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COMPARING METHODS PROPOSED FOR GROUNDWATER RECOVERY TEST

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Abstract— **Previously available methods can determine the Transmissivity and storage coefficient during the pumping period only or under restrictive conditions. After that, a lot of methods are presented to determine the transmissivity and the storage coefficient from recovery data measured after stopping a pumping period of an aquifer test. The reason of this search compared the methods proposed by (Theis 59, Balluraya and Sharma 1991, li zheng, jain-qing, yuping 2005, Chenaf.D and Robert P.Chapuis 2002 , Olivier B. and Lumony M.Bangoy 1996 , Sushil K. Singh 2003 , Nozar Samani & M.Pasandi 2003 for estimated the storativity and transmissivity from recovery test. We applied the proposed methods to estimate the Transmissivity and storage coefficient using data from (Todd 1980, p 134) and (Groundwater manual, 1981. p117). Was conducted to find a solution to the examples of several equations that have been proposed by several researchers. Was to clarify each equation separately and graph of the variables in their own Excel file attachment with the report and the following table shows the results obtained from Research.**

Keywords— **Transmissivity, Storativity, Recovery test, Groundwater.**

I. INTRODUCTION

An aquifer test or a pumping test is conducted to evaluate an aquifer by "stimulating" the aquifer through constant pumping, and observing the aquifer's "response" (drawdown) in observation wells. Aquifer testing is a common tool that hydrogeologists use to characterize a system of aquifers, aquitards and flow system boundaries.

Aquifer tests are typically interpreted by using an analytical model of aquifer flow (the most fundamental being the Theis solution) to match the data observed in the real world, then assuming that the parameters from the idealized model apply to the real-world aquifer. In more complex cases, a numerical model may be used to analyze the results of an aquifer test, but adding complexity does not ensure better results.

When the pump is shut down after a pumping test, the water levels in the well and the piezometers will start to rise. This rise in water levels is known as residual drawdown, s'. It is expressed as the difference between the original water level before the start of pumping and the water level measured at a time t' after the pump has been turned off. The figure below shows the change in water levels with time during and after a pumping test Measuring the residual drawdown allows T to be calculated, and can be used to check the results of the of the pump test. Residual drawdown data are often more reliable than pump test data because recovery occurs at a constant rate.

The Theis nonequilibrium solution and the Cooper-Jacob (1946) approximation are commonly used to calculate the transmissivity (T) and storage coefficient (S) of infinite homogeneous, isotropic, confined aquifers from a constant rate pumping test data. Almost all books on hydrogeology recognize that, in most cases, the residual drawdown plot cannot be used to determine the storage coefficient, although it is valid for calculating the transmissivity. Aquifer parameters can be calculated from the recovery data using the Theis or Cooper-Jacob methods, in the same manner as a pumping test with a negative pumping rate when steady-state conditions are obtained prior to recovery; in other words, when pumping time effects can be ignored. In many instances, recovery tests with short pumping times are conducted. Thus, there is a need for generating recovery (buildup) type curves, which account for the effect of pumping time.

II. PROPOSED METHODS

A. The Theis (1959) recovery method –

The Theis (1959) recovery method for determining the transmissivity T of confined aquifer is applicable when the storativity S remains constant throughout recovery period, the theoretical curve of residual drawdown s' versus log (t/t') and use the following equation to get the transmissivity and the storage coefficient. And it was simple to Applied to two examples we are used in this study and the results shown in the previous table.

T=(2.3 Q)/4πΔS' (1)

Where: Q is the flow rate. Δs is the change of drawdown over one log

Cycle t/t'. The slope obtained from draw the curve between the residual drawdown and t/t' (equivalent time over recovery time) as shown in the following graph.

S=(2.25 Tt0)/r^2 (2)

Where: n=(S' max)/S'

Where T is the Transmissivity .t0 is the time at stop pumping. r is the distance between the pumping well, and observation well. T is the recovery time. S'max is the maximum drawdown

B. (P.N. Balluraya and K.K. Sharma) method –

The second method we were used (P.N. Balluraya and K.K. Sharma) method used Theis equation to determine the transmissivity T

$T = \frac{2.3\ Q}{4\pi \Delta S'}$ Where: Q is the flow rate. Δs is the change of drawdown over one log cycle t/t'

$S = \frac{2.25\ Tt0}{r^2 (\frac{t}{t - to})^n}$ (2) Where: $n = \frac{S'\ max}{S'}$

Where T is the Transmissivity .t_0 is the

Time at pumping stop r is the distance between the pumping well, and observation well (t) is the recovery time. S'_{max} is the maximum drawdown.

C. R.P.Chapuis method –

Also we used the equations that have been mentioned in the discussion of R.P.Chapuis

$Sp = \left[\frac{Q}{4\pi T}\right] * \ln\left[\frac{t}{t_0}\right]$ Where: Q is the flow rate. t is the recovery time. t_0 is the intercept the curve with axis x in semi-log graph.

Then we find the value of another variable sp-s' is a variable of the drawdown.

$$sp - s' = \left[\frac{Q}{4\pi T}\right] * Ln\left[\frac{t'}{t_0}\right] - Ln\left[\frac{t}{t'}\right]$$

And then draw a linear equation between the column sp-s 'and recovery time (t') in semi-log graph to get the slope Δ (sp-s') and intercept t_0. Then we can get the value of Transmissivity from:

$$T = \frac{[2.30\ Q]}{[4\pi\Delta\ (sp - s')]}$$

And value of storativity from:

$$S = \frac{[2.25 * T * t0]}{r^2}$$

D. USDI Ground water manual (1981) method –

Another method was used in this study USDI Ground water manual (1981, p. 115) gives without reference or demonstration

And we have acquired on the values of T and S the following equations. The USDI method just for determine the storativity coefficient. And we used the Theis equation for obtained the Transmissivity

$T = \frac{2.30\ Q}{4\ \pi\ \Delta S'}$ Where: Q is the flow rate. Δs is the change of drawdown over one log cycle t/t'

$S = \frac{[2.25\ Tt'/r^2]}{\log^{-1}[-\frac{Sp - S'}{\Delta(Sp - S')}-]}$ Where: sp=Δs log $(\frac{t}{t0})$

sp is the pumping period drawdown projected to time t'. s' is the residual drawdown at time, t'. (sp-s') is the recovery at time, t'

E. (Ii Zheng, Jain-qing, Yuping method –

Another method was used in this comparison Ii Zheng, Jain-qing, Yuping method, it's simply and easily method for determining the aquifer Transmissivity and storage coefficient based solely on pumping recovery data.

