

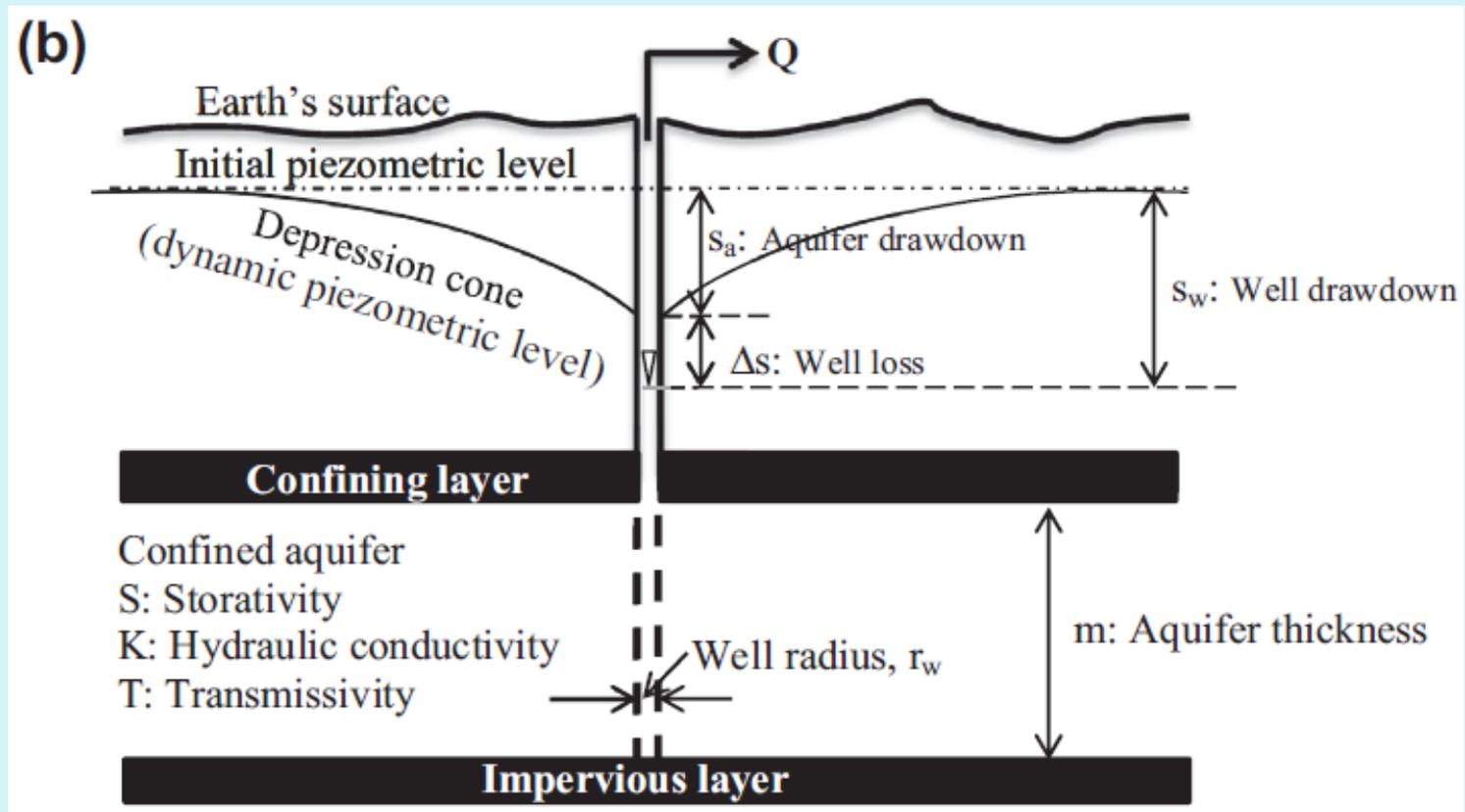
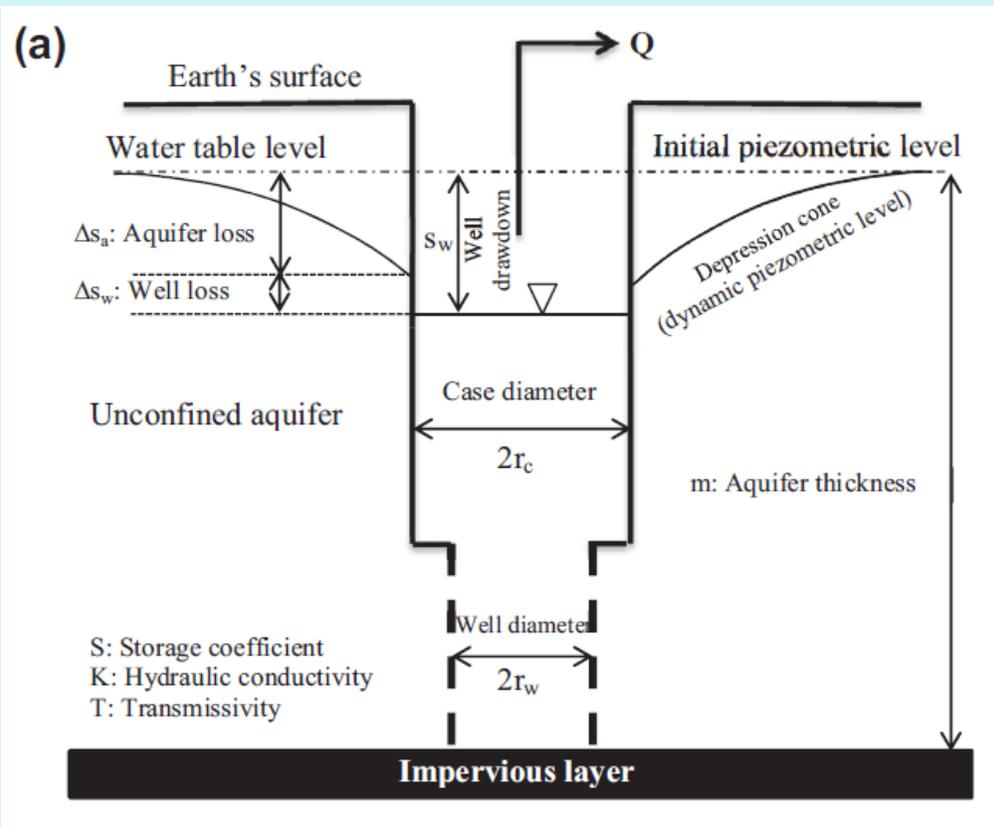
Chapter 3:

Wells and Well Hydraulics

Wells and Well Hydraulics

- Wells are the main hydraulic structures for groundwater abstractions from the potential geological formations.
- The purpose of water wells is to extract groundwater from the saturation zones for domestic, agricultural, industrial or any other use.
- The choice of well shape and dimensions depend on the piezometric level (shallow or deep), subsurface geological layers (permeable, semipermeable or impermeable), recharge possibilities (direct, indirect).
- First classification of the wells is based on their diameter and there are large and small diameter wells.
- Large diameter wells are dug usually in unconfined shallow aquifers; small diameter wells penetrate big depths and they are suitable for deep confined aquifers.

Wells and Well Hydraulics



Large and small diameter-wells have the following comparative advantages:

1. In large (small) diameter wells water is practically available (not available) for abstraction in the well storage for direct usage.

Wells and Well Hydraulics

Large and small diameter-wells have the following comparative advantages:

2. The excavation of large (small) diameter wells does not require (require) sophisticated machines for digging (drilling).
3. For large (small) diameter wells digging (drilling) and operation skilled personnel are not required (required).
4. Large diameter wells are deepened gradually after dry (drought) periods, whereas the small diameter wells are drilled once and for all.
5. In large (small) diameter well piezometric level is (not) close to Earth's surface. Accordingly, in large (small) diameter wells suction (submersible) pumps are usable for groundwater haulage to the surface.
6. Large (small) diameter well is rather cheap (expensive) to construct and maintain.

