Aquifer Parameter Estimation

C. P. Kumar[1], Scientist-F &
Anupama Sharma[1], Scientist-C

1.1 General

Groundwater occurs in many types of formations known as aquifers. An aquifer is best defined as a saturated permeable geologic formation that can transmit significant quantities of water under ordinary hydraulic gradients. Generally, there are two types of aquifers, namely: confined and unconfined. The confined aquifer or artesian aquifer is an aquifer that is confined between two impermeable strata and contains water at pressures greater than atmospheric pressure. On the other hand, the unconfined or water-table aquifer is one in which water-table exists.

An important and needed property of aquifers is their ability to store water in the rock pores, and to transmit it from point to point. These two properties are usually known as the characteristics of an aquifer.

First property is known as "storage coefficient" while the second is known as "transmissivity". When the head in a saturated aquifer changes, water will be either stored or expelled. The storage coefficient or storativity is the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head. It is a dimensionless quantity. Transmissivity is defined as the measure of the amount of water that can be transmitted horizontally by the full saturated thickness of the aquifer under a unit hydraulic gradient

2. 1 Pumping Tests

Pumping test is a field test which done by pumping water from a well with constant rate and measuring the drawdown from an observation well (or wells) with radius of influence r, or it can be read in the pumping well itself as done in this study; the time should be taken at each value of drawdown.

The purpose of this test is the determination of the transmissivity and storativity of any aquifer. A practical use is made in the determination of the hydrogeologic parameters of aquifers. Aquifer properties are obtained from a pumping test by determining the values of storage coefficient (specific yield for unconfined aquifers), hydraulic conductivity, and transmissivity which cause the drawdown predicted theoretical solution to most nearly agree with drawdowns measured in one or more observation wells.

The construction, number and location of observation wells are important considerations. This depends upon the requirement of the test, the finances available, and the particular conditions at the test site. Also, some provision must be made before and during the running of the test. This includes: measuring and controlling the pumping rate, appropriate spacing of observation wells, disposing of the pumped water in a manner that will not affect the test results, measuring static water level (S.W.L.) at the beginning of each pumping test, etc.

[1] Ground Water Hydrology Division, National Institute of Hydrology, Roorkee-247 667 (Uttarakhand).

2.2 Analysis of Pumping Test Data

Because the aquifer properties are determined by matching measured drawdowns with those predicted by theoretical equations, it is important, in the beginning of the test, that the aquifer geometry, boundary conditions, and initial conditions at the test site match those assumed 'in the theoretical equations as possible.

Data that is, usually, obtained from a pumping test includes: pumping discharge, static water level, radius to any observation well, and list of drawdown (s) at specific times (t). At the completion of the test, the drawdown vs. time data at each observation well can be analyzed using the different methods.

It should be noticed that while Theis and Jacob methods are used to determine transmissivity and storativity, recovery method is used only to determine transmissivity. Detailed description of these methods follows.

2.3.1 Theis method

Theis (1935), in what must be considered of the fundamental breakthroughs in the development of hydrologic methodology, utilized an analogy to heat-flow theory to arrive at an analytical solution to the following particle differential equation for unsteady radial flow:

$$\frac{\partial^2 h}{\partial r^2}+\frac{1}{r}\frac{\partial h}{\partial r}=\frac{s}{T}\frac{\partial h}{\partial t} \qquad (2.1)$$

where:

r = radial distance from well
S = storage coefficient, and
T = transmissivity
RHS = transient term of storage

Theis obtained a solution to the governing equation by assuming that the well (pumping Q) is a sink of constant strength and by using boundary conditions:

$h = h_0$ for t = 0 and, $h \rightarrow h_0$ as $r \rightarrow \infty$ for $t \geq 0$

$$h-h(r;t)=\frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}du}{u} \qquad (2.2)$$

Theis Eqn.

$$S=\frac{Q}{4\pi T}w(u) \qquad (2.3)$$

where:

s = drawdown
Q = discharge at the well,
W(u) = well function

$$u = \frac{r^2 s}{4Tt} \qquad (2.4)$$

$$s = h_0 - h = \frac{Q}{4\pi T} W(u) \qquad (2.5)$$

Well function, W(u), is usually expanded by the infinite series:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} \ldots\ldots \qquad (2.6)$$

where:

h_0 = initial height of piezometric surface or water-table above certain datum.
h = final height of piezometric surface or water-table above certain datum.
Q = flow rate from pumping well.
T = aquifer transmissivity.
t = time since pumping began.
S = storage coefficient of the aquifer.
r = radius from pumping well to an observation well.
s = drawdown.