$T = \frac{Q}{4\pi A}$ Where: Q is the pumping rate. A is the intercept the curve when x=0

$S = -\frac{4TB}{A r^2}$ T is the transmissivity. B is the slope the curve obtained from y versus x

X and Y are giving by $X = t' \ln\left(\frac{t' + t_p}{t'}\right)$

Where t' is the recovery time. t_p time at stop the pumping Y=t's'

F. Chenaf.D and Robert P.Chapuis method –

The other methods were used in this study Chenaf.D and Robert P.Chapuis methods, first method (s'/s'_{ini} vs. t/t') or "The normalized residual drawdown method".

$$\log\left(\frac{T}{S}\right) = \frac{1}{\Delta[\frac{s'(t')}{s'_{ini}}]} - \log\left(\frac{2.25 t_A}{r^2}\right)$$

Where: t_A time when the pump stops. t_A is the time at stop the pumping. S'_{ini} is the initial residual drawdown. t' recovery time.

Linear equation represented in the graph with (s'/s'_{ini} vs. t/t') straight line with slope

Δ (s'/s'_{ini}).

The second method was proposed by Chenaf.D and Robert P.Chapuis it's (s'_{ini}-s') vs. t/t', or the water recovery height method .the semi-log graph representation of function (s'_{ini}-s') vs. (t/t') gives the transmissivity, T from the slope Δ (s'_{ini}-s')/cycle.

$$T = T' = -\frac{2.3Q}{4\pi(\frac{\Delta(s'_{ini}-s')}{cycle})}$$

Where: S'_{ini} is the initial residual drawdown. t' recovery time.

Linear equation represented in the graph with (s'_{ini} - s' vs. t/t') straight line with slope Δ (s'_{ini-} s').

$$S = \frac{2.25T\,t_A}{r^2(\frac{t}{t'})_0}$$

Where: t_A time when the pump stops. t_A is the time at stop the pumping. r is the distance between the pumping well, and observation well.

These methods are allowing the explicit determination of pumping and recovery storativity S, S' from recovery data of recovery test.

G. Olivier B. and Lumony M.Bangoy method –

Olivier B. and Lumony M.Bangoy method used too for determine the transmissivity and storativity from recovery data.The proposed method define the values of the decline in drawdown for each well at each measurement time. Then determined the intercept at each linear equation at axis y when r^2 = 0. As well as the determined slope (B) for each linear equation, so we get two new columns A, B.

And we can draw a curve to a linear equation between A and (log t / t') such that we can extract the value of the slope C.

And then we can get the value of the Transmissivity from the equation.

$$C = \frac{2.3\,Q}{4\pi T}$$

Where: Q is the pumping rate.

Then we can draw a linear equation from B and (1/t'-1/t) then we can obtain the slope D

And determine the value of the storativity coefficient from the following equation.

$$D = \frac{Q\,S}{16\pi T^2}$$

H. Sushi K. Singh method –

Sushi K. Singh method used too in this study for determines the transmissivity and storativity from recovery data

- First of all, we have to draw the curve from s' versus t/t'
- After that we can found S_* by Δs change of the drawdown pair one log cycle t/t'

S_*=0.2812 Δs

$$t_* = 1.2913\, t_0$$

Where: t_0 is the intercept on the x-axis giving s=0

- Then we can obtain the transmissivity from:

$$T = 5.152 * 10^{-2}\frac{Q}{S_*}$$

Q is the constant rate of pumping.

- And obtain the storativity from

$$S = 1.7393\,\frac{Tt_*}{r^2}$$

r is the distance between the observation well and the pumped well

J. Nozar Samani & M.Pasandi method –

The last method was used Nozar Samani & M.Pasandi method. The method based on the conversion of residual drawdown to recovered drawdown data plotted versus equivalent time the method uses the recovery data in one observation point only, and does not need the initial water level (h_0).

$$\text{equivalent time} = \left(\frac{\Delta t * t_p}{t_p + \Delta t}\right)$$

tp= time at stop the pumping. Δt= recovery time

$$\text{recovered drawdown} = h_s(\Delta t + t_p) - h_{s(0)}$$

where: hs is the residual drawdown

And we can obtain the Transmissivity from

$$T = \frac{2.30Q}{4\pi\Delta b}$$

Where Δb= change for recovery drawdown pair one cycle equivalent time

And the storativity from

$$S = \frac{2.25T[t_{s0}]}{r^2}$$

III. APPLICATION

- **Example (Todd, 1980, p. 134)**

The recovery data as given by Todd are for a well pumping at the rate of 2500 m3/day and the observations made at distance of 60 meters from the pumping well. 0.79439 m^2/min and the maximum drawdown is 1.12 m. at time t_1=t_0=240 min. And the storativity (S=0.000179685). And the values of T and S obtained from other methods are shown in Table 1.

Theis recovery method

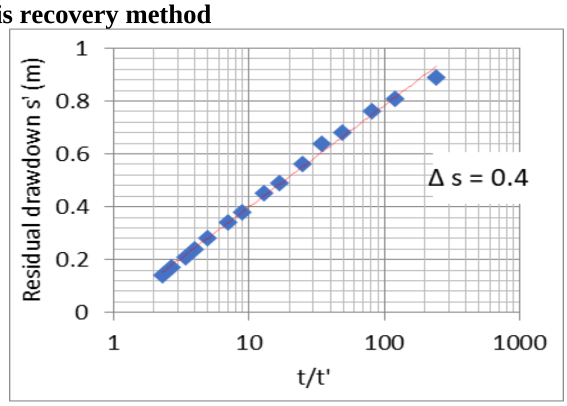

Figure 1. semi-log graph with Straight-line of recovery data and estimate values of slope Δs and intercept (t_o).data from (Todd 1980, p 134).

