Pumping Test

Laboratory 6

HWR 431/531

Introduction:

Aquifer tests are performed to evaluate the capacity of an aquifer to meet municipal or industrial water requirements. Hydraulic characteristics of the aquifer are used to predict the aquifer's response to pumping. Specifically, determination of the *transmissivity* (T) and *storage coefficient* (S) allows one to estimate drawdown for different pumping rates or at different distances from a pumping well.

Background:

Hydraulic Characteristics:

Hydraulic characteristics reflect the potential of an aquifer for water development. The *storage coefficient* (S, [-]) of an aquifer indicates the volume of water that can be removed from storage. This dimensionless quantity is defined as the volume of water an aquifer releases from storage per unit change in head per unit surface area of the aquifer. Figure 7-1 illustrates the differences in S observed in confined and unconfined aquifers. For a given decline in head an unconfined aquifer will drain pore space and therefore release significantly more water to the pumping well than a confined aquifer for which the yield is due to the expansion of water as the pressure decreases.

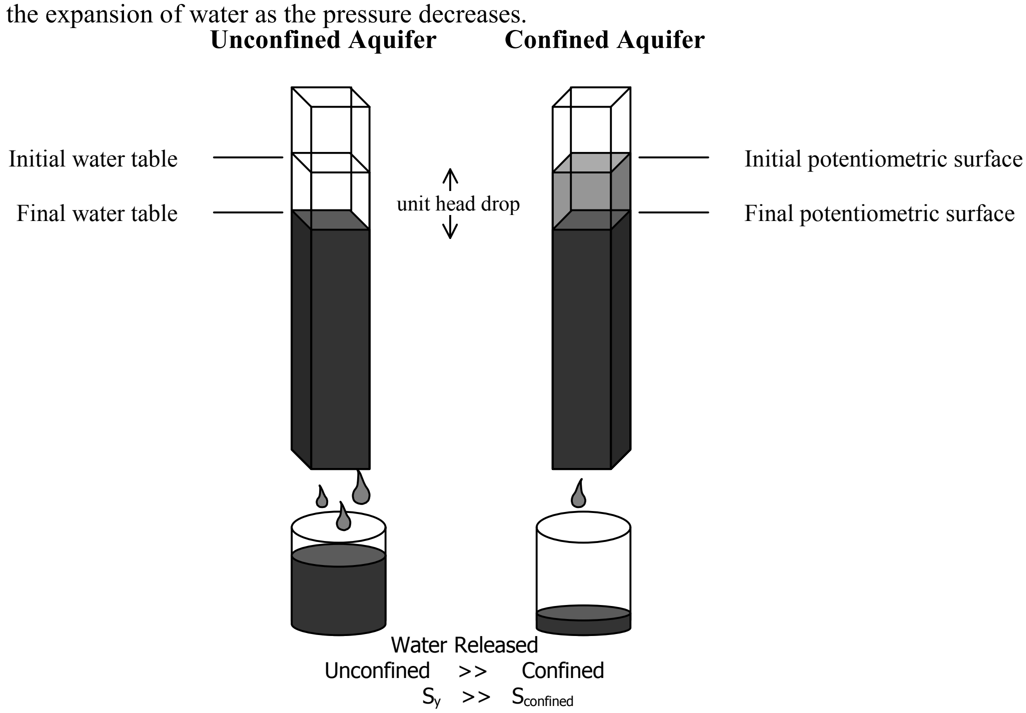


Figure 7-1: The difference in storage between confined and unconfined aquifers.

Transmissivity (T, [L^2T^{-1}]) indicates how easily water can move through a geological formation (Note: T = Kb; K = hydraulic conductivity, b = aquifer thickness). This term is defined as the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. In aquifers with high transmissivities, the cone of depression is shallower, less steep and more extensive than in aquifers with lower transmissivities (see Figure 7.2). Transmissivity commonly ranges from 10-10^4 m^2/d.

