Groundwater Engineering

Chapter 3

Unidirectional flow of groundwater and well hydraulics

3.1. One-dimensional flow of groundwater

- Darcy's law and the fundamental equations governing groundwater movement can now be applied to particular situations. Solutions of groundwater flow to wells rank highest in importance.

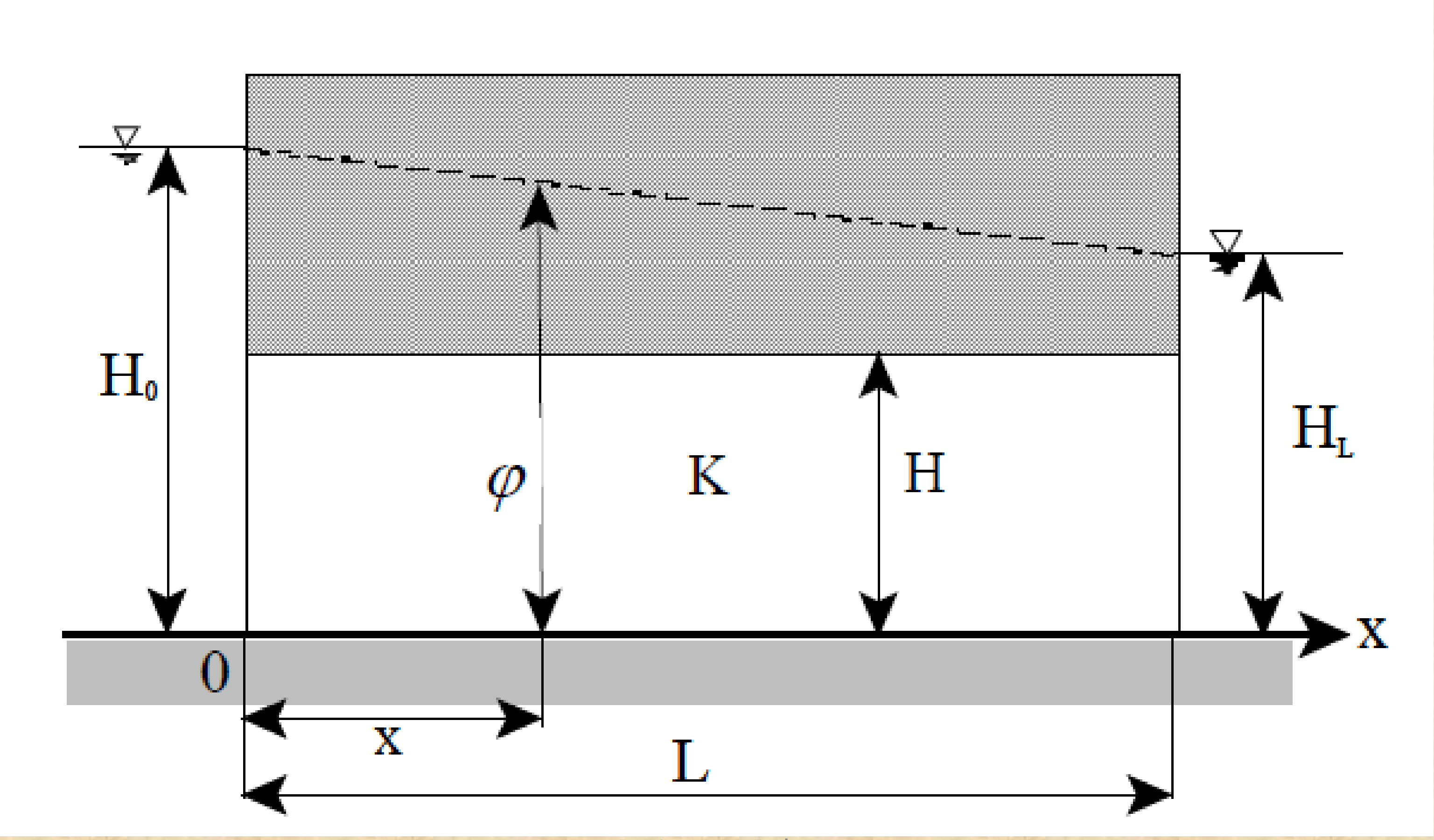
1. Steady unidirectional flow

Steady flow implies that no change occurs with respect to time change. Flow conditions for confined and unconfined aquifers and hence need to be considered separately, beginning with flow in one direction.

$$\frac{\partial h}{\partial t} = 0$$

A. Confined Aquifer

i) For a Constant Thickness



Cont……

- For one-dimensional flow in the X-direction only the continuity equation for steady flow simplifies to:
- $\partial^2 h / \partial X^2 = 0$

Integrating twice $\Rightarrow h = C_1 X + C_2$ The boundary conditions are: At X= 0, h = H_0 hence, $C_2 = H_0$ At X = L, h = H_L hence, $C_1 = -\left(\frac{H_0 - H_L}{L}\right)$

- Up on substitution of the boundary conditions C_1 and C_2 $h = H_0 - \left(\frac{H_0 - H_L}{L}\right) X$ $h = \left[\frac{-v}{K}\right] x + h_1$

Cont..

- By Darcy Law, the discharge per unit width of the aquifer is: $$q = -K\left(\frac{\partial h}{\partial X}\right) = -K * -\left(\frac{H_0 - H_L}{L}\right)$$

$$q = K\left(\frac{H_0 - H_L}{L}\right)$$

ii. For variable thickness

- Consider a confined aquifer with variable thickness Flow through confined aquifer of variable thickness

Cont.....

- Let y = mx + a;   a = y_1 and

$$m = \frac{y_2 - y_1}{L}$$

$$q = AV = (y.1)\left(-K\frac{dh}{dx}\right) = -ky\frac{dh}{dx}$$

$$therefore, h1 = \left[\frac{-q}{Km}\right]\ln a + c \qquad h2 = \left[\frac{-q}{Km}\right]\ln(a + mL) + c$$

At x = 0, h = h_1; at x = L, h = h_2

$$h2 - h1 = -\frac{q}{Km}\left[(\ln(a + mL) - \ln(a)\right] = \frac{q}{Km}\left[-(\ln(a + mL) + \ln(a)\right]$$

$$q = \frac{Km(h_2 - h_1)}{\left[\ln\left(a/(a + mL) \right)\right]}$$

Cont….

iii) Confined aquifer with vertical leakage (Semi-confined aquifer case)

$$q = -Kb\, {dh}/{dx} \Rightarrow \frac{dq}{dx} = -Kb\frac{d^2h}{dx^2} \qquad \frac{dq}{dx} = W$$

$$\frac{d^2h}{dx^2} = -\frac{W}{kb} = -\frac{W}{T} \Rightarrow d^2h = -\frac{W}{T}dx^2$$

$$\iint d^2h = -\frac{W}{T}\iint dx^2 \qquad h = -\frac{Wx^2h}{2T} + C_1x + C_2$$

From boundary conditions, at x = 0; h = h_1 and at x = L; h = h_2 Therefore, $C_2 = h_1$

Cont….

B. Unconfined Aquifers

- ❖ In unconfined aquifers the free surface of the water table, known as *phreatic surface*, has the boundary condition of constant pressure equal to atmospheric pressure.
- ❖ Consider an unconfined aquifer is above a horizontal impermeable base;

- The porous medium is homogeneous (K = constant);

- The aquifer receives uniform recharge (w = constant) on the top; w is defined as amount of water entering to aquifer per unit length and width per unit time.

- The aquifer is bounded by two rivers of constant stages h0 and hL.

- Although flow is two-dimensional in the cross-section, vertical flow velocity is much smaller than the horizontal flow so that the flow is assumed to be one-dimensional horizontal flow (Dupuit's assumption).

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i) Simple water table condition

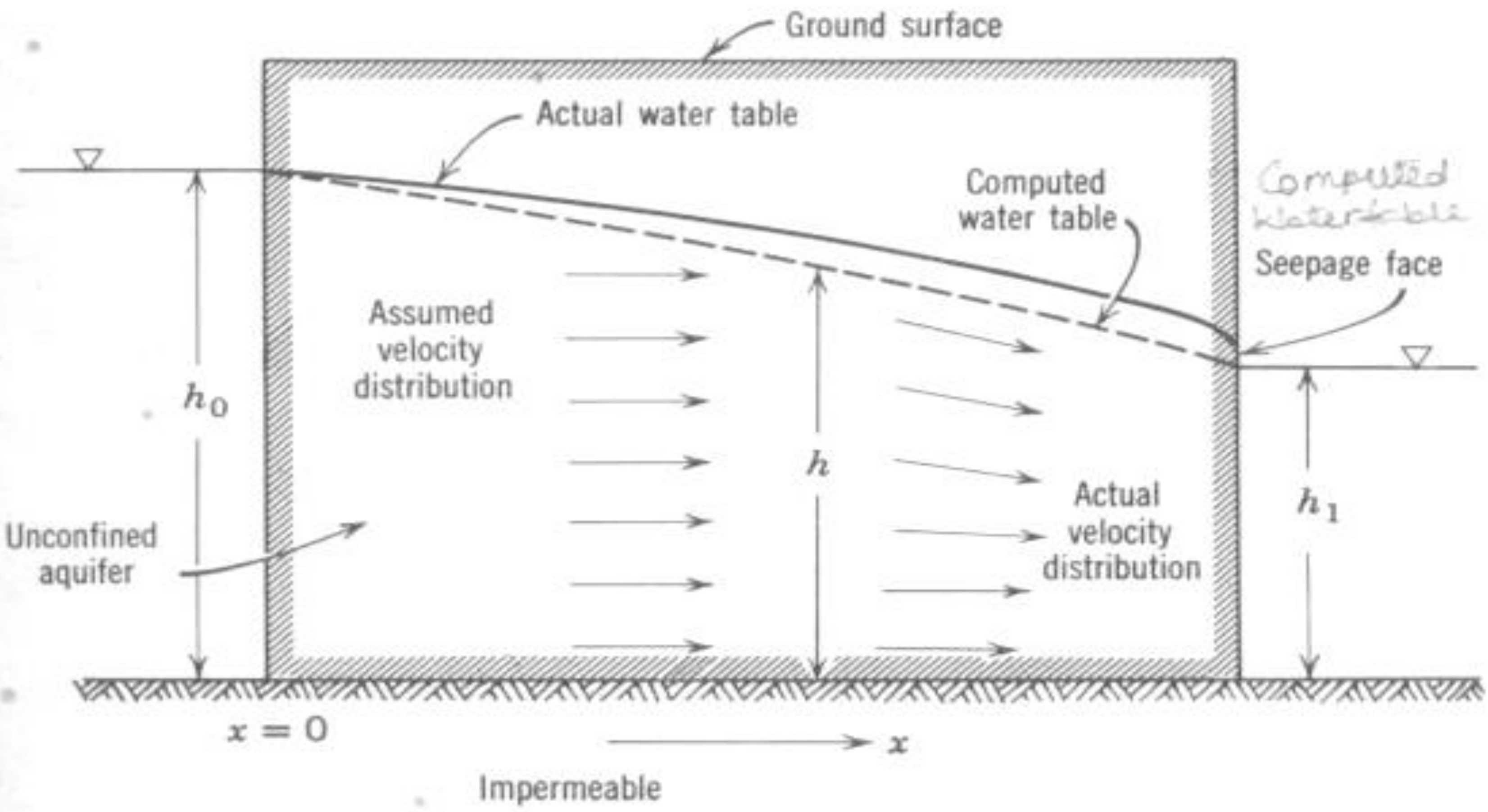


Fig. 4.2 Steady flow in an unconfined aquifer between two water bodies with vertical boundaries.

Cont..

$$q = -\frac{K}{2L}\left[h_2{}^2 - h_1{}^2\right]$$

- At any x value from x = 0, the head h is given by:

$$q = -\frac{K}{2x}\left[h_2{}^2 - h_1{}^2\right]$$

$$h = \sqrt{h_1{}^2 + \frac{x}{2}\left[h_2{}^2 - h_1{}^2\right]}$$

Cont.....

ii)Flow in to horizontal galleries

- The flow in to horizontal galleries dug down to the impervious soil layer is shown below.

