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HYDROGEOLOGY OF THE LOW FOLDED ZONE

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ABSTRACT

The Low Folded Zone extends in the northern and northeastern parts of Iraq. It is roughly of oblong shape, and elongated from northwest to southeast. It is characterized by thick sedimentary cover, and well defined folding system. The folding system is characterized by a series of narrow and elongated anticlines of different amplitudes, trending NW – SE, separated by broad synclines, which usually are occupied by synclinal valleys, except Sinjar Mountain at the western side has a trend of E – W. The broad synclinal valleys form the major groundwater basins, and they are filled by sedimentary sequence ranges in age from Late Miocene to Recent.

The Low Folded Zone is divided into thirteen hydrogeological Sub provinces, which are: Sinjar – Rabee'a, West Tigris River, Khazir – Gomel, Dohuk – Alqosh, Erbil, Altun Kupri, Dibiga, Makhmour, Kirkuk – Hawija – Tuz Khurmatu, Cham Chamal – Qadir Karam – Qara Too, Kalar – Khanaqeen, Qara Tappa – Al-Sa'adiyah and Mandili – Zurbatiya – Teeb.

The main water bearing formations at the western part of the Low Folded Zone; west of the Tigris River are represented by: Injana and Fatha formations, and Quaternary sediments. While Bai Hassan and Mukdadiya formations are considered as the main water bearing formations in the other parts; to the east of the Tigris River, beside Injana Formation and Quaternary sediments.

The source of recharge water within the Low Folded Zone is mainly from direct rainfall, and from the High Folded Zone at the northeast. The Mesopotamia Plain and Al-Jazira Area represent the discharge zones to the Low Folded Zone. The general trend of the groundwater movement at the western part of this zone is mainly from north and northwest towards south and southeast, while at the eastern part, the main direction of flow is 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 increases generally from north to south. It increases from the high lands, which represent the recharge areas, towards the discharge areas along the Mesopotamia Plain and Al-Jazira area. The quality of the groundwater is mainly bicarbonate at the recharge areas, and becomes sulphatic at the discharge areas. The hydraulic conditions

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and chemistry of aquifers within the Low 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 Low Folded Zone, it can be considered as the most promising zone for groundwater development in Iraq.

هيدروجيولوجية نطاق الطيات الواطئة

حاتم خضير الجبوري و نصير حسن البصراوي

المستخلص

يمتد نطاق الطيات الواطئة في شمال وشمال شرق العراق، وهو يمثل تقريبا شكلا مستطيلا بامتداد شمال غربي جنوب شرقي. يتميز بوجود غطاء سميك من الرسوبيات وبنظام طيات واضح. نظام الطيات يمتاز بوجود سلاسل جبلية طويلة وضيقة وعلى ارتفاعات مختلفة وباتجاه شمال غرب – جنوب شرق، تحصر بينها سهول ووديان واسعة، ما عدا جبل سنجار، حيث يكون امتداده باتجاه شرق – غرب. الوديان والسهول الواسعة تشكل الأحواض المائية الرئيسية، وتكون ممتلئة بالرسوبيات التي تتراوح في أعمارها ما بين المايوسين المتأخر والعصر الرباعي.

تم تقسيم نطاق الطيات الواطئة إلى ثلاثة عشر مقاطعة هيدروجيولوجية ثانوية وهي: سنجار – ربيعة، غرب نهر دجلة، الخازر – گومل، دهوك – ألقوش، أربيل، آلتون كوبري – كويسنجق، ديبكة، مخمور، كركوك – حويجة – طوز خورماتو، چمچمال – قادر كرم – قرة تو، كلار – خانقين، قرة تبة – السعدية ومندلي – زرباطية – الطيب.

التكوينات الرئيسية الحاملة للمياه في الجزء الغربي من نطاق الطيات الواطئة والواقعة إلى الغرب من نهر دجلة تكون متمثلة بتكويني إنجانة والفتحة، بالإضافة إلى ترسبات العصر الرباعي. بينما يشكل تكويني باي حسن والمقدادية الخزان الجوفي الرئيسي لعموم الأجزاء الواقعة إلى الشرق من نهر دجلة، بالإضافة إلى تكوين إنجانة وترسبات العصر الرباعي في مناطق متفرقة من هذه المنطقة.

إن مصدر التغذية للمياه الجوفية ضمن نطاق الطيات الواطئة هو الأمطار الساقطة مباشرة على المنطقة، بالإضافة إلى نطاق الطيات العالية، الواقع إلى الشمال الشرقي منه. يمثل السهل الرسوبي ومنطقة الجزيرة منطقة تصريف بالنسبة لهذا النطاق. الاتجاه العام لحركة المياه الجوفية في الجزء الغربي من النطاق يكون على العموم من الشمال والشمال الغربي باتجاه الجنوب و الجنوب الشرقي، بينما في الجزء الشرقي من هذا النطاق تكون الحركة على العموم من الشمال والشمال الشرقي باتجاه الجنوب والجنوب الغربي، مع وجود اتجاهات موقعية مختلفة نتيجة للوضع التركيبي والطوبوغرافي للمنطقة. وهنالك اتصال هيدروليكي واستمرارية لمستوى المياه الجوفية ضمن التكوينات الحاملة للمياه في هذا النطاق، يعتمد على الوضع البيزومتري للتكوينات الحاملة للمياه.

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

تزداد ملوحة المياه الجوفية بصورة عامة من الشمال إلى الجنوب، حيث إنها تزداد من المناطق العالية والتي تمثل مناطق التغذية باتجاه مناطق التصريف المتمثلة بمنطقة السهل الرسوبي ومنطقة الجزيرة. تكون نوعية المياه الجوفية في الغالب بيكاربوناتية ضمن مناطق التغذية، وتتحول في الغالب إلى كبريتاتية ضمن مناطق التصريف.

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

INTRODUCTION

The Low Folded Zone extends in the central 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 east and southeast, while the High Folded Zone forms its northern and northeastern boundary. The Mesopotamia Plain and Al-Jazira area form its southern and southwestern boundaries, and Iraqi – Syrian borders forms its western boundary. Part of the Low Folded Zone is represented by plain and gently rolling areas, dissected by rivers and streams, while the remaining parts are characterized by hilly and mountainous areas, with elevation exceeds 1000 m; above sea level in the northern and northeastern parts. The main rivers that drain the Low Folded Zone are: Diyala, Adhaim, Lesser Zab and Greater Zab, with their general NE – SW trend. The Tigris River dissects this zone in a general N – S trend. From the regional tectonic point of view, the Low Folded Zone forms the central unit of the Unstable Shelf of Outer Platform (Fouad, 2012) of Nubio – Arabian Platform, and it is characterized by thick sedimentary cover and well defined folding system (Buday and Jassim, 1987 and Fouad, 2012). This zone forms a series of narrow and elongated anticlines of different amplitudes, with NW – SE trend, and separated by broad synclinal valleys. Exceptionally, Sinjar Anticline, at the western side of the zone has an E – W trend. The broad synclinal valleys form the main groundwater basins, and are filled by sedimentary formations range in age from Late Miocene to Recent (Sissakian, 2000), namely from oldest: Fatha, Injana, Mukdadiya and Bai Hassan, in addition to the Quaternary sediments. In the core of the anticlines, there are exposures of older formations, which are attributed to Cretaceous – Lower Miocene in age.

Many hydrogeological studies were carried out on different parts of the Low Folded Zone by different researchers (Parsons, 1955 and 1957; Ingra, 1967; Hassan, 1981; Krasny, 1982a, b and c; Alsam and Hanna, 1983; Araim, 1990; Al-Jawad *et al*., 2001; Stevanovic and Iurkiewicz, 2004; Al-Jiburi, 2004, 2005a, b and c, 2006a and b, 2007a, b and c, and 2008; Ahmid *et al*., 2005; Krasny *et al*., 2006; Al-Basrawi, 2006; Al-Tamimi, 2008 and Al-Jiburi and Al-Basrawi, 2010). These studies reflect the conditions of groundwater system in terms of groundwater flow direction, salinity and chemical type of water.

The climate of the Low Folded Zone is mainly semi arid, with clear effect of the Mediterranean climate on the northern and northeastern parts. It is characterized by dry and hot summer, and cold with moderate wet 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 200 mm, within the southern parts to more than 600 mm, at the northern parts. The annual relative humidity is within the range of (46 – 48) %, the annual evaporation is about 3100 mm, within the southeastern parts to about 2000 mm, at the northern parts. The annual mean temperature ranges from about 23° C, at the extreme southeastern parts to about 20° C, at the northern parts and the annual mean wind speed ranges from 3.5 m/sec, at the southern parts to 2.0 m/sec, at the northern parts.

The main aim of this study is to express the general hydrogeological conditions of the groundwater in the Low 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.

In this study, the evaluation of hydrogeological and hydrochemical information is carried out for more than 5000 drilled wells, which are available in the hydrogeological data bank of the Low Folded Zone, which is updated recently. Only representative wells are mentioned within the present study (Fig.1 and Table 1).

