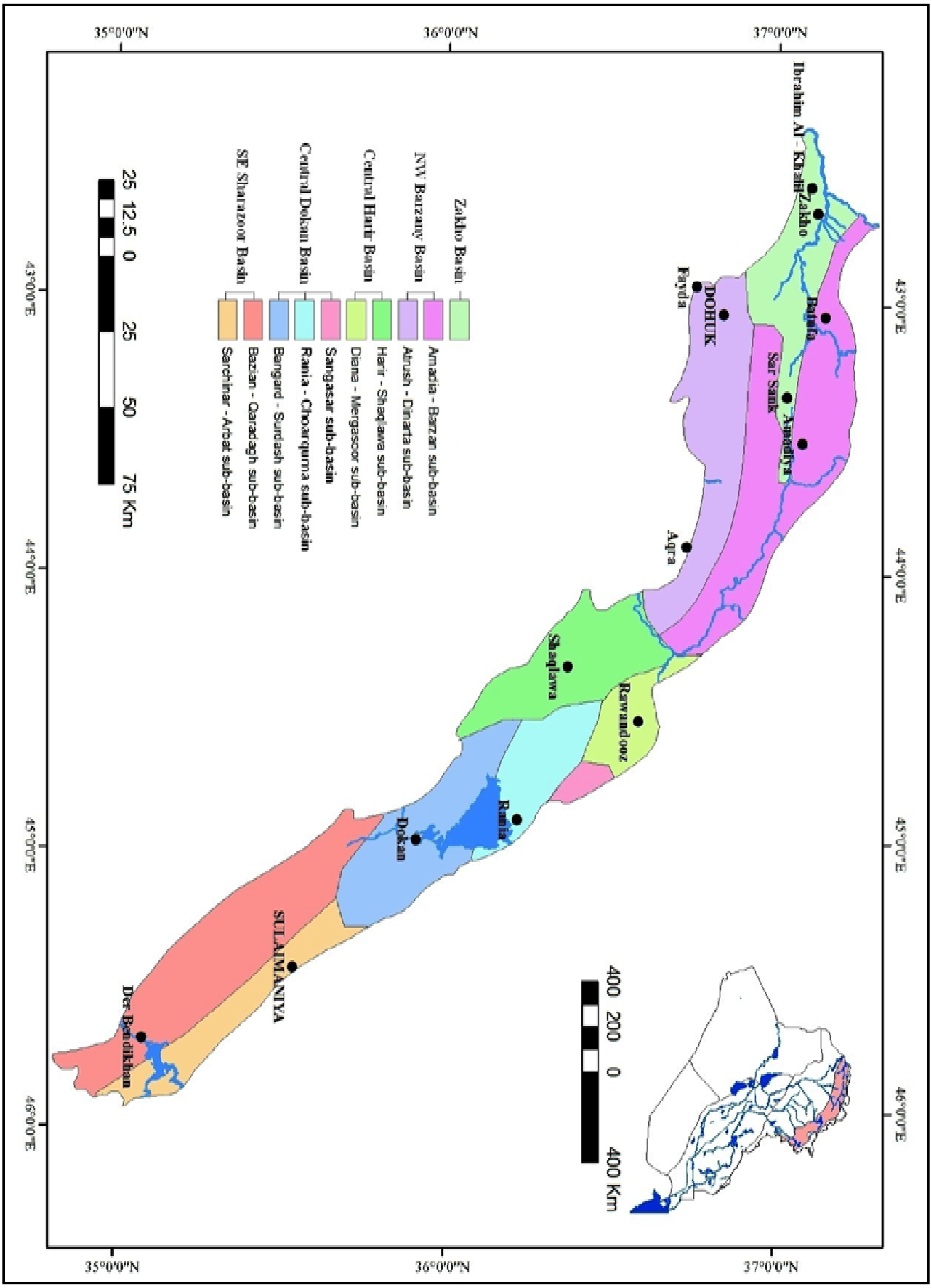

Fig.2: Hydrogeological basins of the High Folded Zone (modified after Stevanovic and Iurkiewicz, 2004)