H = depth of GWT above impervious layer

h_1 = depth of WT in the gallery

- The quantity of water flowing in to the gallery from both sides is

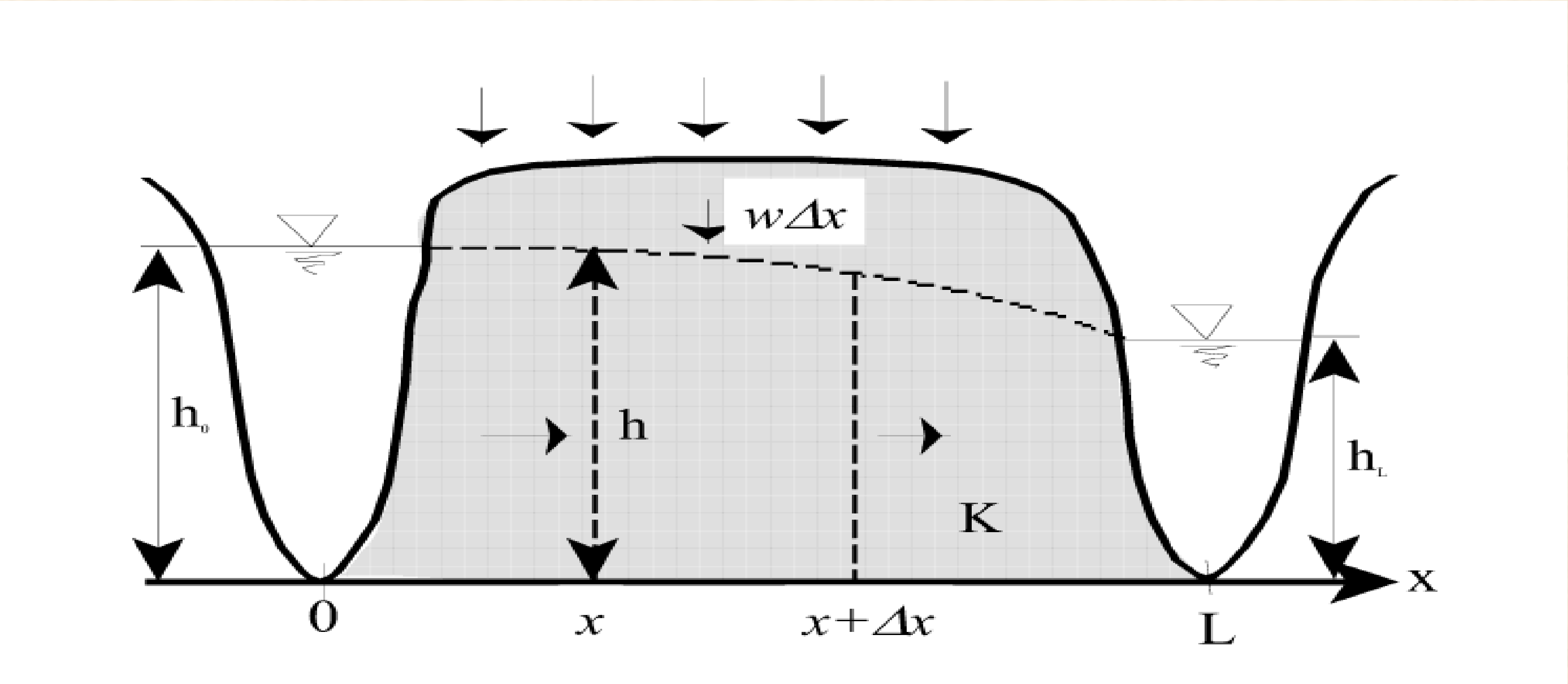
$$Q = (2q\ell) = 2\ell \frac{K}{2L}\left(H^2 - h_1^2\right)$$

$$Q = \frac{K\ell}{L}\left(H^2 - h_1^2\right)$$

- Where *l*-the length of the gallery and L is the water flow path

Cont….

iii) Steady Unconfined aquifer with recharge



$$dq = Wdx \qquad q_x = Wx + \frac{-K}{2L}\left[(h_2{}^2 - h_1{}^2) + \frac{WL^2}{K}\right]$$

3.2. Well Hydraulics

3.2.1. Steady radial flow to a well

- Steady state implies that the drawdown is a function of location only.
- The drawdown at a given point is the distance the water level is lowered.
- In three dimensional the drawdown curve describes a conic shape known as the cone of depression.
- Also the outer limit of the cone of depression defines the area of influent of the well.
- The derivation of well flow equation is generally based on the following assumptions.

✓ The well is pumped at constant rate or discharge (Q = Constant)

Cont….

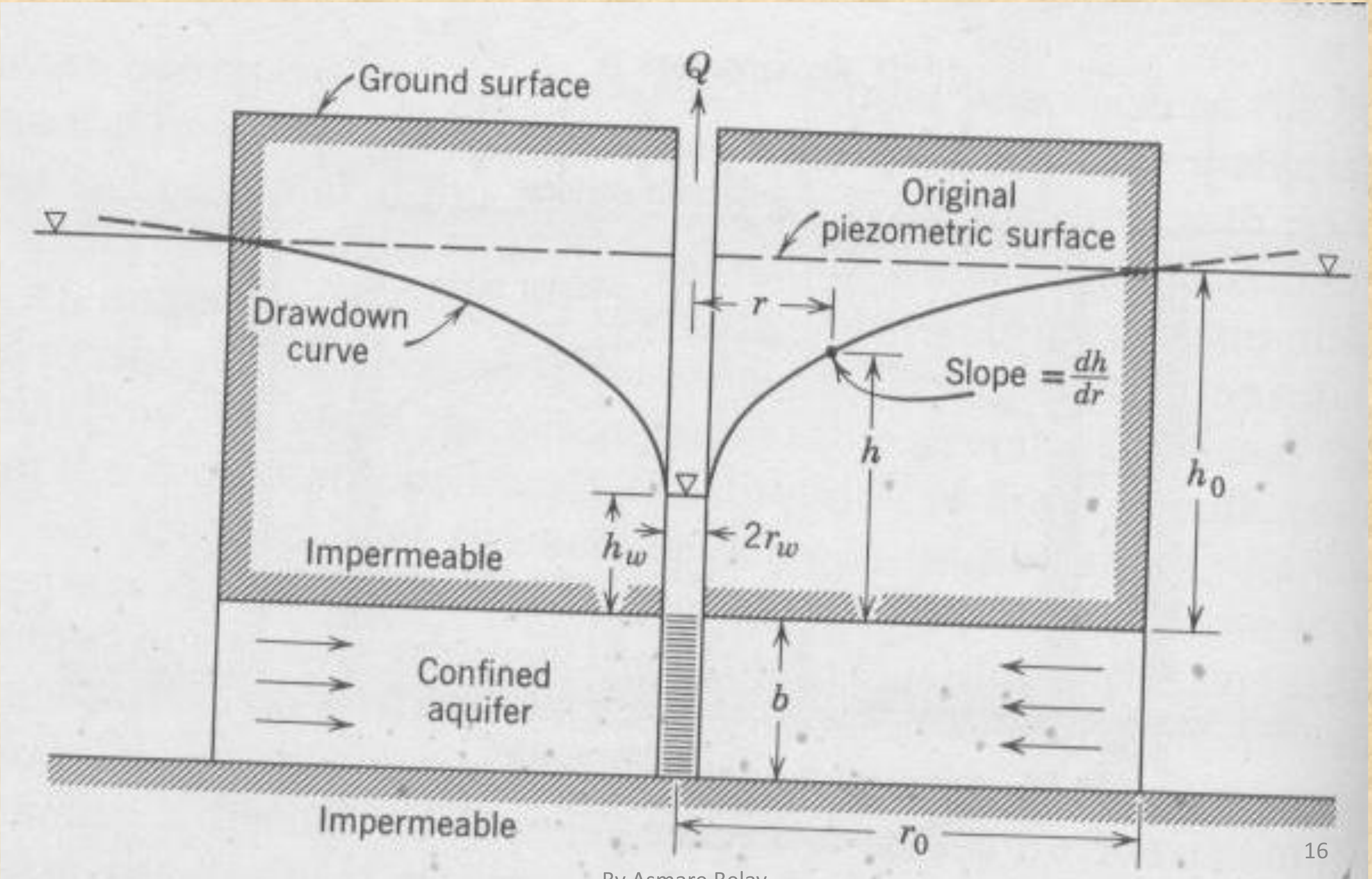
- ✓ The well is fully penetrating the aquifer and the screen is perforated or otherwise open for the height of the aquifer
- ✓ The aquifer is homogenous, isotropic, of uniform thickness and of infinite areal extent
- ✓ Water is released from storage in aquifer in immediate response to a drop in water table or piezometric surface.
- ✓ The well diameter is sufficiently small so that storage within the well can be neglected

Cont…

- Prior to pumping, the initial water level (the piezometric surface) is horizontal.
- Darcy's law is valid
- All flow is radial toward the well
- Groundwater flow is horizontal

Cont….

I. Steady radial flow in Confined Aquifer



Cont…

- Using the plane polar coordinates for the well and its surrounding; the well discharge at any distance r from the well equals:-

$$Q = AV = 2\pi rbK * \frac{dh}{dr}$$

Integrating the above equation yields

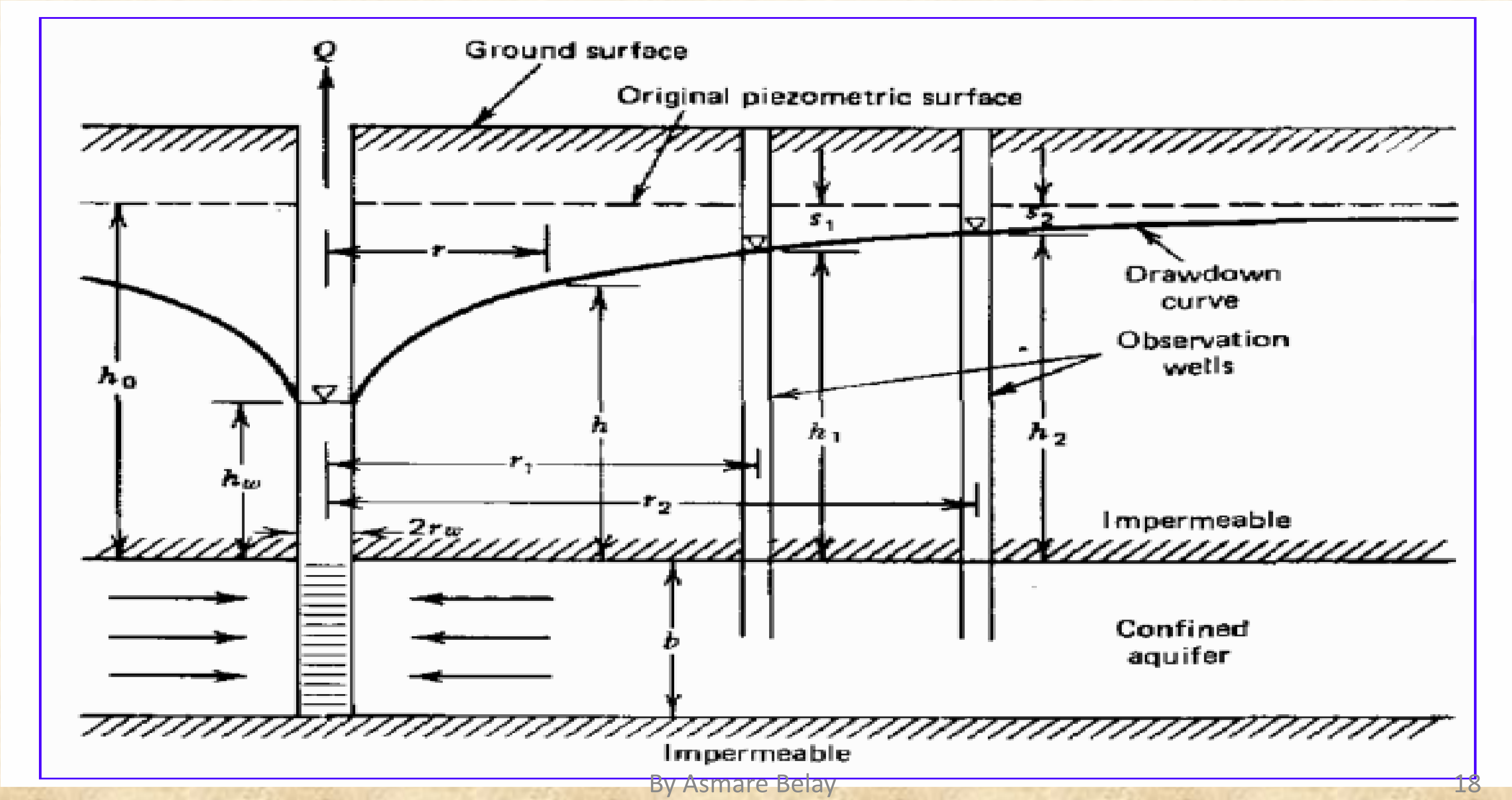
$$Q \int_{r_w}^{r_o} \frac{d_r}{r} = 2\pi bK \int_{h_w}^{h_o} d_h$$

$$Q = \frac{2\pi bK(h_o - h_w)}{\ln(\frac{\mathrm{r_o}}{\mathrm{r_w}})}$$

- If the values of head(h) are known (h_1 and h_2) at the respective positions of distance r_1 and r_2 respectively from the well, then the flow equation can be written as :-

Cont….

$$Q = \frac{2\pi bK(h_2 - h_1)}{\ln(\frac{r_2}{r_1})}$$ Where $r_2 > r_1$ and $h_2 > h_1$



Cont….