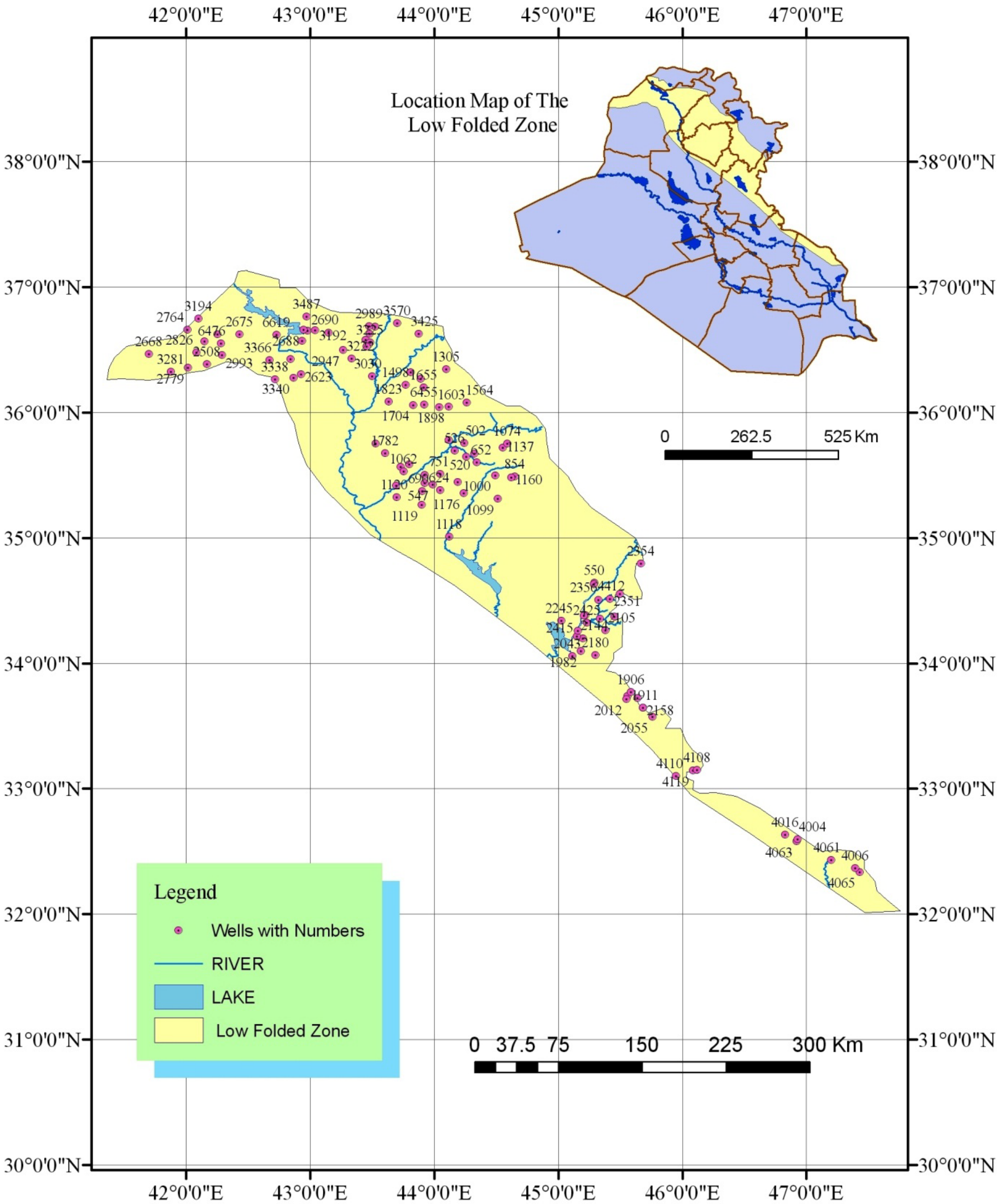

Fig.1: Location map of the available wells in the Low Folded Zone

Table 1: Hydrogeological parameters and hydrochemistry of the groundwater in selected wells within the Low Folded Zone (Al-Jiburi, 2007a, b and c)

Well No.	Latitude N	Longitude E	Aquifer	Elev. a.s.l. (m)	Total Depth (m)	S.W.L. b.g.l. (m)	Discharge (m^3/day)	K (m/day)	T (m^2/day)	Salinity (mg/l)	Type of water
502	35.75833	44.24167	B+M	300	79	36.8	3240	7.5	255	278	Bicarbonate
519	35.64972	44.26000	B+M	337.6	169.8	25.8	2742	1.9	179	428	Bicarbonate
520	35.67500	44.32500	B+M	330	100.7	22.3	1510	3.6	282	230	Bicarbonate
526	35.70000	44.16667	B+M	305	173	71	736	3	302	451	Bicarbonate
547	35.42639	43.98750	B+M	235	67.5	50.2	327	22.5	203	2145	Sulphatic
550	34.64583	45.29167	B+M	220	90	21.9	162	11.2	148	405	Bicarbonate
624	35.38333	44.05000	B+M	320	95	34	981	1.2	61	3900	Sulphatic
652	35.60417	44.34444	B+M	380	78	28.5	194	1.2	59	374	Bicarbonate
690	35.37722	43.90472	B+M	205.5	156	25	976	–	–	1316	Sulphatic
751	35.51250	44.05000	B+M	280	98	31	594	0.5	29	1179	Sulphatic
854	35.49306	44.64917	B+M	788.3	200	105	259	0.1	5	520	Bicarbonate
1000	35.50278	44.49167	B+M	470	44	–	972	–	–	304	Bicarbonate
1037	35.45000	44.19167	B+M	260	85	20	842	16.3	244	1512	Sulphatic
1047	35.44083	43.92639	B+M	240	103	43	583	4.6	128	859	Sulphatic
1057	35.59083	43.80000	B+M	240	96	21	324	0.2	11	1890	Sulphatic
1062	35.53333	43.75556	B+M	215	68	35	940	5.1	91	287	Bicarbonate
1063	35.50556	43.92500	B+M	240	115	51	455	1.7	67	524	Bicarbonate
1074	35.75500	44.59167	B+M	600	97	35	389	0.3	14	204	Bicarbonate
1099	35.31389	44.51389	B+M	350	78	35	389	1.3	22	324	Bicarbonate
1118	35.01250	44.12083	B+M	170	164	11	583	0.1	21	7581	Sulphatic
1119	35.26667	43.90000	B+M	200	160	9	583	0.9	19	6209	Sulphatic
1120	35.32833	43.70000	B+M	195	90	15	778	0.5	32	4546	Sulphatic
1137	35.72500	44.55417	B+M	700	69	9	648	0.6	22	239	Bicarbonate
1160	35.48333	44.62444	B+M	700	130	37	551	0.4	12	163	Bicarbonate
1176	35.35833	44.23889	B+M	250	100	18	713	1.1	85	3163	Sulphatic
1295	36.27111	43.89306	B+M	350	86	15	4378	4.9	282	366	Bicarbonate
1302	36.32333	43.81194	B+M	306.3	57	24	3539	24	782	273	Bicarbonate
1305	36.35000	44.10000	B+M	510	78	23	1041	1.2	52	233	Bicarbonate
1324	35.75333	43.53000	B+M	240	78	9	660	0.6	36	7223	Sulphatic
1456	35.42139	43.69528	B+M	299.9	84	58	878	0.8	61	1517	Sulphatic
1461	35.78333	44.11667	B+M	265	130	9	990	7.4	141	206	Bicarbonate
1498	36.22278	43.77000	B+M	419.1	147	35	594	6.4	307	281	Bicarbonate
1538	35.56833	43.73167	B+M	225	85	37	396	3.5	153	3616	Sulphatic
1564	36.08333	44.26250	B+M	650	136	60	528	0.9	61	166	Bicarbonate
1603	36.04500	44.04333	B+M	440	120	36	881	1	84	150	Bicarbonate
1655	36.20500	43.91667	B+M	390	170	23	1452	1	132	200	Bicarbonate
1704	36.06333	43.83333	B+M	315	178	90	1166	30.4	800	301	Bicarbonate
1782	35.67833	43.60500	B+M	260	134	15	–	–	–	4346	Sulphatic
1823	36.09000	43.63333	B+M	260	136	11	1452	1.1	143	900	Bicarbonate
1898	36.04833	44.11833	B+M	500	125	36	924	1.8	84	150	Bicarbonate
1906	33.77417	45.58778	Qt	167.3	65	6.6	3960	23.2	1382	1400	Sulphatic
1911	33.74194	45.55889	B+M	121	124	10.9	792	0.9	54	1575	Sulphatic
1982	34.10000	45.18333	Qt	155	33	25	594	10.8	136	2522	Sulphatic
2012	33.71667	45.55000	B+M	110	300	5	201	7.2	29	1500	Sulphatic
2043	34.06111	45.11639	B+M	103.4	96	7.5	193	2.2	20	3000	Sulphatic
2055	33.57389	45.75972	B+M	122.7	38	21	660	2.2	96	2500	Sulphatic
2105	34.26667	45.38333	B+M	290	56	18	881	10.6	469	384	Bicarbonate
2144	34.21722	45.15000	B+M	127.2	150	21	792	2.6	63	280	Bicarbonate

…cont. table 1

Well No.	Latitude N	Longitude E	Aquifer	Elev. a.s.l. (m)	Total Depth (m)	S.W.L. b.g.l. (m)	Discharge (m^3/day)	K (m/day)	T (m^2/day)	Salinity (mg/l)	Type of water
2158	33.65000	45.68333	Qt	118	30	17.5	864	18.5	278	2934	Sulphatic
2165	33.65000	45.68333	Qt	118	55	5.5	665	16	112	3021	Sulphatic
2180	34.06667	45.30000	B+M	195	99.5	20	1296	6.4	486	2170	Sulphatic
2196	34.20000	45.20000	B+M	170	90	10.9	562	2.9	115	2097	Sulphatic
2229	34.35722	45.33694	B+M	168.2	91	7.5	283	0.2	5	860	Sulphatic
2245	34.34389	45.02667	B+M	110	45	13.4	2268	1.4	102	1150	Sulphatic
2338	34.37500	45.45556	B+M	250	80	3	401	–	–	2035	Sulphatic
2347	34.38333	45.20833	B+M	148	27	9	525	7.3	124	340	Bicarbonate
2348	34.38528	45.21833	B+M	142.5	55	8.5	550	12.1	175	310	Bicarbonate
2351	34.51667	45.41667	B+M	300	98	6	648	8	80	298	Bicarbonate
2354	34.80000	45.66667	B+M	550	32	20	858	6.3	130	213	Bicarbonate
2356	34.50833	45.32500	B+M	190	50	6	462	0.5	17	384	Bicarbonate
2370	33.72500	45.64167	Qt	150	70	15	664	2.4	126	1038	Sulphatic
2376	34.55833	45.50000	B+M	450	100	24	648	1.9	63	280	Bicarbonate
2415	34.26389	45.15833	B+M	115	70	11	663	0.7	39	304	Bicarbonate
2425	34.32778	45.23333	Qt	145	37	7	648	2.8	71	613	Bicarbonate
2508	36.25000	42.19444	I	330	65.4	8.4	141	2	62	2073	Sulphatic
2612	36.02500	41.94583	I	300	123	18.3	156	2.1	21	2075	Sulphatic
2623	36.30694	42.92750	F	377.4	174	53	113	8.1	105	1120	Sulphatic
2636	36.63722	43.14917	B+M	381.2	60	10	173	0.5	12	430	Bicarbonate
2668	36.47000	41.70000	Car	500.4	65	4	110	0.2	6	1107	Sulphatic
2675	36.62667	42.43222	I	342.9	90	10	99	0.4	31	991	Sulphatic
2688	36.66389	42.94889	B+M	302.7	117	22	135	0.5	10	450	Bicarbonate
2690	36.65333	42.98028	B+M	326.6	62	14	137	1.3	17	606	Bicarbonate
2751	36.63167	43.47889	B+M	36204	180	16.5	2592	12.6	133	322	Bicarbonate
2764	36.70000	42.01000	I	360	265	3.4	2160	0.4	99	876	Sulphatic
2779	36.26000	42.01611	I	378.6	100	8	518	0.6	17	870	Sulphatic
2823	36.17500	41.90833	I	352	116	10.7	1102	2.3	71	280	Bicarbonate
2826	36.48333	42.08333	I	465	95	5	130	0.3	4	600	Bicarbonate
2943	36.56917	42.14889	I	407.2	120	2.4	518	0.4	25	4550	Sulphatic
2947	36.50000	43.26667	B+M	365	105	22	968	1.7	137	457	Bicarbonate
2970	36.68833	43.52500	B+M	400	90	9	990	1.2	86	327	Bicarbonate
2979	36.58278	43.44889	B+M	346	95	10.6	1254	5.5	464	320	Bicarbonate
2985	36.52944	43.45806	B+M	409.9	178	24.3	396	0.1	14	180	Bicarbonate
2989	36.69333	43.47500	B+M	385	82	34	396	1	41	320	Bicarbonate
2993	36.30833	42.28833	I	315	90	5	858	0.5	24	1960	Sulphatic
3030	36.29167	43.50000	B+M	270	120	24	264	0.4	7	1317	Sulphatic
3113	36.57500	42.93667	F	310	175	–	–	–	–	7766	Sulphatic
3192	36.65861	43.04250	B+M	387.6	173	31	198	0.1	6	670	Bicarbonate
3194	36.80361	42.10000	I	387	136	27	188	1.3	62	538	Bicarbonate
3222	36.43528	43.33583	B+M	318	120	22	778	0.5	46	660	Bicarbonate
3225	36.56278	43.48444	B+M	335.9	100	5	1685	10	950	194	Bicarbonate
3241	36.62528	42.25250	I	380.7	100	15	588	0.8	25	6280	Sulphatic
3247	36.42833	42.84111	F	303.8	120	56	225	0.4	23	2656	Sulphatic
3281	36.33000	41.88000	Car	550	60	29	392	–	–	294	Bicarbonate
3338	36.26667	42.70556	F	345	55	12	1188	3.7	139	2717	Sulphatic
3340	36.27833	42.86833	F	340	250	33	528	–	–	6090	Sulphatic
3366	36.42000	42.67500	F	350	152	5	138	0.3	31	5082	Sulphatic
3425	36.63222	43.87583	B+M	555.2	200	55	432	0.1	17	1060	Sulphatic
3487	36.76750	42.97056	B+M	452.2	95	22	842	0.9	53	320	Bicarbonate