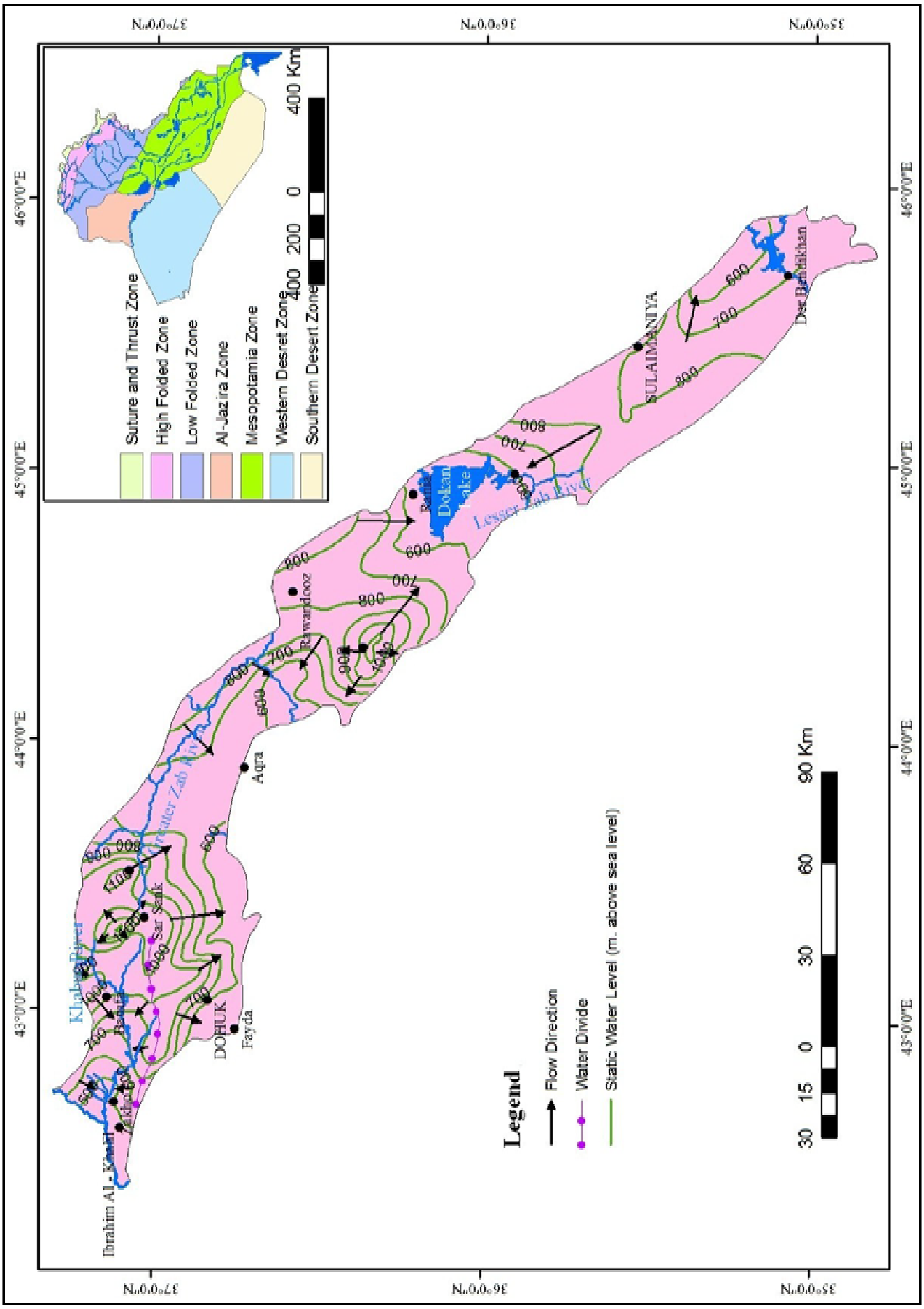

Fig.3: Hydrogeological map of the High Folded Zone, shows static water level, water divide and flow direction of the groundwater