- The above equation is an equilibrium equation or Theim Equation enables one to determine the values of hydraulic conductivity (K) and Transmissivity (T) of a confined aquifer from pumping test data.
- Prove that equation for flow of water in confined aquifer towards a well is given by
- $Q = \frac{2\pi T(S_1 - S_2)}{\ln(\frac{r_2}{r_1})}$

Cont….

II. A well in Unconfined Aquifer for steady flow

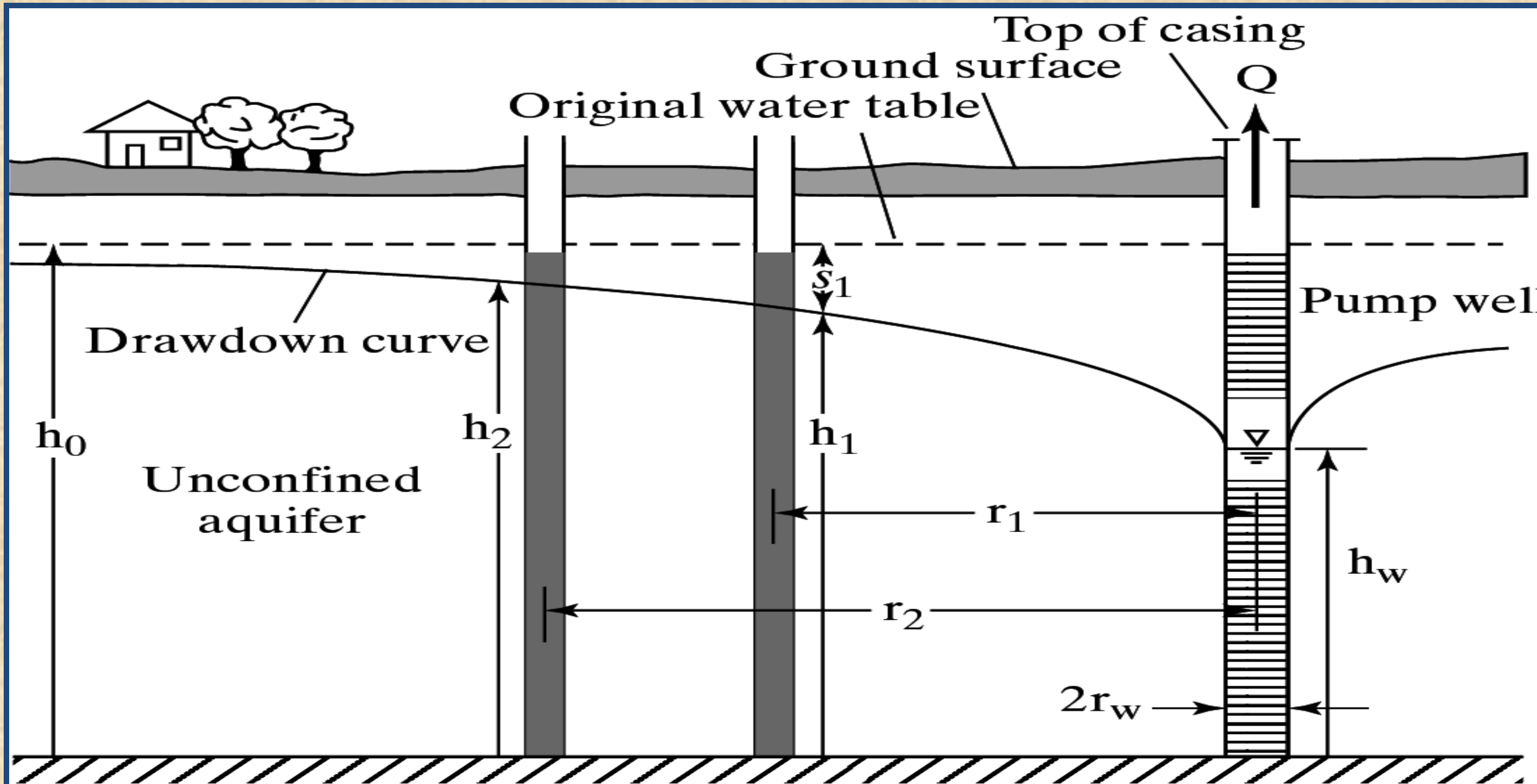


Figure 8.15

Radial flow to a well penetrating an unconfined aquifer.

Cont….

- Using Dupuit's equation, the well discharge Q is given by:-

$$Q = AV = -2\pi rhK * \frac{dh}{dr}$$

- Which when integrated between the limits h= h_w at r = r_w and h = h_0 at r = r_o yields

$$\text{Therefore}, Q = \frac{\pi K({h_o}^2 - {h_w}^2)}{\ln(\frac{r_o}{r_w})}$$

- Converting heads and radii at two observation wells (as shown in figure above)

$$\text{Therefore}, Q = \frac{\pi K({h_2}^2 - {h_1}^2)}{\ln(\frac{r_2}{r_1})}$$

Cont….

- In practice drawdowns should be small in relation to the saturated thickness of the confined aquifer. Then the average Transmissivity can be estimated from the equation:-

- $T = K\frac{(h_2 + h_1)}{2}$

- And the Transmissivity for the full thickness becomes:

$$T = h_o k = \frac{Q}{2\pi\left[\left(s_1 - \frac{s_I{}^2}{2h_0}\right) - \left(s_2 - \frac{s_2{}^2}{2h_0}\right)\right]} \ln\left({}^{r_2}\!/_{r_1}\right)$$

Cont….

3.2.2. Unsteady radial flow to a well

A. for a well in confined aquifer

- The primary importance of well hydraulics is to determine the aquifer parameters Transmissivity (T) and Storage coefficient (S).
- Since flow towards well consists mainly of unsteady state and it takes time for the flow to come to steady state (equilibrium state) after a long period of pumping.
- Besides this, the parameters T and S obtained from steady state computation are more approximate than that of the unsteady state case.

Cont…

- The non-steady GW flow equation in two dimensions is given by

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t}$$

Or in polar coordinates $$\frac{\partial^2 h}{\partial r^2} + \frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}$$

- The solution of this equation, in which the flow near a well is governed by, when referred to an aquifer of infinite extent, is given by:

$$s = \frac{Q}{4\pi T}\int_u^\infty e^{-u}\frac{du}{u}$$

- Where s = drawdown, Q = well discharge and u = dummy variable (dimensionless). u is given by:

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

Cont…

- The above equation is called the Theis equation and it is non-linear equation. The integral term

$$\int_u^{\infty} e^{-u} \frac{du}{u}$$

- is the well function defined by W (u) and can be expressed by a convergent series as:

$$W(u) = -0.577216 - \ln(u) + u - \frac{-u^2}{2.2!} + \frac{u^3}{3.3!} - .... + \frac{u^n}{n.n!}$$

$$= -0.577216 - \ln(u) + \sum_{i=1}^{n} \frac{\left((-1)^{n+1} u^n\right)}{n.n!}$$

- Because of the mathematical difficulties encountered in applying the above equation, several investigators developed simpler approximate solutions that can be readily applied for field purposes.

Cont…

A. Theis curve matching
B. Jacob approximate method(With Time- DD relationship)
C. Jacob approximate method(With distance – DD relationship)
D. Chow method of solution

A. Theis curve matching (Time- DD relationship)

- The drawdown in an observation well due pumping occurred in a test well at any time can be given by:

$$s = \frac{Q}{4\pi T} W(u) \qquad u = \frac{r^2 S}{4Tt} \Rightarrow \qquad \frac{4T}{S} u = \frac{r^2}{t}$$

- It can be seen that the relation between W (u) and u and also (r^2/t) and s are similar. Having these trend of similarities in mind, Theis developed a curve (log- log plot) called Theis type curve which is a plot of W (u) and u and suggested to develop a field curve (log –log plot of s vs r^2/t) to be matched each other so that the values of S and T can be computed.

Cont…

Procedure to determine T and S using Theis Curve matching (From pumping test data)

I. Prepare or obtain the logarithmic plot of W (u) vs u or W (u) vs 1/u (graph after Theis).
II. Prepare a field curve from the observed DD, s, vs (r^2/t) or (t/r^2) vs s.
III. Superimpose field curve over type curve
IV. Select match point by making the abscissa and ordinates of the two curves/graphs quite parallel.
V. Obtain the values of W (u), u, r^2/t and s on the match point.
VI. Determine the values of T and S by inserting the values (step 5) in the above equations.

Cont….

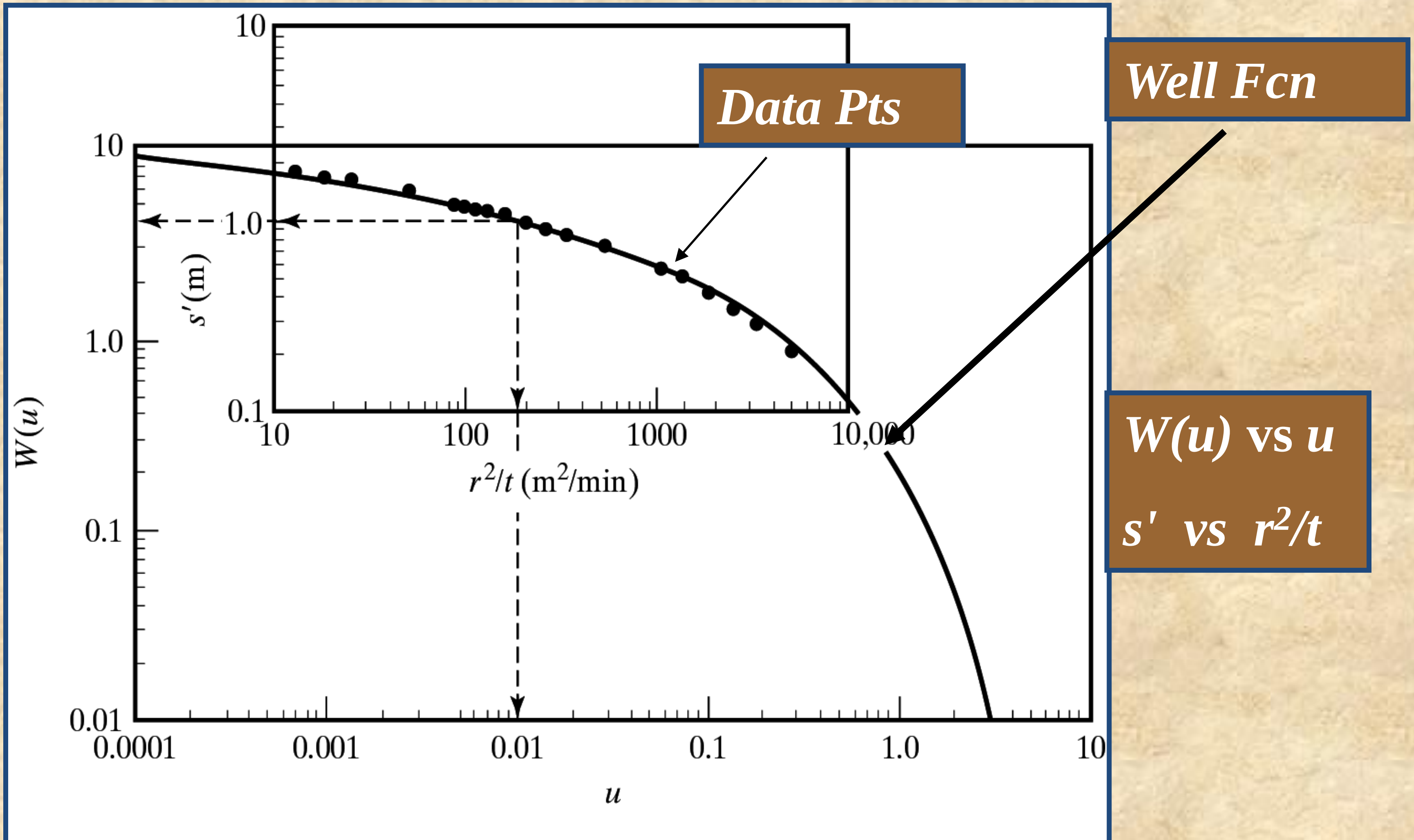


Figure 8.20

Theis method of superposition for solution of the nonequilibrium equation.