…cont. table 1

Well No.	Latitude N	Longitude E	Aquifer	Elev. a.s.l. (m)	Total Depth (m)	S.W.L. b.g.l. (m)	Discharge (m^3/day)	K (m/day)	T (m^2/day)	Salinity (mg/l)	Type of water
3570	36.71750	43.70139	B+M	470.7	129	17.6	778	2.5	279	161	Bicarbonate
4004	32.59722	46.93333	B+M	88	37	15.6	407	3.8	59	3200	Sulphatic
4006	32.36778	47.39472	B+M	123.2	49	21	537	2.4	52	440	Bicarbonate
4016	32.63556	46.82861	B+M	49.5	52	4.7	657	4.2	80	2742	Sulphatic
4061	32.43333	47.20000	B+M	60	70	10	365	0.5	13	4743	Sulphatic
4063	32.58389	46.92528	B+M	88.8	80	46	544	1.7	44	840	Sulphatic
4065	32.33806	47.43083	B+M	172.7	100	64	432	2	64	4500	Sulphatic
4108	33.11167	46.10778	Qt	130.7	36.5	7.2	660	4.8	1096	3015	Sulphatic
4110	33.10056	45.93861	B+M	62.1	127.2	1.5	726	0.3	28	3372	Sulphatic
4119	33.14750	46.08750	Qt	125	10	8.5	211	8.7	174	5000	Sulphatic
4412	34.63333	45.28889	B+M	218	86	13	–	–	–	250	Bicarbonate
6455	36.06417	43.91944	B+M	344.5	196	25	1183	2.3	96	670	Bicarbonate
6476	36.55333	42.28000	I	420	165	18	429	0.1	12	570	Bicarbonate
6619	36.62500	42.73000	I	450	201	30	35	–	–	1537	Sulphatic
2377	34.72916	45.14583	B+M	530	100	12	648	1.1	39	392	Sulphatic
2460	36.20333	44.02138	B+M	160	83	7	778	6.2	471	338	Bicarbonate
30	32.39444	47.35000	B+M	175	260	15.4	1620	4.1	209	2400	Sulphatic
584	34.44583	44.60916	B+M	185	96	21	648	14.5	87	3060	Sulphatic
8129	34.70833	44.95833	B+M	283	90	24	664	0.7	40	2275	Sulphatic
4413	34.84305	45.21111	B+M	570	86	5	810	1.4	34	300	Bicarbonate
8206	36.12166	43.02000	B+M	292	70	9	1160	8.4	430	3345	Sulphatic
8117	37.05000	42.53333	I	523	174	37	165	0	0	2497	Sulphatic
3471	36.96000	42.67583	I	506	195	5	842	0	0	354	Bicarbonate
4014	32.83333	46.51666	B+M	110	73	13	583	3.6	163	2700	Sulphatic
4176	32.91250	46.44861	B+M	120	70	45	518	3.3	67	3700	Sulphatic
4173	32.96972	46.08666	B+M	40	70	15	518	0.7	32	5855	Sulphatic
2545	36.33333	41.35555	I	725	70	20	90	0.6	24	3351	Sulphatic
3234	36.19444	41.61111	I	430	150	9	1180	0.7	85	2422	Sulphatic
4177	33.28889	45.95644	B+M	88	90	13	238	0.1	6	3700	Sulphatic
2361	34.36222	44.60055	B+M	83.4	70	20	648	2.6	57	1667	Sulphatic
2439	34.45000	44.56111	B+M	90	96	20	713	0.6	46	1276	Sulphatic
814	34.88333	44.21111	B+M	170	92	3	2124	0	0	1467	Sulphatic
2	35.19580	44.89666	B+M	380	103	33	52	0	0	1120	Sulphatic
564	35.15000	43.65000	B+M	168	112	35	198	0.6	40	2487	Sulphatic
4587	35.49722	44.84222	B+M	712	190	13	330	0.8	5	233	Bicarbonate
2614	35.70833	43.06166	B+M	180	18	6	147	16.3	134	4170	Sulphatic
2683	35.44444	43.21111	B+M	238	60	4	63	0.5	3	5617	Sulphatic
3261	35.47833	43.44444	B+M	200	49	16	194	1.2	35	4644	Sulphatic

S.W.L. = Static water level, K = Permeability (Hydraulic Conductivity), T = Transmissivity

Q = aquifer in Quaternary Sediments
B + M = aquifer in Bai Hassan and Mukdadiya formations
I = aquifer in Injana Formation
F = aquifer in Fatha Formation
Car = aquifer in Carbonate formations

HYDROGEOLOGICAL CONDITIONS OF THE LOW FOLDED ZONE

The geological formations of the Middle Miocene to Recent are considered water-bearing, and form the main groundwater aquifers within the Low Folded Zone. Injana Formation represents the major groundwater aquifer; west of the Tigris River, including Sinjar – Rabee'a Sub province, while Mukdadiya, Bai Hassan formations form the main groundwater aquifers in the other parts of the zone, particularly east of the Tigris River, in addition to Injana Formation and Quaternary sediments in some locations.

The Fatha Formation crops out in many areas north and south of Mosul, and in the central and eastern parts of the Low Folded Zone. Fatha Formation is characterized by cyclic sedimentation, each cycle consist of claystone or marl, limestone and gypsum in a regular order. The limestone and gypsum are practically impervious rocks, if they devoid fractures, joints and caverns. When this formation is rich in gypsum beds, it certainly yields poor quality water; as a result of high solubility of gypsum, and therefore, is considered as a source of contaminants to the groundwater; mainly in the form of Calcium Sulphate. On the other hand, this formation stores good quantity of the groundwater through caverns, joints and fissures. Consequently, Fatha Formation does not lack groundwater, but the water is of poor quality. The water-bearing beds were tapped at depth between (6 – 240) m below ground surface, and the water could be present under hydraulic pressure with claystone or marl serving as confining beds. The salinity increases with depth; generally it ranges between (2300 – 114110) mg/l (Araim, 1990).

The Injana Formation crops out west of the Tigris River and also in the eastern part, but with less extent. It is composed of alternation of claystone or mudstone, fine to coarse grained sandstone and siltstone. The sandstone beds serve as a good groundwater reservoir, and the water presents in these beds either under hydraulic pressure; when the siltstone and claystone or marl serve as a confining beds, or under water table conditions. The water-bearing layers of this formation were tapped by wells drilled throughout the region mainly in Sinjar – Rabee'a Sub province. According to the available data from the performed pumping tests of the drilled wells in Injana Formation (Al-Jiburi, 2007a, b and c), the transmissivity ranges between (2 – 1274) m^2/day, permeability ranges between (0.1 – 18.5) m/day, well discharge ranges between (1 – 3960) m^3/day, and static water level ranges between (self flowing – 100) m; below ground surface. Injana Formation yields water of variable qualities, the salinity in terms of total dissolved solids ranges from fresh water of 300 mg/l, of bicarbonate type to brackish water attaining total dissolved solids of more than 10000 mg/l, of sulphatic water type (Al-Jiburi, 2007a, b and c) (Table 1).

The Mukdadiya Formation crops out along the flanks of many anticlines, it is composed of alternation of sandstone (similar to sandstone of Injana Formation, but contains pebbles), claystone, calcareous sandstone.

Bai Hassan Formation consists of alternating beds of conglomerates, claystone, silty-sandy claystone and sandstone. The lower parts consist of alternation of conglomerates, claystone and sandstone, while the middle part consists of coarse conglomerates and claystone, whereas, the upper part consist of very thick claystone beds alternated with thin and fine conglomerate. The conglomerates may be impervious, if well cemented with argillaceous and calcareous materials.

In some cases, it was difficult in the field to differentiate between Mukdadiya Formation from the underlying Injana Formation, due to the similarity between lithologic characteristics of water-bearing layer of the sandstone. This condition is also true, considering Bai Hassan Formation and the overlying Quaternary water bearing sediments.

