HYDROGEOLOGY OF THE MESOPOTAMIA PLAIN

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ABSTRACT

The Mesopotamia Plain is characterized, topographically as a flat plain that slopes gently between Baghdad and Basrah, but it is gently undulated in its northern parts. It is totally covered by Quaternary sediments. These sediments are composed of alternation of clay, silty clay, clayey silt, silt, sand and gravel. Fine sediments represent the aquitards, while sand and gravel form the aquifers. These sediments have abrupt lithologic changes, both laterally and vertically, therefore, are considered regionally as a lithologically complex aquifer system. There is a hydraulic continuity within the entire Quaternary aquifer system, but the degree of the continuity differs from place to another, depending on the lithological characteristics of water bearing sediments. It is assumed that, a hydraulic continuity is present between surface water and groundwater aquifers, to some extent. Therefore, effluent and influent river phenomena exist throughout the plain. Moreover, there is a hydraulic continuity between Quaternary aquifer system, in the plain and the underlying pre-Quaternary formations.

The groundwater level fluctuations throughout the Mesopotamia Plain depend, mainly on the natural conditions and to some extent on artificial conditions. Generally, water bearing Quaternary sediments, of the plain are considered quantitatively promising, but the problem is concerned with the quality of the groundwater. High salinity of the groundwater prevails throughout the plain, but the groundwater, which is close to rivers and main irrigation channels may be in better condition for exploitation, particularly where phenomenon of induced seepage of fresh water exists, also in areas along Low Folded Zone, where recharge water zones exist.

The direction of the groundwater flow is towards the center of the Mesopotamia Plain, from all neighboring regions, because the plain represents a regional discharge zone for the whole Mesopotamian Aquifer Mega System of Iraq. The piezometric level of the groundwater is generally inclined from north and northwest (it is < 200 m, a.s.l., near Makhoul Mountain) towards south and southeast (2 m, a.s.l., near Basrah city). The salinity of the groundwater increases generally from the recharge areas towards discharges areas, within the plain. The chemical quality of the groundwater changes from sulphatic to chloridic type from recharge to discharge areas, respectively, being in accordance with the groundwater movement.

هيدروجيولوجية الســهل الرســوبي

حاتم خضير الجبوري و نصير حسن البصراوي

المستخلص

يمتاز السهل الرسوبي بكونه سهل منبسط ينحدر تدريجيا بين بغداد والبصرة ويكون متموجا بعض الشيء في أجزائه الشمالية. يغطى السهل الرسوبي كليا بترسبات العصر الرباعي، وتتكون هذه الترسبات بصورة عامة من تتابع الطين والغرين والرمل والحصى. إن الترسبات الناعمة تشكل الطبقات العازلة بينما يشكل الحصى والرمل الخزانات الجوفية للمياه.

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تمتاز ترسبات السهل الرسوبي بالتغير المفاجئ لخواصها الصخارية أفقيا وعموديا، حيث تشكل نظاما إقليميا معقدا للمياه السطحية والمياه الجوفية ضمن مناطق السهل الرسوبي، إذ تظهر ظاهرة التغذية والتصريف على طول مجاري الانهار والقنوات الاروائية الرئيسية، بالإضافة الى وجود إتصال هيدروليكي بين الخزانات المائية للسهل الرسوبي وخزانات المياه للتكوينات الأقدم منها. يعتمد التغير في مستوى المياه الجوفية ضمن مناطق السهل الرسوبي بصورة رئيسية على الظروف الطبيعية، وبعض الشيء على الظروف الاصطناعية.

تعتبر الترسبات الحاملة للمياه الجوفية في منطقة السهل الرسوبي بصورة عامة واعدة من ناحية الكمية، ولكن المشكلة تكمن في نوعيتها، حيث تعتبر المياه الجوفية في السهل الرسوبي، بصورة عامة عالية الملوحة، لكن يمكن الحصول على مياه قليلة الملوحة أو ملائمة لبعض الاستخدامات المختلفة ضمن المناطق المحاذية لمجاري الأنهار والقنوات الإروائية، حيثما تكون هنالك تغذية للمياه الجوفية من تلك المصادر العذبة، وكذلك على امتداد نطاق أقدام التلال، حيث مناطق التغذية.

إن حركة المياه الجوفية يكون باتجاه السهل الرسوبي ومن جميع المناطق المجاورة له، حيث يعتبر منطقة تصريف للمناطق المحيطة به. ينخفض مستوى المياه الجوفية بصورة عامة من الشمال والشمال الغربي باتجاه الجنوب والجنوب الشرقي، وتزداد ملوحة المياه بصورة عامة من مناطق التغذية باتجاه مناطق التصريف تبعا لحركة المياه الجوفية، كذلك الحال بالنسبة لنوعية المياه حيث تتغير من النوعية الكبريتاتية الى النوعية الكلوريدية وبنفس الاتجاه السائد لحركة المياه الجوفية.

INTRODUCTION

The Mesopotamia Plain is considered topographically as a flat plain that slopes gently between Baghdad and Basrah, but it is gently undulated in its northern parts. Its elevation ranges from (60 – 150) m, above sea level, in its boundary with the Low Folded Zone, gradually decreases south and southwards to become about 35 m in Baghdad, (10 – 12) m in the central parts and reaches (1 – 3) m at the southern parts, within the Arabian Gulf Area. It is partly covered by marshes and swamps, as well as depressions at its central and southern parts, south of Baghdad. Sand dunes, in areas west of Al-Gar'raf River, cover considerable portions of the plain, also between Wadi Tharthar and Baiji and east of Shari Lake; towards Himreen Mountain. Habbaniyah and Tharthar Lakes exist at its western border, while only the northern portion of Raz'zaza Lake is included within the plain (Fig.1). Tigris and Euphrates Rivers form the main drainage system in the Mesopotamia Plain; they flow through the plain and merge north of Basrah at Qurna to form Shatt Al-Arab that flows to the Arabian Gulf. Numerous valleys or intermittent streams flow from the high lands, along the northeastern border with the Low Folded Zone towards southwest, towards the low land in the east of the Tigris River. Diyala and Adhaim Rivers are two main tributaries of the Tigris River, and have their confluences within the plain.

From the tectonic point of view, Mesopotamia Plain forms a tectonic zone that belongs to the Unstable Shelf (Al-Kadhimi *et al*., 1996 and Fouad, 2010) and represents a subsiding area, which is characterized by thick sedimentary column. The plain forms a trough with NW – SE trend.

The Mesopotamia Plain is totally covered by Quaternary sediments. These sediments are composed mainly of alternation of clay, silty clay, clayey silt, silt, sand and gravel. Clay and silt form the aquitards, while sand and gravel form the aquifers (Figs.2 and 3).

The evaluation of the hydrogeological conditions of the Mesopotamia Plain was carried out by different workers, among them are Parsons (1955 and 1957); Krasny (1982a, b, c, d, e and f); Araim (1990); Al-Jiburi and Al-Basrawi (2001); Al-Wa'ily *et al*. (2002); Al-Dabbaj and Al-Khashab (2004); Al-Jiburi (2002, 2004, 2005, 2006 and 2008); Ahmad and Al-Jiburi (2005); Al-Basrawi (2004 and 2006) and Krasny *et al*. (2006) in Jassim and Goff (2006). These studies reflect the conditions of the groundwater system in the Mesopotamia Plain in terms of groundwater flow direction, salinity and chemical type of water.

