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DOHUK SYNCLINE AS AN ARTIFICIAL RECHARGE AQUIFER, NORTHERN IRAQ

Nabeel K. Al-Azzawi*[1], Myasar S. Al-Saraj[1] and Jalal H. Younis[2]

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ABSTRACT

Artificial recharging was carried on Dohuk Syncline. The syncline is located between Baikher Anticline to the north and Dohuk Anticline to the south. Dohuk city occupies the surface area of this structure. The syncline extended about 17.1 Km in a generally east-west direction. It is a narrow syncline due to its location between two steep limbs of Baikher and Dohuk anticlines. Moreover, the syncline is very narrow near Itut village which represents the eastern plunge of the syncline and becomes wider towards the west near Aloka village. Alluvial deposits, vegetation and urbanization cover the surface of this syncline where the Fatha and ridges of Pila Spi formations surround it.

The distinct property of the Pila Spi Formation of being well-jointed limestone makes it an excellent and adopted aquifer for water storage. Moreover, it underlys Fatha Formation and overlys Gercus Formation, which are considered as aquitard and aquiclude confining beds respectively.

The geometry and the shape of this syncline were determined by mathematical (Lagrangian Interpolation) method. It was used to obtain the subsurface or the hidden parts of the syncline depending on the bore-holes data and the available seismic sections. This method was applied on three transverse sections. Finally, SURFER program was utilized to display the final geometrical shape of Dohuk Syncline in three dimensions.

The project is an attempt to determine the capability of this syncline for artificial recharge of water and to be used as an aquifer for the city domestic uses. The size of this aquifer is estimated as 7.38 Km^3 and the pore size is 1476452509.2 m^3 depending on the limestone porosity of 20%. In addition, the infiltration of rainfall is determined as 2521116 m^3/year. Consequently, the aquifer needs very long time to be fully recharged. Subsequently, natural recharging is not enough and necessitates a proposal for recharging the aquifer artificially. Moreover, some ideas were proposed to achieve this purpose.

[1] Department of Geology, University of Mosul, Iraq, *e-mail: nabazzawi@yahoo.com
[2] Department of Applied Geosciences, University of Dohuk, Iraq

طية دهوك المقعرة كخزان جوفي اصطناعي، شمالي العراق

نبيل قادر بكر العزاوي، ميسر سمير السراج و جلال حسن يونس

المستخلص

أختيرت طية دهوك المقعرة كمشروع لاستخدامها لغرض الخزن الاصطناعي للمياه. تنحصر طية دهوك بين طيتي بيخير ودهوك المحدبتين. وتمتد مدينة دهوك على سطح هذه الطية التي تمتد على طول ١٧.١ كم باتجاه شرق- غرب وهي طية ضيقة لوقوعها بين جناحين عاليي الميل للطيتان المحدبتان سابقتي الذكر، وتضيق هذه الطية باتجاه الشرق ويزداد عرضها باتجاه الغرب. وقد غطت الترسبات الحديثة، والغطاء النباتي والتوسع الحضري اجزاء واسعة من سطح هذه الطية بينما ينكشف تكويني البلاسبي الفتحة حولها.

ان الصفة المميزة لتكوين البلاسبي كونه جيد التكسر (الفواصل) لذا فانه يمكن ان يكون خزان للمياه صناعيا. اضافة الى وجود تكويني الفتحة فوق هذا التكوين والجركس تحته ما جعله يتصف بمواصفات الخزان الارتوازي.

ان شكل وهندسية هذه الطية قد حسب بطريقة رياضية هي طريقة اندراج لاكرانج وهي احد طرق التحليل العددي. وقد استعملت لإيجاد هندسية الاجزاء المطمورة من الطية واعتمادا على المعلومات المتوفرة من الآبار المائية المحفورة وعلى المقطع الزلزالي. كما واستخدم البرنامج SURFER لعرض شكل وهندسية هذه الطية في ثلاث مقاطع وشكلها الكامل. كما استعملت طريقة المربعات الصغرى Least Squares Method لحساب مساحات المقاطع.

المشروع هو محاولة لدراسة امكانية استخدام هذه الطية كخزان جوفي للمياه وبالتالي استخدامه كمشروع يغذي المدينة. لقد قدر حجم الخزان بـ (٧.٣٨) كم٣ وحجم الفراغات بـ (١٤٧٦٤٥٢٥٠٩.٢) م٣ اعتمادا على ان مسامية الحجر الجيري وهي ٢٠%. وقد حسب مقدار ترشيح مياه الامطار بـ (٢٥٢١١١٦) م٣/سنة. وهذا يجعل الخزان ان يحتاج فترة طويلة جدا لكي يمتلئ. لذا التغذية الطبيعية ليست كافية ومن الضروري اقتراح تخزين المياه فيه اصطناعيا. وقد عرض المشروع بعض المفترحات بذلك.

INTRODUCTION

The study area is located in the northern part of Iraq within Dohuk governorate. It is delimited by the longitudes 42° 57' 29" – 43° 04' 00" East, and Latitudes 36° 50' 10" – 36° 53' 15" North (Fig.1). The study area is about 67 Km^2, comprising the entire district of Dohuk syncline which approximately has17.1Km length and (3.5 – 8) Km width (Fig.2). The main body of this syncline is subsurface except the northern and southern ridges of limestone rocks.

Stratigraphically, the area of this syncline is composed of several geologic formations ranging in time span within the Tertiary period. It embraces the following formations in ascending order. The Gercus Formation (Middle Eocene) is composed of red and purple shales, mudstones, sandy and gritty marls. The formation comprises lenses of Avanah Limestone. The Pila Spi Formation (Middle to Late Eocene) consists of well-jointed beds, hard, chalky appearance, porous or vitreous, bituminous or white and poorly fossiliferous limestone. The Fatha Formation (Middle Miocene) consists of gypsum and salt intercalated with thin beds of limestones, marls, siltstone and sandstone. Finally the Injana Formation (Late Miocene) is composed of sub-continental and continental purple, red, brown and grey marls, silts, siltstones, sandstones and grits. The brief description of the lithology of each formation was taken from Van Bellen *et al*. (1959) and Jassim and Goff (2006).