The Mukdadiya and Bai Hassan formations are tapped by the majority of wells drilled in the areas east of Tigris River; particularly in the areas of broad synclinal valleys within the Low Folded Zone (Al-Jiburi, 2006a and b; 2007a, b and c). Performed pumping tests in wells discharging from Bai Hassan and Mukdadiya aquifers showed that: the transmissivity ranges between (3 – 2800) m^2/day, permeability ranges between (0.1 – 24) m/day, well discharge ranges between (19 – 5472) m^3/day, and the static water level ranges between (– 1.5 – 118.2) m; below ground surface. These formations yield, for rather extensive areas in the zone, good quality water (total dissolved solids less than 1000 mg/l, of bicarbonate water type). Exceptionally, they yield poor quality water in some other areas; with total dissolved solids more than 4000 mg/l (Figs.2, 3 and 4).

The Quaternary sediments cover vast areas mostly within the broad synclinal valleys. Their thickness and lithologic characteristics differ from place to another, depending on the morphologic features and the parent rocks. They consist mostly of river terraces, flood plain sediments and the most extensive polygenetic synclinal filling sediments. The thickness of the Quaternary sediments ranges from few meters; on the slopes and valleys to about 120 m or perhaps more within the broad synclinal valleys (Araim, 1990). These sediments are tapped by some wells drilled in the zone, either individually or in combination with the older formations. Performed pumping tests in wells discharging from Quaternary sediments showed that: the transmissivity of aquifer ranges between (5 – 539) m^2/day, permeability ranges between (0.1 – 47.3) m/day, well discharge ranges between (26 – 1623) m^3/day, and the static water level ranges between (0.3 – 28) m below ground surface. The yield water is of different salinity, which ranges from (less than 1000 – 6000) mg/l (Al-Jiburi, 2006a and b; 2007a, b and c). The chemical water type is bicarbonate; for fresh water and sulphatic or mixed (sulphatic and chloridic); usually for water of high salinity.

From the hydrogeological point of view the Low Folded Zone is divided by Krasny (1982b) into three main provinces and eight Sub provinces, and it is divided by Araim (1990) into four main provinces and nine Sub provinces. It is also divided by Krasny *et al*. (2006) into ten Sub-systems, including Zakho Sub-system, which is actually located within the High Folded Zone, but its hydrogeological character is similar to the aquifers of the Low Folded Zone. However, (Krasny *et al*., 2006) have excluded the areas west of Tigris River from the Low Folded Zone, and included this area within the Jazira area. In this study, the Low Folded Zone is divided into **thirteen Sub provinces** (Fig.5), according to their hydrogeological, geological, structural and topographic characteristics of the basins, they are described, hereinafter.

- **Sinjar – Rabee'a Sub Province**

The Injana Formation covers more than half of the region followed by Fatha Formation, while Mukdadiya Formation is exposed within restricted area; north of Sinjar Mountain. Quaternary sediments overly the older formations in considerable parts of this Sub province, particularly at its central and western parts. At the extreme western parts, the groundwater basin and the hydrogeological boundaries are quite well extending inside Syria. Sinjar Mountain and its neighboring structures form a water divide between south Sinjar Plain and north Sinjar – Rabee'a Plain. These structures control the groundwater flow pattern. In the north of Sinjar – Rabee'a Plain, the direction of the groundwater movement is initiated from Sinjar Mountain towards north and northwest, mostly inside Syrian, while from this mountain and its neighboring structures to the east; the groundwater movement is northeasterly towards the Tigris River.

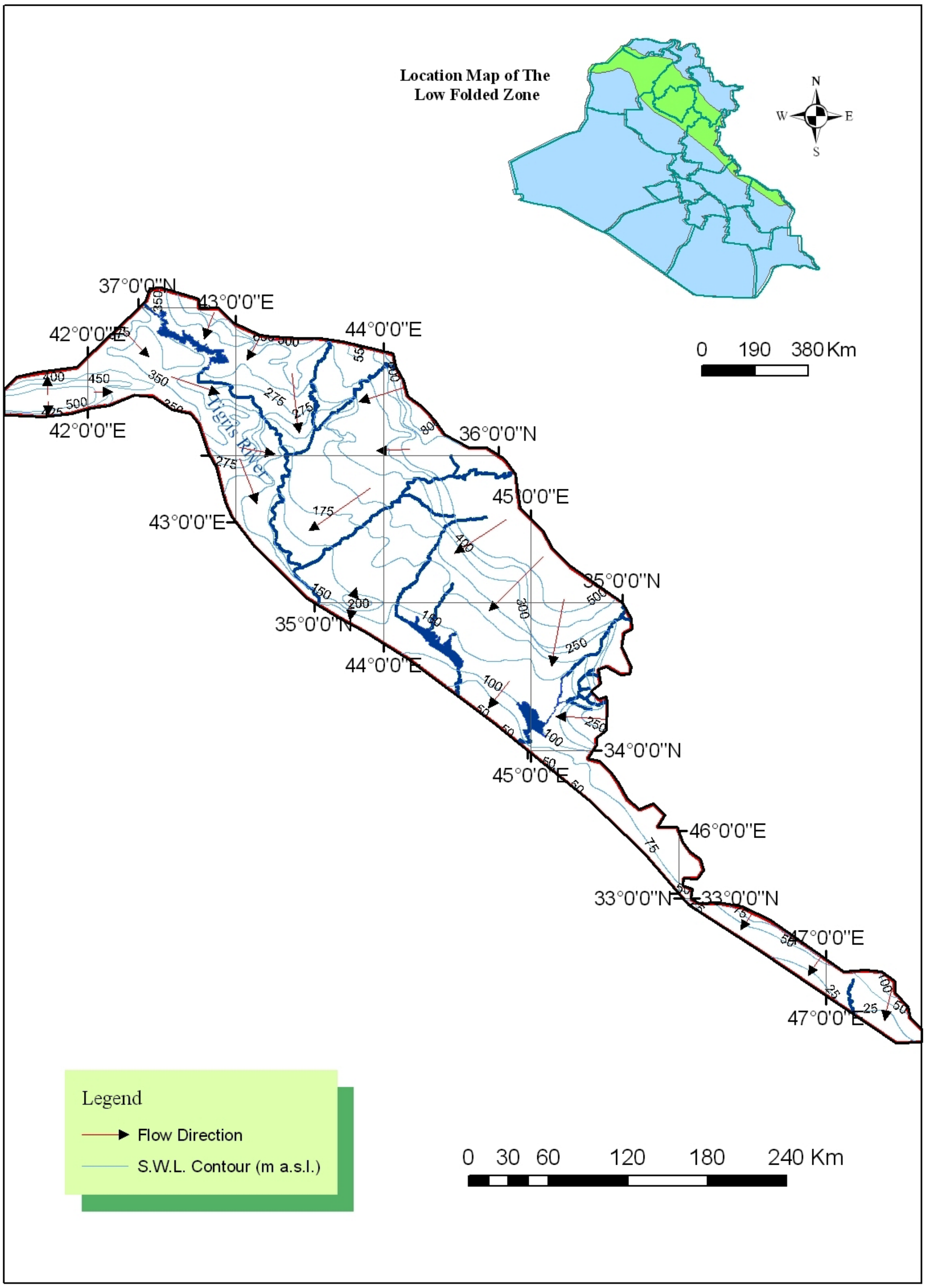

Fig.2: Hydrogeological map of the Low Folded Zone, shows static water level and direction of the groundwater flow

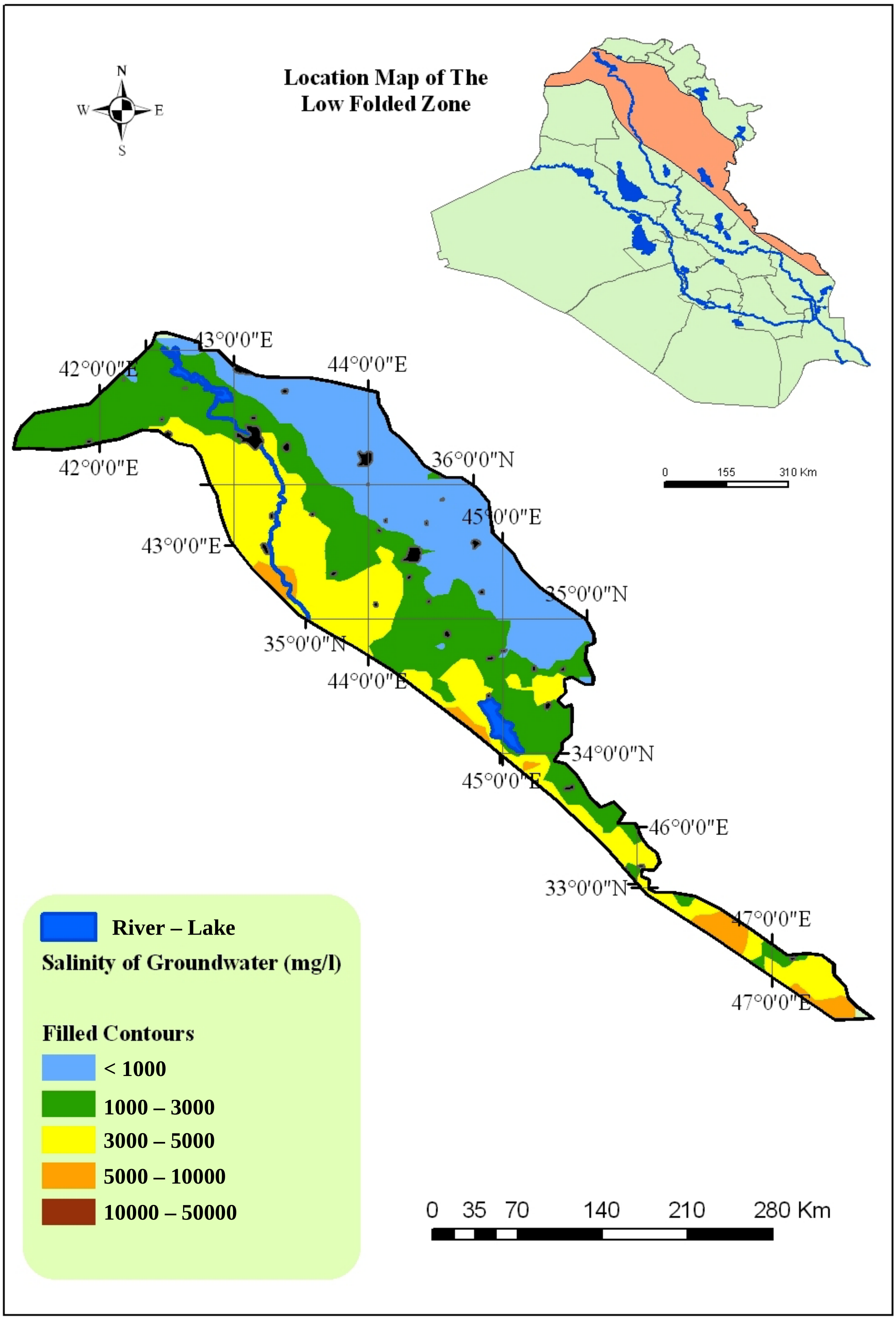

Fig.3: Hydrogeological map of the Low Folded Zone, shows the salinity of the groundwater (mg/l)