The relation between W(u) and u is called Type Curve . Values of W(u) Vs u are displayed in Table (2.1). Theis equation can be used to obtain aquifer constants S and *T* by means of pumping tests at fully penetrating wells.

The "Theis" Assumptions:

a) The aquifer is homogeneous, isotropic, of uniform thickness, and of infinite a real extent.

(b) Before pumping, the piezometric surface is horizontal.

(c) The well is pumped at a constant discharge rate.

(d) The well diameter is infinitesimal so that storage within the well can be neglected.

(e) Water removed from storage is discharged instantaneously with decline of head.

(f) Flow is everywhere horizontal within the aquifer to the well.

Steps to determine T and S using Theis method are as follows:

(1) Plot the function W(u) versus u on long-log paper, which is known as type curve Table (2.1).

(2) Plot the measured $\frac{r^2}{t}$ versus drawdown values that were obtained from field data, on log-log paper of the same size and scale as the type curve.

(3) Superimpose the field curve on the type curve keeping the coordinate axes parallel. Adjust the curves until most of the observed data points fall on the type

curve.

(4) Select an arbitrary match point and read off the paired values of W(u), u, s, and $\frac{r^2}{t}$ at the match point.

(5) Using these values, together with the pumping rate Q, calculate T from Eq. (2.3) which becomes:

$$T = \frac{QW(u)}{4\pi s} \tag{2.7}$$

(6) Calculate S from the relationship (2.4) which becomes:

$$S = \frac{4uT}{\frac{r^2}{t}} \tag{2.8}$$

Note that Theis method is a graphical method which use type curve to obtain solution of Eq. (2.1).

Table 2.1: values of W(u) for values of u

u	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
1	0.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
10^{-1}	1.82	1.22	0.91	0.70	0.56	0.45	0.37	0.31	0.26
10^{-2}	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
10^{-3}	6.33	5.64	5.23	4.95	4.73	4.54	4.39	4.26	4.14
10^{-4}	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
10^{-5}	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
10^{-6}	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
10^{-7}	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
10^{-8}	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
10^{-9}	10.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
10^{-10}	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.25
10^{-11}	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
10^{-12}	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.87	24.86
10^{-13}	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
10^{-14}	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
10^{-15}	33.96	33.96	32.86	32.58	32.35	32.17	32.02	31.88	31.76