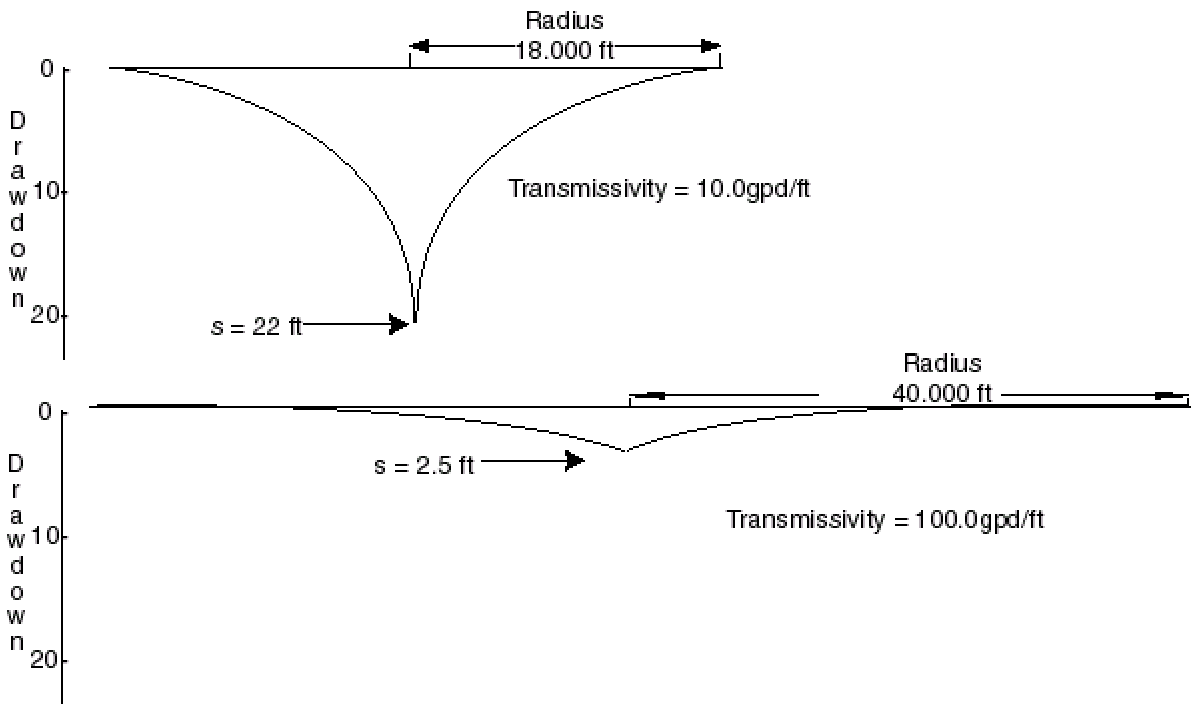


Figure 7-2: The effect of transmissivity on the cone of depression.

Analytical Solutions:

Data generated from aquifer tests can be used to calculate T and/or S by means of mathematical models describing groundwater flow towards the well. These models (flow equations) are derived using a mass balance approach and may therefore apply to equilibrium or non-equilibrium flow conditions. In this laboratory exercise, the **Thiem** (1906), **Theis** (1935) and **Jacob** (1946) equations are employed.

Equilibrium Flow Equation: Thiem Solution:

If the cone of depression surrounding a pumping well is stabilized (i.e. drawdown and radius of influence are static) the Thiem equation is used to determine the hydraulic conductivity for the aquifer (note: the storage coefficient *cannot* be found under steady state conditions). For an unconfined aquifer with two observation wells:

$$K = \frac{Q \log\left(r_2 / r_1 \right)}{1.366(h_2^2 - h_1^2)} \tag{1a}$$

where: r_1 = distance to the nearest observation well

r_2 = distance to the farthest observation well

h_x = saturated thickness at the given observation well

Q = pumping rate

This equation adapted for confined aquifers is:

$$K = \frac{Q}{2.73b(h_2 - h_1)} \log\left(r_2 / r_1 \right) \quad \Rightarrow \quad T = \frac{Q}{2.73(s_1 - s_2)} \log\left(\frac{r_2}{r_1} \right) \tag{1b}$$

where: b = thickness of aquifer

h_x = head in observation well

s_x = drawdown in observation well

The transmissivity of an aquifer can be directly obtained from equations 1a & b.