Cont…

B. Cooper and Jacob Approximate method (Time- DD relationship)

- For small values of u ($u \leq 0.01$) or large values of t ($t > (r^2S/0.04T)$), keeping r constant, the series in the original Theis equation can be approximated by the first two terms That is, W (u) = -0.577216-lnu = ln (0.56146/u), therefore, s, can be given as

$$s = \frac{Q}{4\pi T}\left[-0.577216 - \ln u\right] \Rightarrow s = \frac{Q}{4\pi T}\ln\left(0.56146/U\right)$$

$$s = \frac{0.183Q}{T}\log_{10}\left(\frac{2.25Tt}{r^2 s}\right)$$

Cont…

- The value of T can be obtained from a time draw down plot. For drawdowns at a well in different times, t1 and t2 the draw downs are s1 and s2 can be given as:

$$s_1 = \frac{0.183Q}{T}\log_{10}\left(\frac{2.25Tt_1}{r^2 s}\right) \qquad s_2 = \frac{0.183Q}{T}\log_{10}\left(\frac{2.25Tt_2}{r^2 s}\right)$$

And the change in draw down can be given as

$$s_2 - s_1 = \Delta s = \frac{0.183Q}{T}\log_{10}\left(\frac{t_2}{t_1}\right)$$

- For per log cycle plot, from large data points, t2/t1 =10 →$\log_{10}$ (10) = 1, The value of T can be computed from :

$$\Delta s = \frac{0.183Q}{T}$$

Cont….

- The storage coefficient can also be obtained from

$$s = 0 = \frac{0.183Q}{T}\log_{10}\left(\frac{2.25Tt_0}{r^2 s}\right)$$

C) Cooper and Jacob Approximate method (Distance DD Relationship)

- The case in (B) was for draw down observed in a well at a fixed distance from the pumping well. It is also possible to determine the aquifer parameters from the distance – DD relationship derived from the original Theis equation and approximated by Cooper and Jacob.
- From above relation, s (drawdown) is given as

$$s = \frac{2.303Q}{4\pi T}\log_{10}\left(\frac{2.25Tt}{r^2 s}\right)$$

Cont…

- For a fixed time t, the draw down at distances r1 and r2 is s1 and s2 respectively. Thus in terms of r, s can be determined as:

$$s_1 = \frac{2.303Q}{4\pi T}\log_{10}\left(\frac{2.25Tt}{r_1^{\,2}s}\right) \qquad s_2 = \frac{2.303Q}{4\pi T}\log_{10}\left(\frac{2.25Tt}{r_2^{\,2}s}\right)$$

$$s_2 - s_1 = \frac{2.303Q}{4\pi T}\log_{10}\left(\frac{r_1^{\,2}}{r_2^{\,2}}\right) \qquad s_2 - s_1 = \Delta s = \frac{4.606Q}{4\pi T}\log_{10}\left(\frac{r_1}{r_2}\right)$$

- Then for a per log cycle, i.e., (r1/r2 = 0.1 and $\log_{10}$ (0.1) = -1) Δs can be determined from a plot of r-s graph and T or S can be determined.

$$\Delta s = \frac{-4.606Q}{4\pi T}$$

Cont….

B. For a well in unconfined aquifer

- The first and by far the simplest approach is to use the same flow situation as for the case of confined aquifer provided the basic assumptions are satisfied.
- If the drawdown in the monitoring well does not exceed 25% of the saturated thickness, the Theis equation can be applied to unconfined aquifers with certain adjustments.
- For the drawdown that is less than 10% of the aquifer's pre-pumping thickness, it is not necessary to adjust the recorded data since the error introduced by using the Theis equation is small.
- When the drawdown is kept between 10% and 25%, it is recommended to correct the measured values using the following equation derived by Jacob:-

$$S' = s - s^2/2h$$

Where s' = is the corrected drawdown

s = measured drawdown in monitoring well

h = the saturated thickness before pumping started

Cont…

- If the DD in the monitoring well is more than 25%, the equation (Theis and Theis based) should not be used in the unconfined aquifer analysis.
- There are different methods of analysis for unconfined aquifer, when the drawdown due to pumping is remarkably large. Neuman, Boulton, Hantush etc…

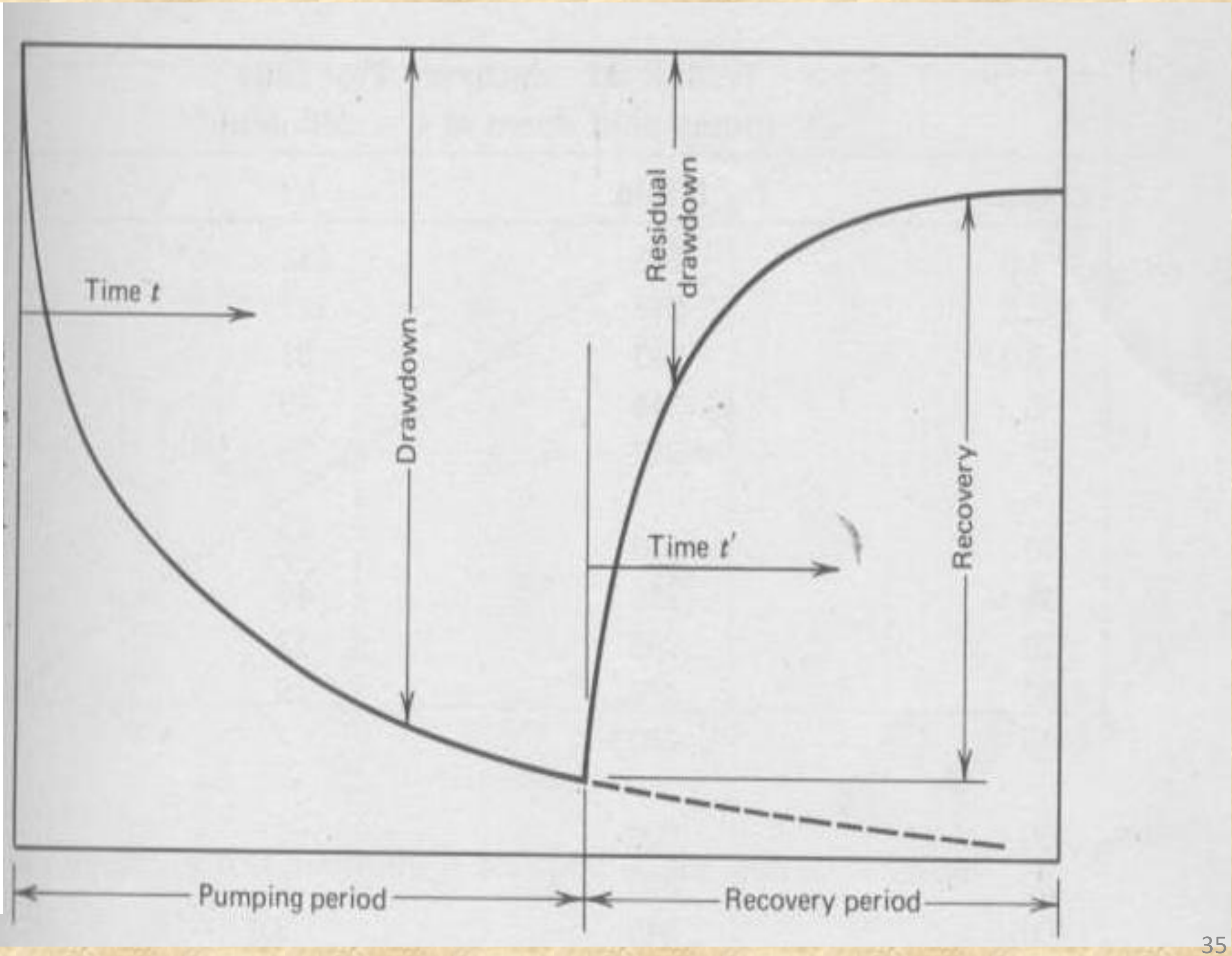
3.3. Recovery of a well/aquifer

At the end of a pumping test, when the pump is stopped, the water levels in the pumping and observation wells will begin to rise.

- If the well is pumped for a known period of time and then shut down, the draw down there after will be identically the same as if the discharge had been continued and a hypothetical recharge well with the flow were superposed on the discharging well at the instant the discharge is shut down.

Cont….

Water level below original non-pumping level



Cont…

- From this principle, Theis showed that, the residual draw down s’ can be given as

$$s' = \frac{Q}{4\pi T}\left[W(u) - W(u')\right] \qquad u = \frac{r^2 S}{4Tt} \; and \; u' = \frac{r^2 S}{4Tt'}$$

- And t and t’ are defined in figure. For r small and t’ large, the well functions can be approximated by the first two terms of the Theis equation and can be written as

$$s' = \frac{2.30Q}{4\pi T}\log_{10}\frac{t}{t'}$$

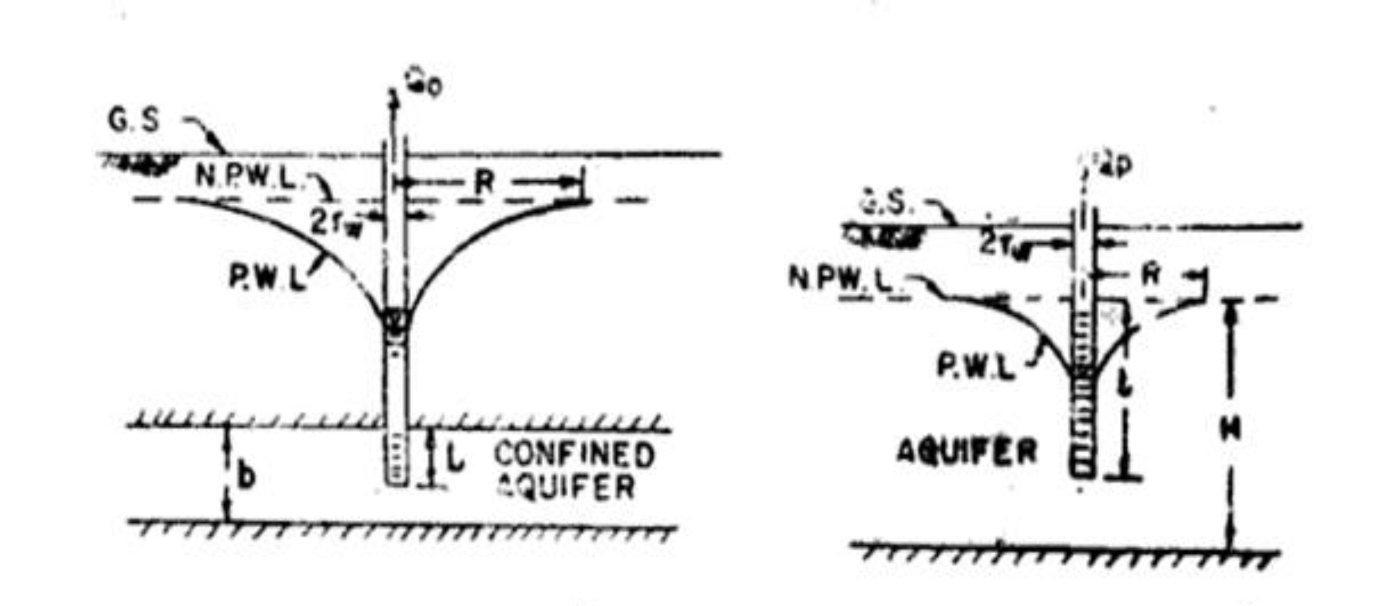
- Thus, a plot of residual draw down s’ versus the Logarithm of t/t’ forms a straight line. The slope of the line equals 2.30Q/4T so that for Δs’, the residual draw down per log cycle of t/t’, the transmissivity becomes

$$T = \frac{2.30Q}{4\pi\Delta s'}$$

Cont….

3.4. Partially penetrating wells

- The discharge from a partially penetrating well depends up on the depth of penetration of the well in the aquifer. The partially penetrating well may be gravity well or an artesian well depending up on the type of aquifer



a. Confined aquifer: $\alpha = \frac{l}{b}$ b. Water table aquifer: $\alpha = \frac{l}{H}$

Cont….