There is no specific geologic study for this syncline, the few of them focused on the northern Baikher and the southern Dohuk anticlines. The southern limb of Baikher and the northern limb of Dohuk anticlines had made the northern and southern limbs of this syncline connected by subsurface narrow hinge zone due to the narrow syncline. The importance of studying this syncline is to evaluate how artificially this aquifer can be recharged. For this

purpose geometric simulation of fold geometry was applied. Calculations for the syncline parameters were done and some opinions for artificial recharging were recommended.

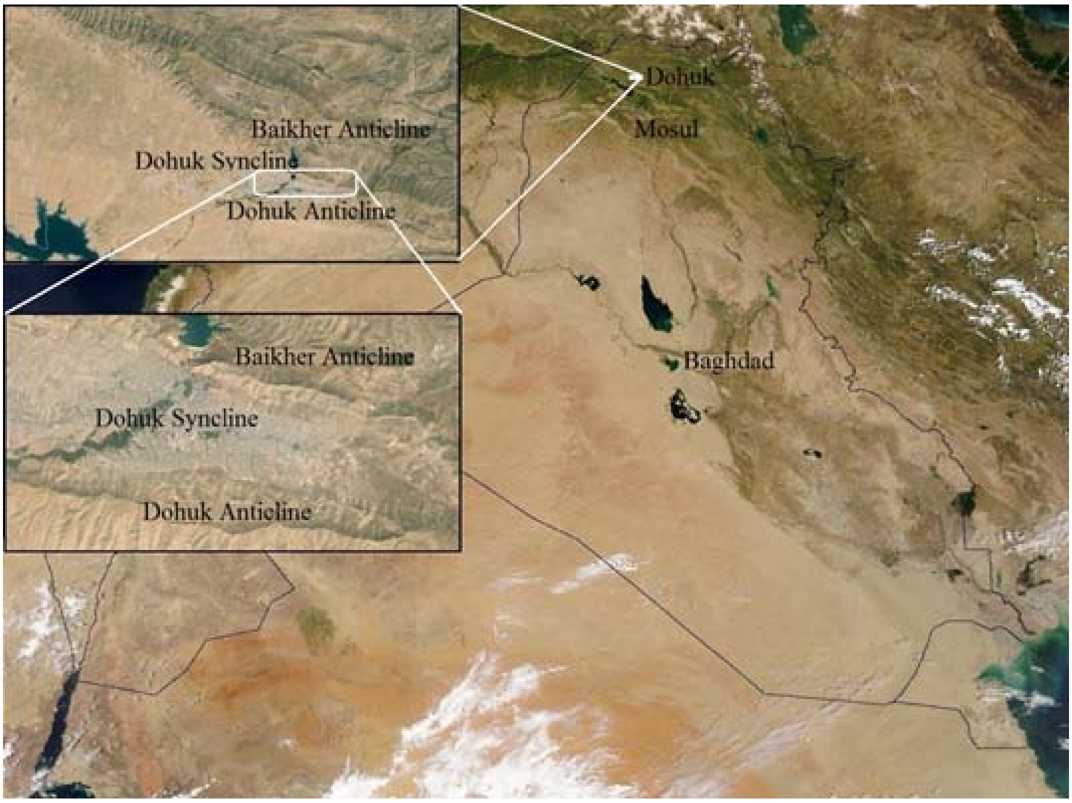

Fig.1: Location map of the study area

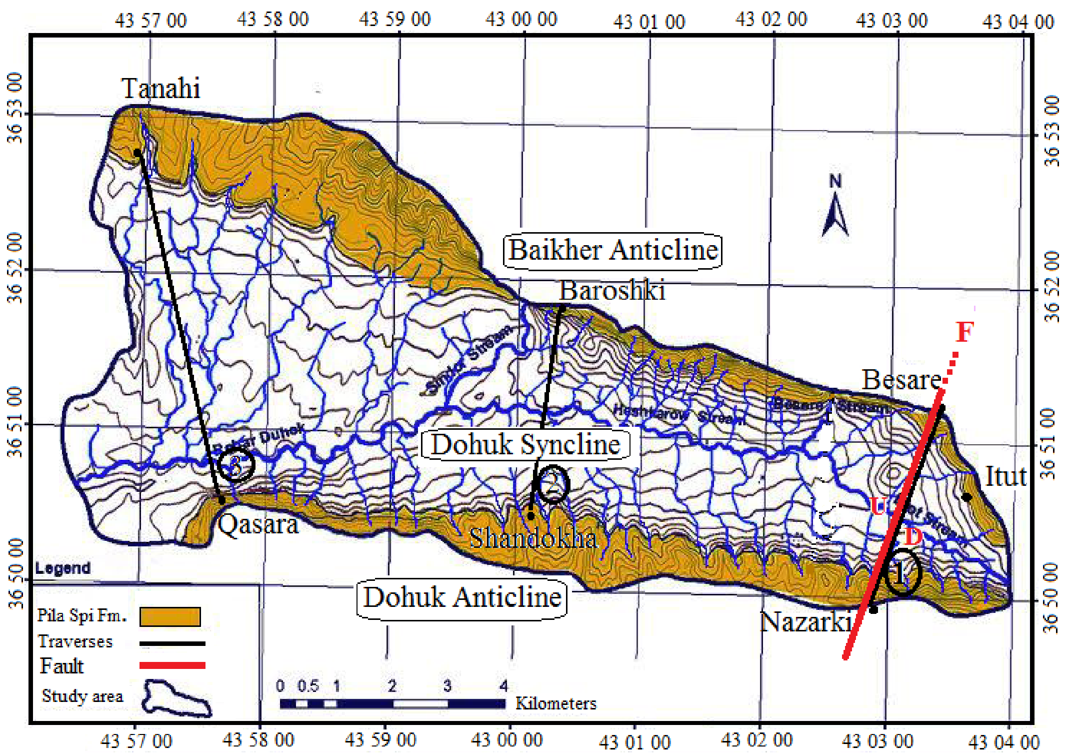

Fig.2: Details of the study area

Three previous studies involved the surrounding areas. The first was made by Al-Azzawi and Al-Hubiti (2009). They studied the tectonic style variations of Baikher Anticline along its axis and described the anticline as a double plunging asymmetrical fold. They divided the anticline into four parts with different vergence due to different listric fault orientations influencing them. In addition, this study showed that the anticline verging towards the south (the southern limb is steeper). The second study was carried out by Hamdoon (2002). He described the geomorphology of Dohuk Anticline using satellite images. Whereas the third one (Al-Kadhum, 2009) studied the structure and tectonics of Dohuk Anticline. It is generally, concluded that the fold is verging towards the north (the northern limb is the steeper).