Non-equilibrium Flow Equations: Theis Solution:

Using a model describing the flow of heat from a heat source, Theis (1935) derived a mathematical equation for the transient flow of groundwater to a well. The equation was originally developed for a fully penetrating well in a confined aquifer, but may also be used for unconfined aquifers if the drawdown is considerably smaller than the saturated thickness.

Theis developed a standard type curve which relates the theoretical response of an aquifer to pumping. The type curve is obtained by plotting W(u) (the well function of u) vs. 1/u where:

$$W(u) = -0.5722 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \ldots \tag{2a}$$

$$u = \frac{r^2 S}{4Tt} \tag{2b}$$

where: r = distance from the pumping well to the observation well

t = time

According to Theis, the drawdown of an aquifer (s) at a given distance, r, from the pumping well at time, t, is related to W(u):

$$s = \frac{Q}{4\pi T} W(u) \tag{3}$$

Using equations 2 and 3 with time-drawdown data from an aquifer test, S and T for the aquifer can be calculated. Unfortunately, an analytical solution for the equations is involved and a graphical solution is commonly used instead.

In order to solve for S & T, a Theis type curve is prepared from Table 1 on log-log paper. From the aquifer test data, plot log s vs. log (t/r^2) on another piece of log-log paper **of the same scale**. By superimposing the two graphs such that the type curve overlies the data (while keeping the axis from both graphs parallel to each other) one may then pick an arbitrary match point. The values of s, t/r^2, 1/u and W(u) at the match point must be recorded and then used directly in equations 2b and 3 to calculate S and T, respectively. The Theis solution may also use distance-drawdown data from multiple wells instead of time-drawdown measurements from a single well.

Table 1 – Values of the Well Function for the Theis Solution
NOTE: The Theis Type Curve for a NON-LEAKY aquifer is given when r/B=0

1/u	r/B							
	3	1	0.3	0.1	0.03	0.01	0.003	0
0.33	0.0071	0.0122	0.013	0.013	0.013	0.013	0.013	0.013
0.5	0.021	0.04444	0.0485	0.0488	0.0489	0.0489	0.0489	0.0489
1	0.0534	0.1855	0.2161	0.219	0.2193	0.2194	0.2194	0.2194
1.43	0.0639	0.2996	0.3663	0.3729	0.3737	0.3738	0.3738	0.3738
2	0.0681	0.421	0.5453	0.5581	0.5596	0.5598	0.5598	0.5598
3.33	0.0694	0.601	0.8713	0.9018	0.9053	0.9056	0.9057	0.9057
5	0.0695	0.7148	1.1602	1.2155	1.222	1.2226	1.2226	1.2226
10		0.819	1.6704	1.805	1.8213	1.8227	1.8229	1.8229
20		0.8409	2.1371	2.4271	2.4642	2.4675	2.4679	2.4679
33.333		0.842	2.411	2.8873	2.9523	2.9584	2.959	2.9591
50			2.5688	3.2442	3.3444	3.3536	3.3546	3.3547
100			2.7104	3.815	4.0167	4.0356	4.0377	4.0379
200			2.7428	4.296	4.6829	4.7212	4.7256	4.726
333.33			2.7448	4.5622	5.1627	5.2267	5.2342	5.2348
500			2.7449	4.7079	5.5314	5.6271	5.6383	5.6393
1000				4.8292	6.1202	6.3069	6.3293	6.3313
2000				4.853	6.6219	6.975	7.0197	7.0237
3333.333				4.8541	6.9068	7.4534	7.5274	7.543
5000					7.0685	7.8192	7.929	7.939
10000					7.2122	8.3983	8.6109	8.6308

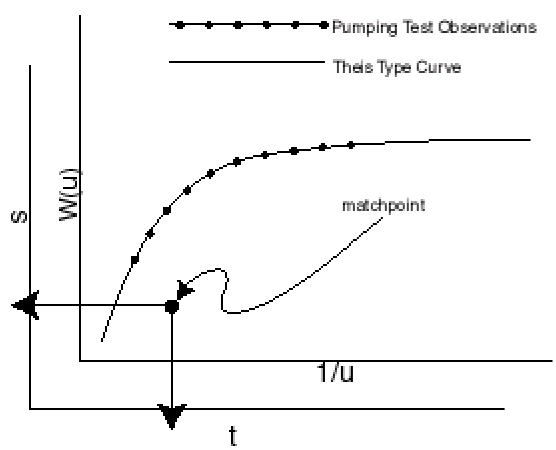


Fig. 7-3: Curve matching pumping test data with the Theis Type Curve.