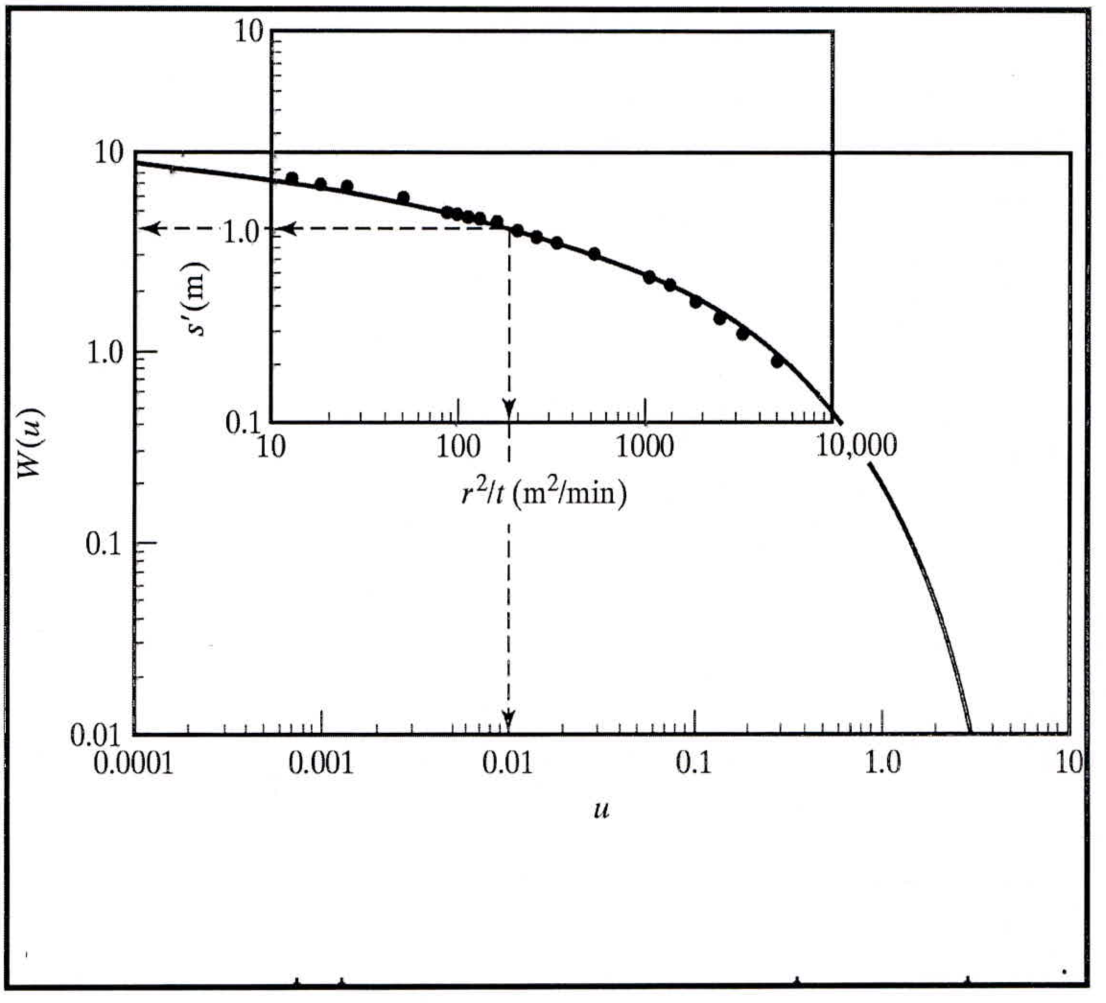

Fig. 2.1: Theis Method - Graphical Solution.

The relationship between W(u) and u must be the same as that between s and $\frac{r^2}{t}$ because all other terms are constants. - therefore, plotting:

$$W(u) \text{ vs. } u, \text{ and } s \text{ vs. } \frac{r^2}{t}$$

2.3.2 Cooper-Jacob Method of Solution

It was noticed by Cooper and Jacob (1946) that for small values of r and large values of t, u is small s that the series terms in the equation [2.9].

$$s = \frac{Q}{4\pi T}(-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - ....) \tag{2.9}$$

become negligible after the first two terms. As a result, the drawdown can be expressed by the asymptote.

$$s = \frac{Q}{4\pi T}(-0.5772 - \ln\frac{r^2 s}{4Tt}) \qquad (2.10)$$

Rewriting and changing to decimal logarithms, this reduces to

$$s = \frac{2.3 * Q}{4\pi T}\log\frac{2.25Tt}{r^2 s} \qquad (2.11)$$

Since Q, r, T, and S are constants, it is clear that s versus log t should plot as a straight line. If s is the drawdown for one log cycle of time and t_0 is the time intercept where the drawdown line intercepts the zero drawdown axis, it follows from further manipulation with Eq. (2.11) that the values of T and S, in consistent units, are given by:

$$T = \frac{2.3Q}{4\pi\Delta s / \log cycle} \qquad (2.12)$$

$$S = \frac{2.25Tt_0}{r^2} \qquad (2.13)$$

The steps for the solution are:

(1) Plot the measured drawdown versus time on a semi log paper.