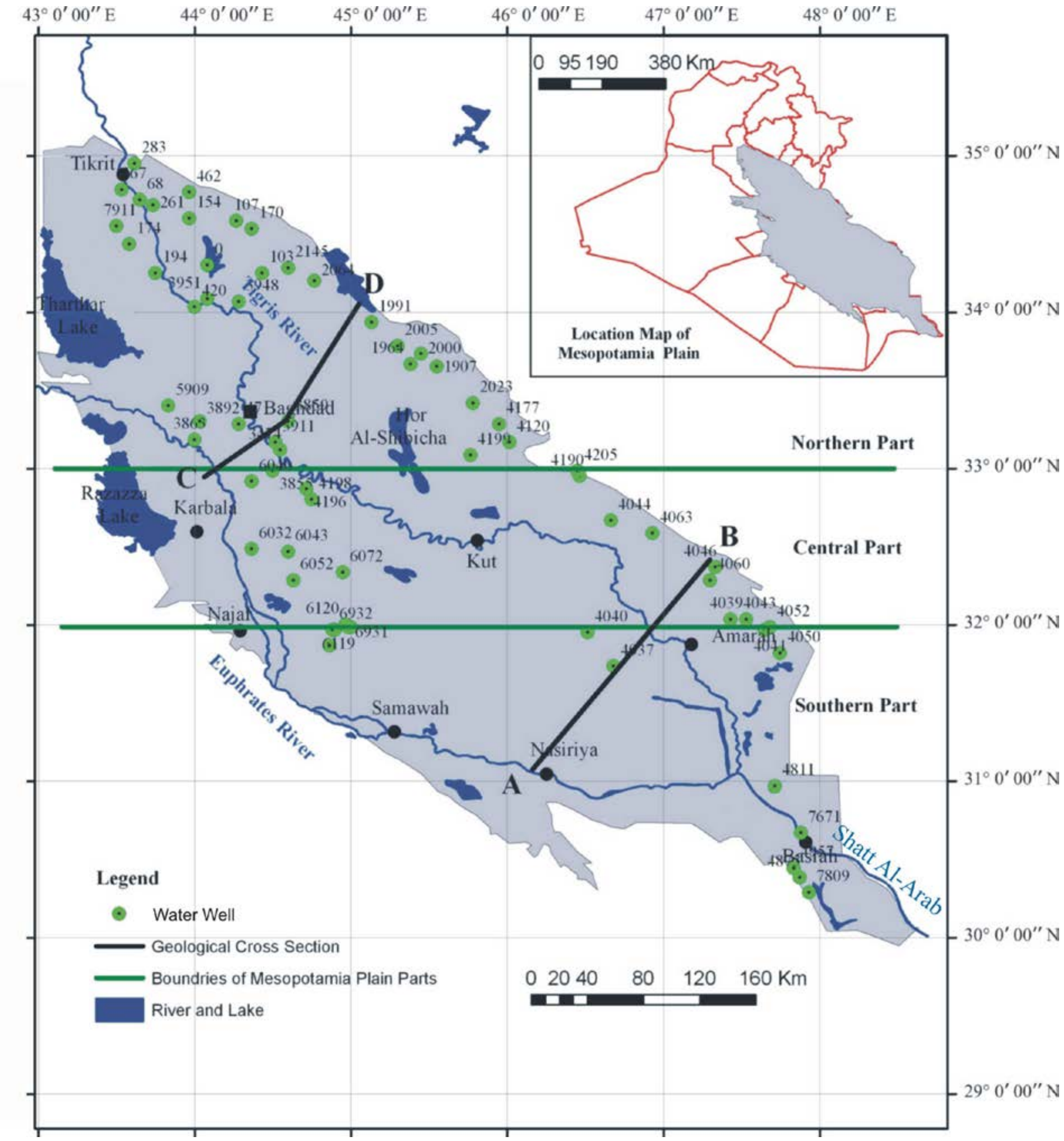

Fig.1: Location map of the Mesopotamia Plain showing location of some selected water wells (modified after Araim, 1990)

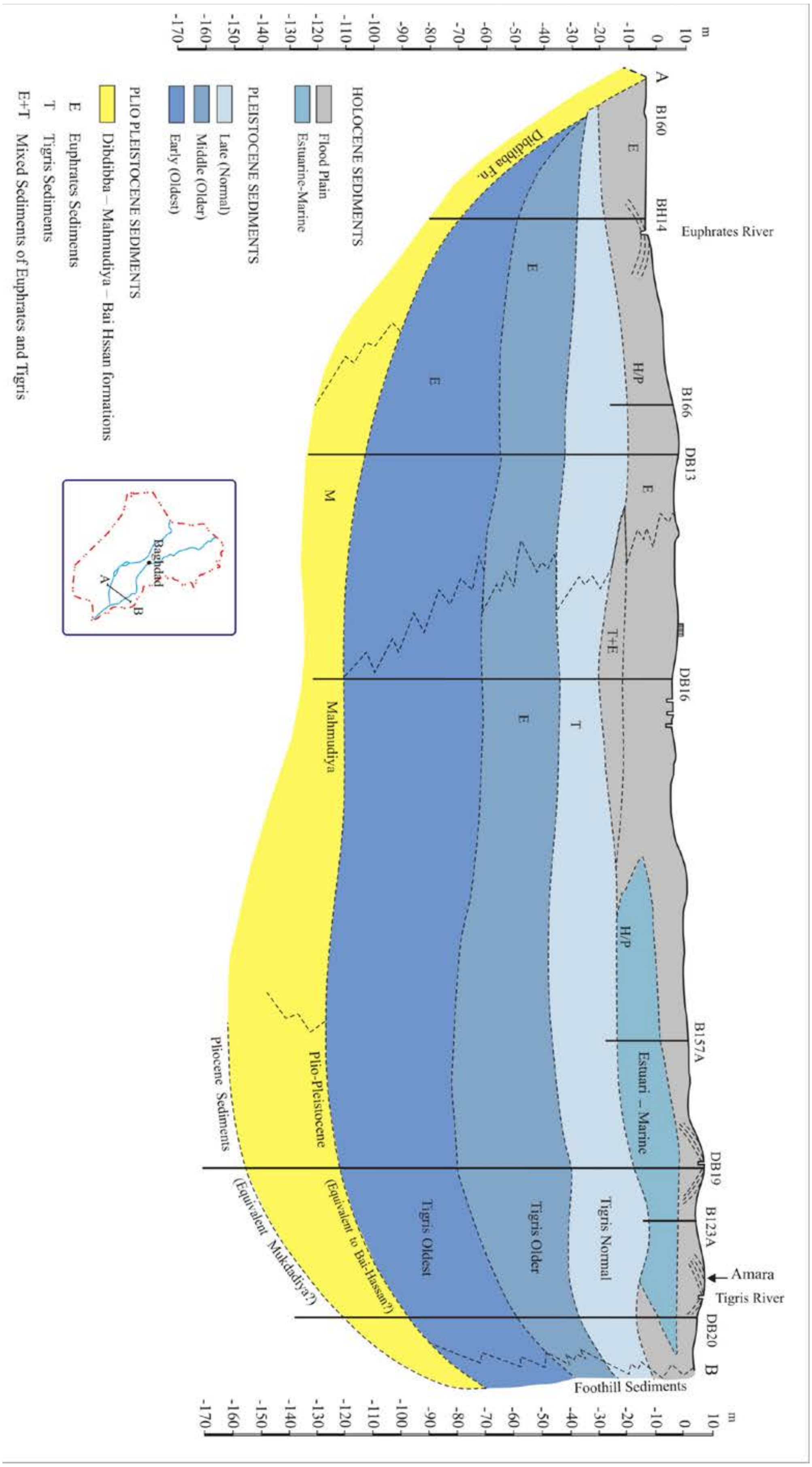

Fig.2: Geological cross section from Nasiriyah to Amara (A – B) (after Yacoub *et al.*, 1985)