Non-Equilibrium Flow Equations: Jacob Approximation:

It was recognized that the terms beyond 1n(u) in the expanded series of the well function (*W(u)*) can be neglected if u is sufficiently small. Thus the Theis solution (Eq.3) becomes simply:

$$s = \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{r^2 S}\right) \tag{4}$$

The resulting Jacob method can utilize measurements of drawdown vs. distance from the pumped well or drawdown in a single well vs. time. As a general guideline, the application of this method is only valid for values of u less than about 0.05 (Driscoll, 1986).

If Q and r are constant, equation 4 takes on the following form:

$$s = A \log t + B \tag{5}$$

which is a straight line with slope A and intercept B where:

$$A = \frac{2.3Q}{4\pi T}$$

$$B = \frac{2.3Q}{4\pi T} \log\left(\frac{2.25T}{r^2 S}\right)$$

These equations can be rewritten to give the solutions for T & S:

$$T = \frac{2.3Q}{4\pi} \frac{\Delta(\log t)}{\Delta s} \tag{6a}$$

$$S = \frac{2.25Tt_o}{r^2} \tag{6b}$$

where: Δs = change of drawdown for a given change in log(t)

Δ(log *t*) = change in time (note: Δlogt = 1 for one log cycle)

t_o = intercept of the straight line with zero drawdown

It should be noted that since u must be small, early-time data are not used to fit the straight line. Although this application of Jacob's method requires data from only one well, a reliable value of S cannot be calculated using data from the pumped well.

If one chooses to use distance-drawdown data instead of transient measurements, the method is the same as above except that now t is constant and r depends on the distance from the pumping well to the observation wells. The plot would then be drawdown (at a given time) vs. distance to the observation well. Transmissivity and the storage coefficient can then be calculated with the following:

$$T = \frac{2.3Q}{4\pi}\frac{2 \cdot \Delta(\log r)}{\Delta s} = \frac{0.366Q}{\Delta s} \tag{7a}$$

$$S = \frac{2.25Tt}{r_o^2} \tag{7b}$$

where: r_o = intercept of extended straight line with zero drawdown

At least three observation wells should be used with this method. Also, a later value of t should be picked to ensure that u is sufficiently small. Note that a plot of s vs. r at time t gives the radial profile of the cone of depression at that time.

Residual Drawdown vs. Time

When the pumping period of the aquifer test is complete, water levels in the aquifer will begin to rise toward pre-pumping levels. The change in residual drawdown (the difference between the static water level and the water level in the well at a certain time after the pump is shut off) with time indicates the rate of recovery of the aquifer. Using recovery data from an observation well or the pumped well, calculations of T from the pumping data can be checked. Because values of Q, T, S and r are constant, residual drawdown vs. *"time"* [actually, the ratio of the elapsed time since pumping began to the elapsed time since the pump was turned off (t/t')] will plot as a straight line on a semilogarithmic graph. Note that the ratio t/t' decreases during the recovery period and actual time increases from right to left on this graph. Equation 6a becomes:

$$T = \frac{2.3Q}{4\pi\Delta s'} \qquad (8)$$

where: $\Delta s'$ = change in residual drawdown over one log cycle

The plot of residual drawdown cannot be used to calculate the storage coefficient of the aquifer.

Laboratory Assignment:

This is a two-week lab. The first week will consist of inspection of the field area and an assignment. The second week will be conducted in the field where you will conduct a pumping test.

Week 1:

Meet at the usual time in the lab. We will leave promptly to go to the field site where you will map the field site and make background water level measurements in the wells. You will be responsible for understanding how to operate the equipment which you are to use the following week, including the discharge measurement apparatus.

There are two parts to the assignment you must complete.