Nevertheless, the syncline has two steep limbs but it is also asymmetrical with a steeper southern limb.The syncline is very narrow in its eastern part while it becomes wider in the west. Because the syncline is covered by alluvial deposits and urbanization, the syncline geometry was determined by a mathematical method to interpolate the subsurface or the hidden parts and to decide whether it can be used as artificial recharged aquifer or not.

METHODOLOGY

Two main numerical analysis methods are applied in the present work. The first is Lagrangian interpolation whereas the second is Least Square method.

- **Lagrangian Interpolation method**

The theory of this method was described by Gerald and Wheatly (1984). In the present work this method was used to determine the missing or hidden subsurface parts of the syncline. Data were collected in three ways; first, dips and dip directions of beddings are measured for the exposed rocks, the second is the available groundwater bore-holes distributed in the area, third, the analysis of a seismic section. The data are collected from the Pila Spi Limestone which is adopted as a studied aquifer (Table 1).

The application of this method is summarized by applying the collected data (raw data) into mathematical equations in each traverse. So that data must be arranged in this form:

$$X: \quad X_0 \quad X_1 \quad X_2 \text{ -------- } X_n$$

$$F(X): \quad F(X_0) \quad F(X_1) \quad F(X_2) \text{ -------- } F(X_n)$$

And the mathematic equations are:

$$P_n(X) = F(X_0)\, L_0(X) + F(X_1)\, L_1(X) + F(X_2)\, L_2(X) + \text{---} + F(X_n) L_n(X) \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

Or:

$$P_n(X) = \sum_{i=0}^{n} F(Xi) L_i(X) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

And:

$$L_i(X) = \frac{(X-X0)(X-X1)(X-X2)\ldots(X-Xi-1)(X-Xi+1)\ldots\ldots(X-Xn)}{(Xi-X0)(Xi-X1)(Xi-X2)\ldots(Xi-Xi-1)(Xi-Xi+1)\ldots(Xi-Xn)} \quad \ldots\ldots\ldots 2$$

Table 1: Data and data processing
(The datum is the earth's surface and AD means above datum)

Lower surface of Pila Spi Fm.				**Upper surface of Pila Spi Fm.**		
The first traverse						
Raw Data						
No.	**Distance (X)**	**Depth (Y)**		**No.**	**Distance (X)**	**Depth (Y)**
1	834.9	155		1	562.276	155
2	824.1636	775		2	638.94	775
3	690	1395		3	549.49	1395
4	554.76	2015		4	408.92	2015
Interpolated Data after Lagrangian Application						
1	0	582.58		1	0	364.98
2	155	605		2	155	407.44
3	465	617.82		3	465	455.47
4	775	597.21		4	775	463
5	1085	544.24		5	1085	440.42
6	1395	500		6	1395	398.18
7	1705	445.55		7	1705	346.66
8	2015	402		8	2015	296.31
The second traverse						
Raw Data						
No.	**Distance (X)**	**Depth (Y)**		**No.**	**Distance (X)**	**Depth (Y)**
1	531.75	200		1	531.75	21
2	3105.42	211		2	3105.42	11
3	3211.77	204		3	3211.77	4
Interpolated Data after Lagrangian Application						
1	0	154.53		1	0	-15.09
2	212.7	174.49		2	212.7	0.911
3	425.4	192.09		3	425.4	14.82
4	638.1	207.31		4	638.1	26.65
5	850.8	220.17		5	850.8	36.38
6	1063.5	230.67		6	1063.5	44.02
7	1276.2	238.79		7	1276.2	49.57
8	1488.9	244.55		8	1488.9	53.03
9	1701.6	247.95		9	1701.6	54.40
10	1914.3	248.97		10	1914.3	53.68
11	2127	247.64		11	2127	50.87
12	2339.7	243.93		12	2339.7	45.96
13	2552.4	237.86		13	2552.4	38.97
14	2765.1	229.42		14	2765.1	29.88
15	2977.8	218.61		15	2977.8	18.70
16	3190.5	205.44		16	3190.5	5.44
17	3403.2	189.90		17	3403.2	-9.9

Continue Table 1:

Data and data processing						
Lower surface of Pila Spi Fm.				**Upper surface of Pila Spi Fm.**		
The third traverse						
Raw Data						
No.	**Distance (X)**	**Depth (Y)**		**No.**	**Distance (X)**	**Depth (Y)**
1	170.16	120		1	170.16	6
2	999.69	140		2	999.69	40
3	1914.3	152		3	1914.3	43
4	3084.15	174		4	3084.15	55
5	4254	140		5	4254	40
Interpolated Data after Lagrangian Application						
1	0	111.30		1	0	-10.54
2	212.7	121.82		2	212.7	9.46
3	425.4	129.20		3	425.4	23.29
4	638.1	134.33		4	638.1	32.32
5	850.8	137.98		5	850.8	37.75
6	1063.5	140.78		6	1063.5	40.66
7	1276.2	143.25		7	1276.2	41.95
8	1488.9	145.78		8	1488.9	42.39
9	1701.6	148.65		9	1701.6	42.59
10	1914.3	152		10	1914.3	43
11	2127	155.85		11	2127	43.92
12	2339.7	160.12		12	2339.7	45.51
13	2552.4	164.58		13	2552.4	47.77
14	2765.1	168.88		14	2765.1	50.55
15	2977.8	172.57		15	2977.8	53.55
16	3190.5	175.04		16	3190.5	56.31
17	3403.2	175.59		17	3403.2	58.23
18	3615.9	173.38		18	3615.9	58.54
19	3828.6	167.45		19	3828.6	56.34
20	4041.3	156.72		20	4041.3	50.56
21	4254	140		21	4254	40
22	4466.7	126		22	4466.7	28
23	4679.4	112		23	4679.4	18

Continuously, the substitution of X values in equation (2), and the substitution of L_i (X) and F (X_i) values in equation (1) form guides to find the value of Pn (X). Therefore, the function of the fold profile is determined. This function in this form is very complicated for manual determination of parameters, so a clip of a GWBASIC computer program LAG has been used to determine the values of (Y) for any value of (X). This means that any subsurface depth (Y) of the syncline profile can be interpolated by substituting the related distance (X). The software SURFER11 was used to display the shape of the syncline for the upper and lower surfaces of Pila Spi Formation in each traverse.