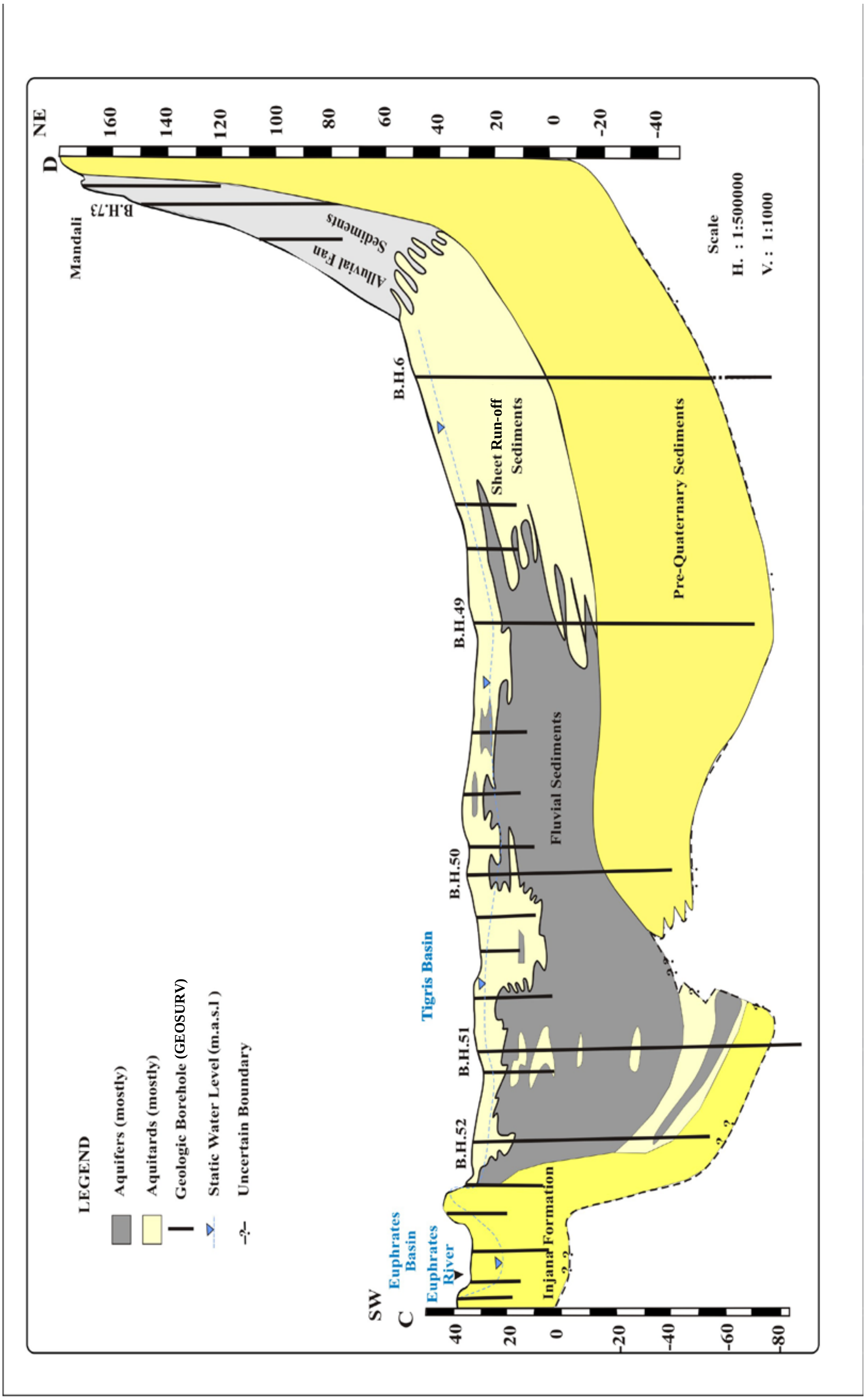

Fig.3: Geological and hydrogeological cross section (C – D) of Mesopotamia Plain (modified after Araim, 1990)

The climate in the Mesopotamia Plain is continental and subtropical, arid to semi arid. According to the meteorological information provided by the Iraqi Organization of Meteorological Information (2000) for the years (1981 – 2000), the annual mean rain fall is around 100 mm, annual relative humidity is about 42%, annual mean evaporation is about 3000 mm and annual mean temperature is 22° C.

The main aim of this study is to compile the hydrogeological and hydrochemical data in order to deduce part of the "Geology of the Mesopotamia Plain", depending mainly on the available data in GEOSURV's archive.

HYDROGEOLOGICAL CONDITIONS

The Mesopotamia Plain is totally covered by Quaternary sediments; the older concerned formations below these sediments are Injana, Mukdadiya, Bai Hassan, and Dibdibba. The beds of Injana and Dibdibba formations dip towards the plain from the Western and Southern Deserts, in the west and south, while the beds of the Bai Hassan, Mukdadiya and Injana formations dip toward the plain from the Low Folded Zone, of the Unstable Shelf, in the east and northeast. The exposed rocks at the western and southern sides of the plain have a gentle dip, while those exposed in Makhoul and Himreen Mountains, at northeast and east, have steep dip toward the plain. Both Makhoul and Himreen Mountains or anticlines that belong to the Low Folded Zone have axial trend of NW – SE. Himreen Mountain continues further along the eastern border of Iraq until the area east of Amara city.

All Quaternary sediments of the Mesopotamia Plain have abrupt lithologic changes, both laterally and vertically. Therefore, no homogenous lithologic units exist throughout the plain, and consequently it is difficult to delineate particular regional aquifers; since no adequate information about aquifer geometry is available. On these bases, the Quaternary sediments of the plain have been considered regionally as a lithologically complex aquifer system, that is neither aquifers nor aquitards seem to be of regional extent, throughout the plain. Consequently, the presentation of the groundwater piezometric level in regional scale is based on the assumption that there is a hydraulic continuity within the entire Quaternary aquifer system, this means that all aquifers are in hydraulic continuity. The degree of continuity differs from place to another, depending on the lithologic characteristics of the water bearing sediments. Locally, an expressive change might occur in lithologic characteristics of water bearing sediments, which may lead to discontinuities in the groundwater distribution. As far as the groundwater flow is concerned, it is also assumed the presence of hydraulic continuity between surface water (rivers, lakes and main irrigation channels) and the groundwater bodies to substantial extent. Rivers, lakes and main irrigation and diversion channels (to some extent) form important hydraulic boundaries to the whole aquifer system. Therefore, effluent and influent rivers phenomena do exist throughout the plain. Another assumption is that, Quaternary Aquifer System and the underlying Bai Hassan and Mukdadiya aquifers are in hydraulic continuity. Therefore, the water table (level) of these aquifers is considered regionally the same and to be continuous. Similar conditions exist between the Quaternary sediments with the underlying water bearing carbonates in the southern and southwestern parts of the plain, respectively (Araim, 1990; Al-Jiburi and Al-Basrawi, 2008).

Generally, the groundwater level fluctuations throughout the Mesopotamia Plain depend on natural conditions and to same extent on artificial conditions. The natural conditions are limited basically to rainfall amount and its distribution, and the rate of evapotranspiration. Along rivers, streams and irrigation channels, the groundwater fluctuations depend largely on the surface water fluctuations. The artificial conditions are limited to the groundwater withdrawal through wells and excess of irrigation. The maximum groundwater level rise is during winter and spring due to rainfall, as well as, water in form of influent seepage from rivers and streams and irrigation channels percolating underground to reach the groundwater body. During summer and autumn, when there is a lack of recharge and high rate of evapotranspiration, the groundwater attains its lowest level.

Generally, the water bearing Quaternary sediments of the Mesopotamia Plain are quantitatively promising, but the problem is concerned with the quality of the groundwater, because groundwater of high salinity prevails throughout the plain, which is unsuitable for domestics and irrigation purposes. However, the groundwater, which is close to rivers and main irrigation channels may be of better condition for exploitation, particularly where phenomenon of induced river recharge exists.

MAIN PARTS OF THE MESOPOTAMIA PLAIN

For more detailed investigation of the hydrogeological conditions, the Mesopotamia Plain is divided into three main parts; according to similarity, to some extent, in geological, hydrogeological and topographic characteristics, these are **1)** The **Northern Part**, which is located north of latitude 33º N. **2)** The **Central Part**, which is located between latitudes (32° – 33° N), and **3)** The **Southern Part**, which is located south of the latitude 32º N (Fig.1). The regional hydrogeological conditions of these parts are described hereinafter, the characteristics of the groundwater is mentioned in Table (1).