- Discharge from a partially penetrating artesian well, Q_p is given by:

$$Q_p = \frac{2\pi K S_w}{\left[\frac{1}{L}\ln\left(\frac{\pi L}{2r_w}\right) + \frac{0.1}{b} + \frac{1}{b}\ln\left(\frac{R}{2b}\right)\right]}$$

- In a partially penetrating gravity well the Kozeny's equation for discharge is given as follows.

$$Q_p = Q\left[\frac{L}{H}\left(1 + 7\sqrt{\frac{r_w}{2L}}\cos\left\{\frac{\pi L}{2H}\right\}\right)\right]$$

Where Q= Discharge for a fully penetrating well

3.5.Multiple well system

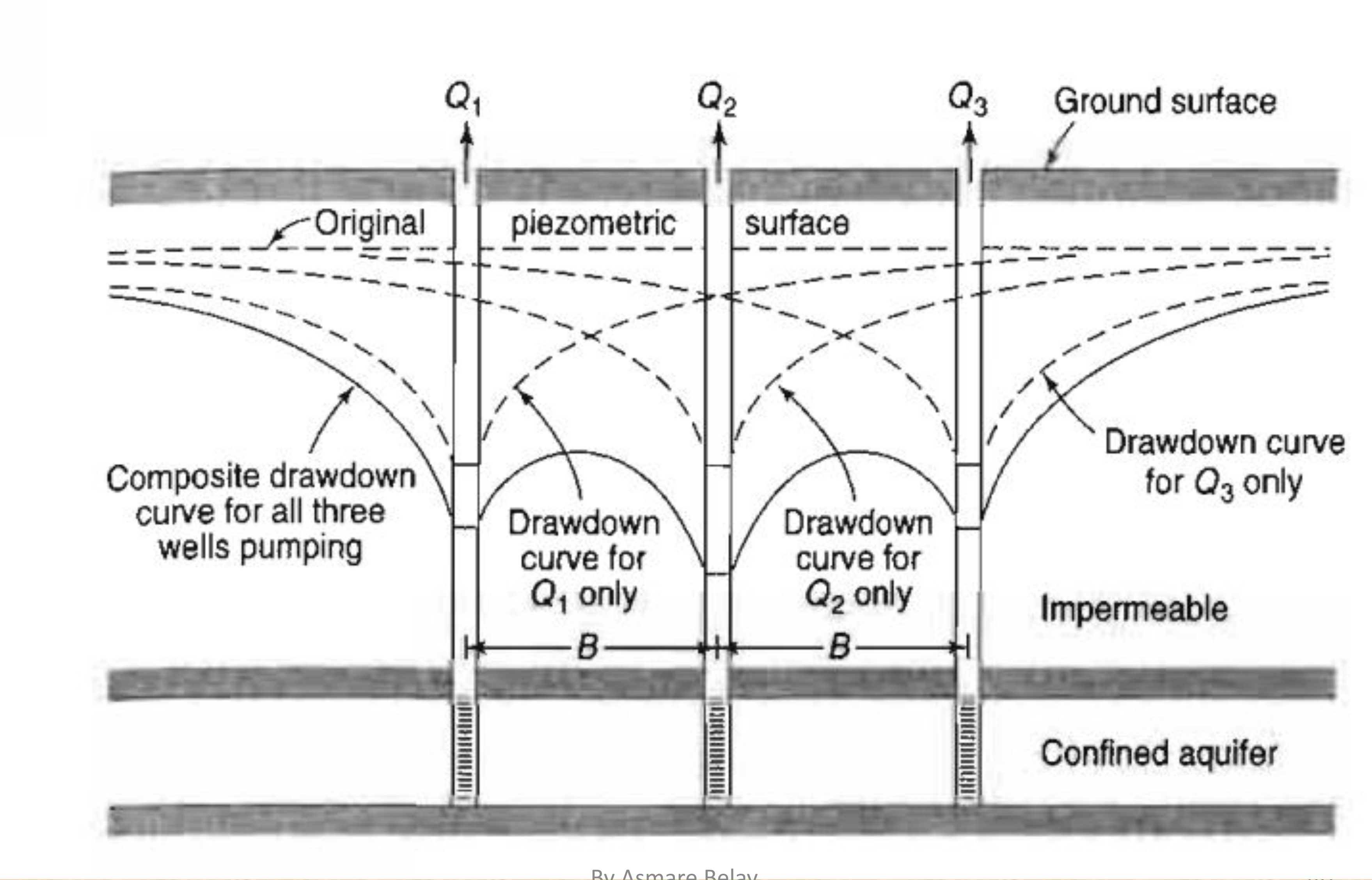
- Multiple well systems are used for lowering the groundwater level in a given area to facilitate subsurface drainage or excavation for foundation work, mining, etc. Steady-state solutions for multiple well systems are determine using three major cases:

(i) drawdown for the well systems parallel to a line source,

(ii) well discharges for different well configurations, and

(iii) required drawdown for the well systems used for dewatering.

Example of multiple wells



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3.6. Well Losses and Specific Capacity

A. Well Loss

- The total DD (s_w) at the well face is made up of:

i. Head loss resulting from laminar flow in the formation, s_f

ii. Head loss resulting from turbulent flow in the zone close to the well face where Re > 1.

iii. Head loss through the well casing and screen

- The components under (ii) and (iii) are contributing to the so called well loss.
- Therefore, well loss can be expressed as the difference between the actual measured DD in the pumping well and the theoretical DD which is expressed by the Theis equation and as the result of GW flow through the aquifer in the undisturbed zone only.

Cont....

- The additional DD , or well loss, which is always present in pumping wells, is created by a combination of various factors such as : improper well development (drilling fluid left in the formation, mud cake along the bore hole is not removed, fines from formation are not removed, poorly designed gravel pack and well screen), turbulent flow near the well and others.
- Therefore, taking the well loss in to account, the total DD can be given as:

$$s_w = s_f + s_e$$

$$s_w = c_f Q + c_w Q^n$$

Cont….

s_f is loss in the formation due to laminar flow (expressed by Theis)

s_e is the well loss (can be observed near the pumping well)

c_f is the formation loss constant.

c_w is the well loss constant

n is the exponent due to turbulent

Jacob suggested n = 2; Rorabough given n = 2; Linnox(1966) n = 3.5. And if Q = is small and if there is small turbulence near the pumping well, then n< 2.

Evaluation of Well Loss

To evaluate the well loss we can have two methods:-

- Analysis of time – DD data of pumping and monitoring wells.
- Step DD test

Cont….

i. Analysis of time – DD data of pumping and monitoring wells

- Procedure:-

a) Have or obtain the time- DD data of pumping and monitoring well (at least three monitoring wells)

b) Compute the ratio t/r^2 for each well

c) On the semi- logarithmic paper plot DD vs t/r^2 (DD – linear and t/r^2 –Log) and draw the best fit line across the data points.

d) Observe the line of the curves. The line due to plot of DD vs t/r^2 for the pumping well is above the best fit line of DD vs t/r^2 plot for the monitoring wells.

e) Measure the vertical distance between the two lines and obtain the well loss

Cont…

ii.Step Draw down Test

- This can be done in the pumping well itself
- The equation from above can be further given as:

$$s_w = s_f + s_e$$

$$s_w = c_f Q + c_w Q^n$$

$$s_w / Q = c_f + c_w Q^{n-1}$$

$$\left(s_w / Q - c_f \right) = c_w Q^{n-1}$$

$$\log_{10}\left(s_w / Q - c_f \right) = \log_{10} c_w + (n-1)\log_{10} Q$$

$$y = b + ax$$

Cont….

- Therefore, plot of ($s_w/Q - c_f$) vs Q on a double logarithmic paper enables one to determine the values of c_f, n and c_w. Thus this needs different values of Q and s_w which could be available from step draw down tests.
- <u>Procedure</u>:-

a) Obtain step – DD data, i.e., different Q values versus different draw down values (conducted at different time intervals) such as for example 30 sec, 60 sec, 120 sec etc).

b) Assume different values of c_f

c) Plot $\log_{10}\left(s_w/Q - c_f\right) vs \log_{10} Q$ (for different c_f values)

d) If a plot gives a straight line, consider that value of c_f as correct value and read the value of c_w and (n-1) from the graph from which it is possible to compute the well loss coefficient.

Cont….

B. Specific Capacity

- It is the ratio of discharge to drawdown in a pumping well. It is the measure of the productivity of a well. The larger the specific capacity, the better the well is.

$$S.\ C. = Q/s_w$$

- Starting from the non – equilibrium equation and including the well losses;

$$s_w = c_f Q + c_w Q^n$$
$$= Q(c_f + c_w Q^{n-1})$$
$$sw/Q = c_f + c_w Q^{n-1}$$

- But the value of c_f can be determined from the theoretical Theis equation.

Cont….

$$s_f = \frac{Q}{2\pi T}\left[\ln\left(\frac{R}{r_w}\right)\right]$$ and since $s_f = c_f Q$; cf = $$c_f = \frac{\ln(R/r_w)}{2\pi T}$$

(if steady state flow condition near the well is achieved)

$$c_f = \frac{\ln\left(2.25Tt / r_w{}^2 S\right)}{4\pi T}$$ (if unsteady sate case is considered) Therefore,

$$s_w / Q = c_f + c_w Q^{n-1} \Rightarrow Q / s_w = \frac{1}{c_f + c_w Q^{n-1}}$$

$$Q / s_w = \frac{1}{\dfrac{\ln\left(2.25Tt / r_w{}^2 S\right)}{4\pi T} + c_w Q^{n-1}}$$

Cont….

C. Well Efficiency

- Well efficiency, usually expressed in percentage, is the ratio b/n theoretical drawdown and the actual drawdown measured in the well.
- Well efficiency = Theoretical DD/Measured DD*100%

$$e_w = \frac{(Q/s_{iw})}{((Q/s_w))} * 100\%$$

$$e_w = s_w / s_{iw}$$

- An efficiency of 70 or 80% is considered good. If a newly developed well has less than 65% efficiency, it should not be accepted.

THANK YOU!!!!!

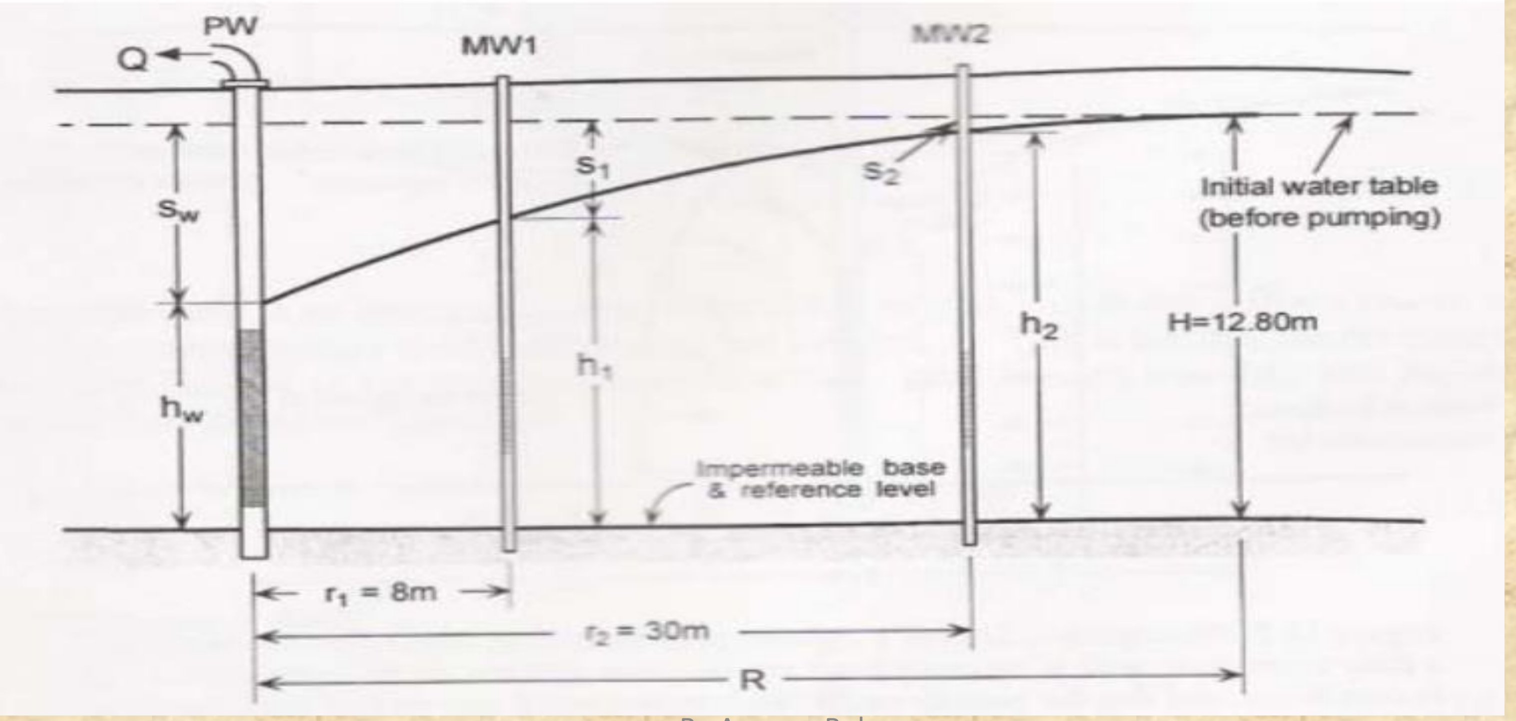
Chapter 5
Pumping Tests of the wells

Pumping test - definition

- Pumping Test is the examination of aquifer response, under controlled conditions & to the abstraction of water.
- Pumping test can be well test (determine well yield and well efficiency), aquifer test (determine aquifer parameters and examine water chemistry).
- Hydro-geologists try to determine the most reliable values for the hydraulic characteristics of the geological formations.
- The objectives of the pumping test are:
  - Determine well yield,
  - Determine well efficiency,
  - Determine aquifer parameters
  - Examine water chemistry

Pumping test

The principle of a pumping test is that if we pump water from a well and measure the discharge of the well and the drawdown in the well and in piezometers at known distance from the well, we can substitute these measurements into an appropriate well flow equation and calculate the hydraulic characteristics of the aquifer.