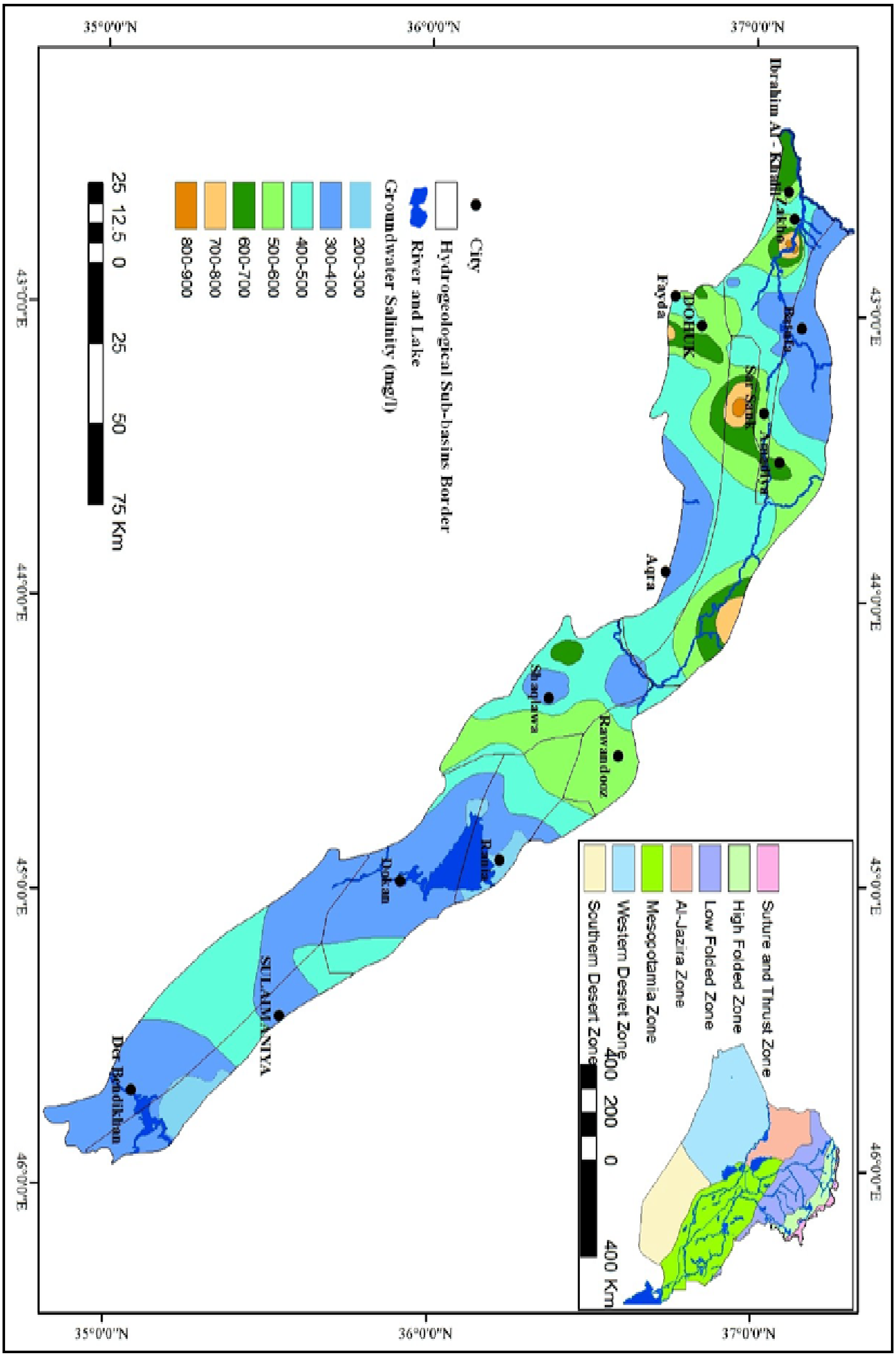

Fig.4: Hydrochemical map of the High Folded Zone, shows the salinity of the groundwater (mg/l)