▪ Northern Part

The general direction of the groundwater flow in the northern part of the Mesopotamia Plain within the vicinity of Samarra is southwesterly, but it changes locally to other directions. In the eastern side of this part, between Tikrit and Baiji towns, the flow is from the highlands in Himreen Mountain southwards to the Tigris River. Between Tharthar Lake and Tigris River, a groundwater divide diverts the flow in two directions, westerly into Tharthar Lake and easterly into Tigris River, due to structural and topographic features; within the area. In the vicinity of Shari Lake, the groundwater flow is from different directions towards the lake, exceptionally in the southern side, where the flow is southwesterly into the confluence of Adhaim River and southeasterly into right bank of the Adhaim River. In the area between Diyala and Adhaim Rivers, the flow is southwesterly, apparently towards Diyala River (Fig.4).

The groundwater discharge zones are located within different areas, namely, Tharthar Lake, Shari Salt Lake, the left bank of Tigris River (between Tikrit and Baiji towns) and along the right bank of the Tigris River. Moreover, part of the groundwater discharges as springs in the slopes of Himreen Mountain. The groundwater recharge is mainly from direct rainfall and infiltration losses from intermittent streams originated from highlands at Himreen Mountain, as well as from rivers and irrigation channels in the form of influent infiltration. The most important zones of influent infiltration are those along the left bank of the Tigris River, downstream between Tikrit and Samarra towns, due to hydraulic gradient.

The main aquifers in the vicinity of Samarra town are: Injana, Mukdadiya, Bai Hassan formations, in addition to Quaternary sediments (Ahmad and Al-Jiburi, 2005). Pumping test results of the wells, which discharge from Injana aquifer show that the transmissivity of the aquifer ranges from (4 – 503) m^2/day, permeability from (0.1 – 47) m/day, well discharge from (58 – 1037) m^3/day and static water level ranges from (1.6 – 69) m, below ground surface (Table 1). The total dissolved solids range from (300 – 6819) mg/l, water type is mainly sulphatic with some chloridic type (Ahmad and Al-Jiburi, 2005). Injana aquifer occupies mainly the western part of the right bank of the Tigris River.

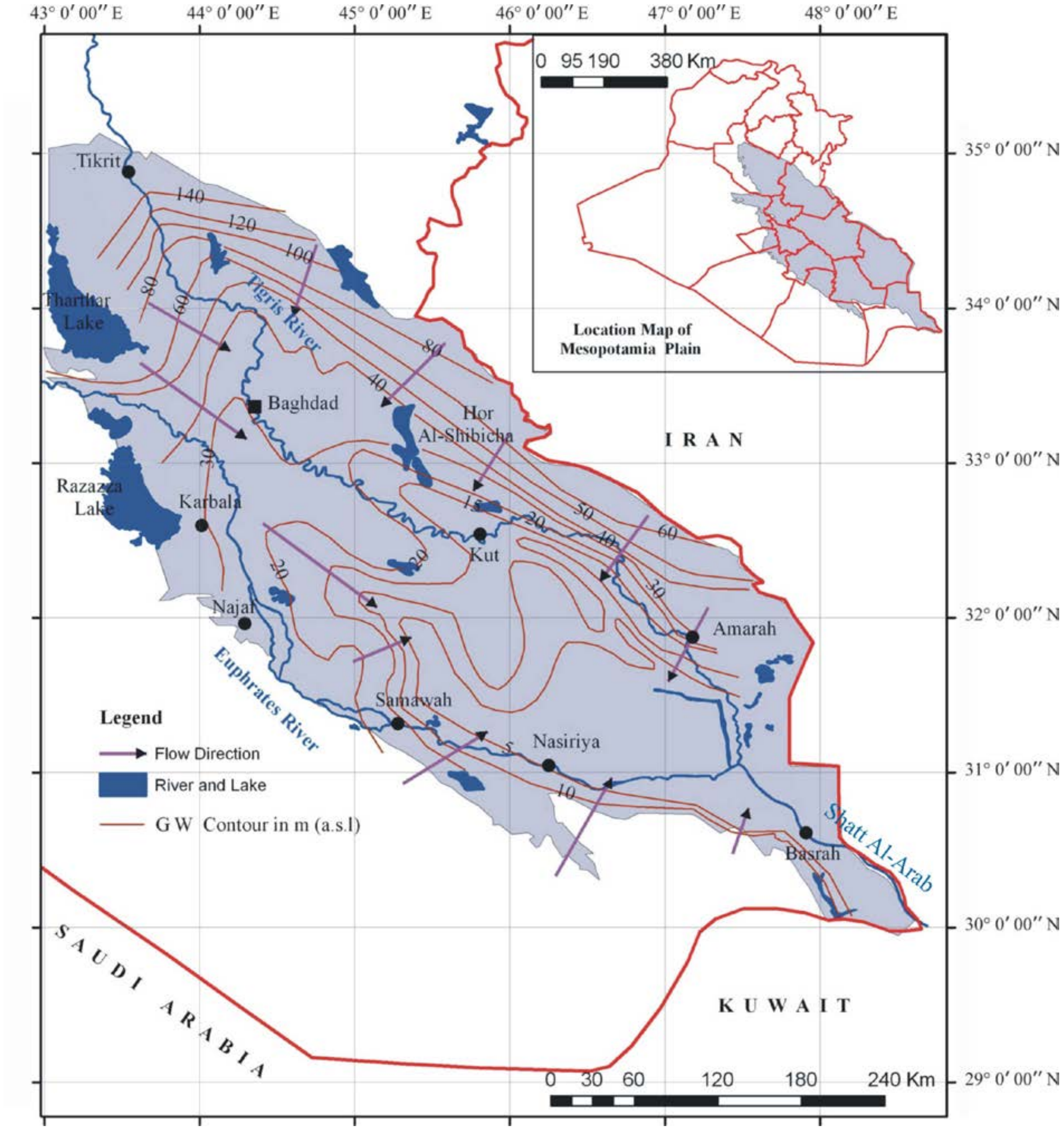

Fig.4: Hydrogeological map of the Mesopotamia Plain, shows static water level and direction of the groundwater flow
(after documented reports in GEOSURV, int. rep. nos. 2705, 2806, 2825, 2865, 2896, 2911, 2915, 2922, 2925, 2941, 2949 and 2964)

Table 1: Hydrogeological parameters and hydrochemistry of the groundwater in selected wells within Mesopotamia Plain

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
283	34º 57'	43º 37'	M	160	95	36	745	5.3	227	5391	Na-Sulphate
367	34º 47'	43º 32'	I	141	222	23	657	1.9	56	2569	Ca- Sulphate
261	34º 41'	43º 44'	M	129	108	22	396	0.3	12	1700	Ca- Sulphate
462	34º 46'	43º 58'	M	130	80	42	838	2.8	278	2450	Ca- Sulphate
154	34º 36'	43º 58'	M	80	71	11	648	3.6	97	2551	Ca- Sulphate
170	34º 32'	44º 22'	M	110	44	28	641	2.7	42	1900	Ca- Sulphate
107	34º 35'	44º 16'	M	110	34	19.1	590	1.2	42	2700	Ca- Sulphate
174	34º 26'	43º 35'	I	120	75	19.2	444	1.3	27	3208	Ca- Sulphate
7911	34º 33'	43º 30'	I	–	121	30	518	0.4	34	2746	Ca- Sulphate
W52	34º 18'	44º 05'	M	–	71	2	–	3.2	300	5562	Na-Sulphate
194	34º 15'	43º 45'	I	95	48	13.6	654	–	–	2982	Ca- Sulphate
103	34º 15'	44º 26'	M	69	62	11.4	654	2.7	49	4200	Ca- Sulphate
68	34º 43'	43º 39'	I	123.2	62	33	520	1.3	51	1300	Mg-Sulphate
420	34º 02'	44º 00'	I	56	100	12.2	29.7	2.5	42	1134	Ca- Sulphate
2145	34º 17'	44º 36'	M	78.1	69	21.5	660	2.2	96	3150	Ca- Sulphate
3948	34º 04'	44º 17'	M	50	59	16.8	648	–	–	4535	Ca- Sulphate
2064	34º 12'	44º 46'	M	75	70	3	614	5.2	219	3150	Ca- Sulphate
409	34º 48'	44º 33'	M	180.3	106	19.5	968	5.9	321	390	Ca- Sulphate