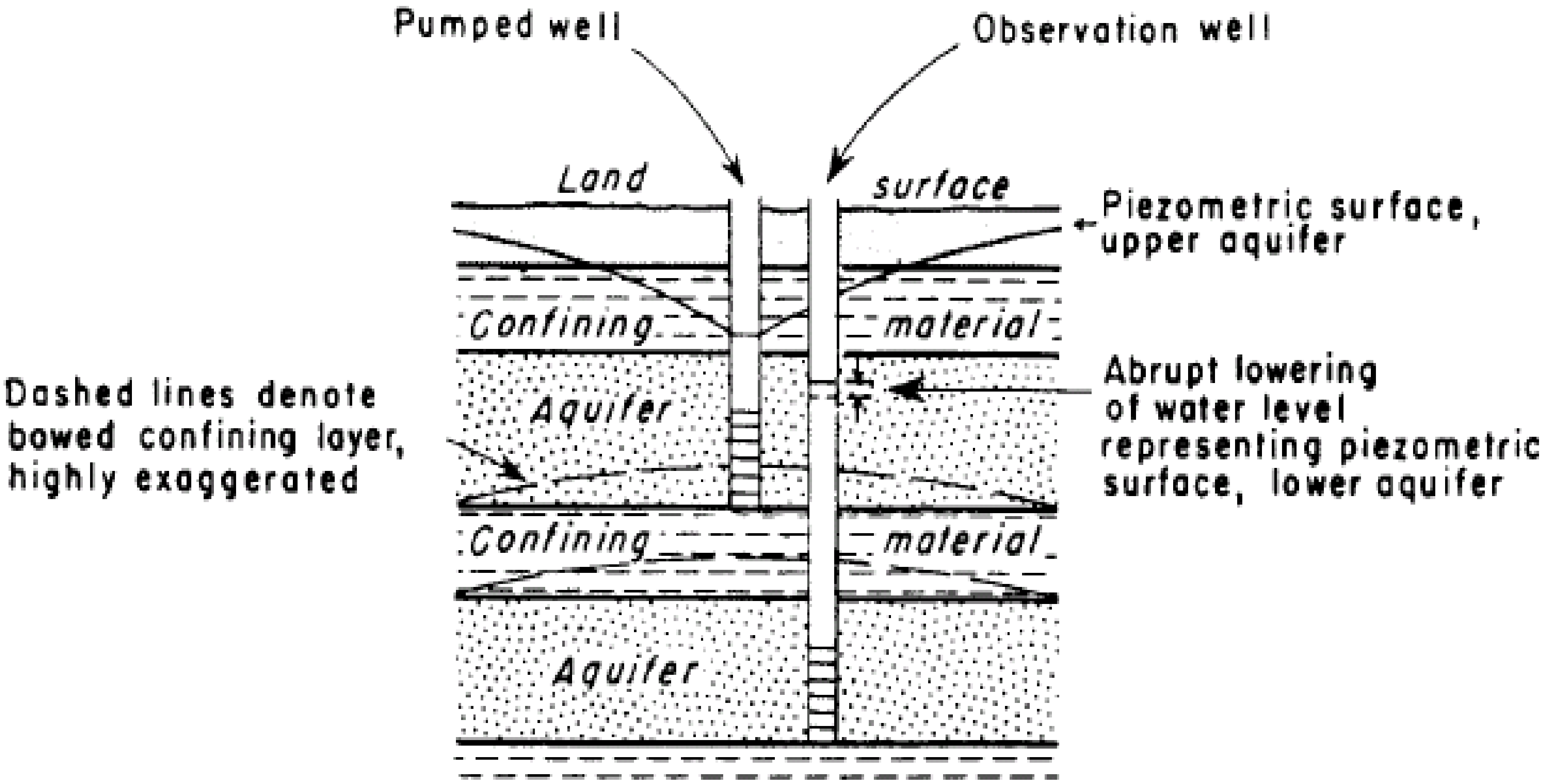
Importance of Pumping Tests

- How much groundwater can be extracted from a well based on long-term yield, and well efficiency?
- The hydraulic properties of an aquifer or aquifers.
- Spatial effects of pumping on the aquifer.
- Determine the suitable depth of pump.
- Information on water quality and its variability with time

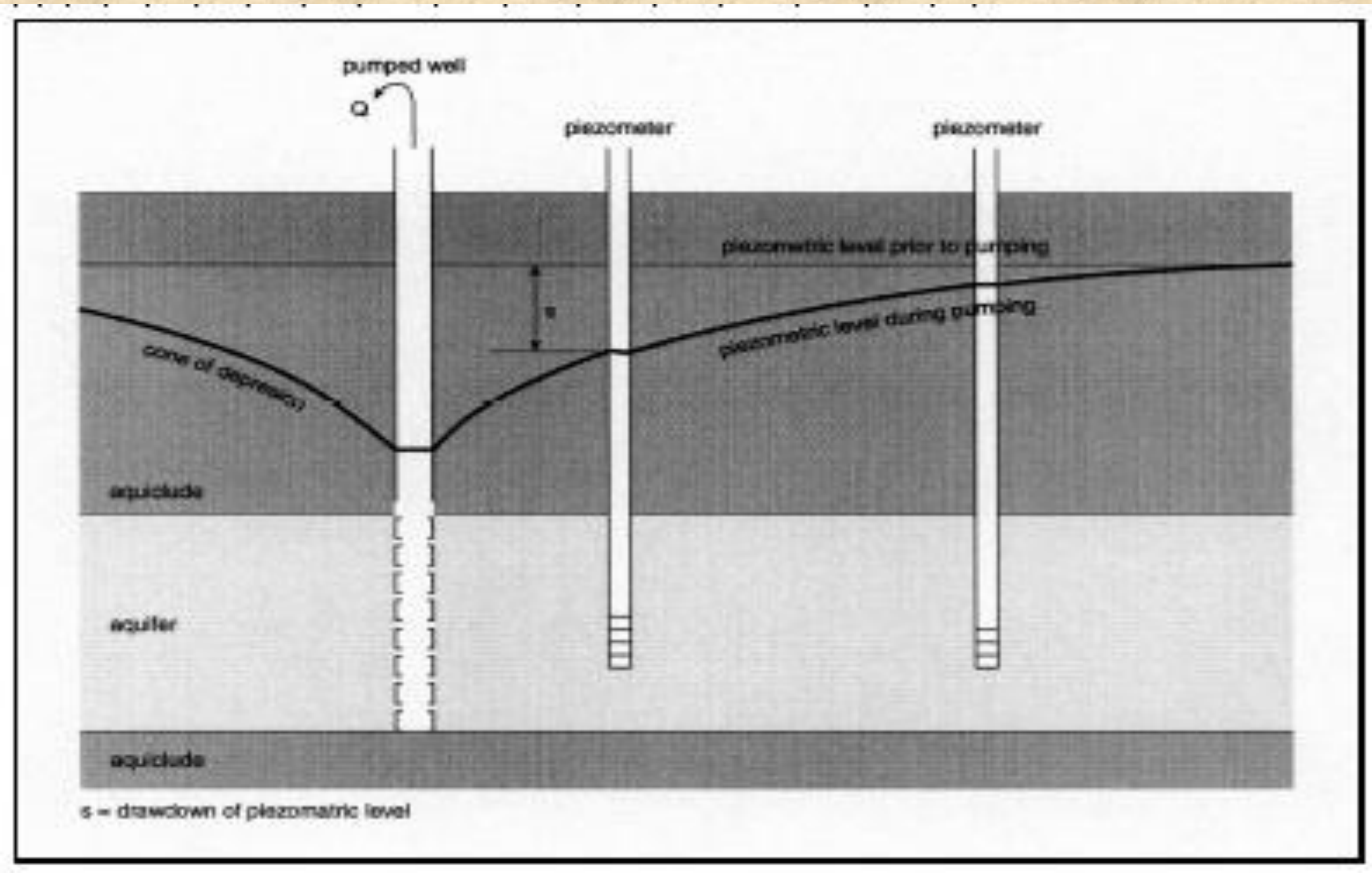
Conceptual model

- ❖ Before conducting pumping test one has to carry out the following preliminary investigations.
- The geophysical characteristics of the subsurface
- The type of aquifer and confining beds
- The thickness and lateral extent of aquifers and confining beds
- Boundary conditions
- Data on the groundwater flow system (horizontal or vertical), flow of groundwater, water table gradients, trends in water level, etc.
- Data on any of existing wells in the area
- Good idea on the well set up!