Part 1 – Each person in the class will be responsible for becoming familiar with each of the following methods of measuring discharge from the pumping well:

i) Circular Orifice Weir

ii) Parshall Flume

iii) Estimating Flow From Horizontal or Inclined Pipes (Farmer's Method)

iv) Flow Gauge

v) Volumetric Method

A **short** paragraph explaining each method along with a data sheet for recording the parameters required for each method **is to be handed in before the start of the pumping test** (keep a copy for yourself, you will need your data sheet during the test).

<u>Part 2</u> – You will analyze the following data obtained during a pumping test using the Theis and Jacob methods.

PROBLEM STATEMENT

An aquifer test has been completed in the Supai aquifer. This aquifer is composed of laminated, clean fine sand and is overlain and underlain by clayey sand units of relatively low permeability. Drilling indicates that the aquifer averages 40m thick in the vicinity of the pumped wells. During the test the hydraulic head of the Supai aquifer remained above the base of the overlying clayey sand unit.

A fully penetrating well was pumped at a rate of 1215 m^3/day. Drawdowns were measured in three fully penetrating observation wells located 30 m to the east, 80 m to the east and 180 m to the north of the pumped well. A record of the drawdown versus time measurements for the three wells is presented in Table 2. After exactly one day of pumping, the pump was turned off. Recovery measurements in the observation well 30 m to the east of the pumped well were taken. Refer to Table 3 for the recovery data.

(NOTE: All data is available in text & Excel format on your CD.)

COMPLETE THE FOLLOWING:

1. <u>Theis Solution</u>

a) Prepare a Theis type curve (you may choose to prepare this on a transparency to ease curve matching)
NOTE: The spreadsheet Quatro Pro will allow you to create graphs of specified dimensions which will allow you to perform curve matching. This program is available on all PCs in the HWR computer lab.

b) Plot drawdown vs. time data for **observation well #1** on another graph

c) Using Eq. 2b & 3, determine T (in m^2/d & gpd/ft) and S for the aquifer.

2. <u>Cooper-Jacob Solution</u>

a) Plot drawdown vs. time for all observation wells on one plot. Calculate values of T (m^2/d & gpd/ft) & S.

b) For each observation well, find the time at which the Jacob approximation *actually* became valid (where data points begin to fall on the straight line). Calculate the corresponding values of u. Was the criteria $u<0.05$ satisfied for these wells?

3. Jacob Solution (Distance-Drawdown)

a) Plot drawdown vs. distance for all wells on one plot for t-0.1days and t=1.0 days. Calculate T & S for each time, are they different from each other? Why? (Consider your answer from 2b)

4. Thiem Solution

a) Drawdown changed slowly at the end of the pumping test and thus flow can be assumed to be approximately steady state. Use the Thiem equation to calculate T & S from wells 1 & 2.

5. Recovery Method

a) After 1.000 days of pumping, the pump was shut off and residual drawdown was measured in the 30 m observation well. Plot residual drawdown (s') vs. t/t'. Calculate T. Recall that t = time since pumping began (i.e. 1 day + t'); t' = time since pump was shut off.

6. Summary

a) Tabulate T and S calculated by all methods. Which results do you think are most reliable? Offer one or two good reasons if your tabulated values of T and S differ vastly.

b) After the aquifer had fully recovered, a second aquifer test is conducted with Q= 1000m^3/day. Using your most reliable set of T and S, calculate the radius of influence of the well after one day of pumping. What can you conclude about drawdown for a specific duration of pumping?

Table 2 – Drawdown Data From Supai Aquifer

Time (days) Since Start of Pumping	Drawdown (meters)		
	OB #1 r = 30m	OB #2 r = 80m	OB #3 r = 180m
1.670E-03	0.024	-	-
2.393E-03	0.048	-	-
3.162E-03	0.075	-	-
4.390E-03	0.115	-	-
5.690E-03	0.153	0.003	-
7.054E-03	0.188	0.006	-
8.473E-03	0.220	0.010	-
1.249E-02	0.293	0.026	-
1.789E-02	0.366	0.052	-
2.543E-02	0.442	0.089	-
3.472E-02	0.511	0.130	0.005
4.998E-02	0.594	0.187	0.015
6.479E-02	0.654	0.233	0.028
8.032E-02	0.704	0.273	0.043
1.004E-01	0.756	0.317	0.062
1.405E-01	0.836	0.387	0.100
1.901E-01	0.907	0.452	0.142
2.606E-01	0.982	0.522	0.192
3.584E-01	1.058	0.593	0.249
5.062E-01	1.139	0.671	0.315
6.517E-01	1.198	0.728	0.366
8.042E-01	1.247	0.776	0.409
1.000E+00	1.298	0.825	0.455