Wells and Well Hydraulics

On the other hand, from disadvantage points of view they can be compared along the following points:

1. Large (small) diameter well is (not) susceptible to contamination or pollution.
2. Large (small) diameter well occupies large (small) space for the well and digging (drilling) material.
3. Large (small) diameter well is dangerous (safe) for small children and animals.
4. Large (small) diameter well is (not) subject to flood sedimentation and debris flow.
5. Large (small) diameter well may get dry in short (long) time periods during drought periods.

Wells and Well Hydraulics

Water well construction includes:

- Selection of appropriate drilling methods
- Selection of appropriate completion materials
- Analysis and interpretation of well and aquifer performance

Consider the water in an unconfined aquifer being pumped at a constant rate from a well.

- Prior to the pumping, the water level in the well indicates the static water table.
- A lowering of this water level takes place on pumping.
- If the aquifer is homogeneous and isotropic and the water table horizontal initially, due to the radial flow into the well through the aquifer the water table assumes a conical shape called *cone of depression*.

Wells and Well Hydraulics

- The drop in the water table elevation at any point from its previous static level is called *drawdown*.
- The areal extent of the cone of depression is called *area of influence* and its radial extent *radius of influence*.
- At constant rate of pumping, the drawdown curve develops gradually with time due to the withdrawal of water from storage.
- This phase is called an *unsteady flow* as the water table elevation at a given location near the well changes with time.
- On prolonged pumping, an equilibrium state is reached between the rate of pumping and the rate of inflow of groundwater from outer edges of the zone of influence.

Wells and Well Hydraulics

- The drawdown surface attains a constant position with respect to time when the well is known to operate under *steady flow* conditions.
- As soon as the pumping is stopped, the depleted storage in the cone of depression is made good by groundwater inflow into the zone of influence.
- There is a gradual accumulation of storage till the original (static) level is reached.
- This stage is called *recuperation* or *recovery* and is an unsteady phenomenon.
- Recuperation time depends upon the aquifer characteristics.

Wells and Well Hydraulics

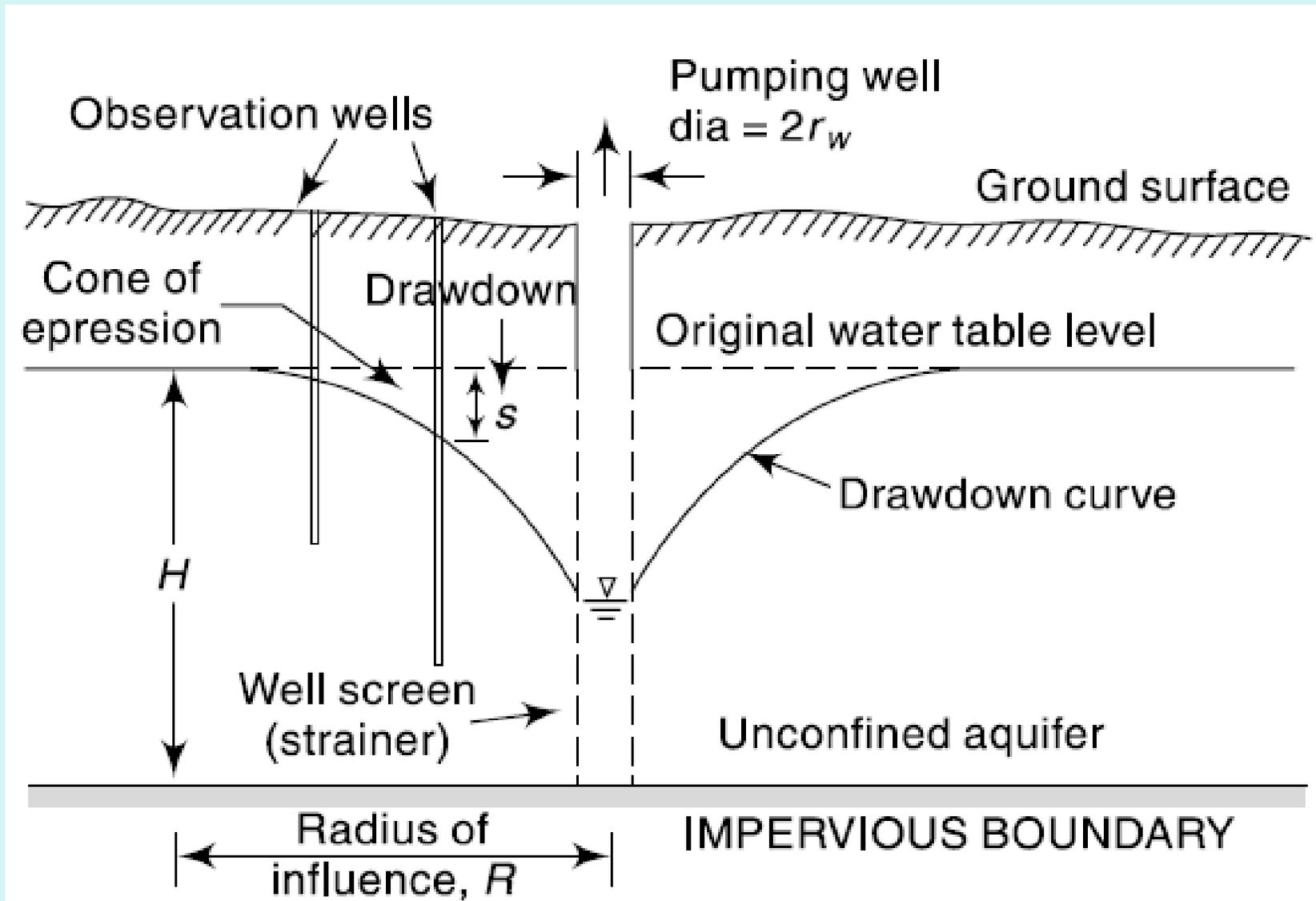
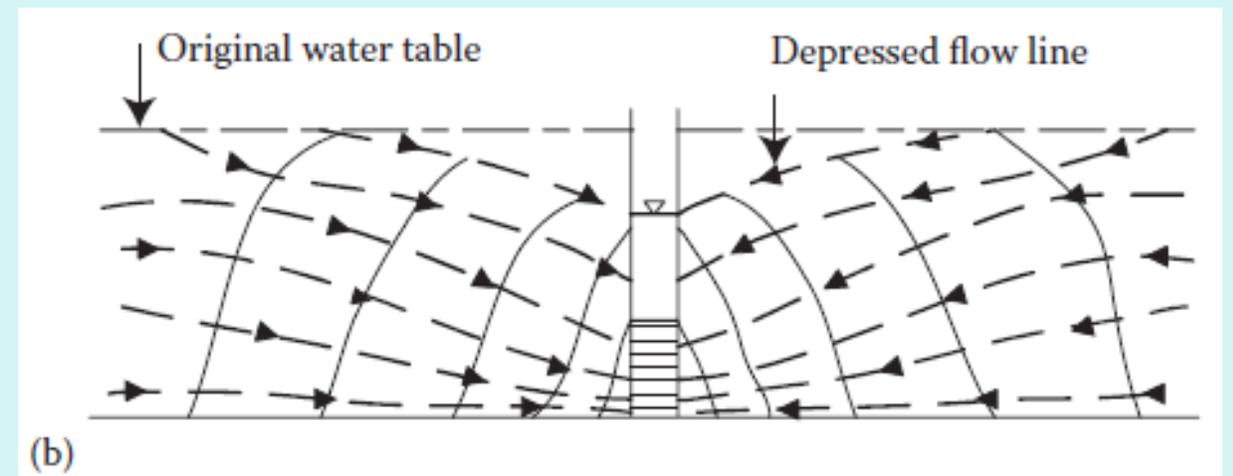
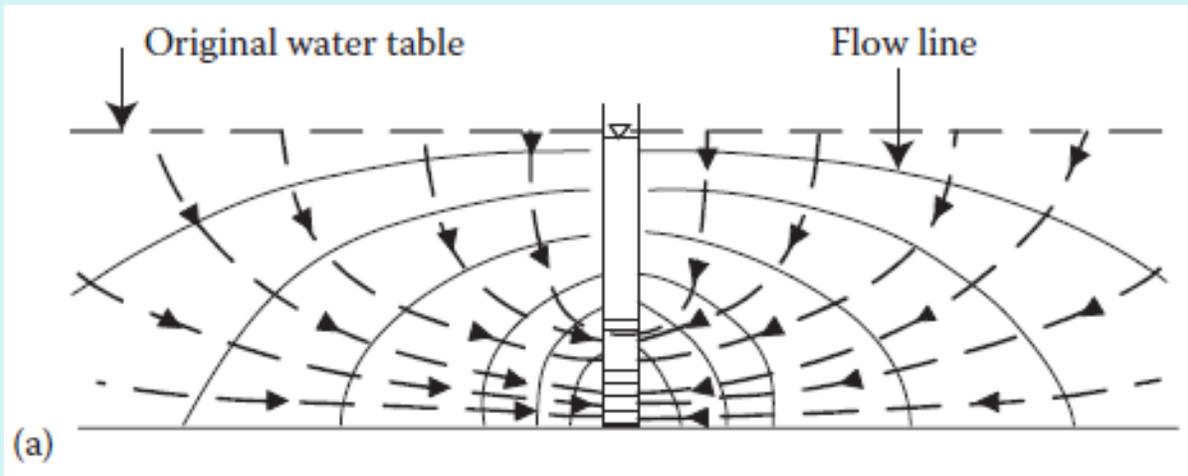