- **Least Square Method**

The description of this method is given in Gerald and Wheatly (1984), the application was described by Al-Azzawi (2004). For simplicity the application of (3*3) matrix is described hereinafter:

1- Finding the summations of (X and Y) below, which were found by Lagrangian method:

$$\Sigma Xi \quad \Sigma Xi^2 \quad \Sigma Xi^3 \quad \Sigma Xi^4 \quad \Sigma Yi \quad \Sigma Xi\,Yi \quad \Sigma Xi^2\,Yi$$

2- Making equations from these parameters according to Least squares formula:

$$a_0 N + a_1 \Sigma Xi + a_2 \Sigma Xi^2 = \Sigma Yi$$

$$a_0 \Sigma Xi + a_1 \Sigma Xi^2 + a_2 \Sigma Xi^3 = \Sigma XiYi$$

$$a_0 \Sigma Xi^2 + a_1 \Sigma Xi^3 + a_2 \Sigma Xi^4 = \Sigma Xi^2 Yi$$

3- Arranging these equations in a form of matrix as shown below:

$$\begin{matrix} N & \Sigma Xi & \Sigma Xi^2 \\ \Sigma Xi & \Sigma Xi^2 & \Sigma Xi^3 \\ \Sigma Xi^2 & \Sigma Xi^3 & \Sigma Xi^4 \end{matrix} \quad * \quad \begin{matrix} a_0 \\ a_1 \\ a_2 \end{matrix} \quad = \quad \begin{matrix} \Sigma Yi \\ \Sigma Xi\,Yi \\ \Sigma Xi^2 Yi \end{matrix}$$

4- Converting this matrix to the upper triangular form:

$$\begin{matrix} b_{1,1} & b_{1,2} & b_{1,3} & : & b_{1,4} \\ b_{2,1} & b_{2,2} & b_{2,3} & : & b_{2,4} \\ b_{3,1} & b_{3,2} & b_{3,3} & : & b_{3,4} \end{matrix}$$

⇩

$$\begin{matrix} b_{1,1} & b_{1,2} & b_{1,3} & : & b_{1,4} \\ 0 & b_{2,1} & b_{2,3} & : & b_{2,4} \\ 0 & 0 & b_{3,3} & : & b_{3,4} \end{matrix}$$

5- Calculating the values of the coefficients a_1, a_2 and a_3 by back substitution:

$$b_{3,3} * a_2 = b_{3,4} \quad so \quad a_2 = b_{3,4} / b_{3,3}$$

$$b_{2,2} * a_1 + b_{2,3} * a_2 = b_{2,4} \; so \quad a_1 = (b_{2,4} - b_{2,3} * a_2) / b_{2,2}$$

And:

$$b_{1,1} * a_0 + b_{1,2} * a_1 + b_{1,3} * a_2 = b_{1,4}$$

$$\text{So} \quad a_o = (b_{1,4} - b_{1,2} * a_1 - b_{1,3} * a_2) / b_{1,1}$$

6- The (3*3) matrix can be formulated as the following function:

$$\boldsymbol{Y = a_2 X^2 + a_1 X + a_o}$$

But in the present work the matrix (5*5) is applied:

Data processing

– **The first Traverse:** It extends about 3 Km from Nazarki village to Galli Besari. Pila Spi Formation is exposed on the southern limb, whereas small outcrop of Fatha associated with Pila Spi Formation appears on the northern limb. Stereogram for this traverse shows that the syncline is asymmetrical with a steeper southern limb. It also extends west northwest-east southeast and plunging toward east southeast (Fig.3). The results of processing data for the upper and lower surfaces of Pila Spi Formation are listed in (Table 1) and the geometry of the syncline is displayed in Figure (4).

– **The second traverse:** It connects Shandokha with Baroshki villages (4 Km) and only Pila Spi Formation outcrops on both limbs (Fig.2). Data are collected from bore-holes and field measurements of bedding planes. The synclinal axis maintaining its trend remains west northwest-east southeast. After processing the data, distances (X) and depths (Y) of the upper and lower surface of Pila Spi Formation are listed in (Table 1). The shape of the syncline is displayed in Figure (5).

– **The third traverse:** This traverse extends about 6 Km and connects Qasara that represent the western plunge of Dohuk Anticline and Tanahi area which is part of Baikher Anticline. Data are collected from bore holes and field measurements of bedding planes. The axis of the syncline was rotated in this traverse to be east northeast-west southwest. Results (distance and depth) for the upper and lower surfaces of Pila Spi Formation are shown in (Table 1) and Figure (6).

