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Determination of Unconfined Aquifer Parameters Using Boulton, Neuman and Streltsova Methods

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Abstract. Analysis of pumping test data to estimate aquifer parameters is normally carried out using standard procedures such as the Theis or Jacob method. These methods, however, were derived with assumptions regarding the type of aquifer and wells that may not be satisfied under some conditions. In unconfined aquifers the effects of delayed yield, partial penetration of wells and other effects make the use of Theis or Jacob methods impractical in many cases. The objective of this work is to analyze pumping test data from seven different well sites of five wadis taking into consideration the effects of delayed yield, partial penetration of wells and the decreased saturated thickness. The methods of Boulton, Neuman and Streltsova were applied on pumping test data from the five unconfined aquifers in the south-western part of Saudi Arabia. The aquifer parameters resulting from the three methods were evaluated and compared to each other. Using the resulting values of aquifer parameters, the drawdowns were recalculated and compared to the original data in order to define best values of aquifer parameters for the seven test sites.

Introduction

Groundwater constitutes most of the available natural water resource in the Kingdom of Saudi Arabia. It is normally found in deep confined or shallow unconfined aquifers.

Unconfined aquifers are found in many parts of Saudi Arabia. Many of these aquifers were formed in wadi systems and sometimes they are called alluvial aquifers. A typical alluvial aquifer is a shallow unconfined aquifer existing below the wadi bed and extending underneath the valley (between the escarpments). Areas around wadis throughout the Kingdom depend on these aquifers for their water supplies. These aquifers are characterized by small saturated thickness, but they receive substantial amounts of recharge.

The most important parameters used in groundwater hydrology to characterize an aquifer are transmissivity and storage coefficient. In case of unconfined aquifers, the latter is called specific yield. Aquifer parameters at a certain site can be estimated by conducting a pumping test. The resulting data is then analyzed using one of the standard methods such as those of Theis or Jacob. These standard methods can be successfully used in analyzing pumping test data in confined aquifers. The assumptions under which these methods were derived are met in most cases in confined aquifers. They are not generally applicable in unconfined aquifers. The major two reasons for this are: delayed yield phenomenon and drawdowns being sometimes large relative to the initial saturated thickness of the aquifer.

Research to model flow in unconfined aquifers taking into consideration the delayed yield phenomenon has started with Boulton work [1,2]. Other prominent works include those of Neuman [3,4,5,6] and Streltsova [7]. These methods, although well known, have not been extensively tested using data from unconfined aquifers.

The objective of this work is to analyze pumping test data from five sites in the south-western part of Saudi Arabia. At these sites, the aquifers are unconfined and the wells are partially penetrating. Preliminary analyses of the tests have shown delayed yield phenomenon and in some cases the initial saturated thickness has been substantially reduced during the tests. The methods of Boulton, Neuman and Streltsova will be applied on the available pumping test data and the resulting aquifers' drawdowns will be recalculated using the obtained parameters and compared to the original drawdowns.

Basic Approaches

When the drawdowns of a pumping test in an unconfined aquifer are plotted versus time on logarithmic paper, they sometime delineate an S-shaped curve. It consists of a steep segment at early times, a flat portion at intermediate times, and a somewhat steeper segment at late times. The physical phenomenon that causes this behavior is known as delayed yield. Unconfined stratified sediments often react to pumping for a short time after pumping begins, as would be a confined aquifer. Gravity drainage is not immediate but water is released instantaneously from storage by the compaction of the aquifer and its associated beds and by the expansion of water itself. The second segment of the time-drawdown curve represents the intermediate stage in the decline of water levels when the cone of depression slows in its rate of expansion as it is replenished by gravity drainage of the sediments. Test data deviate markedly from the nonequilibrium theory (Theis) during the second segment. The third segment, which may begin from several minutes to several days after pumping starts depending largely upon aquifer conditions, represents the period during which the time-drawdown curves conform closely to the nonequilibrium type curve.

There are many methods available in literature to analyze pumping test data in unconfined aquifers. The following is a brief description of those methods used in this study.