Figure. Well operating in an unconfined aquifer.

Wells and Well Hydraulics

- Changes similar to the above take place to a pumping well in a confined aquifer also but with the difference that it is the piezometric surface instead of the water table that undergoes drawdown with the development of the cone of depression.
- In confined aquifers with considerable piezometric head, the recovery into the well takes place at a very rapid rate.



Wells and Well Hydraulics

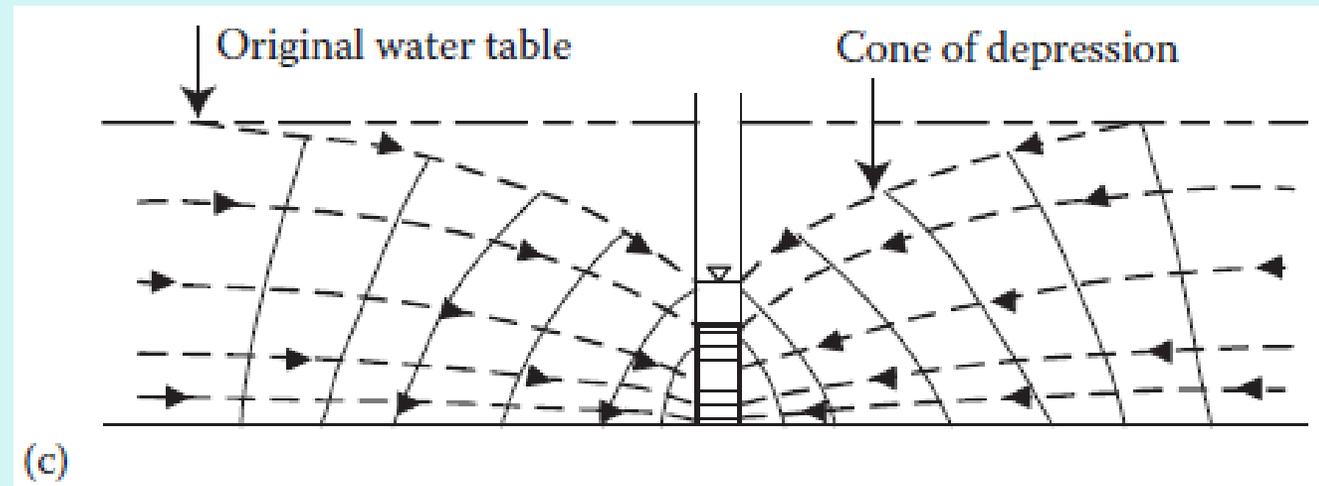
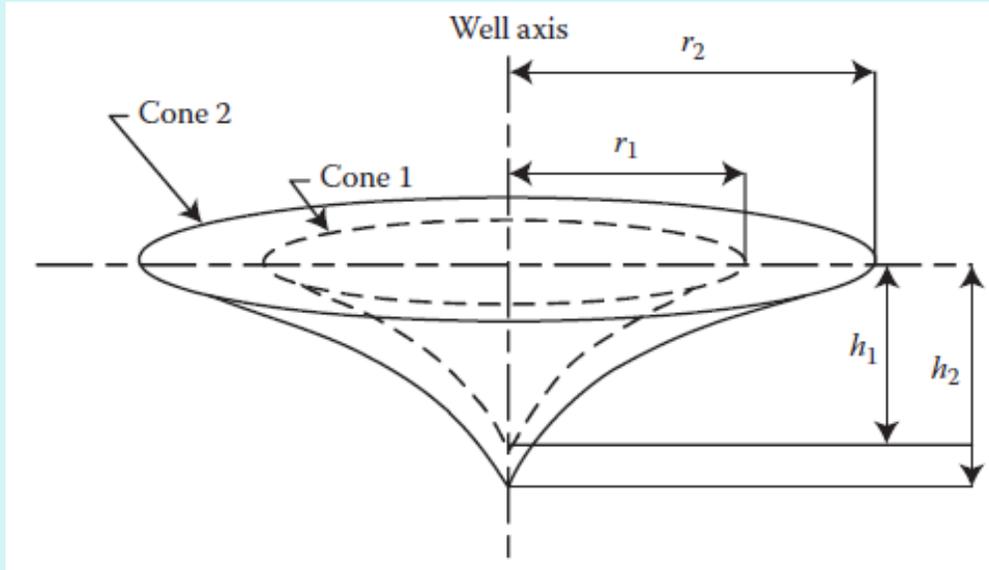


Figure: Development of flow distribution about a discharging well in an unconfined aquifer: (a) initial stage, (b) intermediate stage, (c) steady-state stage.

If pumping continues, more water must be derived from the aquifer storage at greater distances from the bore of the well and the following items are observed:

1. The cone of depression is expanded.
2. The radius of influence of the well increases due to the expansion of the cone.
3. The drawdown is incremented at any point with the increase in the depth of the cone to provide the additional head required to move the water from greater distance.
4. The cone expands and deepens more slowly with time since an increasing volume of stored water is available with horizontal expansion of the cone.