Qt: Aquifer in Quaternary Sediments Bi: Aquifer in Bai Hassan Formation M: Aquifer in Mukdadiya Formation

I: Aquifer in Injana Formation

…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
3951	34º 05'	44º 05'	M	63	86	38.1	660	4.5	32	7000	Na-Sulphate
1991	33º 56'	45º 08'	Qt	62.5	20	2.1	396	1.2	12	5141	Na-Sulphate
2005	33º 47'	45º 18'	Qt	65	26	8	185	11.2	169	4255	Na-Sulphate
1964	33º 40'	45º 23'	Qt	65.3	54	11	277	–	–	4033	Ca-Sulphate
2000	33º 44'	45º 27'	Qt	85	114	4	204	3.5	28	489	Ca-Sulphate
5909	33º 24'	43º 50'	Qt+I	45	50	17	579	1.9	51	4760	Ca-Sulphate
3892	33º 18'	44º 02'	Qt	40.9	51	6	616	1.7	17	16048	Na-Chloride
3863	33º 11'	44º 00'	Qt	38.7	13.2	2.7	523	24.2	138	1311	Ca-Sulphate
47	33º 17'	44º 29'	Qt	120	30	2.1	436	3	48	13000	Na-Chloride
3859	33º 18'	44º 36'	Qt	35	18.9	7.8	156	–	–	1295	Ca-Sulphate
3911	33º 10'	44º 31'	Qt	32	32.5	1.2	611	9.2	134	770	Ca-Sulphate
3474	33° 07'	44º 33'	Qt	32	60.6	5	654	3.2	178	463	Mg-Bicarbonate
3855	32º 59'	44º 30'	Qt	30	25.5	2.7	327	8.6	39	14600	Na-Chloride
6040	32º 55'	44º 22'	Qt	30	12.5	1.8	189	–	–	680	Ca-Sulphate
4196	32º 52'	44º 43'	Qt	35	54	7	596	1.9	60	42200	Na-Chloride
4198	32º 48'	44º 45'	Qt	35	54	6	570	1.8	59	3920	Ca-Sulphate
1907	33º 39'	45º 33'	Qt	72.3	63	12.6	2838	6.5	568	1685	Ca-Sulphate
2023	33º 25'	45º 47'	Qt	70	64	13	673	3.7	70	4000	Na-Sulphate

…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
4177	33° 17'	45° 57'	Bi	88.1	90	13	238	0.1	6	3698	Na-Sulphate
4120	33° 10'	46° 01'	Qt	95	84	4.5	518	0.3	10	3450	Ca-Sulphate
4199	33° 05'	45° 46'	Qt	56	47	2	622	1.9	86	19859	Na-Chloride
4205	32° 59'	46° 27'	Qt	35	20	3.6	198	3.7	22	800	Ca-Sulphate
4190	32° 57'	46° 28'	Bi	37.6	70	14	443	0.5	22	5000	Ca-Sulphate
4044	32° 40'	46° 40'	Qt	50	12	5.6	–	–	–	11500	Na-Chloride
4060	32° 17'	47° 18'	Qt	46.1	32	2.5	648	10.8	285	7970	Na-Chloride
4039	32° 02'	47° 26'	Qt	35	10.5	8	–	–	–	18800	Na-Chloride
4041	31° 58'	47° 39'	Qt	27	22	8	261	36.6	439	11500	Na-Chloride
4052	31° 59'	47° 41'	Qt	28	53	4.8	330	–	–	14500	Na-Chloride
4050	31° 49'	47° 45'	Qt	12.4	40	5.1	525	3.3	46	8400	Na-Sulphate
4040	31° 57'	46° 31'	Qt	16	26	6	363	2.7	43	7000	Na-Sulphate
4037	31° 44'	46° 41'	Qt	8	120.9	49	65	–	–	65952	Na-Chloride
6032	32° 29'	44° 22'	Qt	27	13.2	3	103	16.3	157	822	Na-Bicarbonate
6043	32° 28'	44° 36'	Qt	23	16.8	2.1	166	–	–	2000	Ca-Sulphate
6052	32° 17'	44° 38'	Qt	22	37.5	2.4	–	–	–	445	Ca-Bicarbonate
6072	32° 20'	44° 57'	Qt	21	16.5	5	164	4.9	52	3300	Na-Sulphate
6117	31° 52'	44° 52'	Qt	–	50	4.2	298	0.5	14	64650	Na-Chloride

…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
6120	32º 00'	44º 58'	Qt	25	60	4.6	324	0.4	18	69672	Na-Chloride
4043	32º 02'	47º 32'	Qt+Bi	22.7	32	5.3	343	1.4	35	10000	Na-Sulphate
4046	32º 22'	47º 20'	Bi	75	81	15	396	1.1	75	2400	Ca-Sulphate
4063	32º 35'	46º 56'	Bi	88.8	80	46	544	1.7	44	845	Ca-Sulphate
6931	31º 59'	44º 59'	Qt	25	42	4	778	5.4	108	47982	Na-Chloride
6932	31º 58'	44º 53'	Qt	20	42	3	778	4.7	90	53878	Na-Chloride
6118	31º 58'	44º 54'	Qt	20	60	2.7	583	2.1	88	64459	Na-Chloride
6119	31º 59'	45º 00'	Qt	53	60	3.2	328	0.3	11	43130	Na-Chloride
4811	30º 58'	47º 43'	Qt	16	24	7.4	657	21	349	4280	Na-Sulphate
7671	30º 40'	47º 53'	Qt	–	45	33	462	15.4	162	3733	Na-Sulphate
4875	30º 22'	47º 42'	Qt	10.6	23	8.1	587	33.6	501	4690	Na-Sulphate
4957	30º 26'	47º 44'	Qt	3	20	1.5	207	2.9	27	14000	Ca-Chloride
7809	30º 15'	47º 50'	Qt	–	21	4	660	7.8	101	25169	Na-Chloride

Pumping test results of some drilled wells in Mukdadiya aquifer within the vicinity of Samara town show that the transmissivity of the aquifer ranges from (3 – 774) m^2/day, permeability ranges from (0.1 – 55.4) m/day, well discharges range from (49 – 1452) m^3/day, and static water level ranges from (2 – 95) m; below ground surface (Table 1). The total dissolved solids range from (300 – 12000) mg/l, water type is mainly sulphatic with some chloridic type. Mukdadiya aquifer represents the main aquifer in the left bank of the Tigris River (Ahmad and Al-Jiburi, 2005).

Pumping test results of some drilled wells in Bai Hassan aquifer show that the transmissivity of the aquifer ranges from (4 – 829) m^2/day, permeability ranges from (0.1 – 43) m/day, well discharges range from (20 – 5862) m^3/day, and static water level ranges from (2 – 48) m; below ground surface. The total dissolved solids range from (334 – 11075) mg/l, and the water type is mainly sulphatic with some chloridic type. Bai Hassan Formation represents the main aquifer within the eastern and northeastern areas along highlands (Ahmad and Al-Jiburi, 2005).

Pumping test results of some drilled wells in Quaternary sediments show that the transmissivity of the aquifer ranges from (21 – 555) m^2/day, permeability ranges from (1.5 – 29.7) m/day, well discharges range from (16 – 657) m^3/day, and static water level ranges from (1.5 – 21) m; below ground surface (Table 1). The total dissolved solids range from (458 – 7000) mg/l and the water type is mainly sulphatic; rarely is chloridic type. Quaternary sediments represent the groundwater aquifer in different areas, where their thicknesses are suitable for water bearing (Ahmad and Al-Jiburi, 2005).

With respect to the groundwater flow, within the vicinity of Baghdad, the following features can be observed: **1)** Influent infiltration takes place from the Euphrates River to areas along its left bank. **2)** The left bank of the Tigris River, upstream of the confluence of Diyala River, and its right bank to the south of Baghdad have effluent character; the same characters occur at both banks of Diyala River. This phenomenon is probably enhanced by irrigation activities within the northeastern portion of the area within Tigris and Diyala Rivers. During flood seasons, this character might be is changed into influent one. This is probably the case in Tigris River course, south of Baghdad within the right bank area. **3)** Three main piezometric depressions can be observed in the groundwater level within the areas: between Euphrates and Tigris Rivers (southwest of Baghdad), in the right bank area of Tigris River (northwest of Baghdad), and in the southeastern portion of Baghdad (Al-Jiburi, 2004). These features cause the groundwater flow to have different directions (Fig.4).