Boulton [1] assumed that the amount of water derived from storage within an unconfined aquifer consists of two components. The first is the volume of water instantaneously released from storage (aquifer is behaving like a confined one) while the second component is the volume of water released as a delayed yield. The basic equation governing the flow in unconfined aquifers was then written with the two components. The general solution of that equation is a rather complicated differential equation which symbolically, and in analogy to the Theis equation, may be written as:

$$s = \frac{Q}{4 \pi T} W \ (U_{AB}, \ r/B) \tag{1}$$

where

s	=	Drawdown, [L]
Q	=	Pumping rate, $[L^3/T]$
T	=	Transmissivity of the aquifer, $[L^2/T]$
$W(U_{AB}, r/B)$	=	Well-function of Boulton, [dimensionless]
r	=	Radial distance from test well, [L]
B	=	Leakage factor defined by the equation, [L]

$$B = \sqrt{T/\alpha S_y} \tag{2}$$

where α is an empirical constant and S_y is the specific yield.

Under early-time conditions, equation (1) describes the first segment of time-drawdown curve and it is reduced to:

$$s = \frac{Q}{4 \pi T} W \ (U_A, \ r/B) \tag{3}$$

where

U_A	=	$\frac{r^2 S}{4Tt}$, [dimensionless]
S	=	Storage coefficient, [dimensionless]
t	=	Time, [T]

Under late-time conditions, equation (1) describes the third segment of the time-drawdown curve and it reduces to:

$$s = \frac{Q}{4\pi T} W(U_B, r/B) \tag{4}$$

where

U_B	=	$\frac{r^2 S_y}{4Tt}$, [dimensionless]

Boulton [1] gave values of W (U_{AB}, r/B) in terms of practical ranges of U_A, U_B and r/B. Values of W(U_{AB}, r/B) were plotted against values of $1/U_U$ and $1/B_B$ on logarithmic paper and two families of type curves were constructed. The type curves which lie to the left of the values of r/B are called "Type A curves". They are used to analyze early time-drawdown data. The type curves which lie to the right of the values of r/B are termed "Type B curves" and they are used to analyze late time-drawdown data.

Boulton method of solution was later extended by Boulton [2] and Boulton and Pontin [8] to account for anisotropy and the effect of vertical flow components in the aquifer. The method of using the type curves for finding the value of T, S, S_y and the delay index ($1/\alpha$) was outlined by Pricket [9]. Details of Boulton method can be found in Kruseman and de Ridder [10].

Neuman [3,4,5] showed that the phenomenon of delayed yield can be simulated mathematically by using constant values of specific storage and specific yield without recourse to unsaturated flow theory. Neuman model treats the unconfined aquifer as a compressible system and the phreatic surface as a moving material boundary. It differs from that of Boulton in that it is based only on well-defined physical parameters of the aquifer and no longer involves such semi-empirical quantities as Boulton's delay index. Neuman [6] showed how the new theory can be used to determine the hydraulic characteristics of an isotropic unconfined aquifer from pumping test data. He used two asymptotic families of type curves that are analogous to Boulton [1] and Prickett [9]. He also developed an approach for partially-penetrating wells [4]. That approach requires a type curve to be constructed for each field situation. Mock and Merz [11] show the application of this approach.

Streltsova [7] developed a type curve method to analyze unconfined aquifer pumping test data for the case of partially-penetrating wells. She tabulated her solutions for different amounts of penetration. These solutions were used to draw the type curves used in this study. Walton [12] summarized Streltsova solutions along with other solutions applicable for unconfined aquifers.

There are other methods that consider the effects of well bore storage and finite thickness skin. An example of those methods is the work of Novakowski [13].