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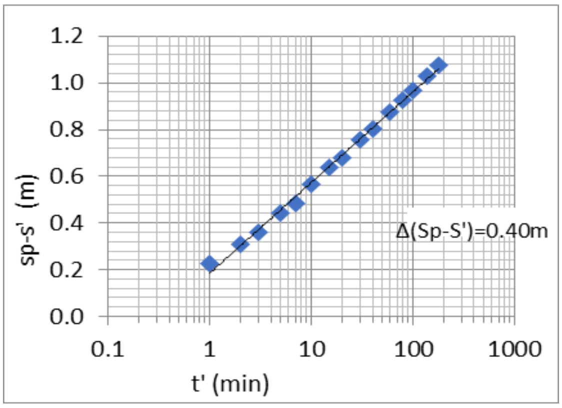


Figure 2. semi-log graph with Straight-line of sp-s' and recovery time estimate values of slope and intercept (t_o).data from (Todd 1980, p 134)

Ii Zheng, Jain-qing, Yuping method.

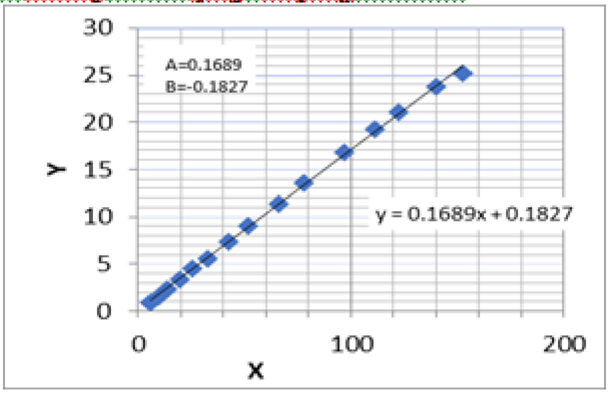


Figure 3. Graph with Straight-line of X and Y and estimate values of slope A and intercept B .data from (Todd 1980, p 134).

Chenaf.D and Robert P.Chapuis methods.

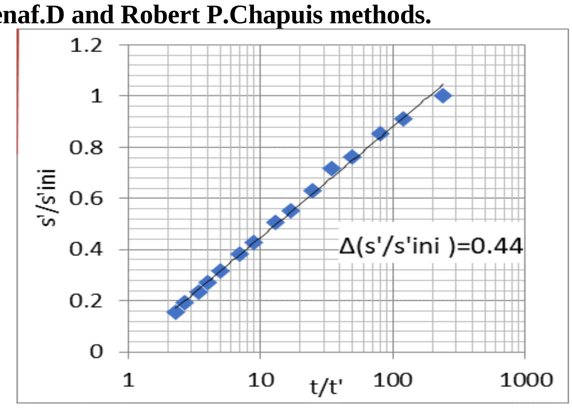


Figure 4. semi-log graph with Straight-line of s'/s'$_{ini}$ and t/t' and estimate values of slope. data from (Todd 1980, p 134).

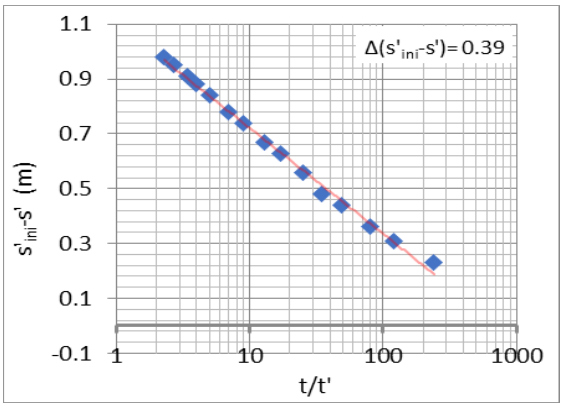


Figure .5. Semi-log graph with Straight-line of (s'$_{ini}$-s') and t/t' and estimate values of slope. Data from (Todd 1980, p 134).

Nozar Samani & M.Pasandi method

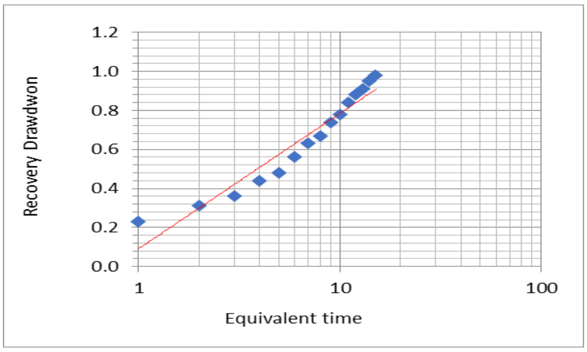


Figure 6. Semi-log graph with Straight-line of recovery drawdown and equivalent time. And estimate values of slope and intercept. Data from (Todd 1980, p 134).

Table1. Estimated Parameters for Example (Todd 1980, p 134).

Method	S	T m^2/min
Theis [35]	0.000179	0.79439
P.N. Balluraya and K.K. Sharma	0.000179	0.79439
R. P. Chapuis	0.000193	0.79439
USDI Ground water	0.000179	0.79439
I zheng , Jain-qing , Yuping	0.000983	0.81794
Chenaf.D and Robert P.Chapuis		
1st Method	T/S =	5822.2
2nd	0.000175	0.81476
Nozar Samani & M.Pasandi	0.000155	0.79439
Sushi K. Singh	0.000468	0.81559

All methods listed in Table 1 gave comparable results, which does not enable us to differentiate the performance of these methods. However, the unique features of approach become obvious when we compare the straight-line plot in Figure 1

- **Example (USDI Ground manual, p. 117)**

A second example we used to compare the results between the methods the data are taken from the USDI Ground manual. The recovery data given in the manual (p.117) are for an observation well showing the effects of a pumping well discharging at the rate of 162.9 ft3/min. the transmissivity has been determined by Theis recovery method to be 34.2705 ft2/min. and the storativity is 0.64413. And the values of T and S obtained from other methods are shown in Table 2.