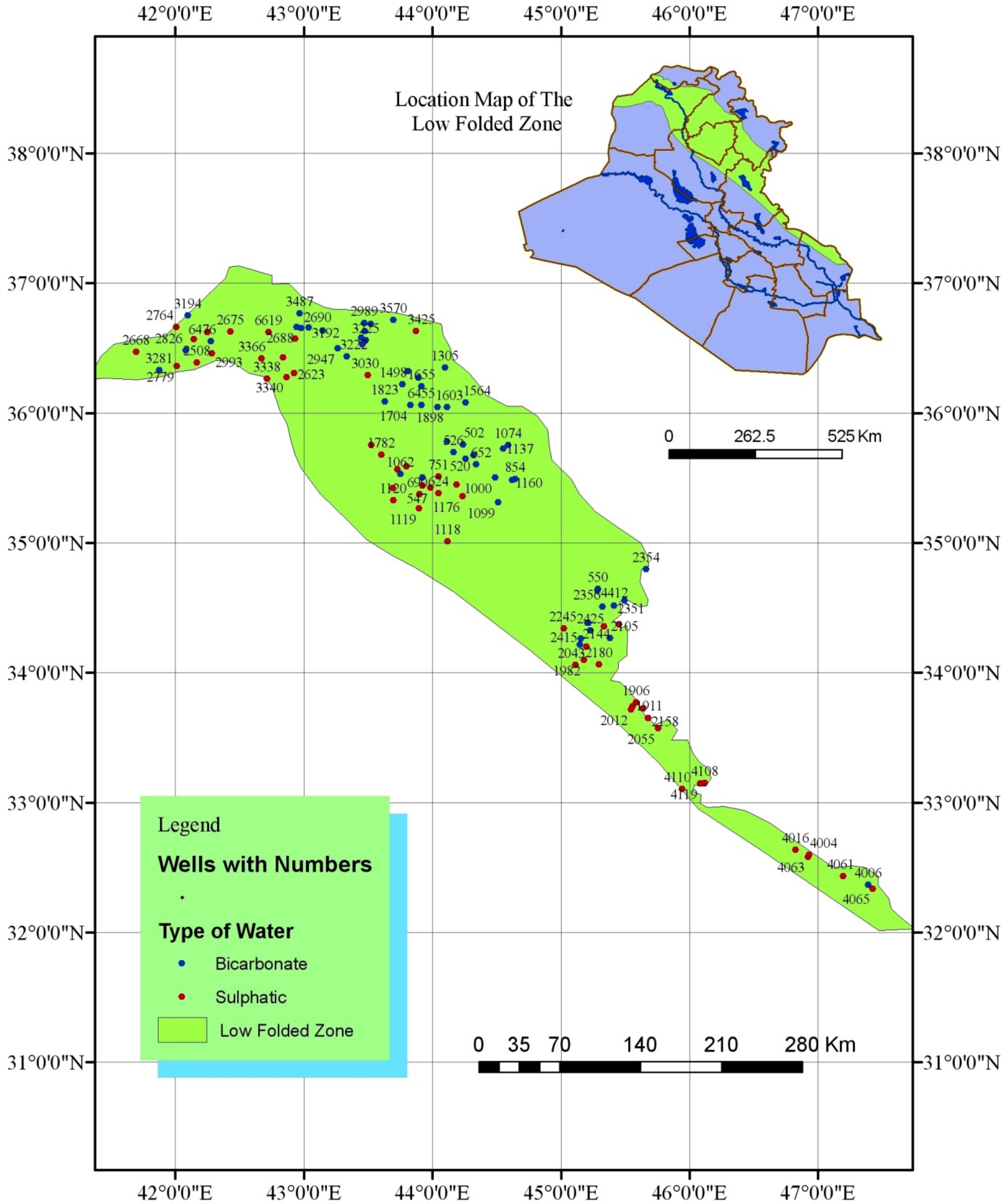

Fig.4: Type of the groundwater in selected wells within the Low Folded Zone

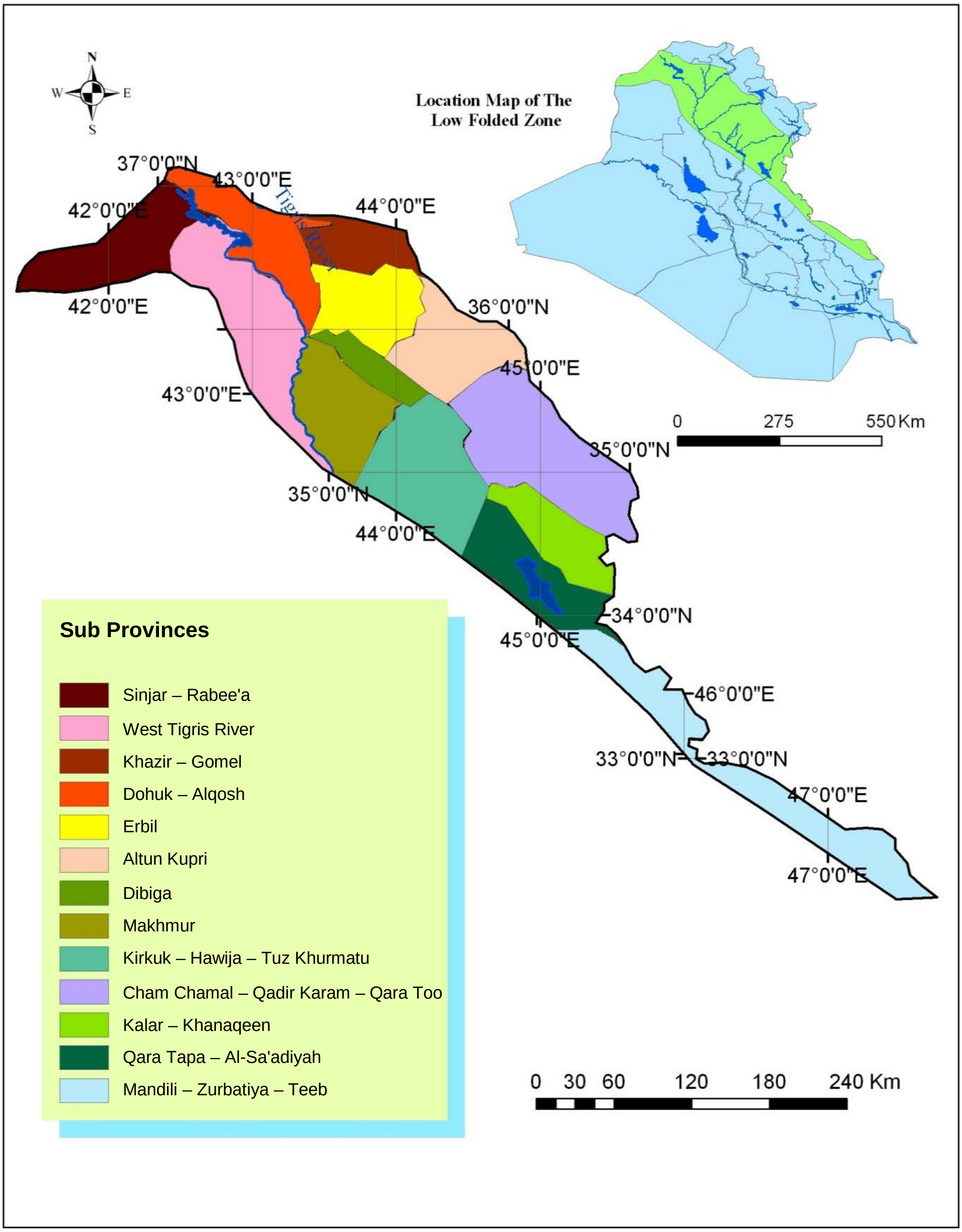

Fig.5: The Sub provinces of the Low Folded Zone

Another flow direction of the groundwater in this Sub province is originated from the highlands of Rabee'a inside Syria, as well as from small structures in the extreme northern part of the plain and takes southeast trend towards the Tigris River. The remaining water divides are minor and have no significant barrier boundaries to the groundwater movement. In the south of Sinjar Mountain, the direction of the groundwater movement is towards the south, southwest and southeast mostly in to the Jazira area. The recharge source of the groundwater is mainly from rainfall, the area receives a good amount of rainfall annually, while the discharge areas are located mainly along the Tigris River in the east, and along the Iraqi – Syrian border, at the west and the Jazira area, in the south.

The performed pumping tests of wells discharging from carbonate formations within Sinjar area showed that: the transmissivity of the aquifer ranges between (4 – 337) m^2/day, permeability ranges between (0.1 – 6.8) m/day, well discharge ranges between (104 – 1804) m^3/day, and the static water level ranges between (8 – 37) m; below ground surface (Al-Jiburi, 2007a and c). The variation of the hydrogeological parameters reflects the differences in the lithological facies of water bearing layer and the availability of fissures, joints, fractures and Karst phenomenon, in addition to the topographic and structural nature of the area, which affect the hydraulic gradient of the groundwater.

The groundwater quality is mainly bicarbonate and sulphatic, with salinity ranges between (160 – 3351) mg/l, but the groundwater is mainly fresh. The performed pumping tests of wells discharging from Injana Formation showed that: the transmissivity of the aquifer ranges between (2 – 1274) m^2/day, permeability ranges between (0.1 – 11.4) m/day, well discharge ranges between (1 – 3960) m^3/day, and the static water level ranges from self flowing (– 0.6) to 67 m; below ground surface (Al-Jiburi, 2007a and c). The groundwater quality is mainly sulphatic and bicarbonate with chloridic type; on local scale. Salinity of the groundwater ranges between (110 – 16970) mg/l, with predominant salinity less than 3000 mg/l. The performed pumping tests of wells discharging from Quaternary sediments showed that: the transmissivity of the aquifer ranges between (15 – 91) m^2/day, permeability ranges between (1.4 – 6.7) m/day, well discharge ranges between (104 – 415) m^3/day, and the static water level ranges between (3 – 8) m, below ground surface (Al-Jiburi, 2007a and c). The groundwater quality is mainly sulphatic, with salinity ranges between (526 – 5627) mg/l (Al-Jiburi, 2007a and c).