Field Data

The field data used in this study were obtained from the Ministry of Agriculture and Water. The Ministry has carried out a comprehensive study on five representative wadis located in the south-western part of the Kingdom of Saudi Arabia. The pumping test data used in this paper came from the groundwater part of that five wadi investigation. These wadis are: Tabalah, Habawnah, Yiba, Liyyah, and Al-Lith. Their locations are shown in Fig. 1. The test site characteristics of all the tests

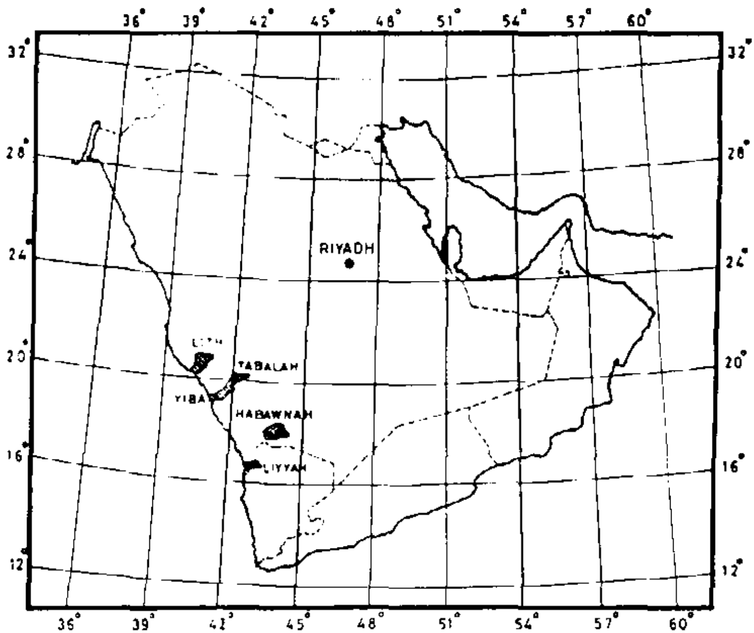

Fig. 1. General locations of the five Wadis

used in this study are shown in Table 1. These characteristics show that all observation wells are located close to test wells and all partially-penetrating. The pumping test data will be shown in graphical form when the recalculated drawdowns are compared to the original drawdowns.

Table 1. Test site characteristics

Well site	Well number	Depth to bedrock (m)	Saturated thickness (m)	Pumping rate (m^3/hr)	Distance to pumping well (m)
Tabalah	3-B-96 (T)	35.00	29.00	43.32	
	3-B-101 (O)	35.00	29.00		19.52
	3-B-98 (T)	21.00	17.70	12.30	
	3-B-103 (O)	17.70			12.65
	3-B-100 (T)	27.00	17.60	4.33	
	3-B-105 (O)	27.00	17.60		9.22
Habawnah	3-N-82 (T)	39.70	12.70	30.78	
	3-N-83 (O)	39.70	12.70		4.70
Yiba	6-T-108 (T)	69.00	63.00	17.10	
	6-T-107 (O)	69.00	63.00		5.60
Liyyah	6-J-159 (T)	49.00	36.00	17.10	
	6-J-161 (O)	49.00	36.00		5.30
Al-Lith	6-T-111 (T)	17.50	12.50	12.30	
	6-T-112 (O)	17.50	12.50		4.95

T = Test well
O = Observation well

Application of the Three Methods

Before applying the three methods, the available drawdown data was adjusted for decreased saturated aquifer thickness if the reduction of the saturated thickness cannot be neglected compared to the original saturated thickness.

Drawdown data was adjusted for decreased saturated thickness using the following equation [6]:

$$s = s_0 - \frac{s_0^2}{2b} \tag{5}$$

s = drawdown that would occur with negligible decrease in saturated aquifer thickness, [L],

s_0 = observed drawdown with appreciable decrease in saturated aquifer thickness, [L] and

b = the saturated aquifer thickness, [L].

Boulton and Neuman approaches are for the case of fully-penetrating wells while Streltsova method applies for the partially-penetrating cases. Therefore, the Boulton and Neuman methods were applied on the data after the correction for partial penetraton using the procedures suggested by Butler [14]. Streltsova method was applied directly to the data of partially-penetrating wells. For each of the three methods, the type curves were constructed on logarithmic paper of the same size as for the drawdown. The data were used in the equations for each method to calculate the aquifer parameters.