Theis recovery method

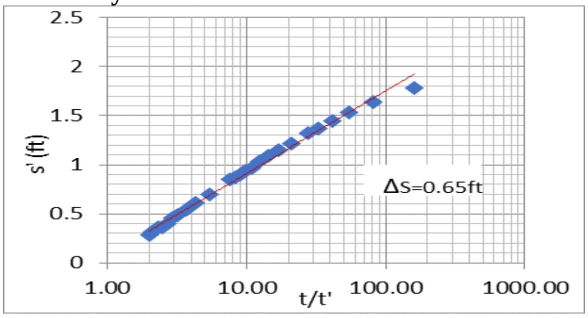


Figure 7. semi-log graph with Straight-line of recovery data and estimate values of slope Δs and intercept (t_o).data from (Ground water manual, 1981. p117).

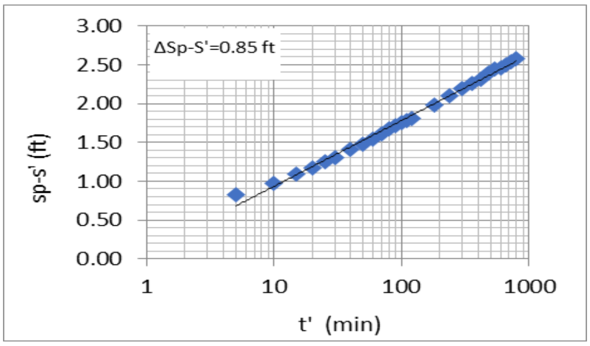


Figure 8. semi-log graph with Straight-line of sp-s' and recovery time and estimate values of slope Δs and intercept (t_o).data from (Ground water manual, 1981. p117).

Ii Zheng, Jain-qing, Yuping method

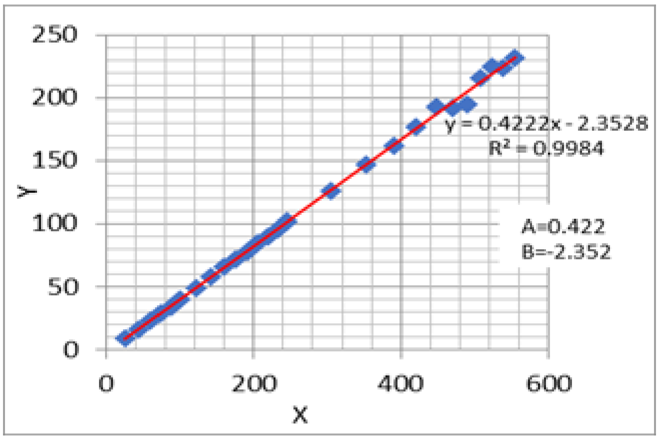


Figure 9. Graph with Straight-line of X and Y and estimate values of slope A and intercept B .data from (Ground water manual, 1981. p117).

Chenaf.D and Robert P.Chapuis methods.

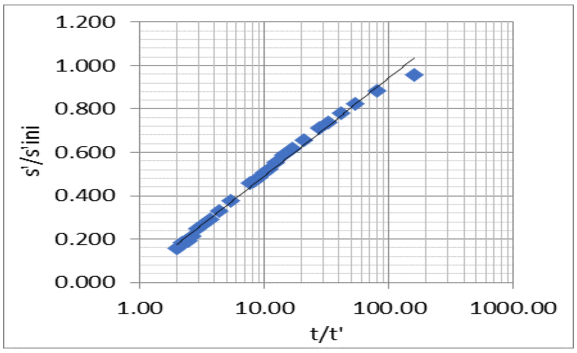


Figure 10. Semi-log graph with Straight-line of s'/s'$_{ini}$ and t/t' and estimate values of slope.(Ground water manual, 1981. p117).

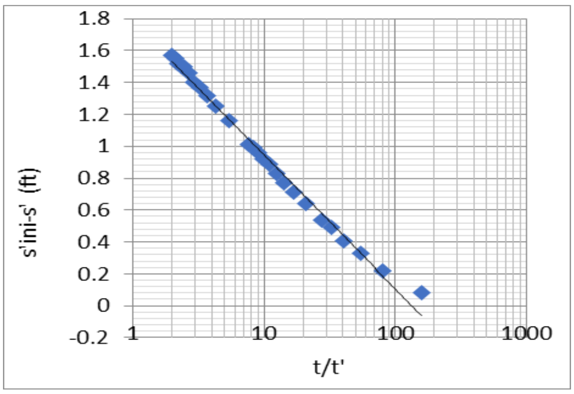


Figure .11. Semi-log graph with Straight-line of (s'$_{ini}$-s') and t/t' and estimate values of slope. data from (Ground water manual, 1981. p117)

Nozar Samani & M.Pasandi method

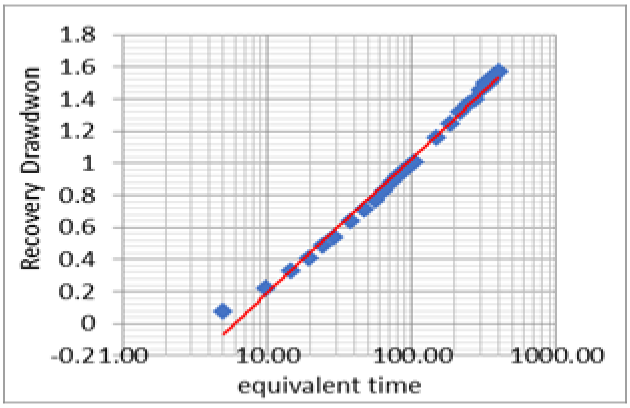


Figure .12. Semi-log graph with Straight-line of recovery drawdown and equivalent time. And estimate values of slope and intercept. data from (Ground water manual, 1981. p117

Table 2. Estimated Parameters for Example (Ground water manual, 1981. p117).