Quaternary sediments represent the main upper aquifer within the vicinity of Baghdad. Pumping test results of some drilled wells that discharge from this aquifer show that the transmissivity ranges from (6 – 1089) m^2/day, permeability ranges from (0.5 – 126) m/day, well discharges range from (7 – 1118) m^3/day, and static water level ranges from (1.0 – 15.2) m; below ground surface. The total dissolved solids range from (< 1000 – 42312) mg/l and the water type is mainly sulphatic and chloridic water (Fig.5) (Al-Jiburi, 2004). Water of low salinity might be found locally throughout many regions; particularly in areas close to rivers and irrigation channels. Along banks of rivers and irrigation channels, the natural or artificial conditions enable infiltration of good quality surface water, thus groundwater quality is improved; to some extent. The locations of areas with low salinity are not presented in the Hydrochemical Map (Fig.5), due to scale limitations.

With respect to the eastern portion of the Northern Part of the Mesopotamia Plain, which is represented by Mandali vicinity, the Quaternary sediments are composed of fluvial, sheet run-off and alluvial fan sediments. The groundwater flows have the same trend of surface drainage that is from northeast toward southwest (Fig.4).

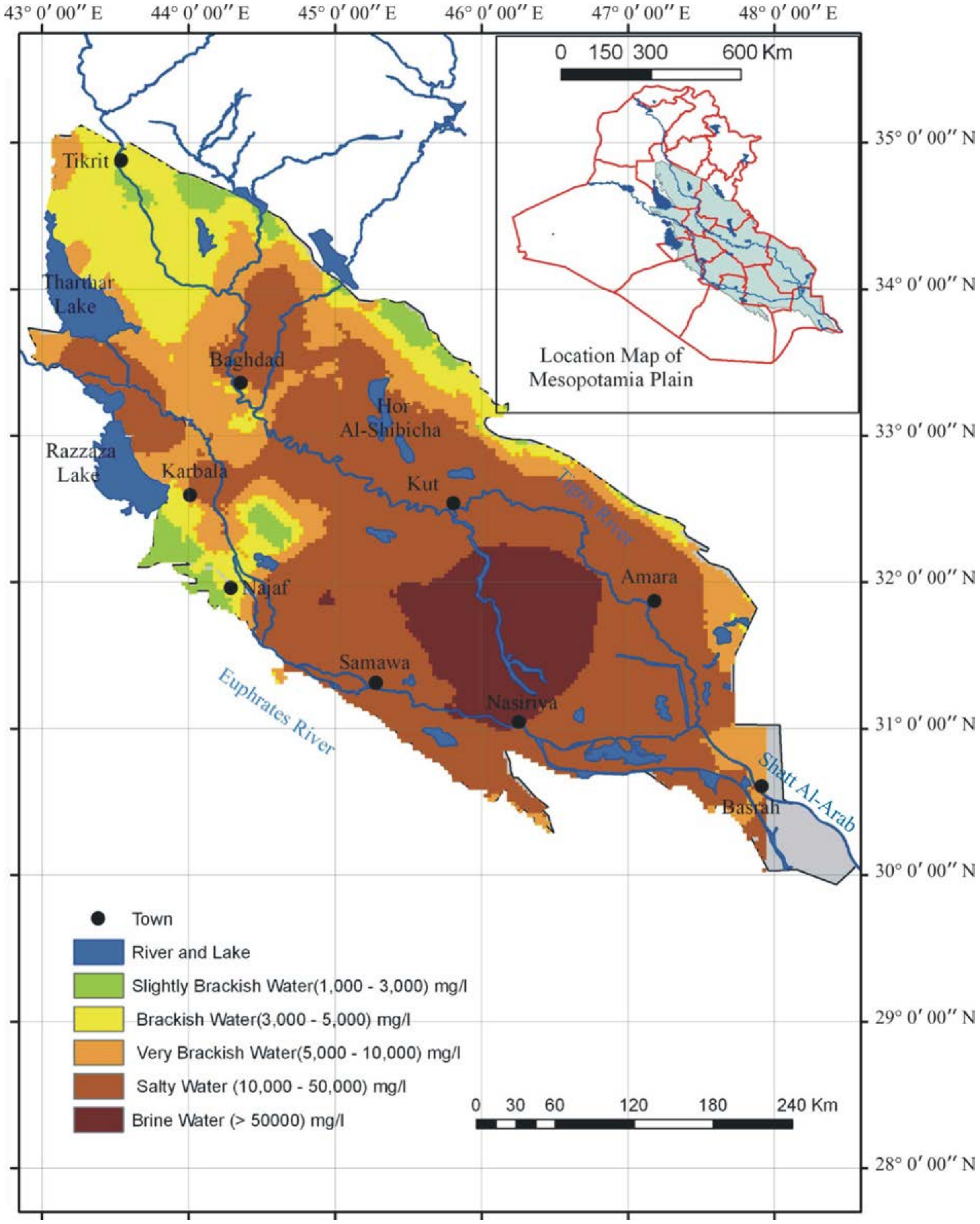

Fig.5: Hydrochemical map of the Mesopotamia Plain, shows salinity zones of groundwater (after documented reports in GEOSURV, int. rep. nos. 2705, 2806, 2865, 2896, 2911, 2915, 2922, 2925, 2941, 2949 and 2964)

The regional discharge zone of Mandali vicinity occurs in the southwestern portion of the Mesopotamia Plain, while the recharge zone is confined mainly to highlands at the eastern border of Iraq with Iran. The main source of the recharge to the groundwater is of river origin, when intensive influent infiltration from rivers during wet seasons were proved in Mandali and Badra vicinities. Direct precipitation throughout the entire Northern Part of the plain also forms a source of recharge. Within the alluvial fans of Mandali vicinity, the groundwater discharge is in form of springs. Discharge in form of evapotranspiration also exists where the groundwater level is near the ground surface.

Pumping test results of some drilled wells, which discharge from the sediments of the alluvial fans, within Mandali vicinity, show that the transmissivity of the aquifer ranges from (4 – 1382) m^2/day, permeability ranges from (0.1 – 374.8) m/day, well discharges range from (100 – 6480) m^3/day, and static water level ranges from (0.6 – 48) m; below ground surface. The total dissolved solids range from (< 1000 – 96000) mg/l and the water types are mainly chloridic and sulphatic water (Table 1) (Al-Jiburi, 2006).

- **Central Part**

The general direction of the groundwater flow in the Mesopotamia Plain, within the vicinity of Karbala city is towards southeast, with some local divergences to the east and south (Fig.4). Influent river phenomenon exists within the Central Part, particularly along the left bank of Euphrates River, as well as along both sides of Al-Hilla River. Recharge to the groundwater is by percolation of surface water from rivers, streams, infiltration of rain and irrigation water. Another source of recharge is possibly in form of lateral and upward leakage from the groundwater of carbonate aquifers at the western part of the Mesopotamia Plain (Araim, 1990 and Al-Jiburi, 2002). The natural discharge of the groundwater is mainly in form of evapotranspiration.

Pumping test results of some drilled wells within the vicinity of Karbala city show that the transmissivity of the aquifer ranges from (10 – 165) m^2/day, permeability ranges from (1 – 27) m/day, well discharges range from (35 – 596) m^3/day and static water level ranges from (0 – 7) m; below ground surface. The total dissolved solids range from (< 1000 – 42200) mg/l and the water type is mainly chloridic with sulphatic water type within the areas along Euphrates River (Al-Jiburi, 2002) (Fig.1). Better quality of groundwater with lower salinity can be found at shallow zones in the areas where influent infiltration from irrigation channels and rivers exist; also the type of the water may vary considerably.