Results and Discussion

Table 2 shows the values of transmissivity (T), storage coefficient (S), and specific yield (S_y) resulting from applying Boulton, Neuman, and Streltsova methods on the pumping test data. Two sets of values for transmissivity are shown in the Table; one from the analysis of data from test wells while the other is from observation wells. The values of T obtained by the three methods from test wells are always smaller than the ones obtained from observation wells. Since it is always better to trust values obtained from observation wells, the values of transmissivities for the different aquifers shown in the Table based on observation wells are the ones accpeted in this study. It is interesting to note that if the T values (based on observation wells) are the ones accepted, the prediction of Boulton and Neuman methods are relatively close to each other with Streltsova method predicting lower values except in one of the pumping tests. Table 3 shows the saturated hydraulic conductivity (K) values at the different sites. These values were calculated by dividing the average transmissivity at the particular location by the saturated thicknesses given in Table 1.

The storage coefficient (S) and specific yield (S_y) values given in Table 2 are all reasonable values for these types of aquifers. Table 4 gives representative values of specific yield and hydraulic conductivity for different types of alluvial deposits. The effective storage coefficient for each aquifer can be found by adding S to S_y. However, since all values of S given in the Table are very small compared to S_y, the effective storage coefficient can be approximated by S_y alone.

Table 2. Summary of aquifer parameter's values

Test site	Boulton			Neuman			Streltsova		
	$T, m^2/min$	S	S_y	$T, m^2/min$	S	S_y	$T, m^2/min$	S	S_y
3-B-96 (T)	0.27	–	–	0.24	–	–	8.0×10^{-2}	–	–
3-B-101 (O)	0.73	3.78×10^{-4}	0.31	0.89	2.15×10^{-4}	0.30	0.85	8.74×10^{-4}	0.31
3-B-98 (T)	1.0×10^{-2}	–	–	1.0×10^{-2}	–	–	1.5×10^{-2}	–	–
3-B-103 (O)	1.27	2.92×10^{-2}	0.27	1.44	2.35×10^{-2}	0.20	0.10	3.98×10^{-2}	0.25
3-B-100 (T)	1.78×10^{-2}	–	–	1.55×10^{-2}	–	–	3.94×10^{-2}	–	–
3-B-103 (O)	2.35	1.84×10^{-2}	0.28	2.35	1.04×10^{-3}	0.29	0.42	1.46×10^{-3}	0.21
3-N-82 (T)	5.64×10^{-2}	–	–	4.08×10^{-2}	–	–	4.24×10^{-2}	–	–
2-N-83 (O)	0.27	1.84×10^{-3}	0.39	0.31	2.84×10^{-3}	0.40	0.15	2.17×10^{-3}	0.38
6-J-159 (T)	3.5×10^{-3}	–	–	3.65×10^{-3}	–	–	1.90×10^{-3}	–	–
6-J-161 (O)	0.22	1.48×10^{-3}	0.24	0.17	2.17×10^{-3}	0.16	0.12	1.59×10^{-3}	0.19
6-T-108 (T)	0.34	–	–	0.32	–	–	0.19	–	–
6-T-107 (O)	2.79	4.12×10^{-3}	0.27	2.68	7.83×10^{-3}	0.26	0.84	5.50×10^{-3}	0.25
6-T-111 (T)	0.85	–	–	0.99	–	–	0.68	–	–
6-T-112 (O)	5.26	3.44×10^{-2}	0.26	5.63	6.89×10^{-3}	0.34	1.25	8.36×10^{-3}	0.30

(T) Test Well
(O) Observation Well

Table 3. Saturated hydraulic conductivity values for different sites

Test site	K (m/day)
Tabalah	
3-B-101	40.2
3-B-103	110.2
3-B-105	192.7
Habawnah	
3-N-83	32.9
Liyyah	
6-J-161	7.8
Yiba	
6-T-107	62.5
Al-Lith	
6-T-112	627.3

Table 4. Representative values of specific yield and hydraulic conductivity, Todd [15, p. 535]

Material	Specified yield percent	Hydraulic conductivity m/day
Gravel, coarse	23	150
Gravel, medium	24	270
Gravel, fine	25	450
Sand, coarse	27	45
Sand, medium	28	12
Sand, fine	23	2.5
Silt	8	0.08
Clay	3	0.0002