Method	**S**	**T ft^2/min**
Theis [35]	0.06367	34.2705
P.N. Balluraya and K.K. Sharma	0.06441	34.2705
R. P. Chapuis	-----	35.0768
USDI Ground water	0.06310	34.6689
I zheng , Jain-qing ,Yuping	0.06848	30.7184
Chenaf.D and Robert P.Chapuis		
1st Method	T/S =	673.071
2nd	0.05171	35.4944
Nozar Samani & M.Pasandi	0.04791	35.4943
Sushi K. Singh	0.06309	34.3034

- **Exemple (Dessureault, R.1975. Hydrogéologie du lac Saint-Jean, p. 72)**

Third data is the confined aquifer at saint-henri-de-Taillon is composed of 1.5 to 4.6 m of fine to gravelly sand overlaid by clay. A pumping test was conducted in a fully penetrating well (17.70 m depth and 15.24 cm diameter) for 48 hours at a mean pumping rate of 13.63 m^3h^{-1}.and for two observation wells located at 15.24 and 30.48 m from the pumping well, respectively. And the values of T and S obtained by the methods are shown in Table 3.

Theis recovery method

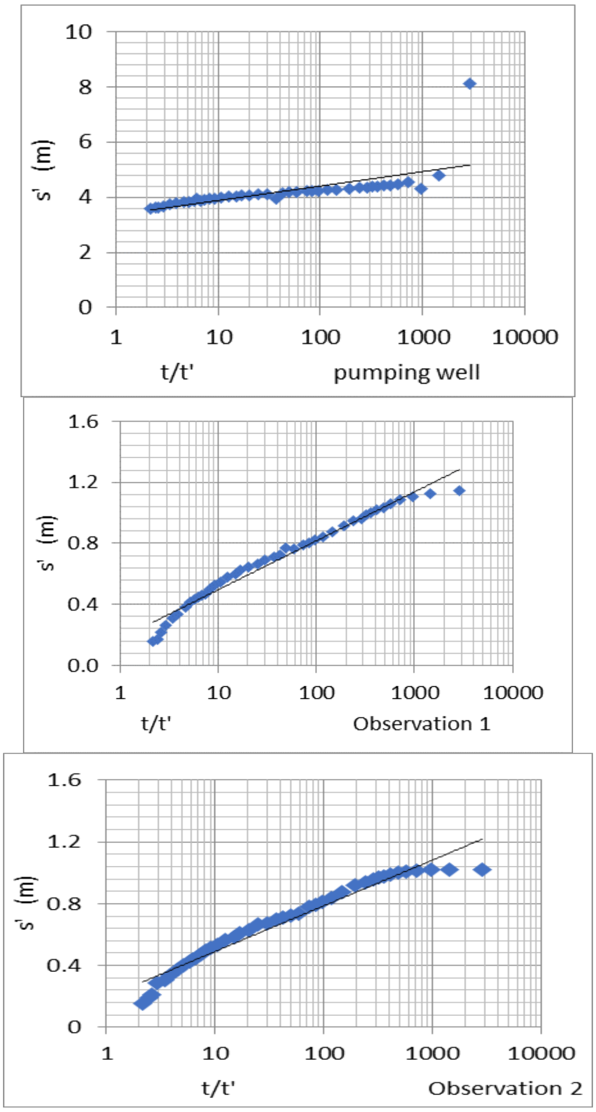
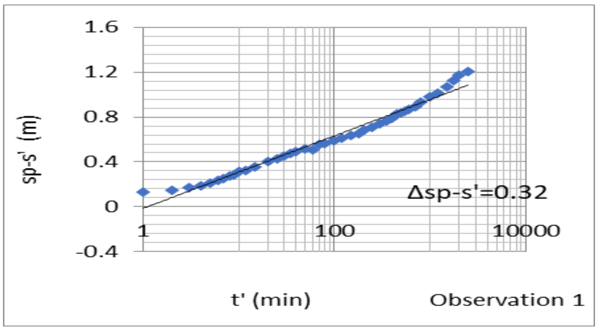


Figure.13. (a.b.c) graph with Straight-line of drawdown and t/t' and estimate values of slope for each well. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

USDI Ground water method



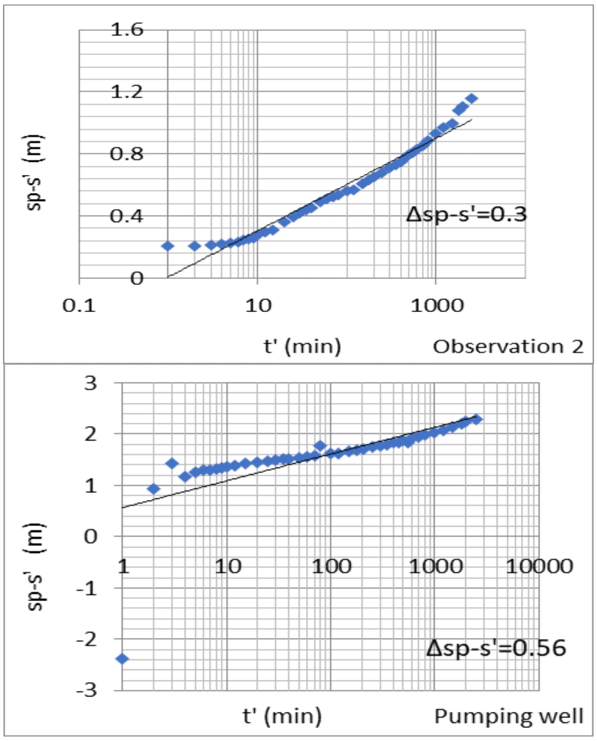
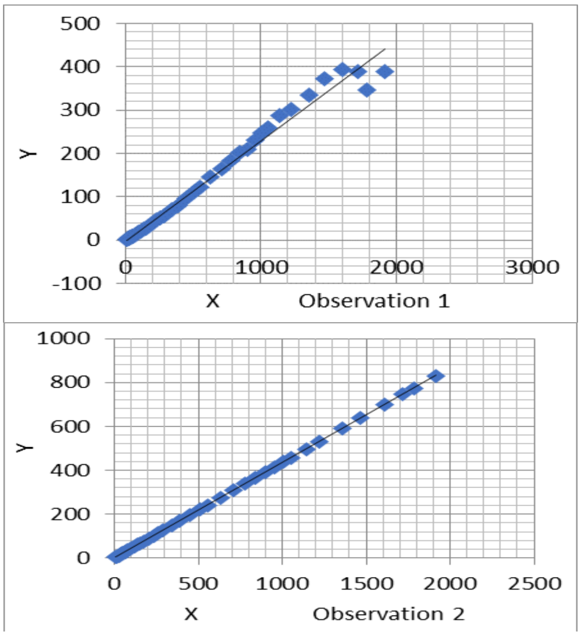