Wells and Well Hydraulics

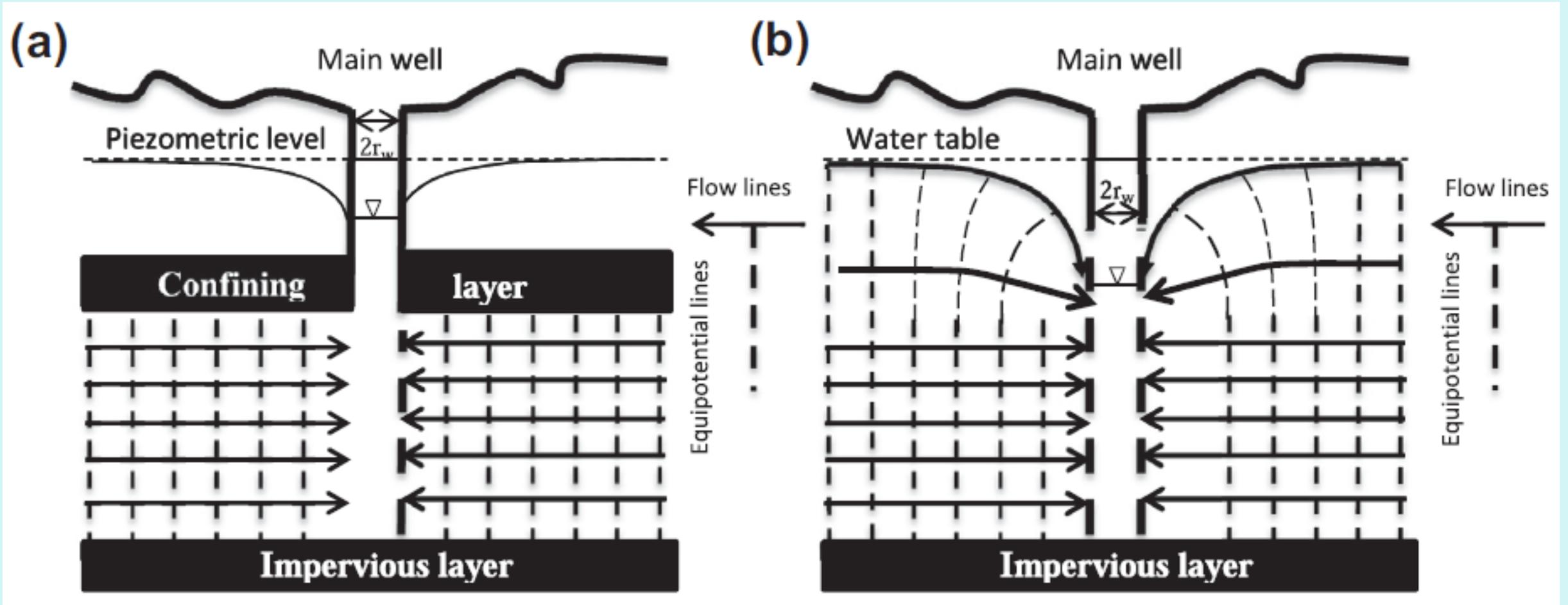


Figure: Full penetration well. (a) Confined aquifer, (b) unconfined aquifer.

Wells and Well Hydraulics

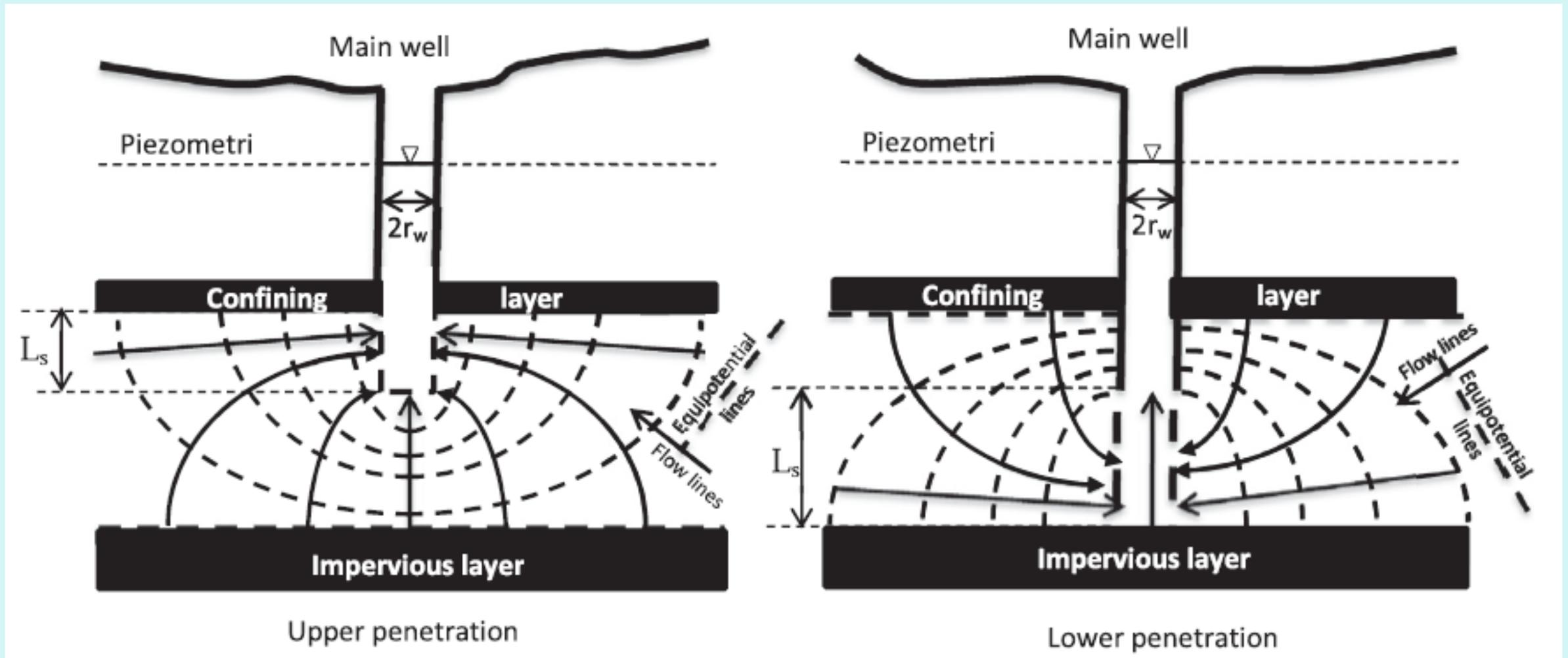


Figure: Confined aquifer partial penetration aquifer.

Steady Flow into a Well

- Steady state groundwater problems are relatively simpler.

Confined aquifer

Figure A. shows a well completely penetrating a horizontal confined aquifer of thickness B . Consider the well to be discharging a steady flow, Q . The original piezometric head (static head) was H and the drawdown due to pumping is indicated in Figure A. The piezometric head at the pumping well is h_w and the drawdown s_w .

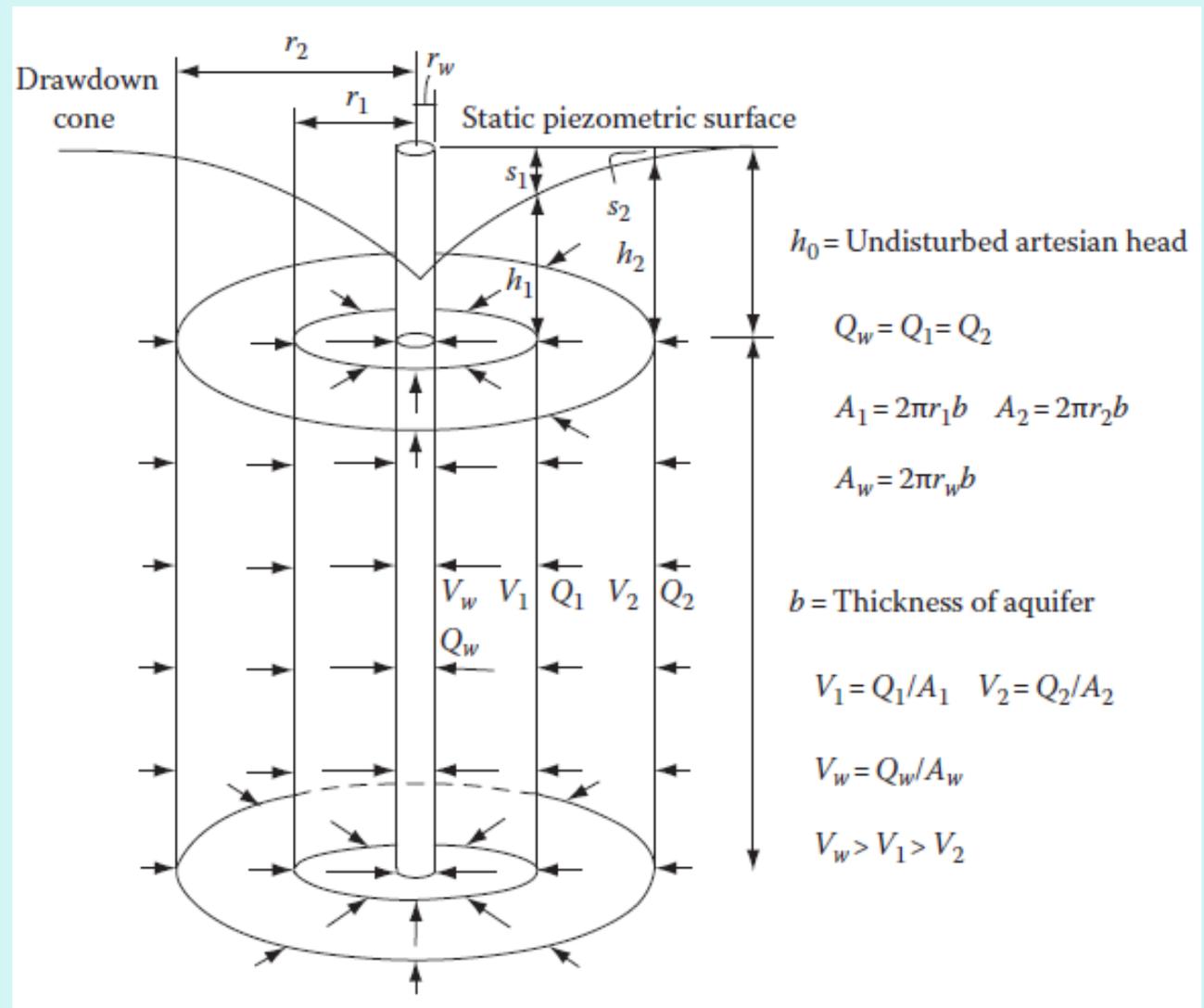


FIGURE. Flow distribution to a discharging well in a confined aquifer.