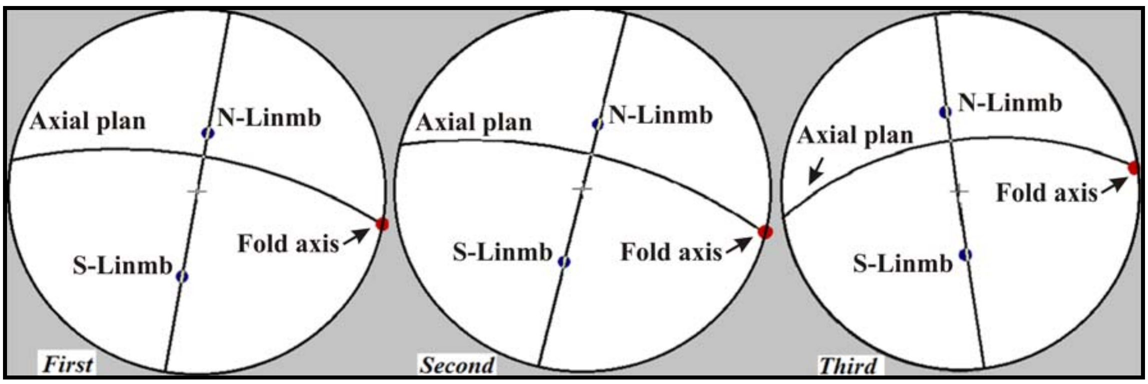

Fig.3: Sterogram for Dohuk Syncline in the three traverse

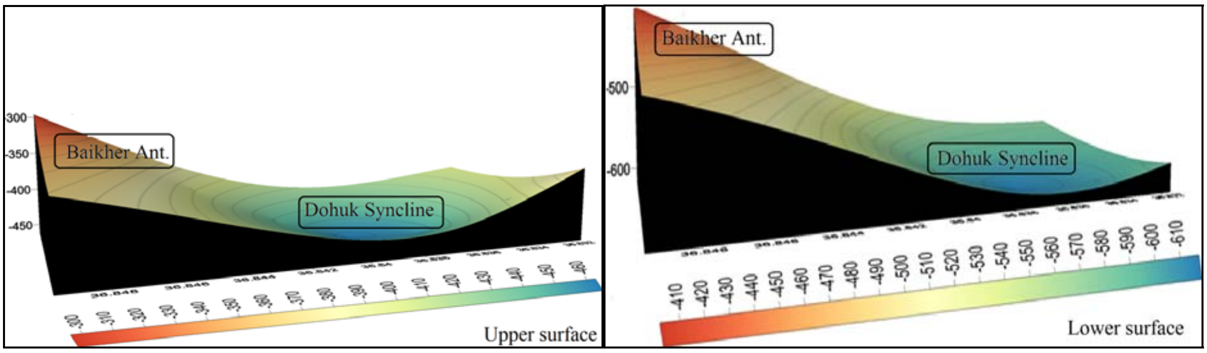

Fig.4: Block diagram for Pila Spi Formation In the first traverse

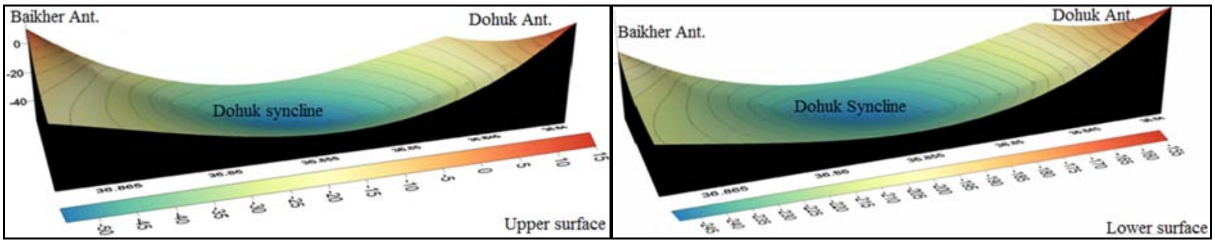

Fig.5: Block diagram for Pila Spi Formation In the second traverse

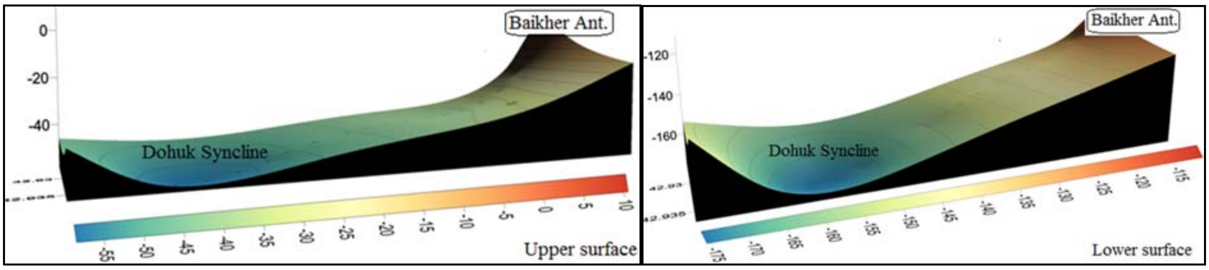

Fig.6: Block diagram for Pila Spi Formation In the third traverse

The compilation of the three traverses gives the entire shape of the syncline (Fig.7), the figure shows that there is a large difference in depths in the western part of the syncline and the shape of this structure becomes more or less abnormal. The main reason for this abnormality is the presence of wrench faults with considerable vertical displacements. This fault transverses the syncline and called Besare fault (Fig.2), (Al-Azzawi and Al-Hubiti, 2009). The displacement suggested by these authors is conformable with what appears in the present work. Results of the first traverse (Nazarki – Besare) revealed that depths of the upper and lower surfaces are very deep; their depths are about (463) m and (617) m respectively. Whereas the depths are 54 m and (249) m in the second traverse (Shandokha – Baroshki) and (48) m and (175) m in the third one (Qasara – Tanahi). This variation in depth indicates that the surfaces of Pila Spi Formation are, generally, plunging toward the east, and this phenomenon is compatible with the field characters of the syncline. In addition to that, there is an abnormal difference between the depths of the first and second traverses which is a distinct phenomenon. The present authors referred this variation to the influence of Besare fault which was mentioned by Al-Azzawi and Al-Hubiti (2009), Fig. (2). This fault bears not only strike-slip component of displacement but also has vertical one (368 – 409) m.