- **West Tigris River Sub Province**

This Sub province represents undulated lands, covered mainly by Fatha and Injana formations, to the west of the Tigris River within the Low Folded Zone north of Al-Jazira area. These formations may be covered by Quaternary polygenetic sediments in different localities. The direction of the groundwater flow is towards the southeast into Tigris River, which is considered as the discharge area of this Sub province. The recharge source of the groundwater is mainly from rainfall and from the western areas of Sinjar – Rabee'a Sub province. Pumping tests of wells discharge from Fatha Formation showed that: the transmissivity of aquifer ranges between (8 – 360) m^2/day, permeability ranges between (0.1 – 8) m/day, well discharge ranges between (7 – 13320) m^3/day, and the static water level ranges between (3 – 65.5) m below ground surface (Al-Jiburi, 2007a and c). Groundwater quality is mainly sulphatic with chloridic water type on local scale. Salinity of the groundwater ranges between (2100 – 10000) mg/l. Pumping tests of wells discharge from Injana Formation showed that: the transmissivity of aquifer ranges between (3 – 626) m^2/day, permeability ranges between (0.1 – 18.5) m/day, well discharge ranges between (27 – 2970) m^3/day, and the static water level ranges from self flowing (– 1.2) to 100 m below ground surface (Al-Jiburi, 2007a and c). Groundwater quality is mainly sulphatic and bicarbonate with chloridic type on local scale. Salinity of the groundwater ranges between (450 – 7000) mg/l, with predominate salinity less than 5000 mg/l.

- **Khazir – Gomel Sub Province**

It is bounded in the north and south by high mountain ridges of Aqra, Maqloub and Barda Rash Mountains. Its western boundary follows the groundwater divide close to Ain Sifni. In the east, this Sub province comprises parts of Aqra – Barda Rash and Harir basins (Stevanovic and Markovic, 2004 and Krasny *et al*., 2006).

The Pliocene – Pleistocene sediments of Mukdadiya and Bai Hassan represent the main aquifers within this Sub province. The main source of the groundwater recharge is the direct rainfall in the area, and the High Folded Zone to the north and northeast, which is considered as the recharge area to the Low Folded Zone; in general. The main discharge area of the groundwater in this Sub province occurs at the confluence area of Khazir and Gomel Rivers, in addition to the discharge along the Greater Zab River. There are self-flowing wells exist in this Sub province, where the groundwater yields from deep aquifer with piezometric heads may reach several tens of meters. There are two main aquifers, unconfined and confined, with clay beds serve as an aquitard separating them. The groundwater level in the elevated areas was found at depth from (30 – 40) m; below the ground level. With respect to unconfined aquifer, the determined transmissivity of the water bearing layers attains 7000 m^2/day, in the central part of this Sub province, while decreases to 100 m^2/day near the hydrogeological boundaries. The specific capacity of this aquifer ranges between (0.001 – 0.21). For the second confined deep aquifer, the transmissivity is about 360 m^2/day, and the storage coefficient is 1.6×10^{-4} (Araim, 1990). The mineralization of the groundwater in terms of the total dissolved solids ranges from (200 – 400) mg/l, increases slightly along the southern and western boundaries of this Sub province, and somewhere exceeds 650 mg/l. The chemical type of the groundwater is mainly Calcium – Magnesium – Bicarbonate.

- **Dohuk – Alqosh Sub Province**

This Sub province extends between the western banks of both Khazir – Gomel and Erbil Sub provinces, and the Tigris River. The Injana Formation covers the area of this Sub province. In the east, outcrops of Fatha and Pila Spi formations and occasional anticlinal ridges divide this Sub province into separate portions. Quaternary sediments; mainly terraces are found in restricted areas. The source of the recharge of the groundwater is mainly direct rainfall in the area, and the adjacent High Folded Zone, at the northeast of this Sub province. The discharge area of the groundwater is along the Tigris River; mainly. The general water flow direction is towards southwest mainly, with occasional deviation due to the presence of local water divides, especially at the eastern parts of the Sub province.

The performed pumping tests of wells discharging from the main aquifer of Injana Formation showed that: the transmissivity of the aquifer ranges between (6.5 – 622) m^2/day, permeability ranges between (0.1 – 16.8) m/day, well discharge ranges between (25 – 2890) m^3/day, and the static water level ranges between (5 – 90) m, below ground surface. The groundwater quality is mainly sulphatic and bicarbonate, with salinity ranges between (450 – 4750) mg/l (Al-Jiburi, 2007b). The performed pumping tests of wells discharging from carbonate formations (mainly Pila Spi) showed that: the transmissivity of the aquifer ranges between (4 – 375) m^2/day, permeability ranges between (0.1 – 5.1) m/day, well discharge ranges between (60 – 2722) m^3/day, and the static water level ranges between

(6 – 108) m, below ground surface. The groundwater quality is mainly bicarbonate with sulphatic water in local scale. Salinity of the water ranges between (187 – 1224) mg/l. The presence of sulphatic water is mainly due to exposures of Fatha Formation, which causes deterioration of the groundwater (Al-Jiburi, 2007b).

- **Erbil Sub Province**

This Sub province represents the catchment areas of the lower reaches of the Khazir and Great Zab Rivers, forming extensive plains to the south of Barda Rash and Pirmam Mountains. Its southwestern boundary is represented by the northwestern extension of Kirkuk Structure; the west and east boundaries are represented by the groundwater divides. The general groundwater flow is towards west, where the majority of the groundwater is discharged along the Greater Zab River, and partly towards the Khazir River. In the southern portion of this Sub province, the flow is towards the Lesser Zab River (southwest). The source of the recharge of the groundwater in this Sub province is mainly from direct rainfall, through infiltration of highly permeable sediments, or through faults, fissures, joints and fractures of carbonate formations. Also, the recharge of the groundwater takes place through surface run-off in rivers and valleys. In general, the topographic boundaries represent water divides according to the gradient of the area. The geological, hydrogeological and topographic characteristics of the area play an important role in determining the recharge zones. Erbil Sub province is considered as one of the most important promising areas for the groundwater resources in the Low Folded Zone, due to the presence of thick terregenous sediments at the middle of the plain, which reach up to 850 m in thickness, with groundwater depth ranges from (25 – 30) m, below ground surface (Krasny *et al*., 2006).

The performed pumping tests of wells discharging from Mukdadiya and Bai Hassan formations showed that: the transmissivity of the aquifer ranges between (3 – 1296) m^2/day, permeability ranges between (0.1 – 30.4) m/day, well discharge ranges between (5 – 4790) m^3/day, and the static water level ranges between (25 – 40) m; below ground surface. The groundwater quality is mainly bicarbonate and sulphatic with chloridic water, on local scale. Salinity of the groundwater ranges between (100 – 600) mg/l and extremely exceeds 1000 mg/l (Al-Basrawi, 2006). The performed pumping tests of wells discharging from Quaternary sediments showed that: the transmissivity of the aquifer ranges between (10 – 1225) m^2/day, permeability ranges between (0.4 – 35.2) m/day, well discharge ranges between (122 – 2211) m^3/day, and the static water level ranges between (10 – 30) m, below ground surface. The groundwater quality is mainly bicarbonate (75%) and sulphatic (25%), with water salinity not exceeding 600 mg/l (Al-Basrawi, 2006).

- **Altun Kupri Sub Province**

This Sub province represents the catchment areas of the upper reach of the Lesser Zab River. It is bounded by Kirkuk Structure from the southwest and by the High Folded Zone from the northeast, while the northwest and southeastern boundaries are represented by groundwater divides. The source of the groundwater recharge is the direct rainfall in the area, in addition to the High Folded Zone, at the northeast of this Sub province, and also from Kirkuk Structure. The regional discharge area for the whole Sub province occurs along the Lesser Zab River. The main upper aquifer within this Sub province is represented by Bai Hassan and Mukdadiya formations.

The performed pumping tests of wells discharging from the aquifer showed that: the transmissivity of the aquifer ranges between (4 – 1738) m^2/day, permeability ranges between (0.1 – 47.9) m/day, well discharge ranges between (22 – 3888) m^3/day, and the static water level ranges between (7 – 90) m, below ground surface. The groundwater quality is mainly bicarbonate with less extent of sulphatic water. Salinity of the groundwater ranges between (152 – 1260) mg/l, with predominance of fresh water within the Sub province (Sa'ood *et al*., 2006).

▪ **Dibiga Sub Province**

This Sub province is bounded by Qara Chouq and Batiwa Mountains, at the southeast and Kirkuk and Quwair anticlines, at the northeast. It is represented by NW – SE trending syncline filled by clastic sediments of Mukdadiya and Bai Hassan formations. The Lesser Zab River forms its southeastern hydraulic boundary, while its northwestern boundary is represented by the Greater Zab River, although this Sub province; in this part is partly opened and continues as a narrow inlet into Erbil Sub province. The groundwater movement is primarily initiated from the major anticlines taking a trend towards the axis of the syncline, and eventually towards northwest into the Greater Zab River and partly into Erbil Sub province, and southeast into the Lesser Zab River. The main source of the groundwater recharge is rainfall, the high lands bound the Sub province represent water divides and sources of the groundwater recharge.

The performed pumping tests of wells discharging from Mukdadiya and Bai Hassan formations showed that: the transmissivity of the aquifer ranges between (5 – 1650) m^2/day, permeability ranges between (0.1 – 28.5) m/day, well discharge ranges between (30 – 3150) m^3/day, and the static water level ranges between (20 – 80) m, below ground surface. The groundwater quality is mainly sulphatic with bicarbonate water. Salinity of the groundwater ranges from fresh water (less than 1000 mg/l) to moderate brackish water (more than 3000 mg/l), but it is mainly between (1000 – 3000) mg/l.

▪ **Makhmour Sub Province**

This Sub province forms a triangular-shaped area, bounded by Qara Chouq Mountain in the northeast, the Tigris River in the west and the groundwater divide between the Lesser Zab and Adhaim Rivers catchment areas, in the southeast, and Himreen Mountain in the southern part. The general groundwater movement is mainly from northeast towards southwest, gradually into the Tigris and Lesser Zab Rivers. The main source of the recharge of the groundwater is from rainfall.