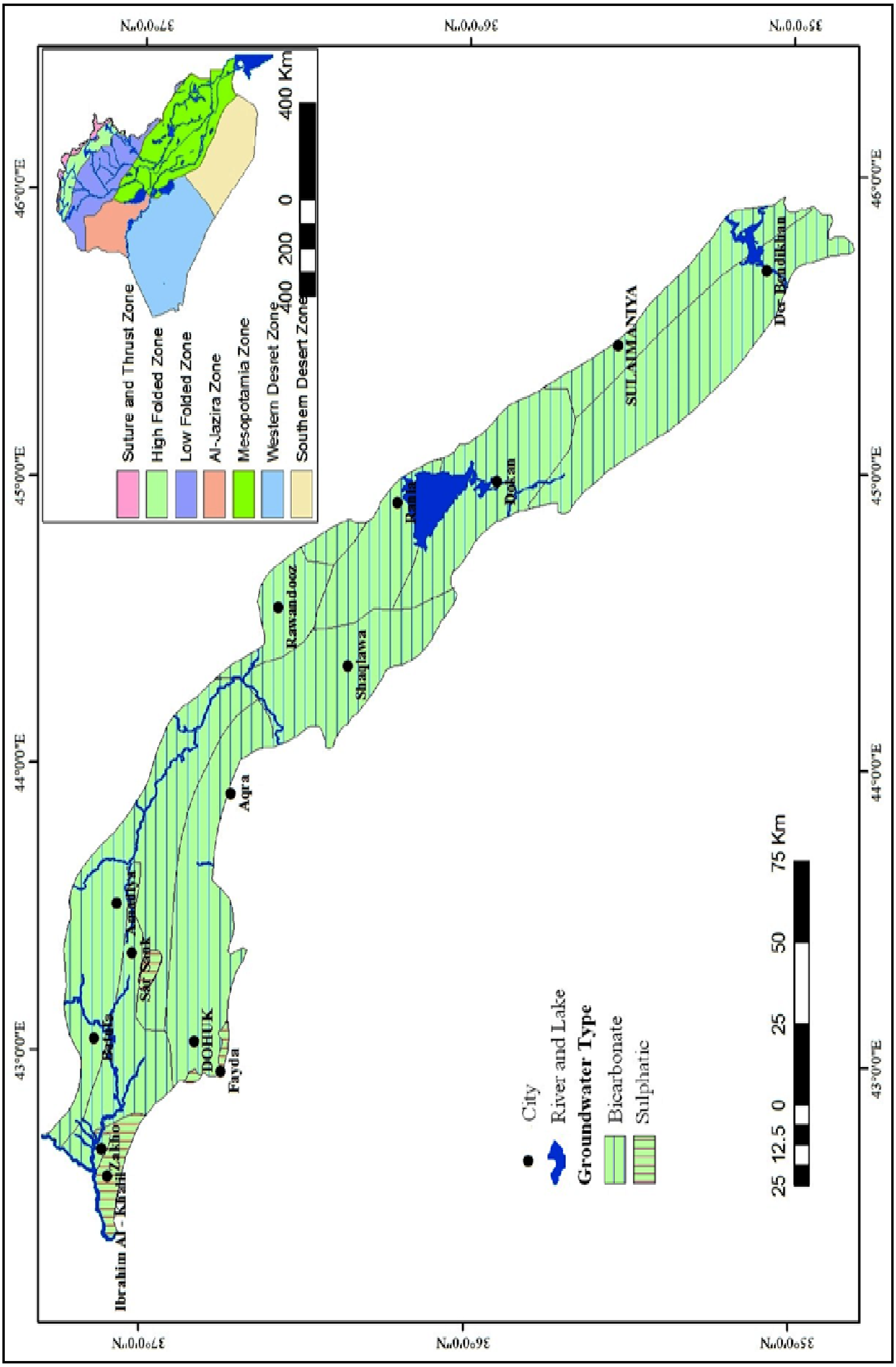

Fig.5: Hydrochemical map of the High Folded Zone, shows the type of the groundwater

▪ **Central Dokan Basin**

The Central Dokan Basin is subdivided into three sub-basins, described as follows:

─ **Sangasar Sub-Basin:** The Sangasar Sub-Basin coverage area is about 165 Km². It's characterized by the presence of karstic and karstic fissured aquifers, which predominate at the edges of the sub-basin. The sub – basin is often filled with highly productive recent sediments. The performed pumping tests of wells discharging from this Sub-basin showed that, the transmissivity of the aquifers ranges between (3 – 540) m^2/day, permeability ranges between (0.1 – 14.6) m/day, discharge of wells ranges between (99 – 1749) m^3/day and the static water level ranges between (6 – 80) m below ground surface. The aquifers are confined and unconfined. The groundwater is mainly fresh water with salinity ranges from (300 – 500) mg/l and of bicarbonate water type in general (Figs.2, 3, 4 and 5).

─ **Rania – Choarqurna Sub-Basin:** The Rania – Choarqurna Sub-basin coverage area is about 1035 Km². It's characterized by the presence of karstic and karstic fissured aquifers, which predominate at the edges of the sub-basin. The sub-basin is often filled with highly productive Quaternary Sediments, it consist of gravel, marl, sand and silt. The depth of the wells ranges between (80 – 150) m. The next formation below Quaternary sediments is Cretaceous (Tanjero, Shiranish and Qamchuqa formations). Shiranish and Qamchuqa formations are also considered as promising aquifers. The performed pumping tests of wells discharging from this Sub-basin showed that, the transmissivity of the aquifers ranges between (15 – 864) m^2/day, permeability ranges between (0.2 – 12.8) m/day, discharge of wells ranges between (3 – 1616) m^3/day and the static water level ranges between (5 – 60) m below ground surface. The flow direction of the groundwater in this Sub-basin is towards Dokan Lake. The aquifers are confined and unconfined. The groundwater is mainly fresh water with salinity ranges from (200 – 600) mg/l and of bicarbonate water type in general (Figs.2, 3, 4 and 5).

─ **Bangard – Surdash Sub-Basin:** The Bangard – Surdash Sub-basin coverage area is about 1725 Km². It's characterized by the presence of karstic and karstic fissured aquifers, which predominate at the edges of the sub-basin, the sub-basin are often filled with highly productive recent sediments. The performed pumping tests of wells discharging from this Sub-basin showed that, the transmissivity of the aquifers ranges between (14 – 597) m^2/day, permeability ranges between (0.2 – 4.4) m/day, discharge of wells ranges between (330 – 1961) m^3/day and the static water level ranges between (0.7 – 35) m below ground surface. The aquifers are mainly unconfined. The groundwater is mainly fresh water with salinity ranges from (200 – 500) mg/l and of bicarbonate water type in general (Figs.2, 3, 4 and 5).

▪ **Sharazoor Basin**

The SE Sharazoor Basin is subdivided into four sub-basins, these are described hereinafter.

─ **Bazian – Qaradagh Sub-Basin:** The Bazian – Qaradagh Sub-basin coverage area is about 2530 Km². It's characterized by the occurrence of karstic and karstic fissured aquifers on the edges of the sub-basin. Quaternary Sediments form the upper aquifer of this Sub-basin, while Pila Spi and Sinjar formations form the second aquifer. The next formation is Kometan. The performed pumping tests of wells discharging from this Sub-basin showed that, the transmissivity of the aquifers ranges between (4 – 749) m^2/day, permeability ranges between (0.2 – 20.6) m/day, discharge of wells ranges between (107 – 1620) m^3/day and the static water level ranges between (6 – 32) m below ground surface. The flow direction is towards the wadis, which end in Lower Zab and Sirwan rivers. The aquifers are confined and unconfined. The groundwater is mainly fresh water with salinity ranges from (300 – 500) mg/l and of bicarbonate water type in general (Figs.2, 3, 4 and 5).