Steady Flow into a Well

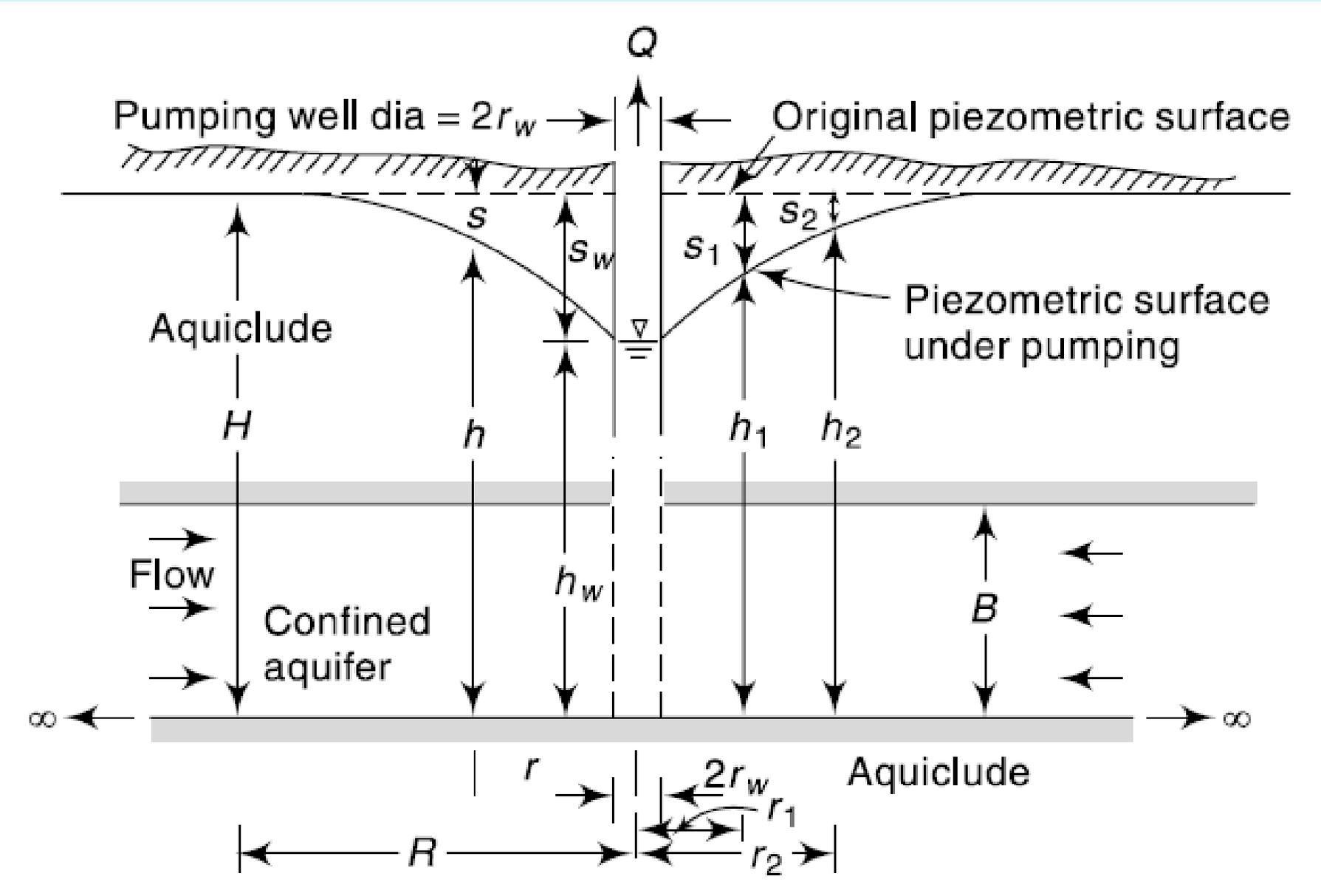


Figure A. Well operated in a confined aquifer.

Steady Flow into a Well

- At a radial distance r from the well, if h is the piezometric head, the velocity of flow by

Darcy's law is:
$$V_r = K \frac{dh}{dr}$$

- The cylindrical surface through which this velocity occurs is $2\pi r B$. Hence by equating the discharge entering this surface to the well discharge,
$$Q = (2 \pi r B) \left(K \frac{dh}{dr} \right) \quad \frac{Q}{2 \pi KB} \frac{dr}{r} = dh$$

- Integrating between limits r_1 and r_2 with the corresponding piezometric heads being h_1 and h_2 respectively,

$$\frac{Q}{2 \pi KB} \ln \frac{r_2}{r_1} = (h_2 - h_1)$$

or

$$Q = \frac{2 \pi KB (h_2 - h_1)}{\ln \frac{r_2}{r_1}}$$

Equation (1)

- This is the equilibrium equation for the steady flow in a confined aquifer. This equation is popularly known as *Thiem's equation*.

Steady Flow into a Well

- If the drawdown s_1 and s_2 at the observation wells are known, then by noting that

- $s_1 = H - h_1$, $s_2 = H - h_2$ and $KB = T$

- Equation (a) will read as:

$$Q = \frac{2 \pi T (s_1 - s_2)}{\ln \frac{r_2}{r_1}}$$

Equation (2)

- Further, at the edge of the zone of influence, $s = 0$, $r_2 = R$ and $h_2 = H$; at the well wall $r_1 = r_w$, $h_1 = h_w$ and $s_1 = s_w$. Equation (2) would then be

$$Q = \frac{2 \pi T s_w}{\ln R/r_w}$$

Equation (3)

- Equation (2) or (3) can be used to estimate T , and hence K , from pumping tests. For the use of the equilibrium equation, Equation (1) or its alternative forms, it is necessary that the assumption of complete penetration of the well into the aquifer and steady state of flow are satisfied.

Steady Flow into a Well

Example: A 30-cm diameter well completely penetrates a confined aquifer of permeability 45 m/day. The length of the strainer is 20 m. Under steady state of pumping the drawdown at the well was found to be 3.0 m and the radius of influence was 300 m. Calculate the discharge.

Solution:

In this problem, referring to Figure A,

$$r_w = 0.15 \text{ m} \quad R = 300 \text{ m} \quad s_w = 3.0 \text{ m} \quad B = 20 \text{ m}$$

$$K = 45 / (60 * 60 * 24) = 5.208 * 10^{-4} \text{ m/s}$$

$$T = KB = 10.416 * 10^{-3} \text{ m}^2/\text{s}$$

Steady Flow into a Well

Solution: By Equation (3)

$$Q = \frac{2\pi T s_w}{\ln \frac{R}{r_w}} = \frac{2\pi * 10.416 * 10 - 3 * 3}{\ln \frac{300}{0.15}} = 0.02583 \text{ m}^3/\text{s}$$

Example: For a well in the previous example, calculate the discharge (a) if the well diameter is 45 cm and all the other data remain the same as in Example above. (b) if the drawdown is increased to 4.5 m and all the other data remain unchanged as in Example above.