Conditions:

Pumping Rate (Q) = 1215m^3/day

Drawdown measured in 3 observation wells:

- OB #1 - 30 m East of pumping well
- OB #2 - 80 m East of pumping well
- OB #3 - 180 m North of pumping well

Table 3 – Recovery Data From Supai Aquifer

t' Time Since Pump Shut Off (minutes)	s' Residual Drawdown (meters)	t/t'
1	1.297	
2	1.284	
3	1.264	
4	1.238	
6	1.197	
10	1.112	
15	1.043	
20	0.984	
25	0.942	
30	0.906	
40	0.841	
50	0.794	
90	0.666	
140	0.571	
200	0.495	
300	0.411	
400	0.356	
500	0.315	
600	0.283	
800	0.239	
1000	0.207	

Week 2 – Pumping Test:

Meet outside of the Harshbarger building before your lab is to commence. We will leave for the field site promptly and will not wait for latecomers.

On the day of the test, the morning lab will monitor the pumping and the afternoon lab will monitor the recovery.

A brief outline of field activities is as follows:

1. **Morning lab arrives at field site**
2. Meeting with Dennis Scheal / Setup of equipment
3. Groups take positions at different stations (i.e. wells or discharge)
4. Measure static water levels & distance from pumping well to observation wells (r)
5. Commence pumping
6. Monitor drawdown at each well **&** discharge from pumping well
7. Morning lab returns to UA – Compilation of Morning Data
8. **Afternoon lab arrives at field site**
9. Groups take positions at different stations
10. Make several measurements of drawdown at each well
11. STOP PUMPING
12. Monitor recovery in each well
13. Cleanup of equipment
14. Afternoon lab returns to UA – Compilation of Afternoon Data
15. Obtain the complete data set from either the copy center or the HWR431/531 web site.

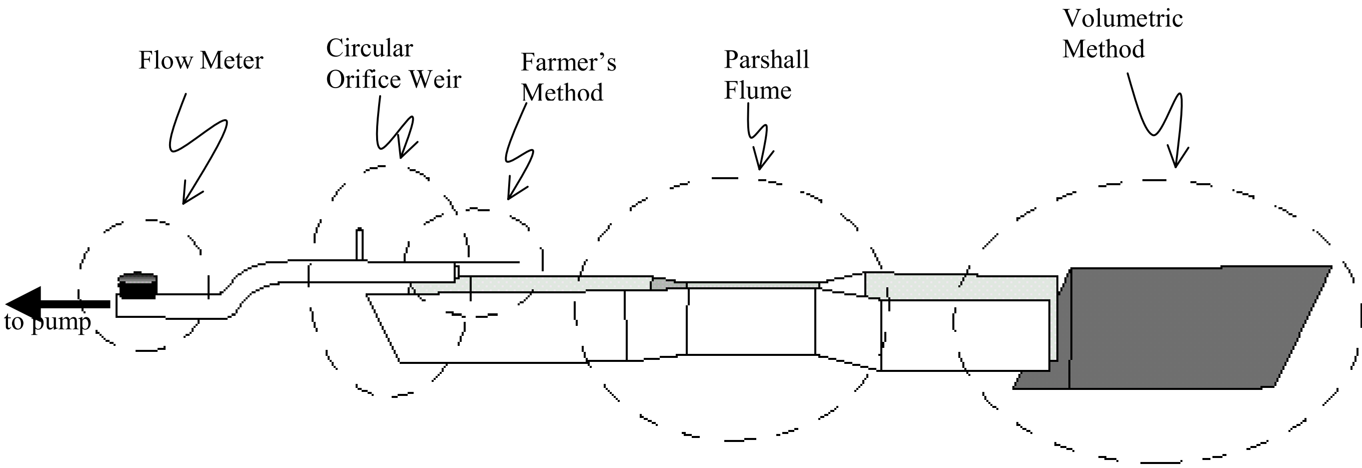
The lab group will be responsible for organizing and running the test. *Be sure that everyone knows what they are responsible for beforehand and that each person knows exactly what they are doing…**hydraulic heads change very quickly at the beginning of the test and it is important <u>not</u> to lose data from this period.***