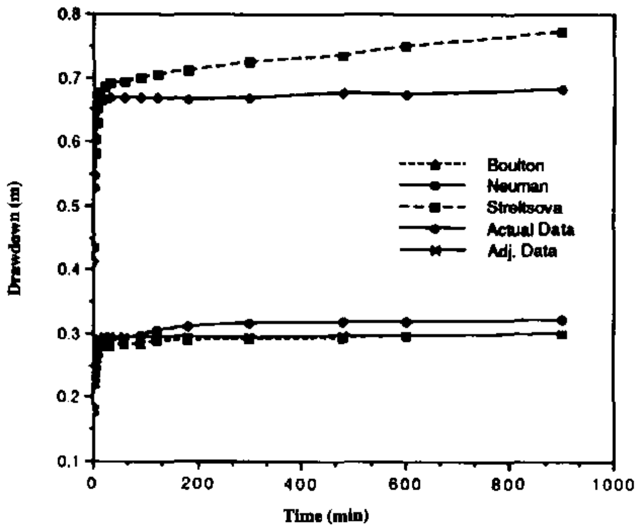

Fig. 2. Recalculated vs. observed drawdown, Test 3-B-101

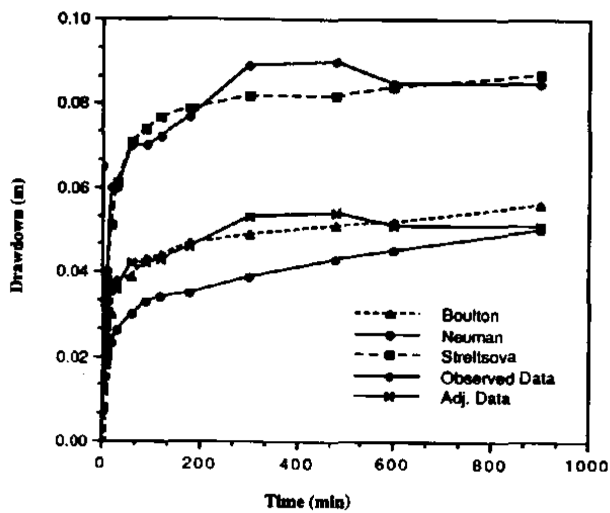

Fig. 3. Recalculated vs. observed drawdown, Test 3-B-103

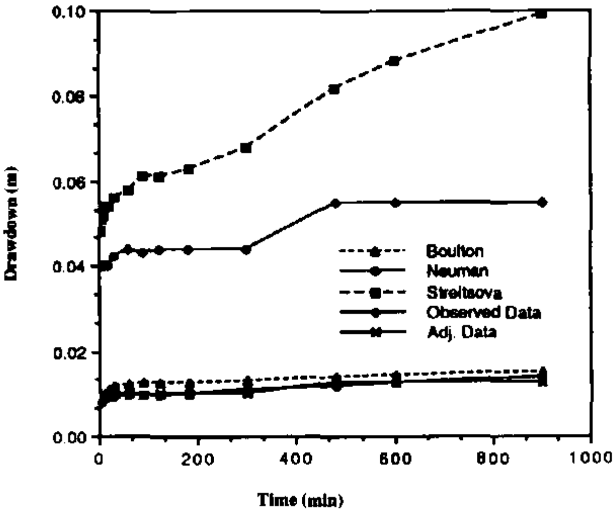

Fig. 4. Recalculated vs. observed drawdown, Test 3-B-105

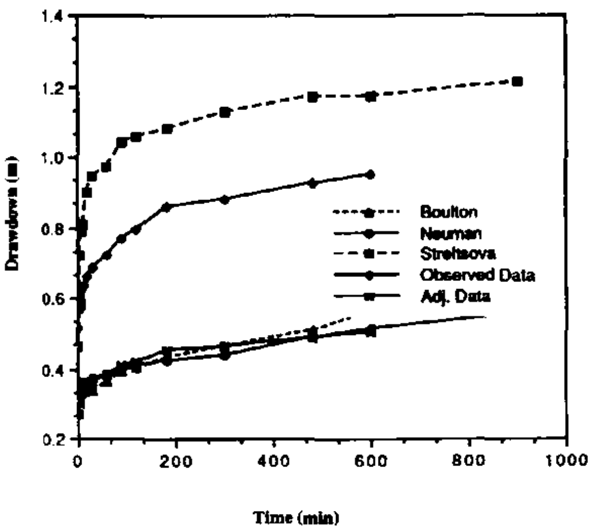

Fig. 5. Recalculated vs. observed drawdown, Test 3-N-83

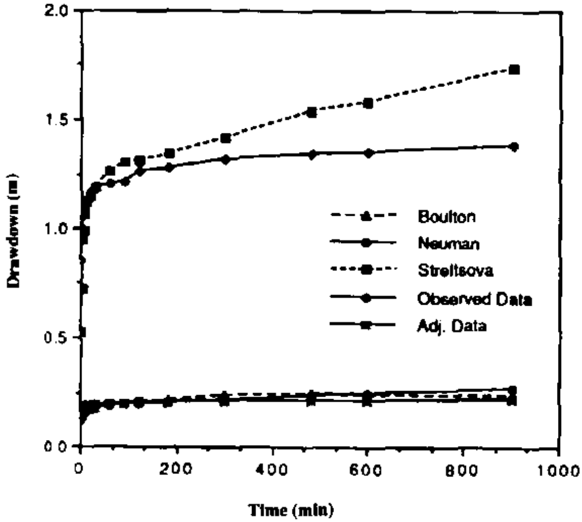

Fig. 6. Recalculated vs. observed drawdown, Test 6-J-161

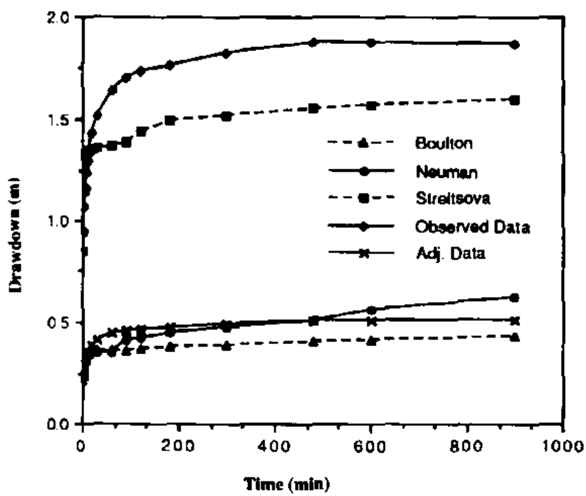

Fig. 7. Recalculated vs. observed drawdown, Test 6-T-107

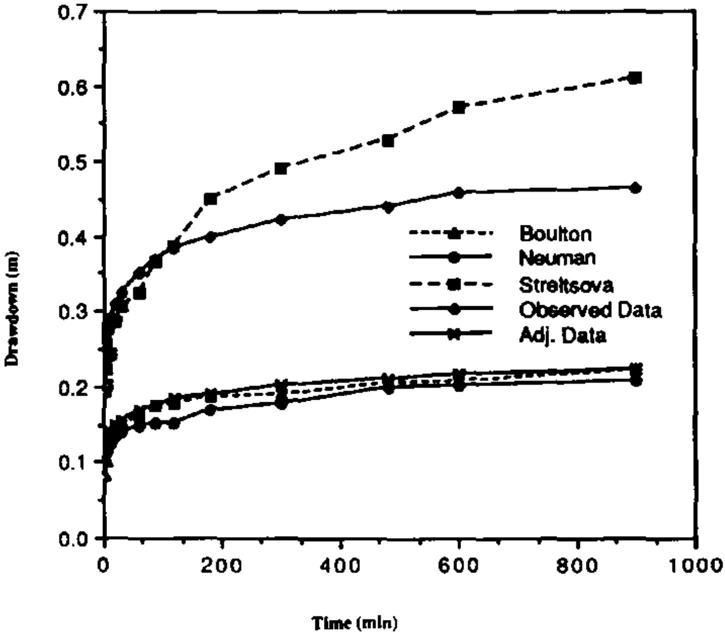

Fig. 8. Recalculated vs. observed drawdown, Test 6-T-112

The results of the three methods for T and S (observation wells only) were then used to recalculate the drawdowns and compare these drawdowns to the original ones (obtained in the field). Figs. 2 – 8 show the estimated drawdowns and their comparison with the observed drawdown data. The Streltsova estimated drawdowns have to be compared to the actual observed field data because that method is designed to be used with partially-penetrating wells data with no adjustment for the partial-penetration effects. The Boulton and Neuman methods results, however, should be compared to the drawdown data after adjustments for partial-penetration effects. The correction for partial penetration was carried out using the procedure outlined by Butler [14]. That procedure gives correction factors for both pumping and observation wells. It presents these