The performed pumping tests of wells discharging from Bai Hassan and Mukdadiya formations and the Quaternary sediments showed that: the transmissivity of the aquifer ranges between (6 – 1350) m^2/day, permeability ranges between (0.1 – 25.6) m/day, well discharge ranges between (20 – 3200) m^3/day, and the static water level ranges between (4 – 60) m, below ground surface. The groundwater quality is mainly sulphatic, with salinity ranges from fresh water (less than 1000 mg/l) to brackish water (more than 7000 mg/l), but it is mainly between (1000 – 5000) mg/l (Al-Jiburi, 2004 and Sa'ood *et al*., 2007).

▪ **Kirkuk – Hawija – Tuz Khurmatu Sub Province**

The northeastern and eastern boundary of this Sub province is formed by a series of low anticlinal ridges with NW – SE trend and arranged by a series of an echelon form, from north to south these are: Kirkuk, Jambur and Pulkhana anticlines. This Sub province is represented by a vast plain area in its western and southwestern parts. It comprises the lower reaches of the Adhaim River catchment areas to the northeast of Himreen Mountain. The general direction of the groundwater flow is towards southwest. The main source of the groundwater recharge is the direct rainfall, in addition to influent seepage from the streams originating beyond the northeastern boundary of the Sub province. The main groundwater discharge areas are along Himreen Mountain and towards the Lesser Zab River.

The performed pumping tests of wells discharging from the main upper aquifer of Bai Hassan and Mukdadiya formations and the Quaternary sediments showed that: the transmissivity of the aquifer ranges between (3 – 2775) m^2/day, permeability ranges between (0.1 – 57.8) m/day, well discharge ranges between (20 – 5460) m^3/day, and the static water level ranges between (1 – 90) m, below ground surface. The groundwater quality is mainly sulphatic, with salinity ranges from (500 – 8750) mg/l. In general, the salinity increases in the direction of the groundwater flow; far away from the recharge areas, with various lithological, structural and topographic influences along the flow direction to the discharge areas.

- **Cham Chamal – Qadir Karam – Qara Too Sub Province**

This Sub province is represented by the upper reaches of the Adhaim River catchment areas and Diyala River, between the High Folded Zone, in the northeast and Kirkuk and Pulkhana Structures in the southwest. The groundwater divide between the Lesser Zab and the Adhaim Rivers catchment areas forms the northwestern boundary, while in the southeast the Sub province extends to the Iraqi – Iranian border. The general direction of the groundwater flow is towards southwest, where significant groundwater discharge areas occur along the anticlines, bordering the Sub province in the southeast, where the rivers leave the area (Krasny *et al*., 2006). The source of the recharge of the groundwater is mainly direct rainfall and the High Folded Zone to the northeast of the Sub province.

Pumping tests of wells discharge from the main upper aquifer of Bai Hassan and Mukdadiya formations showed that: the transmissivity of the aquifer ranges between (3 – 1950) m^2/day, permeability ranges between (0.1 – 42.6) m/day, well discharge ranges between (20 – 3600) m^3/day, and the static water level ranges between (5 – 90) m below ground surface. Groundwater quality is mainly bicarbonate with sulphatic water type. Salinity of the groundwater is mainly within the range of (150 – 1600) mg/l (Al-Jiburi, 2006b; Sa'ood *et al*., 2007 and Al-Jiburi *et al*., 2010).

- **Kalar – Khanaqeen Sub Province**

This Sub province extends between the extension of Kirkuk structure, in the north and Naoduman structure, in the south, while the Iraqi –Iranian border represents its eastern boundary. The Bai Hassan and Mukdadiya formations represent the main aquifer within this Sub province, in addition to the Quaternary sediments when they have suitable thickness for water storage. The direction of the groundwater flow is from north and northeast towards south and southwest, while Diyala River is considered as a discharge area within the Sub province. The source of the groundwater recharge is mainly by rainfall in the area, and neighboring high lands at the north and east, which are considered as a recharge source to this Sub province.

The performed pumping tests of wells discharging from the main upper aquifer of Bai Hassan and Mukdadiya formations showed that: the transmissivity of the aquifer ranges between (15 – 1170) m^2/day, permeability ranges between (0.1 – 24) m/day, well discharge ranges between (22 – 5400) m^3/day, and the static water level ranges between (3 – 45) m, below ground surface (Al-Jiburi, 2006b). The groundwater quality is mainly sulphatic and bicarbonate with chloridic water type on local scale. Salinity of the groundwater is mainly within the ranges from less than 1000 mg/l to more than 3000 mg/l, within the range of fresh water to slightly brackish water. The performed pumping tests of wells discharging from the

Quaternary sediments showed that: the transmissivity of the aquifer ranges between (20 – 540) m^2/day, permeability ranges between (0.4 – 35.5) m/day, well discharge ranges between (90 – 1650) m^3/day, and the static water level ranges between (2 – 25) m, below ground surface. The groundwater quality is mainly sulphatic and bicarbonate water, with salinity ranges mainly from (less than 1000 – 3000) mg/l (Al-Jiburi, 2006b and Al-Jiburi *et al*., 2010).

- **Qara Tappa – Al-Sa'adiyah Sub Province**

This Sub province is bounded from the north by Jallabat and Naoduman anticlines and by Himreen South anticline, from the south, while the Iraqi – Iranian border forms its eastern boundary. The Bai Hassan and Mukdadiya formations represent the main aquifer within this Sub province, in addition to the Quaternary sediments, when they have suitable thickness for water storage. The direction of the groundwater flow is from north and northeast towards south and southwest, while Diyala River is considered as a discharge area within this Sub province. The main source of the groundwater recharge is mainly by rainfall in the area, and neighboring high lands at the north and east. The Mesopotamia Plain represents the discharge area with respect to this Sub province.

The performed pumping tests of wells discharging from the main upper aquifer of Bai Hassan and Mukdadiya formations showed that: the transmissivity of the aquifer ranges between (10 – 1120) m^2/day, permeability ranges between (0.1 – 23) m/day, well discharge ranges between (16 – 4850) m^3/day, and the static water level ranges between (2 – 40) m, below ground surface. The groundwater quality is mainly sulphatic with bicarbonate and chloridic water type on local scale. Salinity of the groundwater is mainly within the ranges from (< 1000 – 5000) mg/l, it is mainly within the range of slightly and moderate brackish water (Al-Jiburi, 2006b and Al-Jiburi *et al*., 2010). The performed pumping tests of wells discharging from the Quaternary sediments showed that: the transmissivity of the aquifer ranges between (12 – 510) m^2/day, permeability ranges between (0.3 – 25.8) m/day, well discharge ranges between (62 – 1480) m^3/day, and the static water level ranges between (2 – 18) m, below ground surface. The groundwater quality is mainly sulphatic with bicarbonate water on local scale, and salinity ranges mainly from (less than 1000 – less than 5000) mg/l, but it is mainly within the range of (1000 – 3000) mg/l of slightly brackish water.

- **Mandili – Zurbatiya – Teeb Sub Province**

This Sub province extends as a belt along the eastern Iraqi – Iranian border. It represents the extreme southeastern extension of the Low Folded Zone along the Iraqi – Iranian border. The main aquifer is considered within Bai Hassan and Mukdadiya formations.

The performed pumping tests of wells discharging from this aquifer in Mandili town and its vicinities showed that: the transmissivity of the aquifer ranges between (3 – 445) m^2/day, permeability ranges between (0.1 – 12.2) m/day, well discharge ranges between (12 – 1620) m^3/day, and the static water level ranges between (1.5 – 64) m, below ground surface. The groundwater quality is mainly sulphatic with chloridic water type on local scale. Salinity of the groundwater ranges from (< 1000 – 5000) mg/l, depending mainly on the nearest source of water recharge from rainfall and valleys, especially during wet seasons, in addition to the geological, structural and topographic nature of the area (Al-Jiburi, 2006a). The performed pumping tests of wells discharging from Bai Hassan and Mukdadiya aquifer at Zurbatiya – Badra vicinity showed that: the transmissivity of the aquifer ranges between (7 – 533) m^2/day, permeability ranges between (0.1 – 14.1) m/day, well discharge ranges between (132 – 2224) m^3/day, and the static water level ranges between (3 – 45) m, below ground surface. The groundwater quality is mainly sulphatic with chloridic water type on local scale. Salinity of the groundwater ranges from (< 1000 – 5000) mg/l, it is mainly < 5000 mg/l (Al-Jiburi, 2005a). The performed pumping tests of wells discharging from Bai Hassan and Mukdadiya aquifer at Teeb and Fakka areas and their vicinities showed that: the transmissivity of the aquifer ranges between (12 – 290) m^2/day, permeability ranges between (0.5 – 15.5) m/day, well discharge ranges between (115 – 1782) m^3/ day, and the static water level ranges between (1 – 64) m, below ground surface. The groundwater quality is mainly sulphatic with bicarbonate and chloridic water type on local scale. Salinity of the groundwater ranges from (< 1000 – 5000) mg/l, it is mainly less than 5000 mg/l (Al-Jiburi, 2005c and 2008).

DISCUSSION

From the hydrogeological point of view, all the geological formations older than the Middle Miocene are considered generally not water-bearing and unpromising for well drilling. This is owing to either their tectonic situation (i.e. exposed as a narrow strip of steep dipping within the mountain chain) and/ or lithological characteristics (i.e. extensive beds of shale, marl and anhydrite). The fractured and weathered limestones as water-bearing layers belong to these formations as in Pila Spi and Sinjar formations, can be found at shallow depth, down to (50 – 60) m. This is practically true in the areas close to the relatively gentle anticlinal structures. Drilled wells in these areas show that the water-bearing layers yield good quality of water, but they are of different abilities of transmitting water.

The exposures of the pre-Middle Miocene formations receive relatively great amount of rainfall annually, up to 700 mm or more. Therefore, water infiltrates through their fractures, fissures and joints, issues either in the form of springs through bedding planes and faults or seeps down dip into the adjacent formations. The remaining part of the rain water drains these formations in the form of surface run off. The formations of the Middle Miocene to Recent are considered mainly as water-bearing and form the main aquifers within the Low Folded Zone.

The geological setting of the Low Folded Zone is strongly influencing the hydrogeology of the zone. The major part of the zone is characterized by a plain controlled by broad synclinal structures with linear hilly belts and anticlines, which are dissected by river valleys. The main groundwater divides coincides with surface water flow, especially in the elevated parts of the Low Folded Zone, where the groundwater discharge occurs along streams and rivers. The possibilities of the groundwater development in areas along these streams and rivers may be important.