You will be responsible for the following analysis:

1. Using the Nonsteady State Leaky Artesian Type Curves (Table 1), determine the transmissivity (T) and storativity (S) using the drawdown data at the **producing well** and **observation well D1**.
2. Using the drawdown-time data at the monitoring well D1 **only** determine T & S using the Jacob method. Do the points fall on a straight line? If not, list *at least* one possible reason why they do not.
3. Using late-time data, plot the equilibrium cone of depression and calculate T using the Thiem equation.
4. Using the recovery data (residual drawdown) from the observation well, determine T using the Jacob recovery method.
5. Do we have an efficient pumping well? We can compare the calculated T's obtained from the producing well and the monitoring well in Question 1. What do your results show? Why? How does a comparison of these two values reflect the efficiency of the pumping well? (Hint: Think not in terms of efficiency of the *pump* but rather of the well itself, i.e. screen, filter pack, etc.)

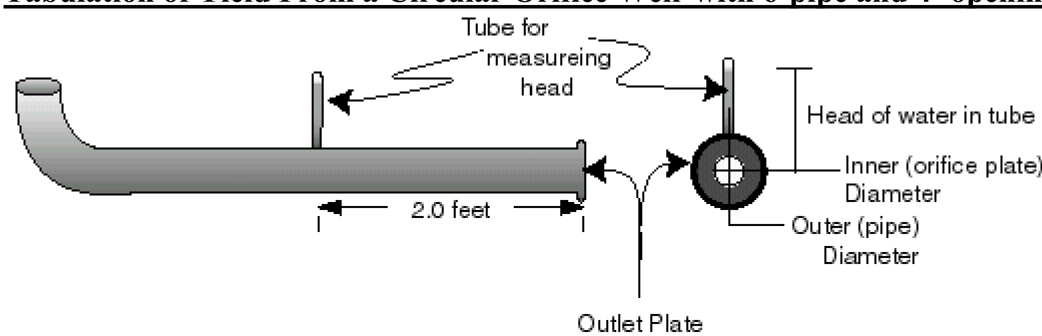
Appendix A – Tables for Measuring Discharge

Diagram of Discharge Apparatus:



Method 1 – Circular Orifice Weir

Tabulation of Yield From a Circular Orifice Weir with 6'pipe and 4' opening



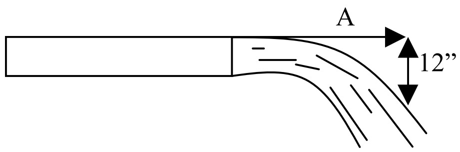
Head of Water in Tube Above Center of Orifice	Discharge per Minute (gpm) for a 6' pipe and 4' opening
5 inches	-
6	158
7	171
8	182
9	193
10	204
12	223
14	241
16	253
18	273
20	283
22	302
25	322
30	353
35	380
40	405
45	430
50	455
60	500