factors (in tabular form) as function of field penetration ratios and geometric configuration of the aquifer. Table 5 shows the average deviations of the estimated drawdowns as compared to the original drawdowns. It is clear from this table that in five of the seven pumping tests, Streltsova method gave higher deviations between observed and estimated drawdowns, than

Table 5. Average deviation of estimated drawdowns

Test site	Average deviation of estimated drawdowns %		
	Boulton	Neuman	Streltsova
3-B-101	4.16	5.23	6.32
3-B-103	7.64	12.52	8.55
3-B-105	14.60	5.19	39.00
3-N-83	3.79	6.13	25.91
6-J-161	9.30	8.10	13.10
6-T-107	5.19	7.85	11.14
6-T-112	6.76	9.8	14.73

the other two methods. On the average, Boulton approach gave slightly less deviation than Neuman method but the two approaches results are within reasonable limits of observed values. Streltsova method is based on type curves that were constructed and based on a certain ratio of partial penetration. The accuracy of the method will therefore depend on whether the actual partial penetration is close to the ratio for the type curve used.

Conclusions

Pumping test data from five wadis in the Kingdom of Saudi Arabia were analyzed using Boulton, Neuman and Streltsova methods. The following conclusions can be drawn from the study:

1. All the three methods used gave reasonable predictions of the specific yield for the type of aquifers under consideration.

2. Boulton and Neuman approaches gave values of transmissivities that are relatively close to each other. Streltsova method underestimated transmissivity for almost all the pumping tests.