– **Sarchinar – Arbat Sub-Basin:** The Sarchinar – Arbat Sub-basin coverage area is about 1080 Km^2. It's characterized by the occurrence of karstic and karstic fissured aquifers on the edges of the sub-basin. The sub – basin is often filled with highly productive Quaternary Sediments, below this sediments Sinjar Formation exist, which is considered as a semi aquifer. It means that, in some places the formation is aquitard, while in others it is water bearing formation. Also, variable permeability and lateral – horizontal changes occur in lithology of the sub-basin. The performed pumping tests of wells discharging from this Sub-basin showed that, the transmissivity of the aquifers ranges between (5 – 409) m^2/day, permeability ranges between (0.2 – 4.9) m/day, discharge of wells ranges between (52 – 1642) m^3/day and the static water level ranges between (3 – 59) m below ground surface, and the flow directions are towards south and southwest and also towards Derbandikhan Lake. The aquifers are mainly unconfined with some confined. The groundwater is mainly fresh water with salinity ranges from (200 – 500) mg/l and of bicarbonate water type in general (Figs.2, 3, 4 and 5).

SPRINGS

In the High Folded Zone, the springs form an important water supply, where most of them are perennial and often the water is used for domestic and irrigation purposes. Enormous numbers of springs are located all over Northern Iraq (Fig.6). It is mainly rich at the fault lines, which extend NW – SE or N – S. Springs are part of the groundwater regime, but some categorize it under surface water resources. Most of these springs are seasonal. Though they are located at the fault lines and the recharge source is mainly from rain and snowfall. Some of them become dry in the dry seasons. But the bigger springs, are fault or contact springs, which means that they originate from deep groundwater sources (UNICEF, 2000a, b and c).

Stevanovic and Iurkiewicz (2004) defined two aquifer spring systems:

- Karstic Bekhme aquifers, that include Sarchinar and Bekhal springs. They are often associated with faults locations, fractures systems and border massive carbonate rocks at their contacts with non-carbonate rocks. Many karst springs are mainly related to their favorable geologic – geomorphic setting (Al-Manmi, 2008).
- Fractured – karstic Pila Spi aquifer, which includes the springs of Dera Boon and Bani Khelan.

Most of the carbonate springs in the High Folded Zone yield fresh water (less than 600 mg/l) of predominately bicarbonate type (Krasny *et al.*, 2006 and Al-Jiburi and Al-Basrawi, 2013). Sulphatic water type rarely predominate; exceptions are found in springs that issue from formations in contact with Fat'ha Formation, yielding water of salinity greater than 1000 mg/l due to contamination with sulphate. To those springs related to the clastic sediments (i.e. Injana, Mukdadiya and Bai Hassan formations), they yield fresh water (less than 1000 mg/l) and of predominantly calcium – bicarbonate water. The alkalinity of water is due to the bicarbonates content, because the pH value of the water sample is above 7 (Collins, 1975). While, hardness ranges from (hard – very hard water) due to the high concentration of calcium and magnesium in water (Todd, 1980); some measured hydrochemical parameters are tabulated in Table (2).