Figure.14. (a.b.c) graph with Straight-line of sp-s' and t' and estimate values of slope for each well. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

Li Zheng, Jain-qing, Yuping method



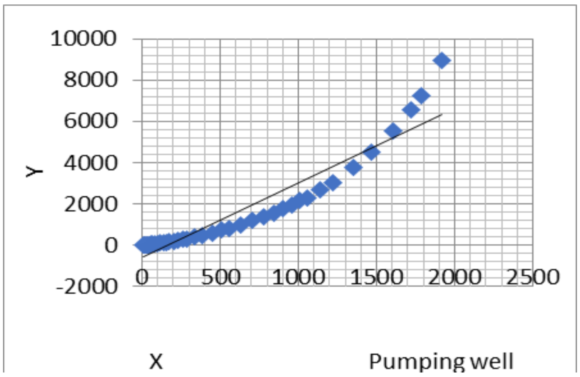


Figure.15. (a.b.c) graph with Straight-line of sp-s' and t' and estimate values of slope for each well. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

Chenaf.D and Robert P.Chapuis first-method.

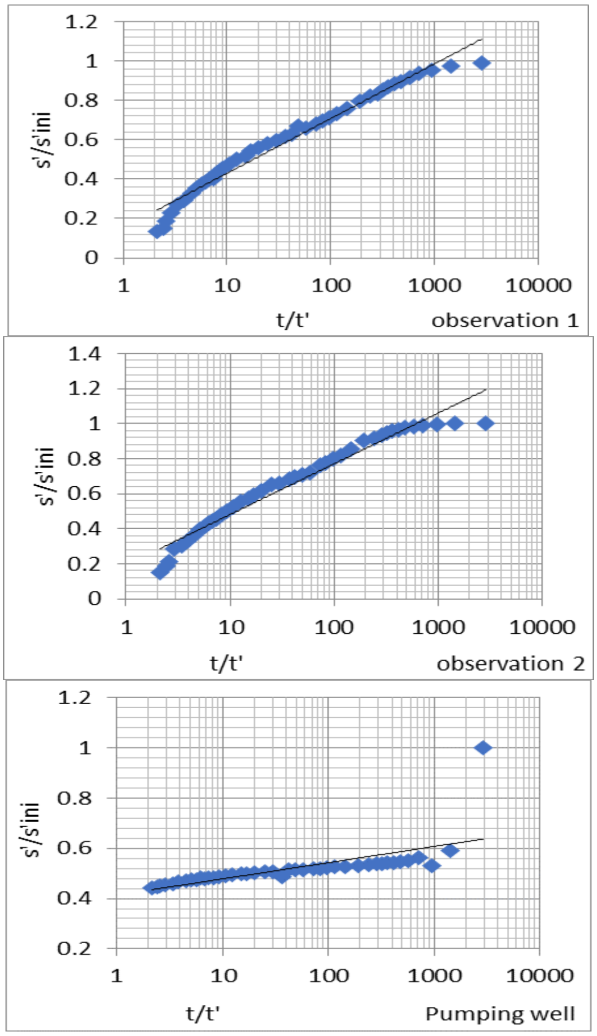


Figure.16. (a.b.c) Semi-log graph with Straight-line of s'/s'_{ini} and t/t' and estimate values of slope for each well. Data from

(Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

Chenaf.D and Robert P.Chapuis second-method.

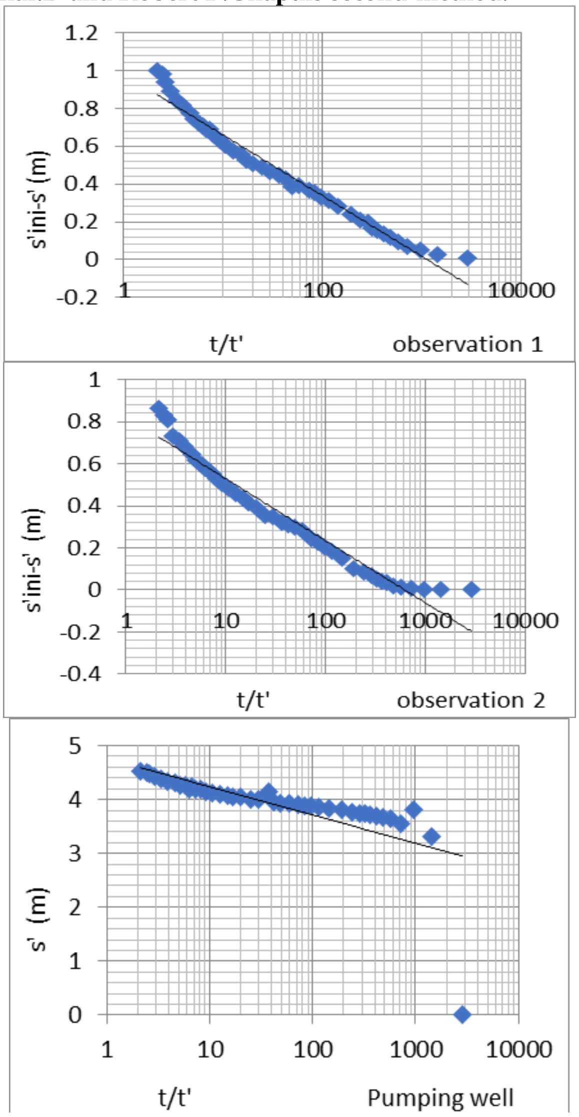


Figure.17. (a.b.c) Semi-log graph with Straight-line of (s'_{ini}-s') and t/t' and estimate values of slope for each well. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