3. When the recalculated drawdowns were compared to observed drawdowns, the deviations between the two resulting from Boulton and Neuman approaches were smaller than those resulting from Streltsova method.

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حساب معاملات التكوين غير المحصور باستخدام نظريات (بولتن) و(نيومان) و(سترلتسوفا)

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ملخص البحث. إن تحليل بيانات اختبارات الضخّ لتقدير معاملات التكوينات الجيولوجية يتم عادة باستخدام الطرق القياسية مثل نظرية (تايس) أو (جيكوب) إلا أن تلك النظريات قد استنتجت بفرضيات تتعلق بنوع التكوين والآبار المدروسة والتي قد لا تتحقق في بعض الحالات فمثلا في التكوينات غير المحصورة فإن تأثير الإنتاج المتأخر وتأثير اختراق الآبار الجزئي للتكوينات وكذلك بعض التأثيرات الأخرى يجعل استخدام نظريتي (تايس) و(جيكوب) غير عملي في معظم الأحيان.

إن الهدف من هذه الدراسة هو تحليل بيانات اختبارات الضخّ المقاسة في سبعة آبار مختلفة والواقعة في خمسة أودية مع الأخذ بعين الاعتبار تأثيرات الإنتاج المتأخر والاختراق الجزئي للآبار وتناقص السماكة المشبّعة للتكوين.

لقد تم تطبيق نظريات (بولتن) و(نيومان) و(سسترلتسوفا) على بيانات اختبارات الضخّ المجمعة من خمسة تكوينات غير محصورة والتي تقع في الجزء الجنوبي الغربي من المملكة العربية السعودية. هذا وقد تم حساب ومقارنة معاملات التكوين المستنتجة باستخدام تلك النظريات الثلاث ومن ثم استخدام تلك القيم لمعاملات التكوين لحساب مقدار الانخفاض في منسوب المياه الجوفية ومقارنة ذلك بالبيانات الحقيقة وذلك لتحديد أفضل معاملات التكوين لمواقع الاختبارات السبعة.