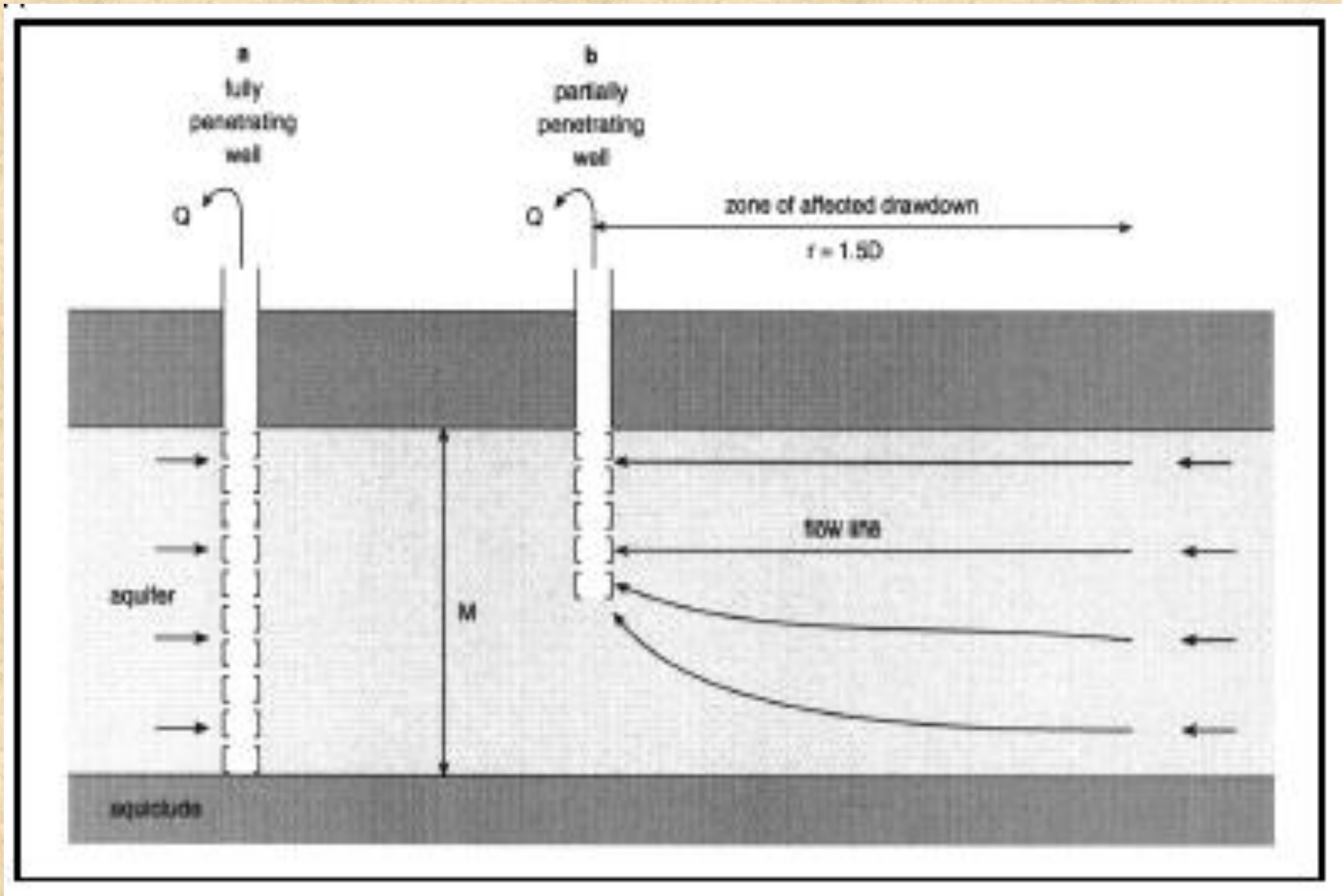
Pumping and observation well



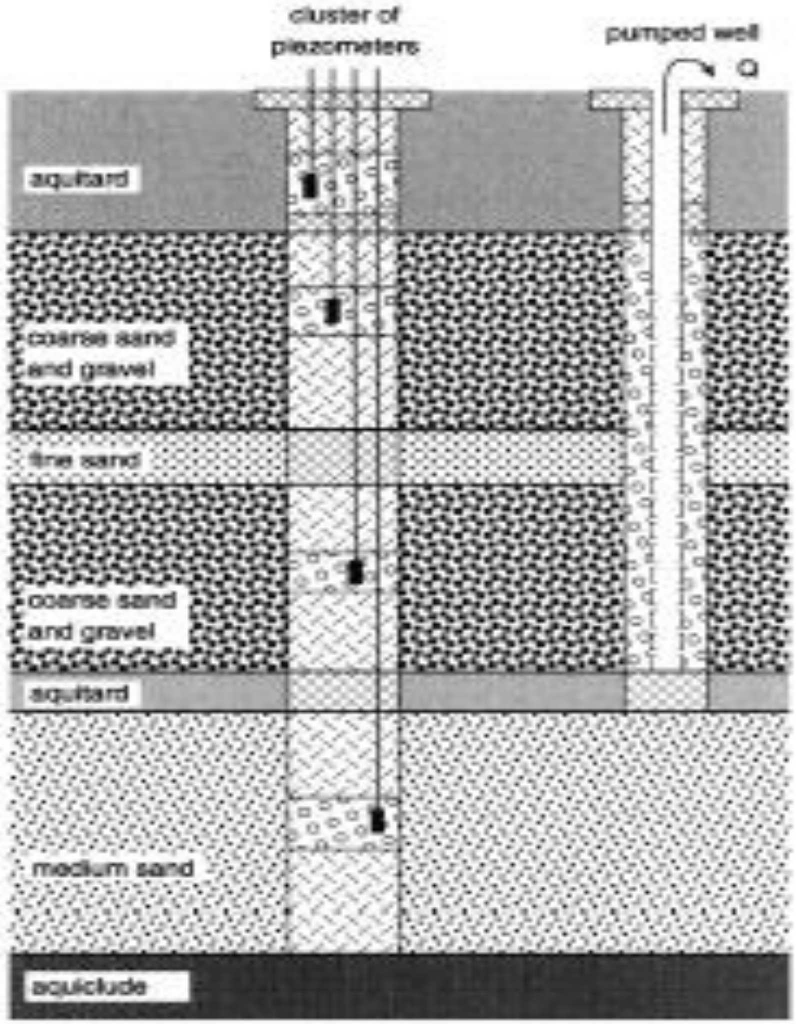
Well and piezometers



Partial penetration



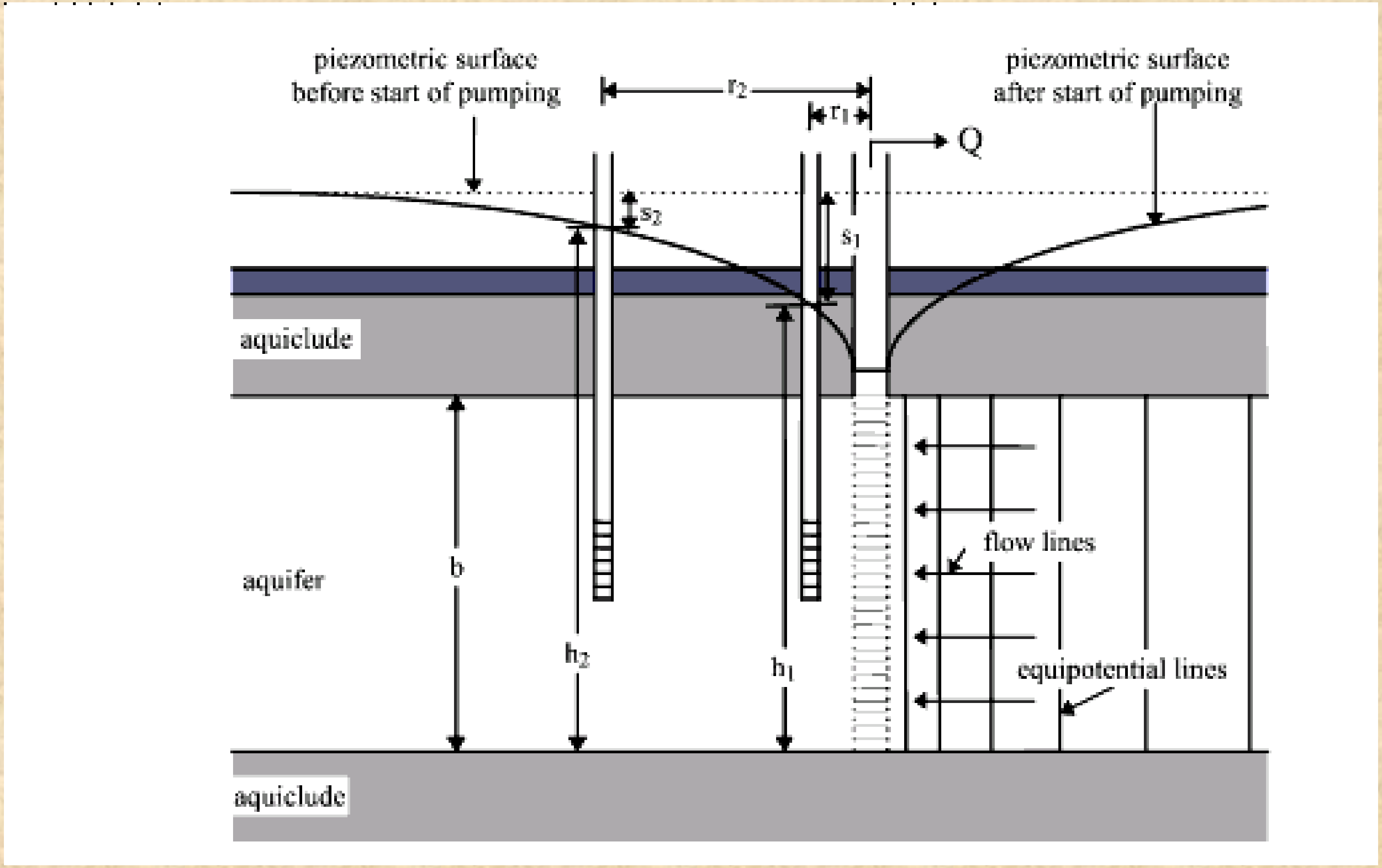
Multi-layer aquifer



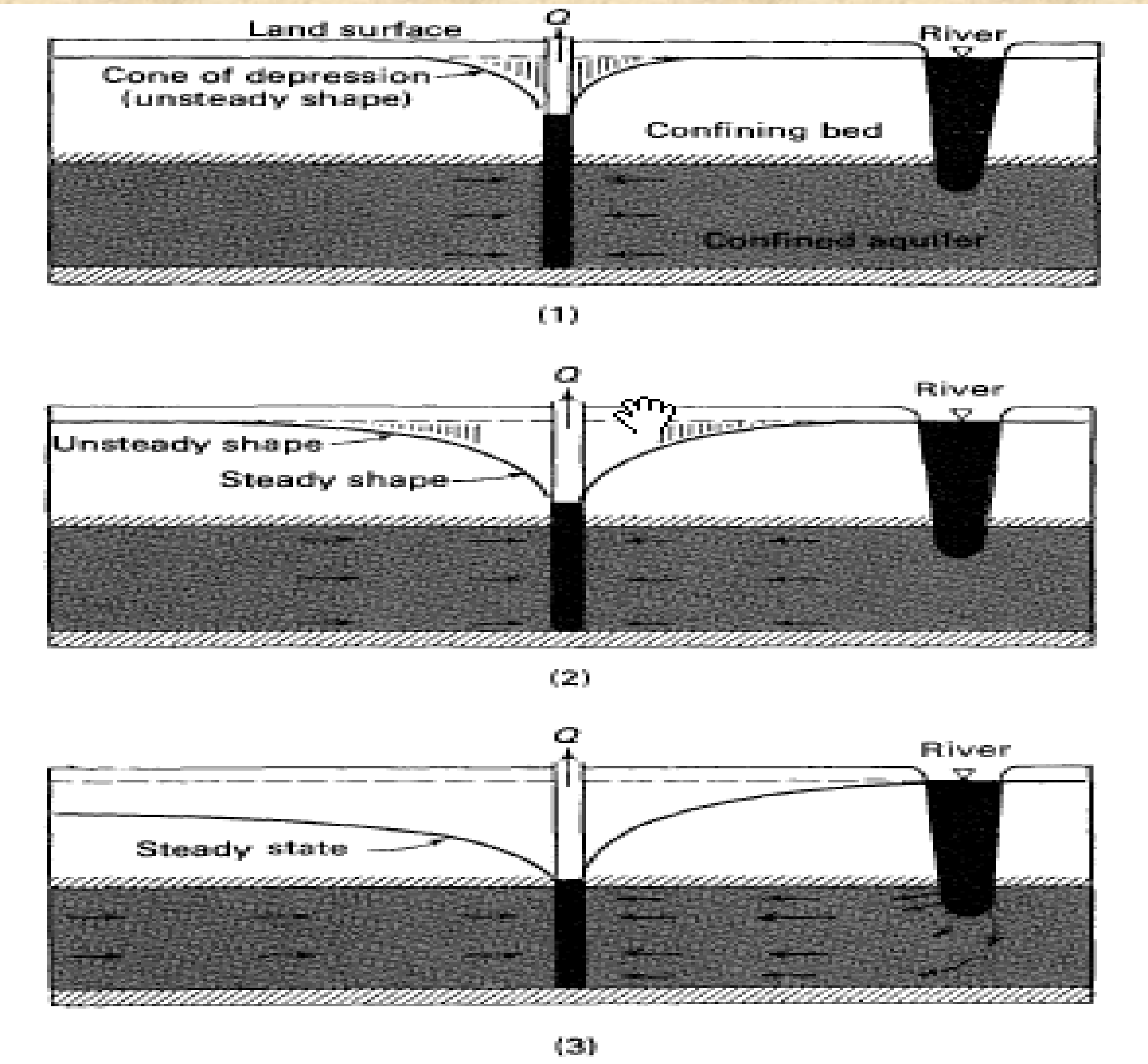
Measurements

- Water level (dynamic and static)
- Discharge rate
- Duration and steps of pumping
- Distance between the well and piezometers
- Pump position
- Aquifer thickness
- Lithological logs
- Set up of blind and screen casings
- Etc.