Method 2 – Parshall Flume

Free Flow Through Parshall Measuring Flumes in Cubic Feet per Second

Head	Throat Width			
Feet	3"	6"	9"	1'
	Flow in cubic feet per second			
0.10	0.028	0.05	0.09	0.11
0.11	0.033	0.06	0.10	0.12
0.12	0.037	0.07	0.12	0.14
0.13	0.042	0.08	0.14	0.16
0.14	0.047	0.09	0.15	0.18
0.15	0.053	0.10	0.17	0.20
0.16	0.058	0.11	0.19	0.23
0.17	0.064	0.12	0.20	0.26
0.18	0.070	0.14	0.22	0.29
0.19	0.076	0.15	0.24	0.32
0.20	0.082	0.16	0.26	0.35
0.21	0.089	0.18	0.28	0.37
0.22	0.095	0.19	0.30	0.40
0.23	0.102	0.20	0.32	0.43
0.24	0.109	0.22	0.35	0.46
0.25	0.117	0.23	0.37	0.49
0.26	0.124	0.25	0.39	0.51
0.27	0.131	0.26	0.41	0.54
0.28	0.138	0.28	0.44	0.58
0.29	0.146	0.29	0.46	0.61
0.30	0.154	0.31	0.49	0.64
0.31	0.162	0.32	0.51	0.68
0.32	0.170	0.34	0.54	0.71
0.33	0.179	0.36	0.56	0.74
0.34	0.187	0.38	0.59	0.77
0.35	0.196	0.39	0.62	0.80
0.36	0.205	0.41	0.64	0.84
0.37	0.213	0.43	0.67	0.88
0.38	0.222	0.45	0.70	0.92
0.39	0.231	0.47	0.73	0.95
0.40	0.241	0.48	0.76	0.99
0.41	0.250	0.50	0.78	1.03
0.42	0.260	0.52	0.81	1.07
0.43	0.269	0.54	0.84	1.11
0.44	0.279	0.56	0.87	1.15
0.45	0.289	0.58	0.90	1.19
0.46	0.299	0.61	0.94	1.23
0.47	0.309	0.63	0.97	1.27
0.48	0.319	0.65	1.00	1.31
0.49	0.329	0.67	1.03	1.35
0.50	0.339	0.69	1.06	1.39
0.51	0.350	0.71	1.10	1.44
0.52	0.631	0.73	1.13	1.48
0.53	0.371	0.76	1.16	1.52
0.54	0.382	0.78	1.20	1.57

<u>Method 3 – Farmer's Method</u>

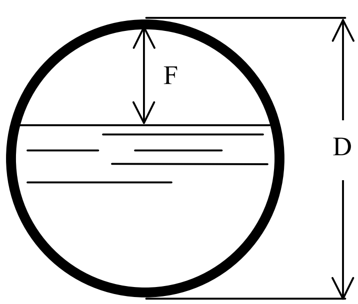


For full pipes:

Measuring the distance the stream of water travels parallel to a pipe in falling 12 inches vertically may make a fairly close determination of the flow from full open pipes.

- Measure the inside diameter of the pipe accurately (in inches) and the distance (A) the stream travels in inches <u>parallel to the pipe</u> for a 1ft.drop (see diagram).
- The flow, in gpm, equals the distance (A) multiplied by a constant K obtained from the following tables.

I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K
2	3.3	4	15.1	6	29.4	8	52.3	10	81.7	12	118
¼	4.1	¼	14.7	¼	31.9	¼	55.6	¼	85.9	½	128
½	5.1	½	16.5	½	34.5	½	59.0	½	90.1	13	138
¾	6.2	¾	18.4	¾	37.2	¾	62.5	¾	94.4	½	149
3	7.3	5	20.4	7	40.0	9	66.2	11	98.9	14	160
¼	8.6	¼	22.5	¼	42.9	¼	69.9	¼	103	½	172
½	10.0	½	24.7	½	45.9	½	73.7	½	108	15	184
¾	11.5	¾	27.0	¾	49.0	¾	77.7	¾	113	16	209



- For partially filled pipes, measure the freeboard (F) and the inside diameter (D) and calculate the ratio of F/D (in percent). Measure the length of the stream exiting the pipe as described above for full pipes and calculate the discharge. The actual discharge will be approximately the value for a full pipe of the same diameter multiplied by the correction factor from the following table:

F/D (%)	Factor	F/D (%)	Factor	F/D (%)	Factor	F/D (%)	Factor
5	0.981	30	0.747	55	0.436	80	0.142
10	.948	35	.688	60	.375	85	.095
15	.905	40	.627	65	.312	90	.052
20	.858	45	.564	70	.253	95	.019
25	.805	50	.500	75	.195	100	.000

Appendix B – Aquifer Pumping Test Data Sheet

Page___ of _____

Date:__________________

Names of observers:____________________________________

____

____

Well Name____________________

Type of Test: *Pumping / Recovery*

Distance To Pumping Well (r):__________________________

Well Discharge:____

Pump On At: __________________

Pump Off At:__________________

Initial Static Water Level At Well:________________________

Measuring Reference Point:______________________________

Clock Time	Time Since Pumping Started t	Time Since Pumping Stopped t’	t/t’	Water level measurement	Water level change s or s’	Comments