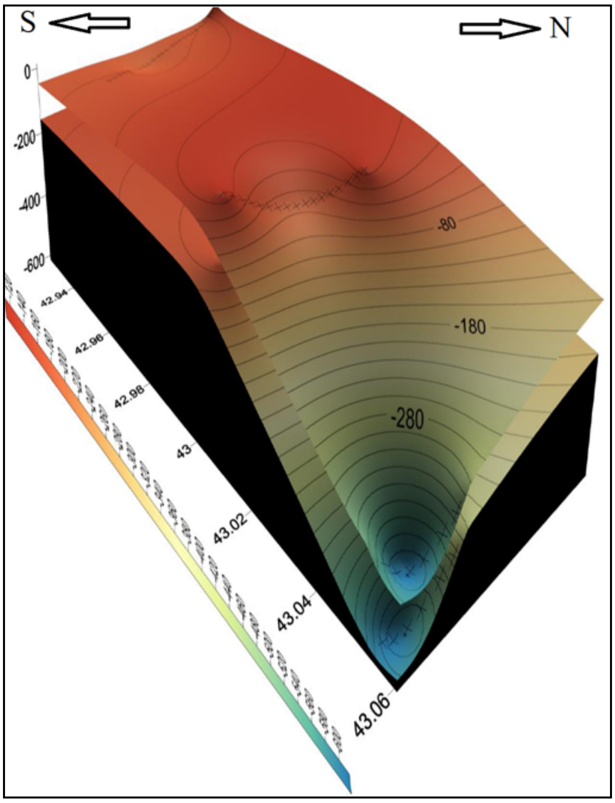

Fig.7: Shows the entire shape of the syncline

Consequently, it becomes very important in the role of structural geology in the hydrogeology of the aquifer. The presence and influence of this displacement are confirmed by the following points:

a- The large differences in depths between data of the first and second traverses.
b- The deeper level of the ground water in the area of the first traverse.
c- The location of the first traverse falls in eastern side of Besare fault (Al-Azzawi and Al-Hubiti, 2009), and the difference in depth may indicate that this side is the subsidized one of the fault.

This fault plays a positive role through the development of this aquifer. The fault plane is sealed because the displacement does not exceed the thickness of the Gercus Formation which is considered as the underlying sealed formation.

Another factor affecting the shape of the syncline is the Gara Baran faults group. This group contains two strike-slip faults; one of them is dextral and the other is sinistral (Al-Azzawi and Al-Hubiti, 2009). The first one lies near the third traverse and nevertheless it has dextral strike-slip movement but the results show it also has a vertical displacement. This vertical displacement slightly influences the shape of the syncline.

- **The investment of the syncline**

As mentioned above, stratigraphically the Pila Spi Formation is suitable to be an artificially recharged aquifer because its rocks are well-fractured which increases the permeability while it is confined by aquiclude and aquitard impermeable rocks (Gercus and Fatha formations respectively). On the other hand, the shape and geometry of the syncline are

appropriate for this purpose including the influence of Besare fault which increases the quantity of water due to increase the aquifer size on the eastern side.

Using the soft-wares {Digital elevation method (Dem)} and (Arc GIS 9.3), a topographic map of the study area was constructed comprising the exposures of Pila Spi limestone around the syncline as a catchment area and the locations of its valleys (mostly transverse), (Fig.2). This map is considered for all the determination taken place in this work.

- **Determination of the Aquifer size**

The estimation of the aquifer size is carried out by implementing the data interpolation using Lagrangian method (Table 1). This was guided for the determination of cross-sectional areas of Pila Spi limestone in each traverse. Finally, from the average cross-sectional area and the length of the syncline, the size of the aquifer has been found.

The area is determined by obtaining the fold profile functions for the upper and lower surfaces of Pila Spi Formation in all three traverses. This was done by applying the Least Squares method (Best fitting curve), which is mentioned above. Moreover, the definite integration of this function produced the cross-sectional area. In order to acquire the best optimized results each surface was divided into left-hand side (a) and right-hand side (b). Consequently, the functions of the upper and lower surfaces of the first traverse are shown below respectively:

$$Y = -9.05216E-10X^4 + 1.321077E-06X^3 - 7.922509E-04X^2 + 0.3683638X + 364.9801 \ldots T1Ua$$

$$Y = 6.501399E-13X^4 - 5.98974E-08X^3 + 6.145515E-05X^2 + 0.1490806X + 296.3119 \ldots T1Ub$$

$$Y = 7.396821E-11X^4 - 4.098881E-08X^3 - 2.198241E-04X^2 + 0.179429X + 582.5799 \ldots T1La$$

$$Y = 1.821154E-10X^4 - 4.577635E-07X^3 + 3.603203E-04X^2 + 6.725885E-02X + 402 \ldots T1Lb$$

T1Ua is for the part (a) of the upper surface of the first traverse.

Functions of the upper and lower surfaces of the second traverse are also shown below:

$$Y = 2.853516E-14X^4 - 1.032887E-10X^3 - 2.298596E-05X^2 + 8.010917E-02X - 15.08918 \ldots T2Ua$$

$$Y = 3.339264E-14X^4 - 1.4998E-10X^3 - 2.288103E-05X^2 + 7.699221E-02X - 9.899972 \ldots T2Ub$$

$$Y = -3.109852E-14X^4 + 1.214143E-10X^3 - 2.63078E-05X^2 + 9.946891E-02X + 154.5268 \ldots T2La$$

$$Y = 3.019374E-12X^4 - 9.663609E-09X^3 - 1.701761E-05X^2 + 7.605644E-02X + 189.9673 \ldots T2Lb$$

Functions related to the third traverse are also listed below:

$$Y = -3.060131E-12X^4 + 2.739085E-08X^3 - 8.426017E-05X^2 + 0.1102959X - 10.39582 \ldots T3Ua$$

$$Y = 4.72652E-11X^4 - 1.370227E-07X^3 + 9.86737E-05X^2 + 3.127067E-02X + 18.01783 \ldots T3Ub$$

$$Y = -5.621004E-12X^4 + 3.922886E-08X^3 - 8.337851E-05X^2 + 6.100364E-02X + 138.8382 \ldots T3La$$

$$Y = 4.747984E-11X^4 - 1.374824E-07X^3 + 9.898078E-05X^2 + 3.120688E-02X + 18.01891 \ldots T3Lb$$

The definite integration was applied to each function to determine the area of each of them. For instance, the area of the first traverse (part a) can be obtained by the following expression (Fig.8):

$$Area - T1Ua = \int_0^{775} -9.0E - 10X4 + 1.32E - 6X3 - 7.9E - 4X2 + 0.36X + 364$$

Accordingly, the areas of synclinal parts calculated are shown in Table (2).