(2) Project the line to axis (s=0), where t becomes equal to(to).

(3) Read the value of Δs, where Δs is the drawdown difference per log cycle of(t).

(4) Calculate T and S by applying eqs. (2.12) and (2.13).

2.3.3 Recovery Method

At the end of a pumping test, when the pump is stopped, the water level in pumping well will begin to rise. This is referred to as the recovery of ground water level, while measurements of drawdown below the original static water level (prior to pumping) during the recovery period are known as residual drawdown. A schematic diagram of change in water level with time during and after pumping is shown in Fig. (2.2).

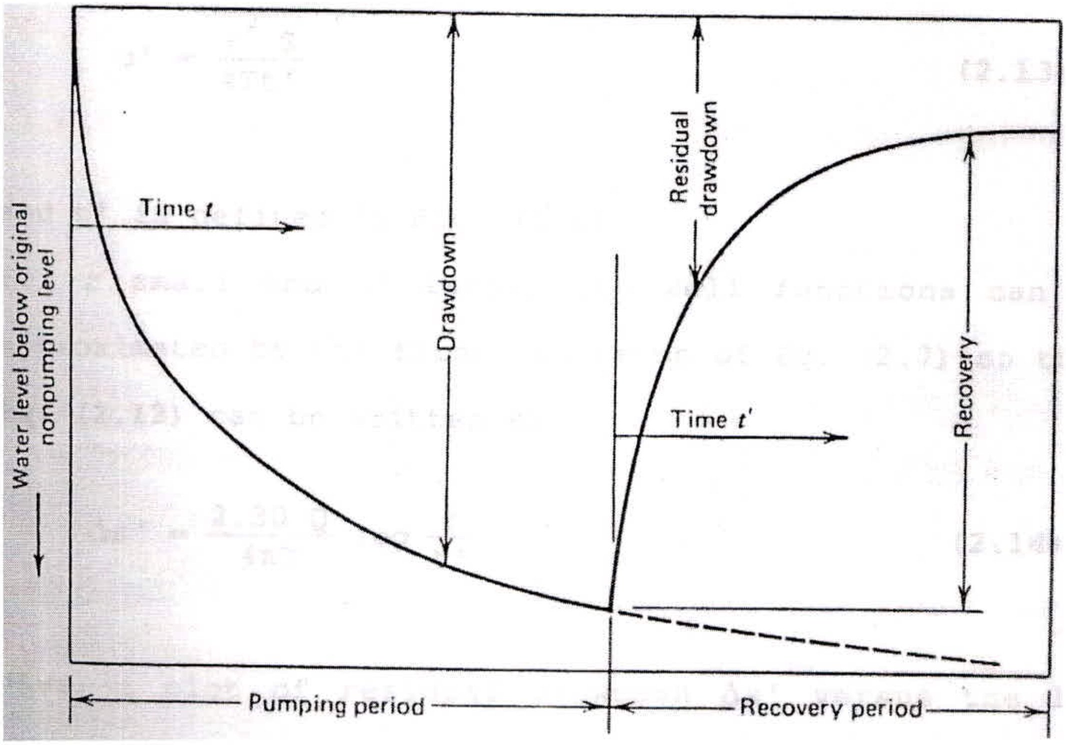

Fig. 2.2: Drawdown and recovery curves in an observation well near a Pumping well.