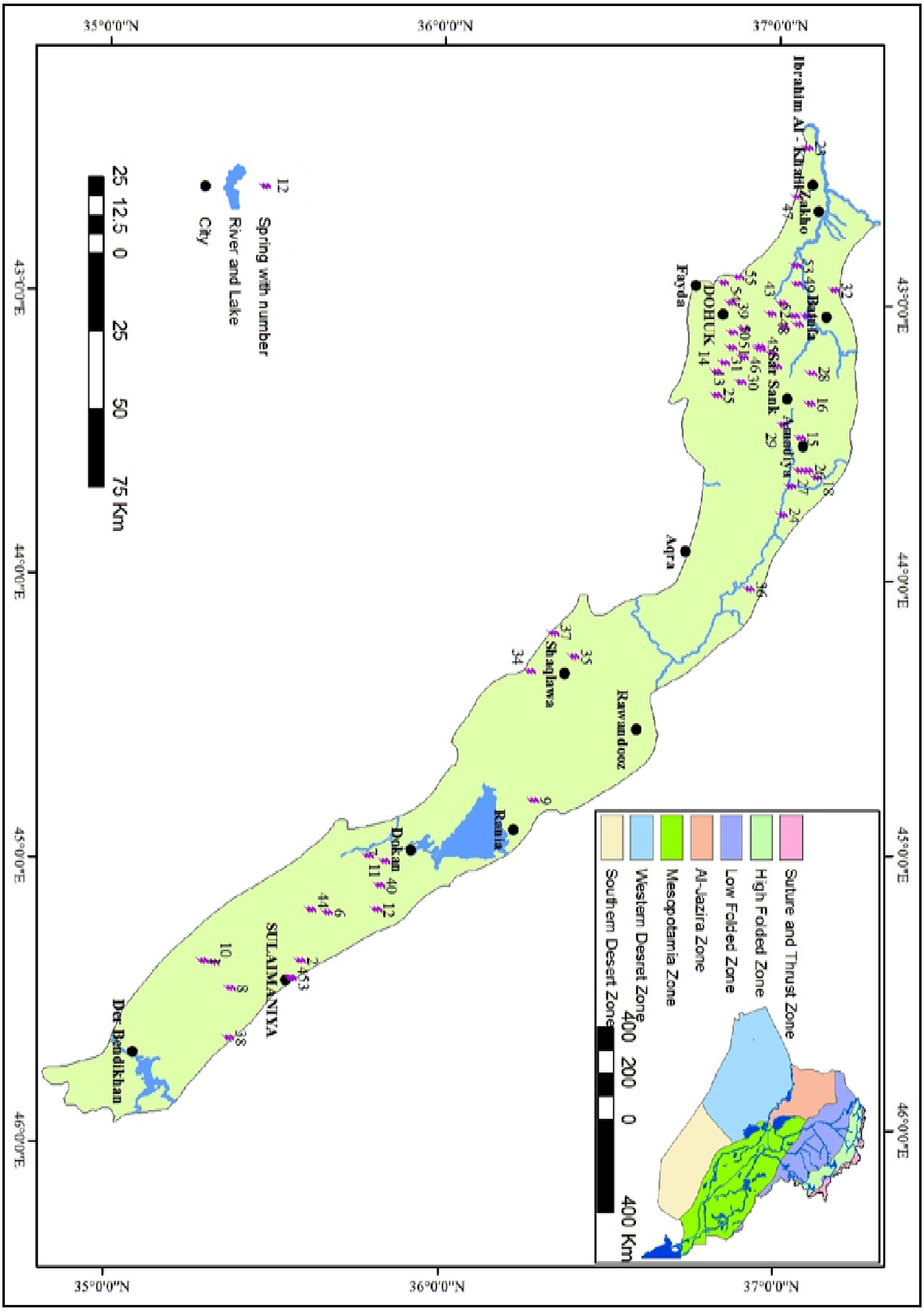

Fig.6: Location map of selected springs within the High Folded Zone

Table 2: Some hydrochemical parameters of selected springs within the High Folded Zone, after UNICEF (2000a, b and c)

Spring No.	Name	Governorate	Longitude	Latitude	Total Hardness	Alkalinity	TDS
1	Arbat Khqaratogan	Dohuk	45.370833	35.304167	332	124	353
2	Sarchanar	Dohuk	45.370833	35.597222	246	156	271
3	Haji Bag	Dohuk	45.433333	35.569444	214	140	268
4	Aziz Agha	Dohuk	45.433333	35.566667	257	147	312
5	Shesh Mahmood	Dohuk	45.433333	35.568056	208	145	249
6	Hassan Tapais	Dohuk	45.2	35.677778	166	96	212
7	Sekanyan Kalakan	Dohuk	45.019444	35.85	378	254	299
8	Kany Shaswar	Dohuk	45.466667	35.386111	340	210	341
9	Sarkapkan	Dohuk	44.8	36.294444	295	164	313
10	Merga Soor	Dohuk	45.375	35.336111	298	228	322
11	Awalan	Dohuk	45	35.8	130	78	142
12	Shaddala	Dohuk	45.190833	35.824722	–	–	–
13	Perool	Erbil	43.219444	36.852778	320	–	363
14	Nordenava	Erbil	43.251389	36.830556	336	–	315
15	Amadiya	Erbil	43.486111	37.083333	320	–	315
16	Ainisky	Erbil	43.3625	37.111111	360	–	372
17	Bakerat Village	Erbil	43.163889	36.955556	372	–	360
18	Shekh Zewa Beramos	Sulaimaniyah	43.627778	37.133333	272	–	301
19	Mangesh	Sulaimaniyah	43.086111	37.027778	296	–	290
20	Swara Tooka	Sulaimaniyah	43.227778	37.008333	308	330	348
21	Qadash	Sulaimaniyah	43.044444	37.095833	320	320	348
22	Gaw Harzy	Sulaimaniyah	43.604167	37.083333	280	260	308
23	Dera Boon	Sulaimaniyah	42.436111	37.088889	544	252	556
24	Maidan	Sulaimaniyah	43.766667	37.031944	320	330	366
25	Atrosh	Sulaimaniyah	43.3375	36.830556	300	250	339
26	Barji	Sulaimaniyah	43.604167	37.108333	300	250	296
27	Dera Lok	Sulaimaniyah	43.661111	37.055556	208	290	307
28	Bamerny	Sulaimaniyah	43.251389	37.113889	340	–	340
29	Sarsang	Sulaimaniyah	43.438889	37.030556	376	–	322
30	Kania Baska	Sulaimaniyah	43.2875	36.902778	372	368	403
32	Mil Arab	Sulaimaniyah	42.948611	37.177778	620	–	518
33	Sindour	Sulaimaniyah	43.097222	36.909722	520	420	534
34	Darbandy Gomespan	Sulaimaniyah	44.3375	36.283333	316	286	310
35	Hujran	Sulaimaniyah	44.283333	36.413889	–	–	280
36	Kani Mizgawt Barzan	Sulaimaniyah	44.033333	36.936111	218	186	189
37	Bekhal	Sulaimaniyah	44.2	36.352778	–	–	280
38	Kurah	Sulaimaniyah	45.644444	35.381667	–	–	–
39	kania kle duhok	Sulaimaniyah	43.001355	36.868757	–	–	–
40	Manba'a Tabeen	Sulaimaniyah	45.104722	35.833611	–	–	–
41	Sro Kane	Sulaimaniyah	43.04436	37.059422	–	–	–
42	Kanya Bezke	Sulaimaniyah	43.181038	36.99417	–	–	–
43	Kania GaliGarm	Sulaimaniyah	43.001308	37.023076	–	–	–
32	Mil Arab	Sulaimaniyah	42.948611	37.177778	620	-	518
54	Sumail	Sulaimaniyah	42.930584	36.84413	–	–	–
46	Kania Gondy A	Sulaimaniyah	43.19682	36.90819	–	–	–
47	Kania Gonday B	Sulaimaniyah	42.612384	37.060217	–	–	–
55	Kania Kivala	Sulaimaniyah	42.909333	36.89067	–	–	–
49	Kania Sarafky	Sulaimaniyah	42.928643	37.066353	–	–	–
50	kanya Blke	Sulaimaniyah	43.109085	36.87491	–	–	–
51	Garaw	Sulaimaniyah	43.165262	36.873366	–	–	–
52	kania khalnki	Sulaimaniyah	43.075209	37.070021	–	–	–
53	Kania Nhaley	Sulaimaniyah	42.86106	37.060827	–	–	–