The direction of the groundwater flow in the Mesopotamia Plain, within the vicinities of Kut city and Ali Al-Gharbi town is generally from the highlands, in the eastern and northeastern areas, towards south and southwest (Fig.4). In the area north and northeast of Kut city, a hydraulic depression was observed, where the flow of the groundwater have different trends, towards this depression. Also there are another two depressions: the first one is between Tigris and Al-Ghar'raf Rivers (Hor Al-Shuwaicha) and the second one is southwest of Kut city, between Nu'maniyah and Afaq (Hor Al-Dalmaj), where the flow is from different directions toward these depressions. All these depressions represent zones of groundwater discharge, where the effect of the evaporation on the surface water and groundwater is high, particularly during dry seasons. The main source of the recharge to the groundwater is from influent infiltration of rivers and irrigation channels, as well as from direct rainfalls.

Pumping test results of some drilled wells within the vicinities of Kut and Ali Al-Gharbi show that the transmissivity of the aquifer ranges from (13 – 742) m^2/day, permeability ranges from (0.8 – 72) m/day, well discharges range from (132 – 864) m^3/day, and static water level ranges from (2 – 14) m; below ground surface (Al-Jiburi, 2005a and b). The total dissolved solids range from (< 1000 – 149000) mg/l (Table 1 and Fig.5), and the water type is mainly chloridic with sulphatic type, enclosed mainly along the highland areas.

Generally, the salinity of the groundwater increases from highland areas, in the east towards the Mesopotamia Plain (Fig.5). In the areas close to rivers and irrigation channels, there is a possibility to find good quality of groundwater with suitable salinity, where a phenomenon of enhanced influent infiltration from rivers exists. Accordingly, three areas are considered as promising zones: **1)** part of the left bank of the Tigris River between Azizziyah and Kut, **2)** the area northwest of Afaq that belongs to the irrigation system fed from Hilla River, and **3)** the area just along Al-Gar'raf River banks (Araim, 1990 and Al-Jiburi, 2005a and b).

▪ **Southern Part**

The coverage area of Nasiriyah, Amara, Souq Al-Shiyoukh and Basrah Quadrangles (scale 1: 250 000) within the Mesopotamia Plain, is covered by vast marshy areas, particularly within Nasiriyah and Amara Quadrangles. The general trend of the groundwater flow is towards south, southeast and southwest. Several piezometric depressions occur in the area along Al-Ghar'raf, Tigris and Euphrates Rivers. These depressions coincide with the most surface depressions, where marshes and swamps exist, and represent groundwater discharge zones. The contact of the plain, in its southwestern side with the carbonate aquifers of the Southern Desert forms an important hydrogeological condition, within this region. Along this contact, zone of springs occurs, which is considered as a zone of groundwater discharge of the Iraqi Southern Desert. The area along this contact is also characterized by the presence of sabkhas and mud flats, where the groundwater reaches to ground surface by upward leakage, it is also characterized by the presence of self-flowing wells (Al-Jiburi and Al-Basrawi, 2001; Al-Wa'ily *et al*., 2002; Al-Basrawi, 2005, and Al-Jiburi and Al-Basrawi, 2008). In this region an assumed tectonic disturbance occur, where intensive fracture systems exist (Araim, 1990).

The groundwater movement concerning the Mesopotamia Plain in the Southern Part is of multi directions, where many expressive hydraulic depressions exist (Fig.4). In the vicinities of Diwaniya and Samawa cities, three expressive depressions are distinguished: **1)** along the right bank of the Euphrates River (southeast of Samawa), **2)** between Al-Hilla and Euphrates Rivers (southeast of Diwaniya), and **3)** in the central portion of the plain between Al-Ghar'raf and Euphrates Rivers. These depressions, most likely represent discharge zones of the groundwater. The regional groundwater flow within the southwestern portions of the plain is towards north and northeast initiated from the Southern Desert (Fig.4). Hor Al-Hammar forms a discharge zone in the area. Near Basrah city, the flow is towards east and southeast, it is influenced by the drainage effect of the low land areas of the Arabian Gulf. In other parts of Basrah Quadrangle, as far as the plain is concerned, the flow of the groundwater relatively coincides with the surface water flow of the Euphrates River and Shatt Al-Arab (Fig.4).

Pumping test results of some drilled wells within the Southern Part of the Mesopotamia Plain show that the transmissivity of the aquifer ranges from (36 – 439) m^2/day, permeability ranges from (1.1 – 36.6) m/day, well discharges range from (65 – 528) m^3/day, and static water level ranges from (2 – 8) m; below ground surface (Al-Wa'ily *et al*., 2002; Al-Jiburi, 2005c; Al-Basrawi, 2006 and Al-Jiburi, 2008). The total dissolved solids range from (2600 – 82000) mg/l (Table 1 and Fig.5), the water type is mainly chloridic with sulphatic type, mainly along the eastern borders with the highland areas.

DISCUSSION

The main important factors that affect the salinity of the groundwater in the Mesopotamia Plain are:

Location of the Mesopotamia Plain: The Mesopotamia Plain forms mainly the central and southern parts of the Iraqi territory; it consists of various (more or less) independent aquifer systems or sub-systems and represents the main regional groundwater discharge zone of the whole Mesopotamian Aquifer Mega System.

The Geological Nature: The nature of the sediments of the Mesopotamia Plain is characterized mainly by lateral and vertical abrupt changes in sediment sequences. The plain is considered as continuously subsiding zone, with thick sequence of Paleogene and older formations, which are covered by Quaternary sediments. The thickness of the Quaternary sediments increases from Himreen Mountain, in the north and northeast, where Neogene pre-Quaternary rocks croup out, to the south and southwest. In the vicinity of Baghdad, the thickness of the Quaternary sediments is estimated to reach some (50 – 80) m (Krasny *et al*., 2006 in Jassim and Goff, 2006). The thickness of flood plain sediments may exceed 200 m, in the southeastern part of the aquifer system. Quaternary sediments of the plain are formed by rapidly alternating horizons of clay, silty clay, clayey silt, silt, sand and gravel (Fig.2). Sand and gravels represent the groundwater aquifers, while clay, silty clay, clayey silt and silt represent aquitards (Fig.3). On regional scale, a hydraulic connection within the entire Mesopotamian Aquifer System of Iraq can be assumed. Although a considerable variation occur in lithological sequences of Quaternary sediments, there are several general hydrogeological features, which can be noticed. The less permeable sediments, almost everywhere, form regionally extended aquitards in the upper part of the sequences. The thickness of this upper aquitard usually reaches 10 m or more, and somewhere even up to 20 m. The upper aquitard is underlain by an aquifer of total thickness of many tens of meters in Tigris basin within the vicinities of Baghdad and Mandali (Al-Jiburi, 2004 and 2006). In the vicinity of Kut, the interconnected aquifer; of the Tigris basin reaches its maximum thickness of at least 200 m. It is formed mainly by fine and middle grained sands with intercalated layers of silty clay and clayey silt of different thicknesses and forms less permeable bodies of aquitards, but sandy layers are mostly thicker, reaching usually few tens of meters (Al-Jiburi, 2005a and b and Krasny *et al*., 2006 in Jassim and Goff, 2006). Alluvial fans border the plain in different areas. The extreme northern part of the Mesopotamian aquifer system is generally built by alluvial fans originating from the Himreen Mountain. The largest and oldest of these fans took its origin at Al-Fatha, north of Baiji town; the thickness of the fan sediments exceeds 50 m (Krasny *et al*., 2006 in Jassim and Goff, 2006). A narrow belt of discontinuous fans border the plain in the northeast and east along the anticlinal structure of Himreen Mountain extending from Mandali to Badra – Zurbatiya and Teeb vicinities. On the southwestern border of the Mesopotamia Plain, Wadi Al-Batin fan exists, which hydrogeologically belongs to the Southern Desert aquifers.

Climatic Conditions: The climatic conditions and the high rate of evaporation, cause increase of groundwater salinity, especially in the low land areas and when the static water level becomes near the ground surface.