If a well is pumped for a known period of time and the: shut down, the drawdown thereafter will be identically the same as if the discharge had been continued and a hypothetical recharge well with the same flow was superimposed on the discharging well at the instant the discharge is shut down. From this principle, Theis showed that the residual drawdown $\Delta s'$ can be given as

$$\Delta s' = \frac{Q}{r\pi T}(W(u) - W(u')) \tag{2.14}$$

where:

$$u' = \frac{r^2 s}{4Tt'} \tag{2.15}$$

and t' is defined in Fig. (2.2). For r small and t' large, the well functions can be approximated by the first two terms of Eq. (2.15) so that Eq. (2.14) can be written as

$$\Delta s' = \frac{2.3Q}{4\pi T}\log\frac{t}{t'} \tag{2.16}$$

Thus, a plot of residual drawdown $\Delta s'$ versus the logarithm of t/t' forms a straight line. The slope of the line equals 2.30*Q/4*π*T so that for $\Delta s'$, the residual drawdown per log cycle of t/t', the transmissivity becomes

$$T = \frac{2.3Q}{4\pi\Delta s'} \tag{2.17}$$

No comparable value of S can be determined by this recovery test method. An important application of the recovery method is to make an estimate of the transmissivity by measuring the recovery in the pumped well, itself, when condition do not permit the construction of observation wells.

More precise data can be obtained during the recovery period than during the pumping period because the water in the well is not disturbed by the pump.

3.1 Aquifer Test Software

Aquifer Test provides a flexible, user-friendly environment that will allow you to become more efficient in your aquifer testing projects. Data can be directly entered in **Aquifer Test** via the keyboard, imported from a Microsoft Excel workbook file, or imported from any data logger file (in ASCII format). Test data can also be inserted from a Windows text editor, spreadsheet, or database by "cutting and pasting" through the clipboard.

Automatic type curve fitting to a data set can be performed for standard graphical solution methods in **Aquifer Test**. However, you are encouraged to use your professional judgment to validate the graphical match based on your knowledge of the geologic and hydrogeologic setting of the test. To easily refine the curve fit, you can manually fit the data to a type curve using the parameter controls.

With **Aquifer Test**, you can analyze two types of test results:

[1] **Pumping tests**, where water is pumped from a well and the change in water level is measured inside one or more observation wells (or, in some cases, inside the pumping well itself). You can present data in three different forms:

- Time versus water level
- Time versus discharge (applicable for variable rate pumping tests)
- Discharge versus water level (applicable for well performance analysis)

The following pumping test analysis methods are available, with fixed analysis assumptions:

- Cooper-Jacob Time Drawdown
- Cooper-Jacob Distance-Drawdown
- Cooper-Jacob Time-Distance-Drawdown
- Theis Recovery

Finally, the following test is available for analyzing well performance

- Specific Capacity Test
- Hantush-Bierschenk Well Losses

[2] **Slug (or bail) tests**, where a slug is inserted into a well (or removed from a well) and the change in water level in the side well is measured. You can have data in one form:

- Time versus water level

The following slug test analysis methods are available:

- Hvorslev (1951)
- Bouwer-Rice (1976)
- Cooper-Bredehoeft-Papadopulos (1967)

4.1 Tutorial Problem on Theis Method and Cooper-Jacob Method of Pumping Test

Problem: A well penetrating a confined aquifer is pumped at a uniform rate of 2500 m^3/day. Drawdowns during the pumping period are measured in an observation well 60 m away; Observation of time and drawdown are listed in the Table below. Determine the transmissivity and storativity by Theis method and Cooper-Jacob method using the Aquifer Test software.

Table 4.1: Pumping Test Data

Time (min)	**Drawdown** (m)
0	0
1.0	0.20
1.5	0.27
2.0	0.30
2.5	0.34
3.0	0.37
4	0.41
5	0.45
6	0.48
8	0.53
10	0.57
12	0.60
14	0.63
18	0.67
24	0.72
30	0.76
40	0.81
50	0.85
60	0.90
80	0.93
100	0.96
120	1.00
150	1.04
180	1.07
210	1.10
240	1.17

Further Reading

Kruseman, G.P. and N.A. de Ridder, 1979, Analysis and evaluation of pumping test data, ILRI, Bulletin 11, Wageningen, The Netherlands.

Johnson, E.E., 1966, Groundwater and wells, E.E. Johnson, Inc., Saint Paul, Minn.

Walton, W.C., 1962, Selected analytical methods for well and aquifer evaluation, Illinois State Water Survey Bull. No. 49.