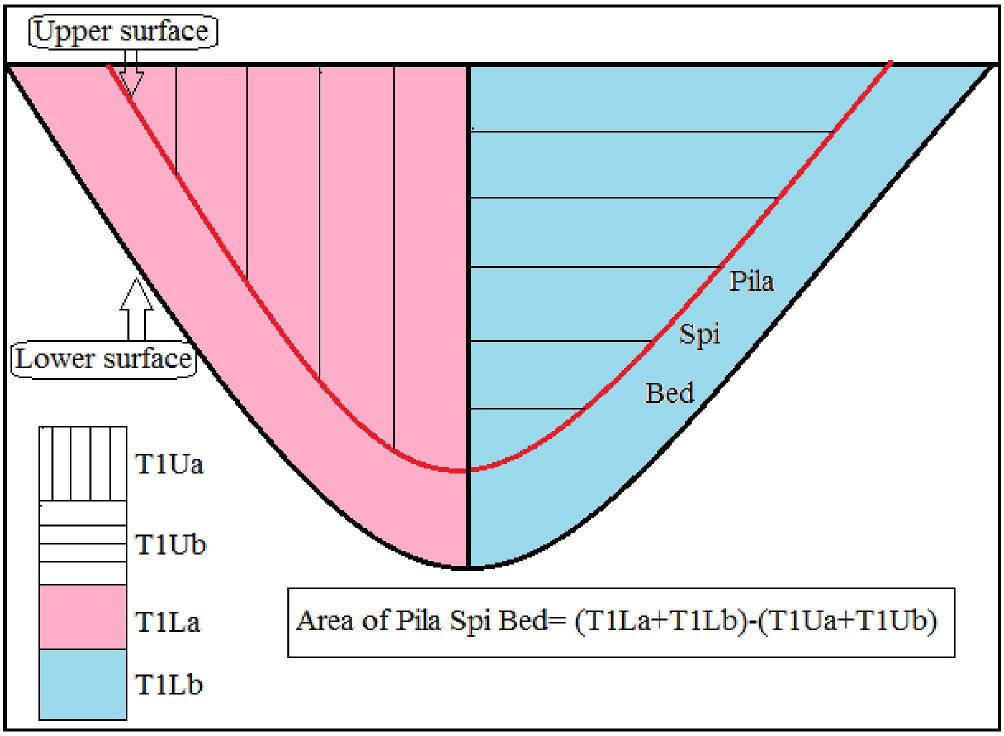

Fig.8: Calaulation of the cross-sectional area Pila Spi limestone for the first traverse (as exampl)

Table 2: shows the results of Aquifer volume calculations

Trav.	Part	Area	Total Area	Pila Spi Area (Lower – Upper)	Average Area in cross-section
1	T1Ua	339085.5	825161.4	261964.9 m^2	**431711.26 m^2 or 0.43171126 Km^2**
	T1Ub	486075.9			
	T1La	471715.3	1087126.3		
	T1Lb	615411.0			
2	T2Ua	52415.21	109236.21	648440.09 m^2	
	T2Ub	56821			
	T2La	363906.7	757676.3		
	T2Lb	393769.6			
3	T3Ua	147893.8	193342.66	384728.79 m^2	
	T3Ub	45448.86			
	T3La	532623	578071.45		
	T3Lb	45448.45			

The average cross-sectional area is multiplied by the length of the syncline measured in Fig. (2), to obtain the entire size of the Aquifer.

$$0.43171126 * 17.1 \text{ Km} = \mathbf{7.382262546\ Km^3}$$

- **Aquifer storage assessment**

Data of monthly rainfall of Dohuk governorate is obtained from Dohuk station for the years (1990 – 2011), (Table 3). Moreover, the area where Pila Spi Formation is outcropping and represents the recharging part of the aquifer is determined using Arc GIS is 23.4 Km^2 (Figs.2 and 9). Therefore the amount of rain that falls on the recharge area of the aquifer can be estimated. According to the empirical tests of Horton (1933) the infiltration ratio of limestone, is considered to be about 20%.

$$pr = 0.0005387 \text{ Km/Year},\ A = 23.4 \text{ Km}^2 \text{ and } F = 20\%$$

pr is the average rainfall per year in Dohuk station, A= catchment area (Pila Spi limestone) and F = the infiltration ratio.

If W is the amount of infiltrated rain,

$$W = pr * A = 0.0005387 * 23.4 * 0.2 = 0.002521116 \text{ Km}^3\text{/year}$$

$$\mathbf{W = 2521116\ m^3/year,} \text{ if the infiltration ratio is 20\%.}$$

The total pore volume of the Pi1a Spi limestone in the syncline can be calculated in this form.

$$V_w = P * V_T$$

When V_w is volume of pores in Pila Spi limestone, P is porosity and V_T is total volume of Pila Spi limestone.

$$V_w = 0.2 * 7.382262546 = 1.4764525092 \text{ Km}^3$$

$$V_w = 14764525092.2 \text{ m}^3$$

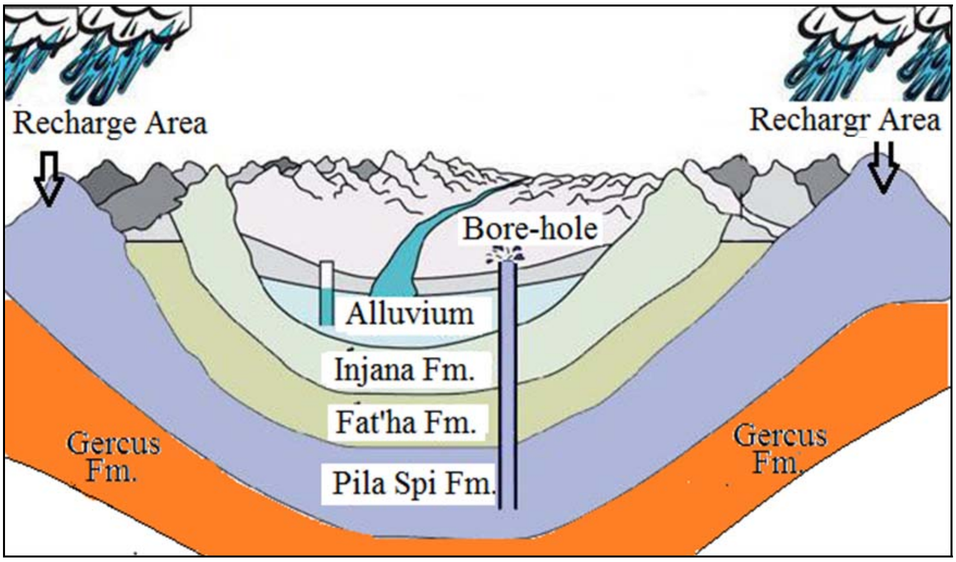

Fig.9: Schematic diagram for the aquifer rechange

Table 3:

Station	Latitude	Longtitude	Altitude	Average
Duhok	36.5049	43.0033	569 m	538.7 mm

The seasonal rainfall in Dohuk city/ Dohuk Station 1990 – 2011														
Year	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Seasonal Time**	**Rainfall depth (mm)**
1990	56.3	111	26	43	0	0	0	0	0	15.7	10.8	39.4	1990 – 1991	389.8
1991	44.3	90	66	80	44	0	0	0	0	16.7	82.7	159.4	1991 – 1992	735.3
1992	164	235	33	18	20	7.0	0	0	0	0	159.9	198.4	1992 – 1993	884.0
1993	76	78	55	110	207	0	0	0	0	51	113	29.5	1993 – 1994	711.2
1994	113.2	76	164	151	14	0	0	0	0	16	194.1	181.9	1994 – 1995	794.0
2995	50	111	152	79	0	10.2	0	0	0	0	21.2	7.8	1995 – 1996	532.3
1996	208.5	72	163	55	4.9	0	0	0	0	5.5	17.7	207.5	1996 – 1997	581.4
1997	53	134	82	75	0.5	7	0	0	0	39.1	33	108.8	1997 – 1998	548.1
1998	86.6	84	140	36	21	0	0	0	0	4	3	9.2	1998 – 1999	215.9
1999	38	72	77	13	0	0	0	0	0	14.8	11.2	58.6	1999 – 2000	437.5
2000	209.7	26	84	33	0	0	0	0	0	12.8	66.8	174.1	2000 – 2001	522.4
2001	36.6	101	84	47	0	0	0	0	0	8	25	91.9	2001 – 2002	539.9
2002	103.8	48	187	72	4.3	0	0	0	0	16.1	23.7	204.9	2002 – 2003	726.6
2003	96.8	211	140	31	3.7	0	0	0	0	21.9	71.2	112	2003 – 2004	559.7
2004	126.8	90	30	91	17	0	0	0	0	8.3	136.2	11.9	2004 – 2005	558.1
2005	183.2	101	57	16	42	208	0	0	0	1.7	29.7	72.9	2005 – 2006	678.9
2006	209.3	179	36	143	8.2	0	0	0	0	100.4	48.9	71.4	2006 – 2007	606.6
2007	82.8	130	58	85	30	0	0	0	0	0.2	17.8	8.3	2007 – 2008	216.2
2008	96.3	51	40	2.2	0.2	0	0	0	3	18.6	76.6	81.7	2008 – 2009	347.2
2009	4	68	64	30	0.5	0	0	0	7	55.4	64.2	194.6	2009 – 2010	599.3
2010	110.1	68	29	27	42	2.7	0	0	0	1.2	0	58.4	2010 – 2011	449.4
2011	106.9	70	17	139	55	1.2	1	0	0.8	5.4	18.7	19.5	2011 – 2012	217.3
2012	101.9	71						0						

CONCLUSIONS

The estimated time needed to recharge the aquifer is thousands of years. Accordingly, the infiltrated water from natural recharge must be supported by artificial one. The amount of rainfall per year recharging the aquifer is very low compared with its storage capacity. This can be overcome by recharging the aquifer artificially. Therefore, opinions can be adopted to improve the potential of the aquifer by increasing the amount of infiltrated water. For this reason three ideas are proposed.

- To set up walls (mini dams) on the downstream of the essential transverse valleys within the catchment area of Pila Spi Fm. Each wall may not exceed one meter in height. This idea can make a rainfall harvesting in the valleys and give additional chance for more runoff water infiltration. The dominating fractured limestone in the valleys can play an important role to increase the infiltration. Such as ac, bc, hko > a, hko > b, hol > c and okl > c (Al-Kadhum,2009; Al-Azzawi and Al-Hubiti, 2009). Another significant property is the openings of ac and hol > c joints which increases the infiltration. The additional amount of infiltrated water by this way can be estimated form the size of each dam reservoir multiplying their number and by the rate of infiltration per time, or it may by checked by control wells.
- The second proposal is to drill shallow bore-holes at the bottom of the valleys within the Pila Spi Formation. This can perforate the catchment area and increase the surface area for infiltration.

Finally, increasing the improvement of the aquifer either via one or both ways leads to increase the recharge of the aquifer. Moreover, maintenance must be done in summer to remove the undesirable deposits at the bottom of dam reservoirs or bore-holes.

- Constructing small dams in the upstream areas outside the catchment area where the water can convey, by gravity, through pipes to recharge shallow wells located downstream.

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About the author

Prof. Dr. Nabeel K. Al-Azzawi, graduated from University of Mosul in 1979, with B.Sc. degree in general geology; he got his M.Sc. and PhD. in 1983 and 2003 respectively in structural geology from the same university and his professorship at 2008. He taught structural geology at the Geology Department of the same university for 32 years. He became head of the Department in 2006. Representative of the College of Science in the University Council in the alternative site of the University of Mosul in Duhok after the displacement (after ISIS). He became member and head of many committees such as Scientific, postgraduate and field geology and head of scientific promotion in the College of Science. Supervised and examined many MSc. and PhD. students and published many papers in the field of structural geology and tectonics and has an interest in geomathemaics.

e-mail: nabazzawi@yahoo.com; nabazzawi2@gmail.com