The direction of the groundwater flow is towards the Mesopotamia Plain from all neighboring regions. Within the plain, the piezometric surface of the groundwater is generally inclined from north and northwest towards south and southeast. It is < 200 m (a.s.l.), near Makhoul Mountain, decreasing slightly towards south and southeast to reach 2 m (a.s.l.), near Basrah city. On regional scale, the piezometric surface can be considered more or less continuous, as there is a hydraulic connection of the entire aquifer system within the plain. However, abrupt changes in lithologic sequences may cause discontinuities in the groundwater aquifer distributions. Taking into consideration the lithology of both Quaternary and pre-Quaternary sediments, especially Bai Hassan and Mukdadiya formations. There is no reason to assume hydraulic separation between them, due to the similarity between their lithological constituents in most cases. In addition, there is a hydraulic interconnection between the groundwater and surface water; to different extents. Therefore, rivers and channels of influent and effluent characters form important external and internal hydraulic boundaries in the aquifer system of the plain.

The salinity of the groundwater increases from north to south and from borders of the Mesopotamia Plain towards its central parts; within the discharge zones (Fig.5). In the northern part of the plain, the salinity ranges generally from (less than 1000 – 10000) mg/l and more, but the most frequent values are between (2000 – 4000) mg/l; within the vicinity of Samarra town and becomes higher in Baghdad vicinity. In the central and southern parts of the plain, the salinity generally increases south and eastwards reaching usually some tens of thousands of mg/l (brine water) within depressions and low land areas of the marshes, which represent discharge zones (Al-Jiburi, 2005a, b and c, and 2008).

Generally, dissolved solids have been brought by the groundwater within the Mesopotamia Plain from different directions and deeper aquifers and/ or horizons. The type of the groundwater changes from sulphatic water; within the northern part of the Mesopotamia Plain to mainly chloridic water type; within the central and southern parts of the plain.

The applied irrigation system within the Mesopotamian Plain causes lost of high amounts of fresh water that infiltrates downward and is mixed with the groundwater and causes increase in the groundwater level, and then deteriorated with the saline groundwater.

Generally, groundwater of low salinity may occur in areas where influent seepages from rivers and irrigation channels take place, and within areas along borders with the Low Folded Zone, where recharge areas are considered.

Generally, more active hydrogeological, hydrological, irrigational and agricultural management is needed in order to decrease salination or to reduce deterioration of soils and groundwater within the Mesopotamia Plain.

The principal hydrogeological problems of practical importance in the Mesopotamia Plain are those connected with land reclamation and the groundwater supply. As to land reclamation, both irrigation and drainage possibilities depend directly or indirectly on the hydrogeological conditions. Excess irrigation would cause rising of the groundwater level and consequently increases the salt content in the soil by evaporation, particularly during hot seasons. To avoid soil salination, the groundwater level is to be decreased below its critical depth, which can be achieved through drainage systems (horizontally and/ or vertically by wells). Achievement of such systems requires a special hydrogeological and hydrological investigation.

CONCLUSIONS

- The Mesopotamia Plain is totally covered by Quaternary sediments. These sediments are composed of alternation of clay, silty clay, clayey silt, silt, sand and gravel. Aquitards are represented mainly by clay, silty clay, clayey silt and silt, while sand and gravel form the aquifers, within the plain.
- Quaternary sediments of the Mesopotamia Plain are considered regionally as a lithologically complex aquifer system. These sediments have an abrupt change in their lithologic characteristics both laterally and vertically, so that no homogenous lithologic unit was revealed throughout the plain.

- There is a hydraulic continuity within the entire Quaternary aquifer system in the Mesopotamia Plain, this means that all aquifers are in hydraulic continuity. The degree of continuity differs locally, depending on the characteristics of water bearing sediments.
- It is also assumed the presence of hydraulic continuity between surface water (rivers, lakes and irrigation channels) and the groundwater aquifers; to substantial extent. Rivers, lakes and irrigation channels form important hydraulic boundaries to the whole aquifer system. Therefore, effluent and influent rivers phenomena exist throughout the Mesopotamia Plain.
- Another assumption is that, Quaternary Aquifer System in the Mesopotamia Plain and the underlying Bai Hassan, Mukdadiya and other aquifers are in hydraulic continuity, so that, the water level for these aquifers is considered regionally the same and also continuous.
- The groundwater level fluctuations throughout the Mesopotamia Plain depend on natural conditions and to some extent on artificial conditions. The natural conditions are rainfall quantity, distribution, and rate of evapotranspiration. Along rivers, streams and irrigation channels, the groundwater fluctuations depend largely on the surface water fluctuations. The artificial conditions are the groundwater withdrawal through wells and excess of irrigation. Maximum groundwater level rise is during winter and spring due to rainfall, as well as, water in form of influent seepage from rivers, streams and irrigation channels percolating underground to reach the groundwater aquifers. During summer and autumn, when there is a lack of water recharge and there is high rate of evapotranspiration, then the groundwater has the lowest levels.
- The water bearing Quaternary sediments of the Mesopotamia Plain are quantitatively promising, but the problem with the quality of the groundwater, high salinity prevails throughout the plain, which is unsuitable for domestic uses and even irrigation purposes. But, the groundwater, which is close to rivers and main irrigation channels may be of better quality for exploitation, particularly where phenomenon of induced seepage of fresh water exists, and in areas along the Low Folded Zone, where recharge water zones are considered.
- Low permeable sediments form, almost everywhere regionally extended aquitard, in the upper part of the sequences. The thickness of the upper aquitard reaches 10 m or more, somewhere even up to 20 m, within the Central and Southern Parts of the Mesopotamia Plain. The upper aquitard is underlain by an aquifer with total thickness that ranges between many meters to many tens of meters, depending on the sediments thickness in the plain.
- Direction of the groundwater flow is towards the Mesopotamia Plain, from all neighboring regions. The plain represents a regional discharge zone of the whole Mesopotamian Aquifer Megasystem of Iraq. The piezometric surface of the groundwater within the plain is inclined from north and northwest towards south and southeast.
- Salinity of the groundwater increases from the recharge areas, mainly in the northern and northeastern areas, along the Low Folded Zone, and along western and southwestern areas bordering the Western and Southern Deserts, towards the discharge areas within the plain.
- Chemical quality of the groundwater changes from sulphatic to chloridic type, from recharge to discharge areas, in accordance with the groundwater movement.

RECOMMENDATIONS

The followings are recommended:

- Monitoring of the groundwater level in selected and representative wells, within the Mesopotamia Plain, in order to acquire new information, which are necessary for executing groundwater regime, and to detect any variations that occur in the groundwater level.
- Continuous collection and analyses of the groundwater samples from representative wells, within the Mesopotamia Plain, based on monthly or seasonal bases, as available aid to

predict any change in chemical composition and water types, which offer an indispensable framework for better water management.

- Drilling deep observation wells, in selected areas, and where no wells are available, especially within assumed promising areas, to acquire new data, to evaluate the hydrogeological and hydrochemical conditions, more precisely and to predict or find new promising areas, with good quality groundwater, mainly for agricultural purposes.
- Construction of small dams on main valleys within the eastern borders of the map area along the Low Folded Zone 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.
- Establishing of gauging stations on basins of valleys, along the Low Folded Zone, in order to record the run off in valleys, this will aid in evaluation of the groundwater resources.
- Installation of hydro-meteorological stations, aiming to acquire observations of the hydro-meteorological parameters, which will aid, also in evaluation of the groundwater resources.
- Preventing the products of urbanization and industrialization, which have caused serious environmental impacts, by contaminating the groundwater within the Mesopotamia Plain.
- Preventing heavy pumping in zones with potentially sufficient groundwater resources that induced along influent river courses and irrigation channels with good quality water. Heavy pumping may gradually deteriorate the groundwater quality and extract volumes of less mineralized (fresh) groundwater.
- To avoid more soil salination, the groundwater depth has to be below its critical depth, which can be achieved through activating old drainage systems or by achievement of new drainage systems (horizontally and/ or vertically by wells).
- More developed management for water resources, irrigational and agricultural techniques in Iraq must be applied to avoid more deterioration of water quality and soils, in accordance with more developed countries, especially in the Mesopotamia Plain.

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