Solution: (a) $Q = \frac{2\pi T s_w}{\ln \frac{R}{r_w}}$ As T and s_w are constants, $\frac{Q_1}{Q_2} = \frac{\ln(R|r_{w2})}{\ln(R|r_{w1})}$

Putting $R = 300 \text{ m}$ $Q_1 = 1550 \text{ lpm}$, $r_{w1} = 0.15 \text{ m}$ and $r_{w2} = 0.225 \text{ m}$.

$$Q_2 = 1550 \frac{\ln 300/0.15}{\ln 300/0.225} = 1637 \text{ lpm}$$

(Note that the discharge has increased by about 6% for 50% increase in the well diameter.)

Steady Flow into a Well

Unconfined Aquifer

Consider a steady flow from a well completely penetrating an unconfined aquifer. In this case because of the presence of a curved free surface, the streamlines are not strictly radial straight lines. While a streamline at the free surface will be curved, the one at the bottom of the aquifer will be a horizontal line, both converging to the well. To obtain a simple solution Dupit's assumptions are made. In the present case these are:

The basic assumptions of Dupit are:

- The curvature of the free surface is very small so that the streamlines can be assumed to be horizontal at all section.*
- The hydraulic grade line is equal to the free surface slope and does not vary with depth.*

Steady Flow into a Well

In the present case these are:

- For small inclinations of the free surface, the streamlines can be assumed to be horizontal and the equipotentials are thus vertical.
- The hydraulic gradient is equal to the slope of the the free surface and does not vary with depth. This assumption is satisfactory in most of the flow regions except in the immediate neighborhood of the well.

Consider the well radius r_w penetrating completely an extensive unconfined horizontal aquifer as shown in figure below. The well is pumping a discharge Q . At any radial distance r , the velocity in the radial flow into the well is

$$V_r = K \frac{dh}{dr}$$

Where h is the height of the water table above the aquifer bed at that location.

Steady Flow into a Well

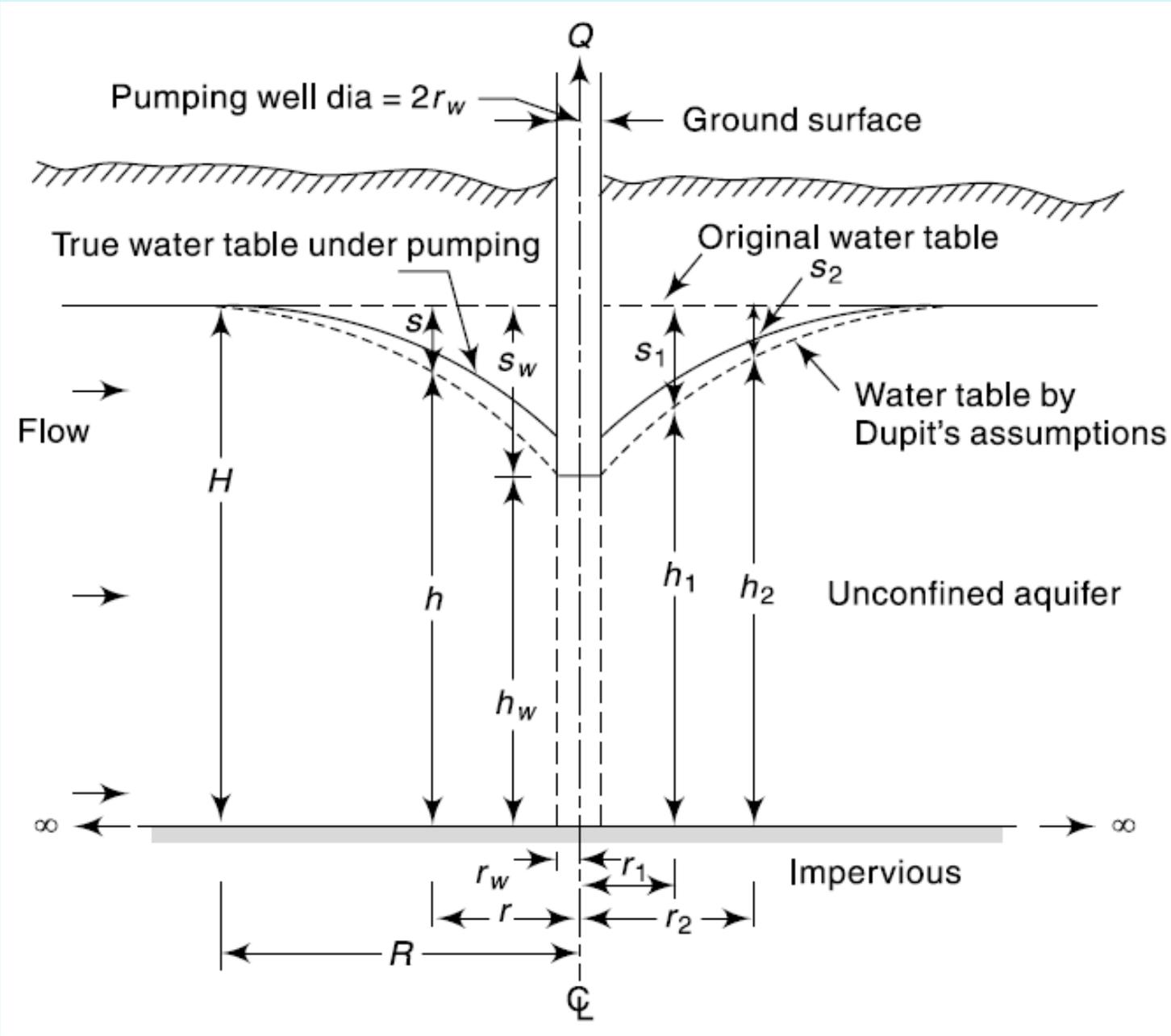


Figure: Radial flow in to a well in an unconfined aquifer.

Steady Flow into a Well

For steady flow, by continuity

$$Q = (2 \pi r h) V_r = 2 \pi r K h \frac{dh}{dr}$$

or

$$\frac{Q}{2 \pi K} \frac{dr}{r} = h dh$$

Integrating between limits r_1 and r_2 where the water-table depths are h_1 and h_2 respectively and on rearranging

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

Equation (4)

This is the equilibrium equation for a well in an unconfined aquifer. As at the edge of the zone of influence of radius R , H = saturated thickness of the aquifer, equation (4) can be

written as

$$Q = \frac{\pi K (H^2 - h_w^2)}{\ln \frac{R}{r_w}}$$

Equation (5)

Where h_w = depth of water in the pumping well of radius r_w .

Steady Flow into a Well

- Equations (4) and (5) can be used to estimate satisfactorily the discharge and permeability of the aquifer by using field data.
- Calculations of the water-table profile by equation (4), however, will not be accurate near the well because of Dupit's assumptions.
- The water-table surface calculated by equation (4) which involved Dupit's assumption will be lower than the actual surface.
- The departure will be appreciable in the immediate neighborhood of the well.
- In general, values of R in the range 300 to 500 m can be assumed depending on the type of aquifer and operating conditions of a well.
- As the logarithm of R is used in the calculation of discharge, a small error in R will not seriously affect the estimation of Q .
- It should be noted that it takes a relatively long time of pumping to achieve a steady state in a well in an unconfined aquifer. The recovery after the cessation of pumping is also slow compared to the response of an artesian well which is relatively fast.

Steady Flow into a Well

Example: A 30-cm well completely penetrates an unconfined aquifer of saturated depth 40 m. After a long period of pumping at a steady rate of 1500 lpm, the drawdown in two observation wells 25 and 75 m from the pumping well were found to be 3.5 and 2.0 m respectively. Determine the transmissivity of the aquifer. What is the drawdown at the pumping well?