Olivier B. and L. M.Bangoy method

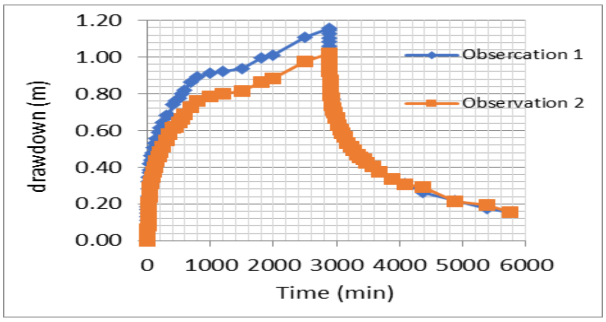


Figure.18. graph for pumping and recovery data from two observation wells. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

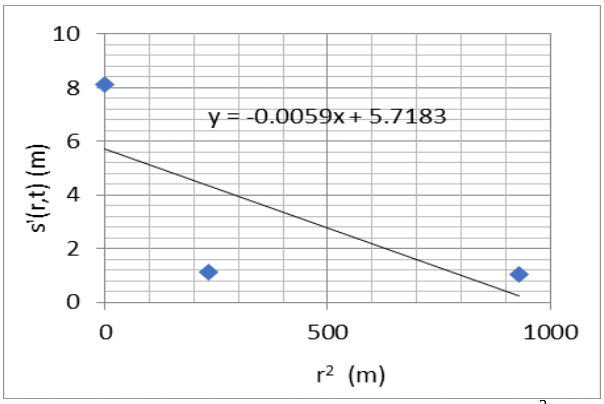


Figure.19. graph with Straight-line of s'(r,t) and r^2 and estimate values of slope and intercept. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

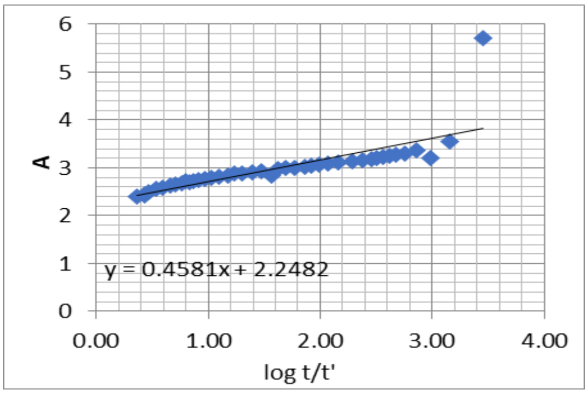


Figure.20. graph with Straight-line of A and (log t/t') and estimate values of slope C. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

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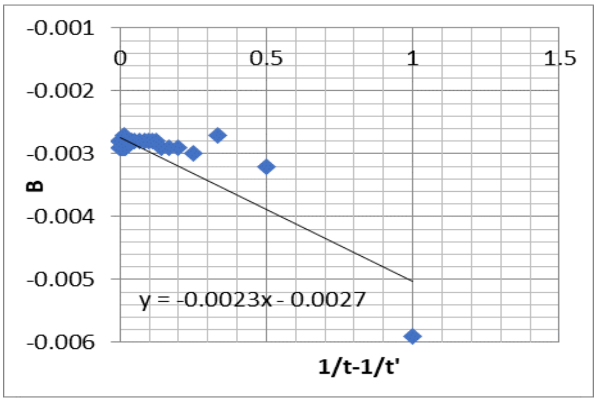


Figure.21. graph with Straight-line of B and (1/t'-1/t) and estimate values of slope D. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

Samani & M.Pasandi method

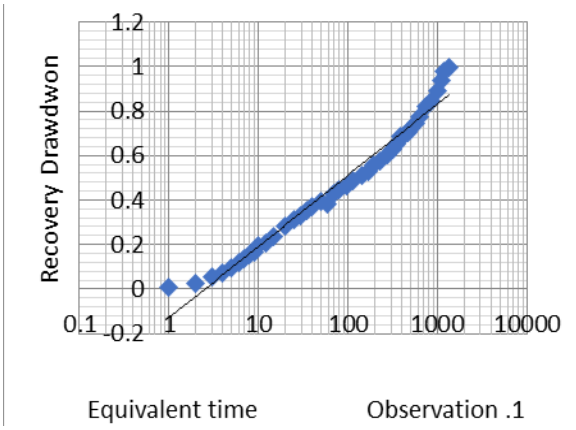
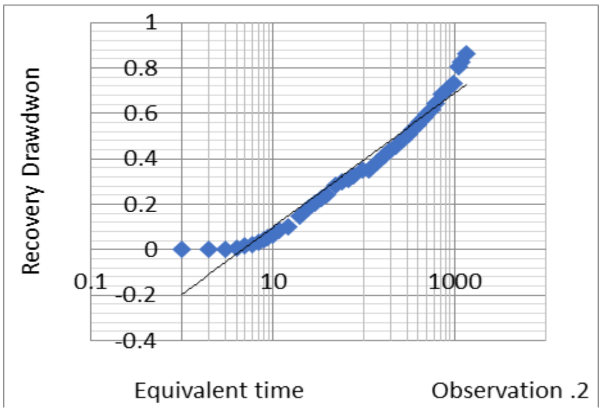


Figure.22. (a) Semi-log graph with Straight-line of recovery drawdown and equivalent time. And estimate values of slope and intercept for each well. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).