DISCUSSION

The lithology of water bearing formations within the High Folded Zone of Iraq is variable; water is present mainly in carbonate and clastic rocks. The clastic rocks are characterized by granular porosity; permeability mainly depends on grain size and it is very high in loose and low cemented sediments and reveals high well discharges. On other hand, carbonate rocks, fissures, fractures and cavities are the most affecting factors on the permeability, but angular porosity has no clear effect on permeability. Therefore, the increase of cavities, fractures and fissures causes an increase of water discharge from wells, in these rocks. The presence of muddy materials within these cavities and fractures causes reduction in water productivity from wells. The carbonate rocks also represent the main predominant extension within this zone, so that the karstic and fractured aquifer systems are considered the most important and widely extending within the zone. There are two main karstic aquifer systems represented by Bekhme Karst Aquifer, which includes Qamchuqa, Dokan and Kometan formations and occupies the northern and central parts of the zone, while Pila Spi Fractured Karst Aquifer includes Sinjar, Khurmala and Avanah formations and occupies the central and the southern parts of the zone. These two aquifer systems represent the main supply of groundwater within the High Folded Zone, with suitable quality that can be used for different purposes. The salinity of the groundwater is not more than 500 mg/l and exceptionally exceed 1000 mg/l. The type of groundwater in these aquifer systems is mainly bicarbonate. The clastic aquifers are represented mainly by Bai Hassan, Mukdadiya and Injana formations especially in Zakho Basin. These formations contain water of different salinity that depends on the lithology and the presence of evaporates mainly in Fatha Formation which may contaminant the groundwater in the basin. The clastic aquifer system in Zakho Basin is similar to the clastic aquifer system in the Low Folded Zone. Tertiary and Quaternary sediments are often hydraulically connected to the carbonate rocks forming a joint aquifer system.

The salinity of groundwater in Zakho Basin is mainly less than 1000 mg/l with bicarbonate and sulphatic water type. Also, some clastic units, such as Kolosh and Tanjero formations are sufficiently permeable to form local fractured aquifers in different parts of the zone as suitable conditions are available. The groundwater occurrence and movement are largely controlled by the geological setting of water bearing strata. Anticlinal structures in the High Folded Zone are rather tectonically complicated, where faulting and folding exists, that would influence the groundwater movement from place to another. The karst phenomena and fracture systems also play important role to determine the flow direction of groundwater. Under such conditions, a hydraulic continuity most likely exists between aquifers of different geologic formations. Porosity of carbonate rocks depends mainly on lithological and structural nature in addition to karstification phenomena, which predominantly occur within the rocks due to solution effects. Secondary porosity in carbonate rocks depends on many factors most important of which are: rock solubility, climatic conditions, presence of acidic solutions, presence of faults, fractures, fissures, joints, cavities within parent rocks, structural and tectonic conditions, geological, geomorphological and topographical nature of the area and movement of ground and surface water (Al-Jiburi and Al-Basrawi, 2009). These factors affect carbonate rocks, which contain water and cause an increase in their permeability and water movement. In recharge regions water movement is generally, from high to low, and the quantities of percolated water depend mainly on lithology, permeability of rocks and presence of fractures, fissures, faults, joints and cavities within these rocks. It also depends on amounts of rain falls and surface run off. While in discharge regions water movement is upwards within springs at different locations in the zone and laterally towards the Low Folded Zone.