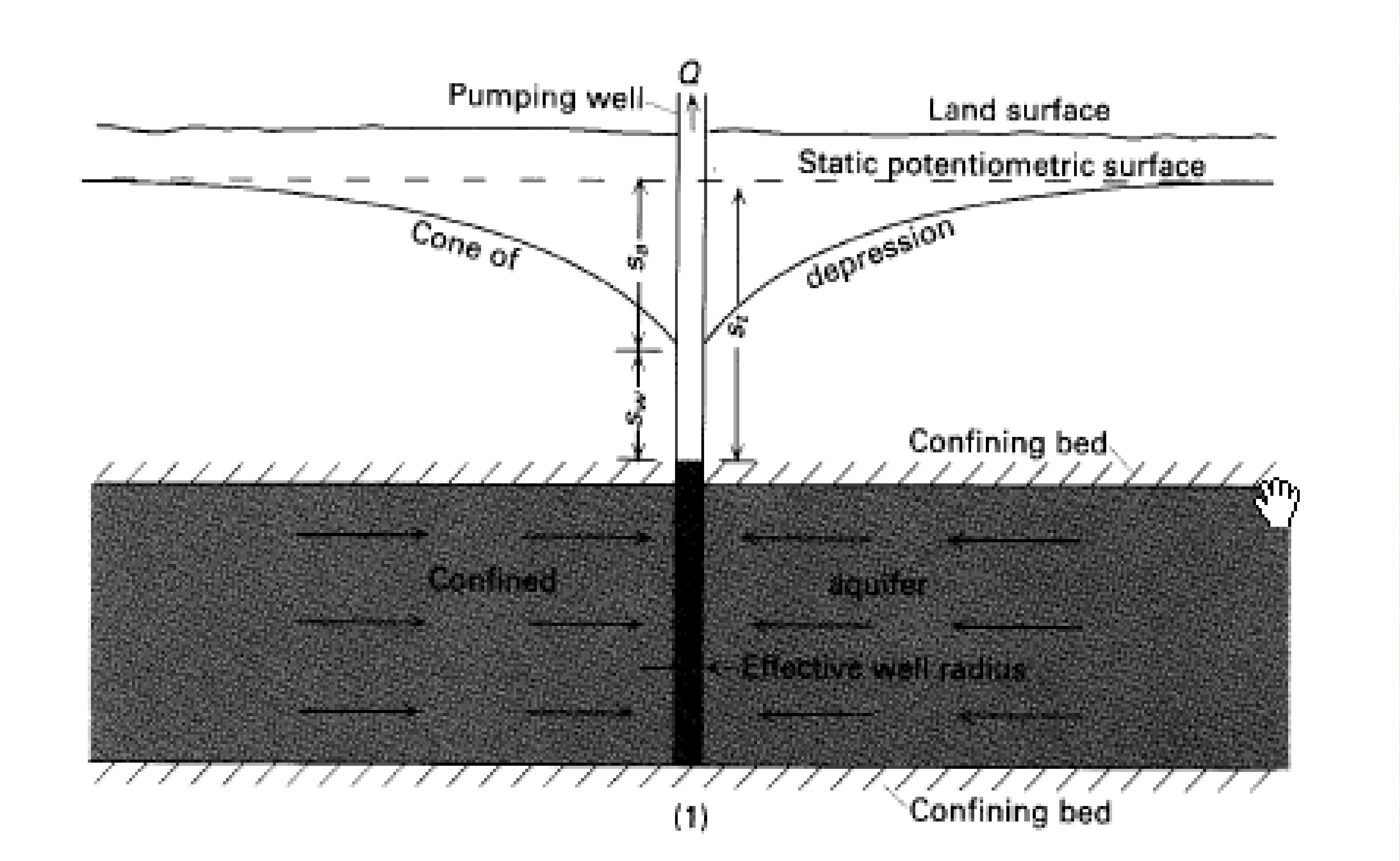
Illustration on measurement



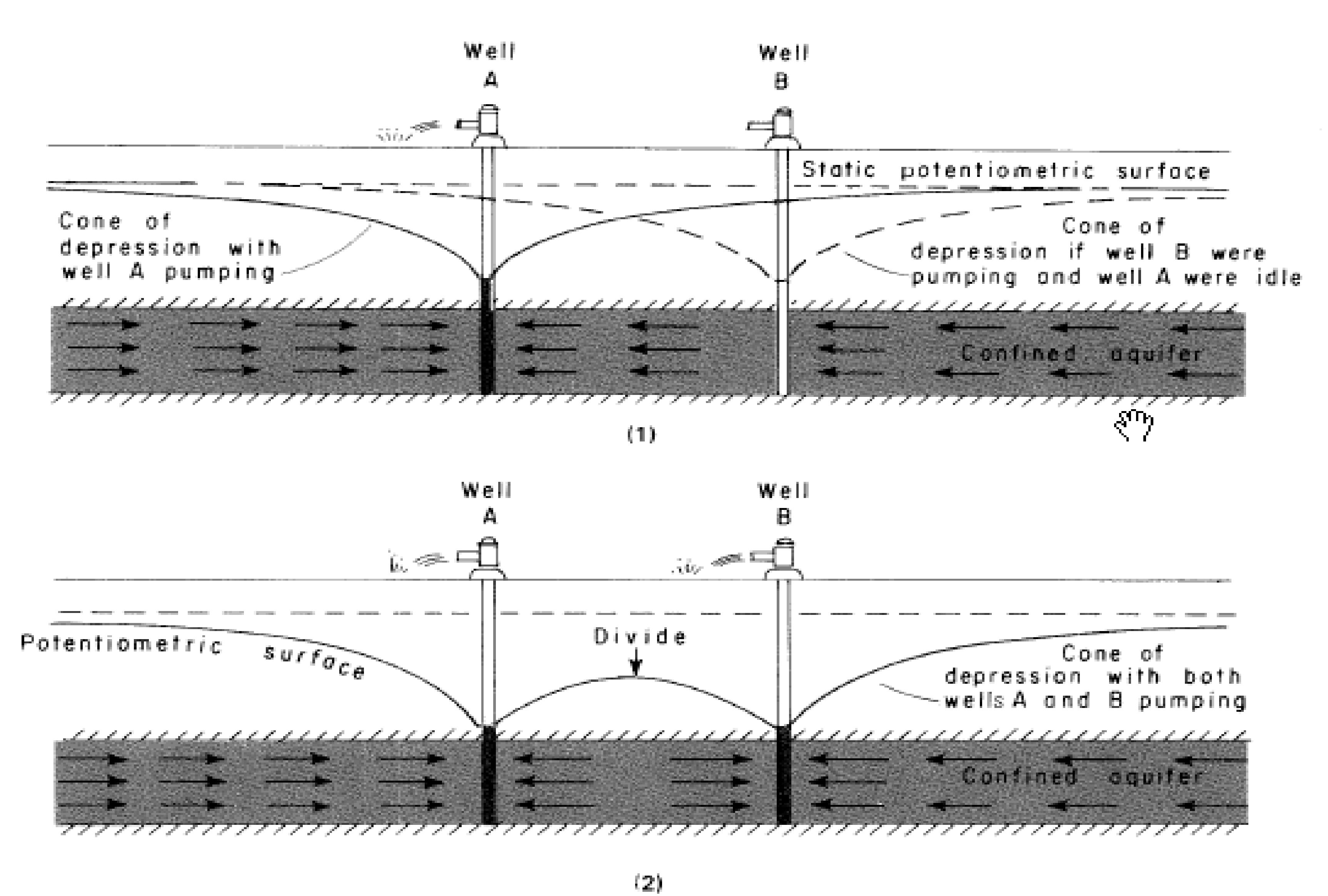
Concept of drawdown



Cone of depression



Well interference



❖The accuracy of drawdown data taken during a pumping test depends on the following factors:

- Maintaining a constant yield during the test
- Measuring the drawdown carefully in the pumping well and in one or two properly placed observation wells
- Taking the drawdown readings at appropriate time intervals
- Determining how changes in barometric pressures, stream levels, and tidal oscillations affect drawdown data
- Comparing recovery data with drawdown data taken during the pumping portion of the test
- Continuing the test for longer times
- How good the pump and deep meter function

- The best site for the pumping well should be:
  - Representative site to characterize an aquifer
  - The hydrogeological condition should not change over a short distance
  - The site should not be near railways and motor ways
  - It should not be in the vicinity of existing discharging wells
  - The pump water should not be recharged back
  - The gradient of the water table should be low
  - Manpower and equipment should reach the site (Accessibility)

Nature of Converging Flow (cone of depression)

- The water level in the vicinity of pumped well under unconfined conditions is lowered when pumping begins, with the greatest drawdown occurring in the well.
- During pumping, water flows toward the well from every direction. As the water moves closer to the well, it moves through imaginary cylindrical sections that are successively smaller in area. Thus, as the water approaches the well, its velocity increases.
- The form of this surface resembles a cone and is called the *cone of depression*. During pumping all wells are surrounded by a cone of depression. Each cone differs in size and shape depending upon the pumping rate, pumping duration, aquifer characteristics, slope of the water table, and recharge within the cone of depression of the well. In a formation with high Transmissivity, the cone is shallow with flat sides and has a large radius.
- When water is pumped from a well, the initial discharge is derived from casing storage and aquifer storage immediately surrounding the well. As pumping continues, more water must be derived from aquifer storage at greater distances from the well. The radius of influence of the well increases as the cone expands.
- Consider issues of well interference during pumping test

Piezometers

- A piezometer is an open-ended pipe, placed in a borehole that has been drilled to the desired depth in the ground.
- The bottom tip of the piezometer is fitted with a perforated or slotted screen, 0.5 to 1 m long, to allow the inflow of water.
- The water levels measured in piezometers represent the average head at the screen of piezometers.
- The question of how many piezometers to place for the pumping test depends on the amount of information needed and the funds available for the test.
- Drawdown data from the well itself or from one single piezometer often permit the calculation of aquifer hydraulic characteristics; it is nevertheless always better to have as many piezometers as condition permit.
- The advantage of having more than one piezometer is that drawdowns measured in them can be analysed in two ways: by the time-drawdown relationship and by the distance-drawdown relationship.
- For financial reasons often a single well test is made (no piezometer)

Water level measurement

- Phreatimeters or deep meters are the most used instrument to measure water level.
- The water levels in the well and in piezometers must be measured many times during a test, and as much accuracy as possible.
- Since water levels are dropping fast during the first one or two hours of the test, the readings in this period should be made at brief intervals. As pumping continues, the intervals can be gradually lengthened.
- The suggested intervals need not be adhered rigidly, as they should be adapted to local conditions, available personnel, etc.
- Usually log-log and semi-log papers are necessary with time in minutes on a logarithmic scale. These helps in checking whether the test is running well and in deciding on the time to shut down the pump.

Duration of the pumping test

- The time needed for pumping test is difficult to decide, because the period of pumping depends on the type of aquifer and the degree of accuracy desired in establishing its hydraulic characteristics.
- In some tests, steady-state conditions occur a few hours after the start of pumping, in others they occur within a few days or weeks, in others they never occur.
- Steady-state condition may reach in leaky aquifers after 15 to 20 hours of pumping, in confined aquifer.
- Generally it is a good practice to pump for 24 hours for constant discharge test, in an unconfined aquifer, because the cone of depression expands slowly, a longer period is required, say 72 hours. For step-drawdown tests, 24 hours is usually sufficient for either type of aquifers.

Specific Boundary Conditions

- A common assumption in well hydraulics is that the pumped aquifer is horizontal and has infinite extent. Common pumping tests are made based on this assumption. But, could be finite and slopping.
- When field data curves of drawdown versus time deviate/differs from the theoretical curves, the deviation is usually due to specific boundary conditions such as partial penetration of wells, well-bore storage, recharge boundaries or impermeable boundaries.
- *Partial penetration of the well* - Theoretical models usually assume that the pumped well fully penetrates the aquifer, so that the flow towards the well is horizontal. With a partially penetrating well, the condition of horizontal flow is not satisfied, at least not in the vicinity of the well.
- *Well bore storage* - All theoretical models assume a line source or sink, which means that well-bore storage effects can be neglected.
- *Recharge or impermeable boundaries* - Recharge or impermeable boundaries can also affect the theoretical curves of all the main aquifer types. The field data curve then begins to deviate more and more from the theoretical curve. If the cone of depression reaches such a boundary, the drawdown will double.

Common Pumping Test Methods

Generally there are three types of pumping tests:

1. *Constant discharge*
2. *Recovery*
3. *Variable discharge (step-drawdown)* test

In each of the three types of tests, there are many methods used, developed by various scholars to determine aquifer parameters and well efficiency for confined, unconfined and leaky aquifers.

Determination of hydraulic properties in confined aquifers

❑ Steady-state Method

The basic assumptions in the constant discharge-pumping test are:

- The aquifer is confined from top and bottom
- The aquifer has infinite aerial extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test
- Prior to pumping, the piezometeric surface is horizontal over the area that will be influenced by the test
- The aquifer is pumped at a constant discharge rate
- The well penetrates the entire thickness of the aquifer and receives water by horizontal flow and also determine by **Thiem Method**

❑ Unsteady-state Flow

- The assumption of unsteady state flow method is similar to steady state ,but a variation of time.
- And also can be determined by **Theis and Jacob Methods** and **Copper – Jacob method**

Determinations of hydraulic properties in unconfined aquifers

- Basic differences exist between unconfined and confined aquifers:
- A confined aquifer will not be dewatered during pumping, it remains fully saturated and the pumping creates a drawdown in the piezometeric surface.
- The water produced by a well in a confined aquifer comes from the expansion of the water in the aquifer due to the reduction of the water pressure, and from the compaction of the aquifer due to increased effective stress.
- The flow towards the well in a confined aquifer remains horizontal, provided that the well is fully penetrating one.
- In unconfined aquifers, the water levels in piezometers near the well often tend to decline at a slower rate than that described by the Theis equation

❑ Steady state method

Some basic assumptions considered in pumping test in this case are:

- The aquifer is unconfined
- The aquifer has infinite aerial extent
- The aquifer is homogeneous and has uniform thickness over the area influenced by the test
- Prior to pumping, the water table is horizontal over the area that will be influenced by the test
- The aquifer is pumped at a constant discharge rate
- The well penetrates the entire aquifer and thus receives water from the entire saturated thickness of the aquifer and also determined by **Dupuit’s and Darcy's equation**

❑ Unsteady-state Flow method

- The assumption of unsteady state flow method of unconfined aquifer is similar to steady state flow of unconfined aquifer ,but a variation of time.
- And also can be determined by **Theis equation, Neumann's Curve Fitting Method and others.**

Thank you!!!!