Solution:

$$(a) \quad Q = \frac{1500 \cdot 10^{-3}}{60} = 0.025 \text{ m}^3/\text{s}$$

$$h_2 = 40.0 - 2.0 = 38.0$$

$$r_2 = 75 \text{ m}$$

$$h_1 = 40.0 - 3.5 = 36.5 \text{ m}$$

$$r_1 = 25 \text{ m}$$

From Equation (4),
$$Q = \frac{\pi K (h_2^2 - h_1^2)}{\ln \frac{r_2}{r_1}}$$

$$0.025 = \frac{\pi K [(38^2) - (36.5^2)]}{\ln \frac{75}{25}} \quad K = 7.823 \cdot 10^{-5} \text{ m/s}$$

$$T = KH = 7.823 \cdot 10^{-5} \cdot 40 = 3.13 \cdot 10^{-3} \text{ m}^2/\text{s}$$

Steady Flow into a Well

Solution:

b) At the pumping well, $r_w = 0.15$ m

$$Q = \frac{\pi K (H_1^2 - h_w^2)}{\ln \frac{r_1}{r_w}}$$

$$0.025 = \frac{\pi * 7.823 * 10^{-5} [(36.5^2) - (h_w^2)]}{\ln \frac{25}{0.15}}$$

$$h_w^2 = 811.84 \quad \text{and} \quad h_w = 28.49 \text{ m}$$

Drawdown at the well, $s_w = 11.51$ m

Open Wells

- Open wells (dug wells) are extensively used for drinking water supply in rural communities and in small farming operations.
- They are best suited for shallow and low yielding aquifers.
- The cross sections are circular or rectangular in shape.
- They are generally sunk to a depth of about 10 m and are lined wherever loose overburden is encountered.
- The flow into the well is through joints, fissures, and such other openings and is usually at the bottom/lower portions of the well.
- In unconsolidated formations (alluvial soils) the wells are usually dug to a depth of about 10 m below water table, circular in cross-section and lined.

Open Wells

- The water entry into these wells is from the bottom.
- These wells tap water in unconfined aquifers.
- When the water in an open well is pumped out, the water level inside the well is lowered.
- The difference in the water table elevation and the water level inside the well is known *depression head*.
- The flow discharge into the well (Q) is proportional to the depression head (H), and is expressed as: $Q = K_o H$
- where the proportionality constant K_o depends on the characteristics of the aquifer and the area of the well.
- Also, since K_o represents discharge per unit drawdown it is called as *specific capacity* of the well.

Open Wells

- There is a *critical depression head* for a well beyond which any higher depression head would cause dislodging of soil particles by the high flow velocities.
- The discharge corresponding to the critical head is called as *critical or maximum yield*.
- Allowing a factor of safety (normally 2.5 to 3.0) a *working head* is specified and the corresponding yield from the well is known as *safe yield*.

Recuperation Test

The specific capacity K_o of a well is determined from the recuperation test described below.

- Let the well be pumped at a constant rate Q till a drawdown H_1 is obtained.
- The pump is now stopped and the well is allowed to recuperate.
- The water depth in the well is measured at various time intervals t starting from the stopping of the well.

Recuperation Test

H_1 = drawdown at the start of recuperation, $t = 0$

H_2 = drawdown at a time, $t = T$

h = drawdown at any time t

Δh = decrease in drawdown on time Δt

At any time t , the flow into the well $Q = K_0 h$

- In a time interval Δt causing a small change Δh in the water level,

where A is the area of the well.

$$Q \cdot \Delta t = K_0 h \cdot \Delta t = -A \cdot \Delta h$$

- In differential form

$$dt = -\frac{A}{K_0} \frac{dh}{h}$$

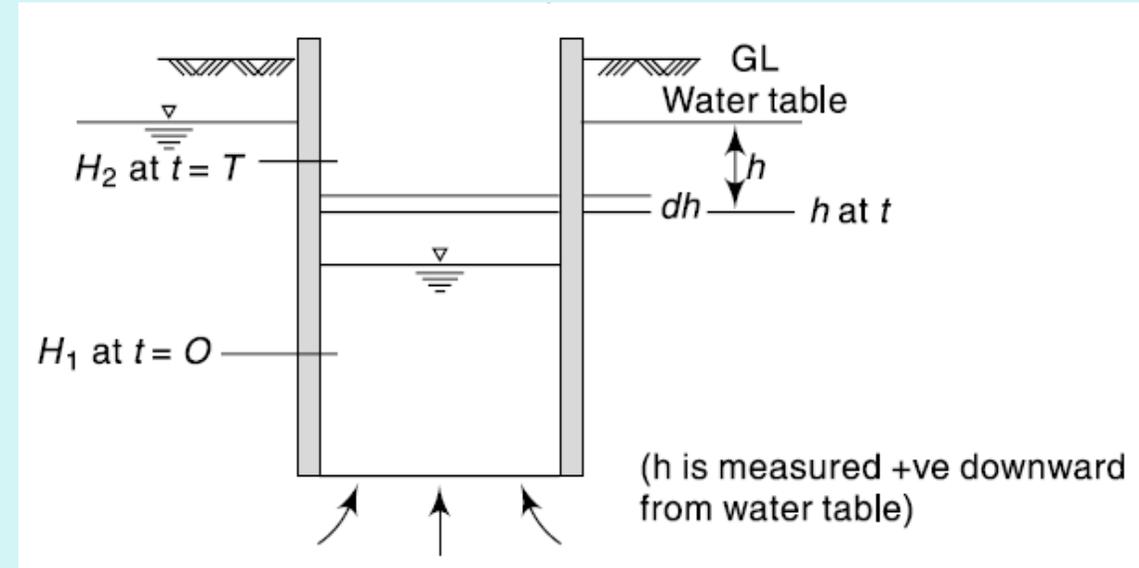


Figure: Recuperation Test for Open well

Recuperation Test

Integrating for a time interval T_r

$$\int_0^{T_r} dt = -\frac{A}{K_0} \int_{H_1}^{H_2} \frac{dh}{h}$$

or

$$T_r = \frac{A}{K_0} \ln \frac{H_1}{H_2}$$

$$\frac{K_0}{A} = \frac{1}{T_r} \ln \frac{H_1}{H_2} \quad \text{equ. (1)}$$

- The term $\frac{K_0}{A} = K_s$ represents *specific capacity per unit well area* of the aquifer and is essentially a property of the aquifer.
- Knowing H_1 , H_2 and the recuperation time T_r for reaching H_2 and H_1 , and the specific capacity per unit well area is calculated by equation (1).
- Usually the K_s of an aquifer, determined by recuperation tests on one or more wells, is used in designing further dug wells in that aquifer.
- However, when such information is not available the following approximate values of K_s , given by Marriot, are often used.

Recuperation Test

Type of sub-soil	Value of K_s in units of h^{-1}
Clay	0.25
Fine sand	0.50
Coarse sand	1.00

- The yield Q from an open well under a depression head H is obtained as term
$$Q = K_s AH \quad \text{Equation (2)}$$
- For dug wells with masonry sidewalls, it is usual to assume the flow is entirely from the bottom and as such A in equation (2) represents the bottom area of the well.

Recuperation Test

Example: During the recuperation test of a 4.0 m open well a recuperation of the depression head from 2.5 m to 1.25 m was found to take place in 90 minutes. Determine the

- (i) specific capacity per unit well area and
- (ii) yield of the well for a safe drawdown of 2.5 m
- (iii) what would be the yield from a well of 5.0 m diameter for a drawdown of 2.25 m?

Solution: $A = \frac{\pi}{4} * (4.0)^2 = 12.566 \text{ m}^2$

From equation (2), $\frac{K_o}{A} = \frac{1}{T_r} \ln \frac{H_1}{H_2}$

Here $T_r = 90 \text{ min} = 1.50 \text{ h}$, $H_1 = 2.5 \text{ m}$, and $H_2 = 1.25 \text{ m}$

(i) $K_s = \frac{K_o}{A} = \frac{1}{1.5} \ln \frac{2.5}{1.25} = 0.462 \text{ h}^{-1}$

(ii) $Q = K_s * A * H = 0.462 * 12.566 * 2.5 = 14.52 \text{ m}^3/\text{h}$

(iii) $A_2 = \frac{\pi}{4} * (5.0)^2 = 19.635$

$$Q = K_s * A_2 * H_2 = 0.462 * 19.635 * 2.25 = 20.415 \text{ m}^3/\text{h}$$

Unsteady Flow in a Confined Aquifer

- When a well in a confined aquifer starts discharging, the water from the aquifer is released resulting in the formation of a cone of depression of the piezometric surface.
- This cone gradually expands with time till an equilibrium is attained.
- The flow configuration from the start of pumping till the attainment of equilibrium is in unsteady regime and is described by Eq. (x). $\nabla^2 h = \frac{S}{T} \frac{\partial h}{\partial t}$
- It is the basic differential equation governing unsteady groundwater flow in a homogenous isotropic confined aquifer. (**Diffusion equation**)
- In polar coordinates, Eq. (x), to represent the radial flow into a well, takes the form

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S}{T} \frac{\partial h}{\partial t}$$

$$Q = \frac{2 \pi KB (h_2 - h_1)}{\ln \frac{r_2}{r_1}} \quad \text{Equation (y)}$$

Making the same assumptions as used in the derivation of the equilibrium formula (Eq. y), This obtained the solution of this equation as:

Unsteady Flow in a Confined Aquifer

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

Equation (A)

- Where $s = H - h =$ drawdown at a point distance r from the pumping well., $H =$ initial constant piezometric head, $Q =$ constant rate of discharge, $T =$ transmissibility of the aquifer, $u =$ a parameter $= r^2 S / 4 T t$, $S =$ storage coefficient and $t =$ time from start of pumping.