Most of recharge water within the High Folded Zone is from rainfall and snow, as well as, run off in the perennial and intermittent valleys, in form of seepage losses into shallow aquifers. Catchment areas extend into the adjacent countries; also percolation through valley beds is the most important ways of recharge.

The annual mean of rainfall in the High Folded Zone ranges mainly between (400 – 950) mm. The other source is the snow fall at the high mountains. These two sources represent the main supply of recharge to the groundwater within the zone. In addition, contribution to the supply from the recharge areas within the Suture and Thrust Zone in Iraq and the high lands in the adjacent countries occur and have higher level of rainfall and snow precipitation than the High Folded Zone. These sources supply the zone with fresh water of low salinity and of mainly bicarbonate water type.

There are five main basins in the zone represented by: Zakho, NW Barzany, Central Harir, Central Dokan and Sharazoor basins. These basins can be considered as the most important areas for developing the groundwater resources in the zone for different purposes, due to the availability of fresh groundwater within wide extended aquifers. The groundwater in these aquifers can easily be extracted and developed. Accordingly, these basins are considered the main promising areas in the High Folded Zone.

CONCLUSIONS

- The main investigated water bearing formations underlying the High Folded Zone are represented by two main aquifer systems within the carbonate rocks represented by: Bekhme Karst Aquifer System which includes Qamchuqa, Dokan and Kometan formations; Pila Spi Fractured Karst Aquifer System which includes Sinjar, Khurmala and Avanah formations. The first aquifer system extends mainly within the northern and central parts of the zone, while the second aquifer system includes the central and southern parts of the zone. Clastic aquifers are present as main aquifers in Zakho Basin which are similar to the clastic aquifer system within the Low Folded Zone. Also, other clastic units in the High Folded Zone can represent aquifers as Kolosh and Tanjero formations, where they are present with the available hydrogeological conditions.
- Groundwater occurring in the High Folded Zone originates mainly from the atmosphere, as rainfall and snow precipitation. Rainfall partly infiltrates through soil and rocks and saturates voids, fissures, cracks, joints and faults. Run off flows in wadis and along their courses partly percolates through pervious bedrocks. These sources represent the main important components in groundwater replenishment. The recharge areas extend outside the zone into the north and northeast Iraq, also outside of Iraqi border into Turkey and Iran.
- A hydraulic continuity is assumed between the aquifers within the aquifer systems in the carbonate and clastic rocks. There is leakage either downward or upward from one aquifer to another, depending on the piezometric relations of the water – bearing layers throughout the region.
- The karstic aquifer systems are considered as the most important regional aquifers in the High Folded Zone due to their wide extent and content of large amount of water.
- The regional trend of groundwater movement is generally towards southwest and south, with the presence of different directions due to the presence of water divides and the complexity of structure and topography of the zone. The Low Folded Zone represents the main discharge area of the High Folded Zone.
- The groundwater is considered of low salinity in the High Folded Zone, due to available fresh water from rainfall and snow precipitation within the same zone and the adjacent

recharge areas at the north and northeast of Iraq and the borders with Turkey and Iran. Salinity of groundwater is mainly less than 500 mg/l, and exceptionally exceeds 1000 mg/l, with chemical water type of Ca – bicarbonate type, mainly and sulphatic water type also present in local areas of the zone.

- High transmissivity values prevail and support the conclusion that numerous karst canals and openings serve as a main transmitting medium, mainly in the carbonate rocks.
- Density of contour lines is not uniform owing to various permeabilities of rocks and barrier effects, mainly due to complexity of the structure and topography. Low water level gradients is due to high permeability of rocks; it becomes higher in low permeability racks. Greater gradient gives the evidence of lower permeability of sediments.
- The aquifers within the High Folded Zone are of two groups :
  a. Carbonate aquifers, which are characterized by double porosity i.e.

primary porosity and secondary porosity mainly developed along bedding planes and fissures system due to karstic phenomena and tectonic disturbances.

b. Clastic aquifers, which are characterized by primary (intergranular) porosity.

- The hydraulic and chemistry of the aquifers are closely linked to the stratigraphic, lithologic structural and topographic features of the water bearing formations within the High Folded Zone.
- According to the hydrogeological investigations many promising basins of good water qualities and quantities were fixed at different locations within this zone, represented mainly by, Zakho, NW Barzany, Central Harir, Central Dokan and Sharazoor basins.

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