The hydraulic parameters differ due to variations in lithology, aquifer thickness, topographic and structural characteristics of the area. Differences in lithology often characterize the type of the aquifer present as: unconfined, semi-confined or confined. The regional distribution of transmissivity within the Low Folded Zone differs according to the geological, hydrogeological and structural conditions of particular location. Transmissivity often increases in the central parts of the synclines, filled by Bai Hassan and Mukdadiya formations. The decrease in transmissivity along the flanks of anticlines is due to the exposure of the less transmissive Fatha and Injana formations. In addition, transmissivity often increases along river courses, buried river channels, confluences of rivers and in buried alluvial fans where more permeable sediments are available (Krasny *et al*., 2006).

The climate of the Low Folded Zone is mainly semi arid, with hot summer and mild to cold winter. Rainfall occurs during autumn, winter, and spring months. In elevated areas, the range of rainfall is from (500 – 700) mm/year. In the southwestern part of the zone, rainfall is about 200 mm/year (Iraqi General Organization for Meteorological Information, 2000). The rainfall represents the main recharge source for the groundwater in the zone.

The regional presentation of the groundwater flows within the Low Folded Zone is based on the assumption that there is a hydraulic continuity between the aquifers within the same individual hydrogeologic basins. Another assumption is that, the surface and groundwater are often in mutual hydraulic continuity, to large extent. The main rivers, which dissect the zone may form an important hydraulic boundaries to some groundwater reservoirs. In the elevated parts of the zone, the groundwater divides are usually expressive and may form important boundaries, when considering the hydrogeologic conditions, while in the plain areas the groundwater divides might be influenced and modified by irrigation and heavy groundwater withdrawal, if they are not greatly controlled by structural features. The main structural features, such as anticlines and faults, usually form important hydrogeological boundaries. Some hydrogeological discontinuities, such as lateral changes in lithofacies and occurrence of weakness zone like fissure, joints, and fractures are of great local hydrogeological importance.

The location of the Low Folded Zone between the High Folded Zone, from the north and northeast and the Mesopotamia Plain, from the south and southeast and Al-Jazira area, from the southwest causes this zone to be recharged from the High Folded Zone. While, it is considered to be the recharge zone with respect to the Mesopotamia Plain and Al-Jazira area. Tigris River and its tributaries such as the Greater and Lesser Zab, Adhaim and Diyala Rivers with their own tributaries represent regional discharge zones within the Low Folded Zone. These rivers may represent influent hydraulic boundaries of some aquifers depending on the piezometric surfaces of the neighboring aquifers.

Generally, the salinity of the groundwater within the Low Folded Zone increases from north to south (Fig.3), it is mainly within the range (< 500 – 5000) mg/l and may be reach > 10000 mg/l, on a local scale. The chemical composition of the groundwater also changes from a prevailing bicarbonate type to sulphate type. The changes in the groundwater quality might be abrupt or gradual, depending on the topographic, structural and geological factors, and other natural conditions controlling groundwater recharge and discharge. Groundwater with low salinity and of bicarbonate water type occurs where there is sufficient fresh water recharge, and where there is adequate discharge enabling leaching of aquifers allowing continuous disposal of salts and preventing retarded flow or stagnation (Krasny *et al*., 2006).

The salinity of the groundwater in the **Sinjar – Rabee'a** Sub province is mainly within the range of (< 1000 – 3000) mg/l, with sulphatic water type in general, also the presence of bicarbonate water in the recharge areas. The salinity of the groundwater within the **Khazir – Gomel** Sub province is mainly within the range of (200 – 500) mg/l, with prevailing chemical type of bicarbonate. Within **Dohuk – Alqosh** Sub province, the prevailing salinity is within the range of (< 1000 – 3000) mg/l and with predominant sulphatic water type, due to the presence of the Fatha Formation within the area, bicarbonate water is also encountered in extensive areas. The salinity of the groundwater in the **Erbil** Sub province is characterized by its low range (250 – 500 mg/l), with predominant bicarbonate water type, the salinity of the groundwater increases in some areas, especially within the discharge areas, with predominant sulphatic water type. Within **Altun Kupri** Sub province, the salinity is mainly within the range of (200 – 500) mg/l, with predominant bicarbonate water type; sulphatic water quality is present locally. The salinity of the groundwater in the **Dibiga** Sub province is within the range of (1000 – 5000) mg/l, but it is mostly not more than 3000 mg/l, with prevailing sulphatic water type, bicarbonate water type in recharge areas and chloridic water type in discharge areas. Within **Makhmour** Sub province, the salinity of the groundwater is within the range of (< 1000 – 7000) mg/l, but it is mainly within the range of (1000 – 5000) mg/l. The groundwater quality is mainly sulphatic. The salinity of the groundwater in **Kirkuk – Hawija – Tuz Khurmatu** Sub province ranges from (500 – 8000) mg/l, with predominant range of salinity from (1000 – 5000) mg/l. Sulphatic water type is prevailing in the area, with bicarbonate water type occurring within the recharge areas. Within **Cham Chamal – Qadir Karam – Qara Too** Sub province, the salinity ranges mainly from (300 – 2500) mg/l, with predominant bicarbonate and sulphatic water type. In **Kalar – Khanaqeen** Sub province, the salinity ranges mainly from (< 1000 – 300) mg/l, with sulphatic and bicarbonate water type. Within **Qara Tappa – Al-Sa'adiyah** Sub province, the salinity of the groundwater ranges mainly from (< 1000 – 5000) mg/l, with predominant sulphatic water type, bicarbonate water occurs locally. In **Mandili – Zurbatiya – Teeb** Sub province, the salinity of the groundwater ranges mainly from (1000 – 5000) mg/l, with predominant sulphatic water type; bicarbonate and chloridic water occur locally.

Generally, the salinity of the groundwater within the Low Folded Zone increases in the direction of the groundwater flow; far away from the recharge areas, with various geological, structural, topographical and hydrogeological influences along the flow direction to the discharge areas.

CONCLUSIONS

- The Low Folded Zone is divided into thirteen Sub provinces, according to hydrogeological, structural, geological and topographic features, the Sub provinces are: Sinjar – Rabee'a, West Tigris River, Khazir – Gomel, Dohuk – Alqosh, Erbil, Altun Kupri, Dibiga, Makhmour, Kirkuk – Hawija – Tuz Khurmatu, Cham Chamal – Qadir Karam – Qara Too, Kalar – Khanaqeen, Qara Tapa – Al-Sa'adiyah and Mandili – Zurbatiya – Teeb.
- The main investigated water bearing formations at the western part of the Low Folded Zone, west of the Tigris River are represented by: Injana and Fatha formations in addition to the Quaternary sediments. Carbonate formations are considered also as a good water bearing formations within Sinjar area. While Bai Hassan and Mukdadiya formations; in addition to Injana Formation and Quaternary sediments are considered as the main water bearing formations in the other parts; east of the Tigris River.
- The source of recharge water within the Low Folded Zone is mainly from direct rainfall, and from the High Folded Zone at the northeastern part. The zone receives a considerable amount of rainfall, reaches to about 700 mm/year; at the high land areas. The Mesopotamia Plain and Al-Jazira Area represent the discharge areas with respect to the Low Folded Zone.
- There is a hydraulic continuity between water bearing formations within the Low Folded Zone to some extent, depending on the piezometric relations of the water-bearing layers, throughout the area.
- The general trend of the groundwater movement at the western part of the zone (to the west of Tigris River), is mainly from north and northwest towards south and southeast, exceptionally the area north of Sinjar Mountain, where the direction of flow is towards the north and west; towards the Iraqi – Syrian border. The direction of the groundwater flow at the eastern parts of the Low Folded Zone (to the east of Tigris River), is from north and

northeast towards south and southwest, with local different directions, due to topographic and structural characteristics of the area.

- The depth of most drilled wells is within the range of (50 – 150) m, below ground surface. The depth of the groundwater increases at the high lands and at the flanks of the synclinal basins, and decreases at the central parts of the basins and at the discharge areas.
- The transmissivity of the aquifers often increases in the central part of the synclinal basins; also, it increases along river courses and within alluvial fans, as more permeable sediments are present.
- Generally, the salinity of the groundwater increases from north to south. It increases from the recharge sources at the high land areas (less than 1000 mg/l), towards the discharge areas along the Mesopotamia Plain and Al-Jazira Area (more than 10000 mg/l). Groundwater quality is mainly bicarbonate at the recharge areas, and becomes sulphatic at the discharge areas.
- The hydraulic conditions and chemistry of aquifers are closely linked to lithological, structural and topographical features of the water-bearing formations, within the Low Folded Zone.
- According to the hydrogeological investigations, and evaluation of the groundwater quality and quantity, the Low Folded Zone can be considered as the most promising zone for groundwater development in Iraq.

RECOMMENDATIONS

According to the hydrogeological and hydrochemical study of the Low Folded Zone, the following are recommended:

1. Monitoring or continuous observations of the groundwater level in selected and representative wells, in each Sub province of the zone, in order to provide new information, which is necessary for executing groundwater regime and to detect any variations that occurs in the groundwater level.
2. Continuous collections and analyses of groundwater samples; from representative wells, based on monthly or seasonal periods, as available aid to predict any change in chemical composition and water types.
3. Drilling new deep observation wells, in selected areas, and where no wells are available, to provide new information in order to evaluate the hydrogeological and hydrochemical conditions, within involved areas, more precisely and to predict or find more new promising areas.
4. Construction of small dams on main valleys, especially, in Mandili – Zurbatiya – Teeb Sub province, to provide surface water recharge to the groundwater aquifers through valley basins, the stored water also can be used for local domestic and irrigation purposes within the region.
5. Establishment of gauging stations on valley basins, in order to record valley's run off, which will aid in evaluation of the groundwater resources.
6. Installation of hydro-meteorological stations, aiming to provide continuous observations of the hydro-meteorological parameters, which will aid in evaluation of the groundwater resources.
7. Continuous observation of the groundwater level and analyses of groundwater samples, from selected wells in the agricultural areas, in order to prevent deterioration and depletion of the groundwater in these regions. The possibility of recharging the groundwater artificially, in some selected areas, when it is necessary.

8. Preventing uncontrolled drilling for groundwater wells, within the zone, especially within the agricultural areas, in order to prevent deterioration and depletion of the groundwater.
9. Preventing products of urbanization and industrialization that have caused serious environmental impacts which consisting a contamination of the groundwater within the Low Folded Zone.
10. Applying new technology in irrigation and agriculture, and selecting more productive generation for different agricultural activities, in order to get high production with low water consumption.
11. Applying new scientific methods in water management for water resources, and applying integrated irrigation system within the areas of available surface water, in order to provide continuous production of different agricultural products along the year.

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