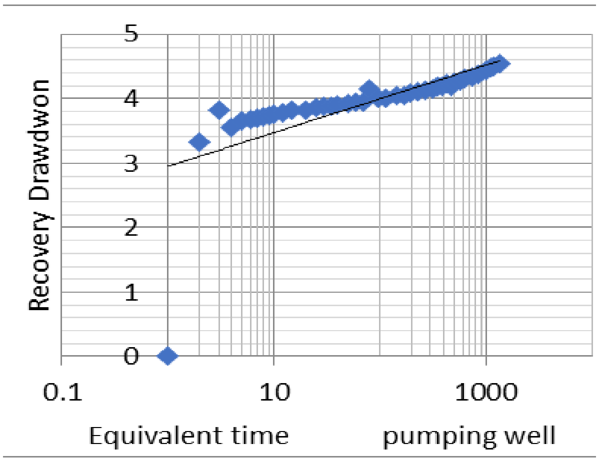


Figure.22. (b.c) Semi-log graph with Straight-line of recovery drawdown and equivalent time. And estimate values of slope and intercept for each well. Data from (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76

Table.3. Estimated Parameters for (Dessurealt, Aquifer of Saint-Henri de Taillon, Quebec, Canada 1975. P 72-76).

Method	**S**	**T m^2/min**
Theis [35]	0.013352	0.12778
P.N. Balluraya and K.K. Sharma	0.013468	0.13871
R. P. Chapuis	0.001100	0.13737
USDI Ground water	0.017765	0.13737
I zheng , Jain-qing ,Yuping	0.012150	0.09279
Chenaf.D and Robert P.Chapuis		
1st Method	T/S=	268.036
2nd	0.0018609	0.13871
Nozar Samani & M.Pasandi	0.0018699	0.13756
Sushi K. Singh	0.0018287	0.13885
Olivier B. and L. M.Bangoy	0.0461812	0.10898

VI. DISCUSSION

A few methods have been proposed to evaluate storage coefficient from recovery data including Jacob (1946), Ballukraya and Sharma (1991). The Ballukraya and Sharma method is Similar to the USDI method for estimating values of storativity. All these methods ignore the pumping time effect; as a result, the aquifer parameter values calculated using them are approximate and contain errors. Chapius (1992) presents a comparison discussion of the various approaches allowing the evaluation of storage coefficient from recovery data. And it's simply obtained at any time t' by extrapolating the straight line in the cooper-Jacob graph, S equation indicates a straight-line relationship between (sp-s') and log t', with slope Δ (sp-s') over a one-time decimal log cycle and a time intercept t'0=t0 when (sp-s') = 0. It is equivalent to the usual cooper-Jacob equation for the pumping period drawdown, and it is valid for similar either u' or t'.

Most of the methods were applied to three sets of field data to show that the values obtained by the methods are close to the ones obtained using the classical Theis method for the drawdown data during the recovery period. Most of the methods gave accurate results and were close to the Theis method in the first and second examples. Except (Banton and Bangoy) equation has not been applied in the first and second field data, because it requires more than two points of data (pumping well and two observation wells). Each method is different from other methods in terms of estimate T and S. Banton and Bangoy (1996) proposed a method using a post-third-term truncation of the Theis well function. Banton and Bangoy's method involves three plots and requires observations from at least two observation points (i.e., the pumping well and an observation well), Based on Theis' exact solution.

Chenaf and Chapuis (2002) proposed two methods for the calculation of aquifer parameters from recovery data. Both methods are based on the Cooper-Jacob approximation (i.e., when pumping duration before recovery is large enough) and use residual drawdown measured in any piezometer at a distance r from the pumping well axis. The values of S and T obtained by the first method cannot be considered as the sole result of recovery data interpretation. These values depend on the quality of values of S and T obtained from pumping data. Consequently, any inaccuracy or errors in the drawdown plot are carried over into the recovery plot (Chenaf and Chapuis 2002). The second method allows the explicit determination of S from recovery data; however, it is still dependent on the theoretical extended pumping drawdown data. And the (Ii Zheng, Yuping 2000) method, is a simple and easy method for determining the aquifer Transmissivity and storage coefficient based solely on pumping recovery data. It depends on the values of this equation are equivalent values and placed in the graph of Cooper Jacob For a linear equation, all the points transformed from the recovery data fall onto a straight line except for late time points. The application of this method in three data may be hindered by conditions that violate the assumptions in the Theis solution. (Sushi K. Singh 2003) method was used too in this study to determine the Transmissivity and storativity from recovery data. A simple method for explicit determination of confined aquifer parameters from the drawdown data. The method does not require curve matching or an initial guess for the parameter values.

(Nozar Samani & M.Pasandi 2003). The method is based on the conversion of residual drawdown to recovered drawdown data plotted versus equivalent time the method uses the recovery data in one observation point only and does not need the initial water level(h_0). However, this method is not free from errors that may have existed and is considered as the first recovery data point.

The authors knowledge we used the data just from a confined aquifer to apply these methods.

IV.CONCLUSION

The proposed methods in this study all adopt a particular method for estimating the variables and finding T, S of recovery data, but they mostly depend on the graph and extract the intercept and the slope of the straight line for the recovery time and residual drawdown (cooper-Jacob approximation). These methods require observations from a minimum of two points (the pumping well and an observation well). For each time during recovery, the drawdown observed in the two wells is first plotted about the distance from the pumping well. The transmissivity was to ensure that the value when the period of pumping and a period of recovery was equal in the three examples used, In the first and the second examples the value of S was equal S' the pumping and recovery period for most of the methods that gave almost similar results, and with short-term test (24h or less). But in the third example, we found that the value of the storage coefficient is equal in (pumping and recovery) periods. We were able to obtain some methods unfit to find the value of the storativity where the value of ($S \neq S'$). And with long-term recovery tests (more than 24h). As well as we note that the following methods can rely on its results when the value of S non-equal S' and the recovery test takes a long period (Chenaf and Chapuis 2002), (Nozar Samani & M.Pasandi 2003), (Sushil K. Singh 2003), because each method and its way to estimate the value of s values decrease.

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