- The integral on the right hand side is called the *well function*, $W(u)$, and is given by

$$W(u) = \int_u^{\infty} \frac{e^{-u}}{u} du = -0.577216 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} \dots$$

Equation (B)

- Table of $W(u)$ are available in literatures. Values of $W(u)$ can be easily calculated by the series equation (B) to the required number of significant digits which rarely exceed 4. For small values of $u (u \leq 0.01)$, only the first two terms of the series are adequate.

Unsteady Flow in a Confined Aquifer

- The solution of Equation (A) to find the drawdown s for a given S , T , r , t and Q can be obtained in a straightforward manner.
- However, the estimation of the aquifer constants S and T from the drawdown vs time data of a pumping well, which involve trial-and error procedures, can be done either by a digital computer or by semi-graphical methods such as the use of *Type curve* or by *Chow's method* described in literatures.
- For small values of u ($u \leq 0.01$), Jacob (1946, 1950) showed that the calculations can be considerably simplified by considering only the first two terms of the series of $W(u)$, Equation (B).
- This assumption leads equation (A) to be expressed

$$s = \frac{Q}{4\pi T} \left[-0.5772 - \ln \frac{r^2 S}{4Tt} \right]$$

Unsteady Flow in a Confined Aquifer

- i.e. $s = \frac{Q}{4\pi T} \ln \left[\frac{2.2Tt}{r^2 S} \right]$ Equation (C)

- If s_1 and s_2 are drawdowns at times t_1 and t_2 ,

$$(s_2 - s_1) = \frac{Q}{4\pi T} \ln \frac{t_2}{t_1}$$
 Equation (D)

- If the drawdown s is plotted against time t on a semi-log paper, the plot will be a straight line for large values of time.
- The slope of this line enables the storage coefficient S to be determined.
- From Equation (A), when $s=0$, $\frac{2.25T t_0}{r^2 S} = 1$ or $S = \frac{2.25T t_0}{r^2}$ Equation (E)
- in which t_0 = time corresponding to "zero" drawdown by extrapolating the straight-line portion of the semi-log curve of s vs t (figure below).
- It is important to remember that the above approximate method proposed by Jacob assumes u to be very small.

Unsteady Flow in a Confined Aquifer

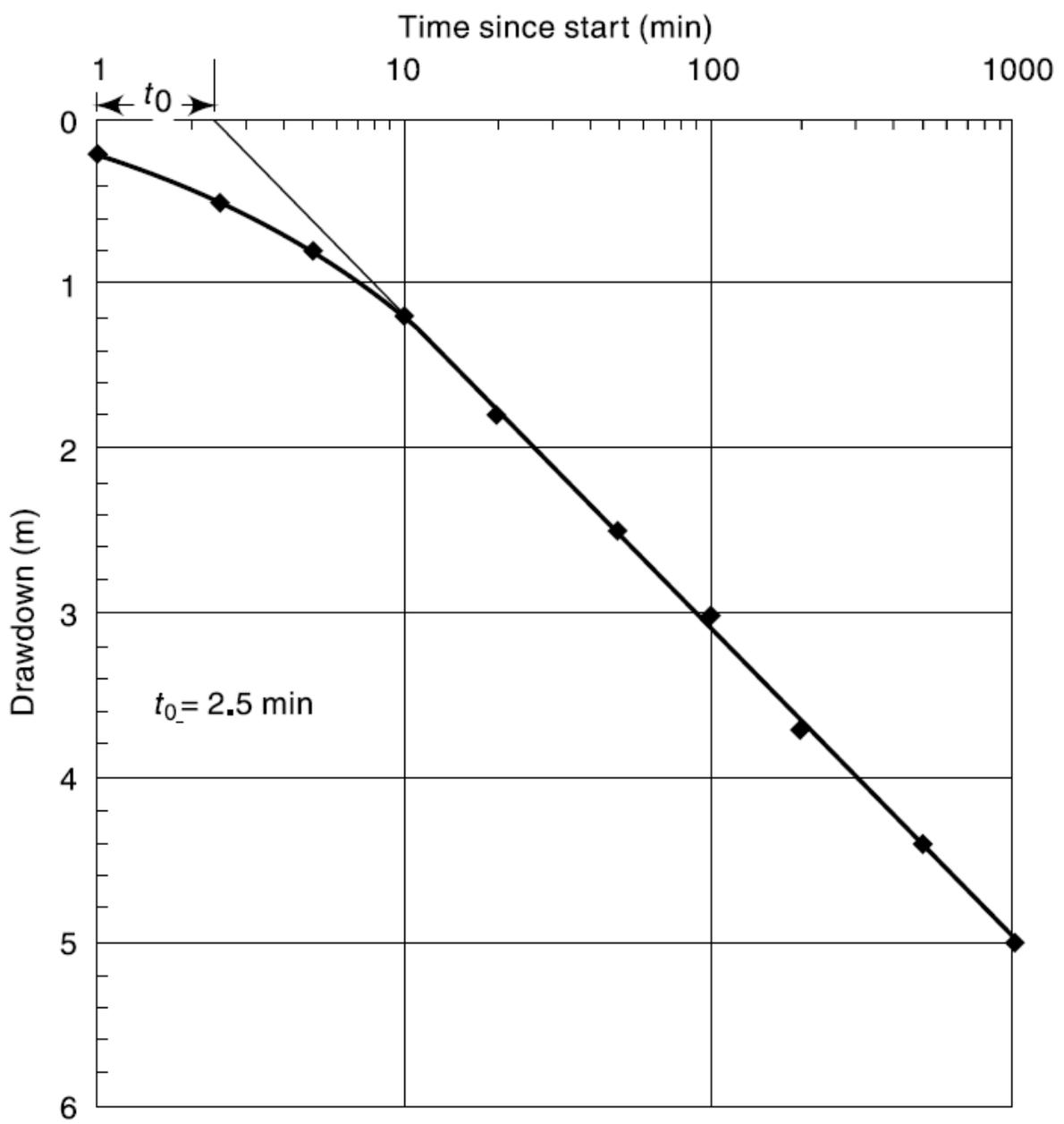


Figure: Time-Drawdown Plot - Example

Unsteady Flow in a Confined Aquifer

Drawdown Test: Equation (C) and (D) relating drawdown s with time t and aquifer properties is used to evaluate formation constants S and T through pumping test.

- The method is known as drawdown test.

Procedure: An observation well at a distance r from the production well is selected.

- The pumping is started and the discharge is maintained at a constant value (Q) throughout the test.
- Values of the drawdown s are read at the observation well at various times, t .
- The time intervals between successive readings could progressively increase to cut down on the number of observations.
- The pumping is continued till nearly steady state conditions are reached.
- This may take about 12 to 36 hours depending on the aquifer characteristics. The best values of S and T are obtained from equation (C) and (D) through semi-log plot of s against time t .

Unsteady Flow in a Confined Aquifer

Example: A well is located in a 25 m confined aquifer of permeability 30 m/day and storage coefficient 0.005. If the well is being pumped at the rate of 1750 lpm, calculate the drawdown at a distance of (a) 100 m and (b) 50 m from the well after 20 h of pumping.

Solution:

$$(a) \quad T = KB = \frac{30}{86400} \times 25 = 8.68 \times 10^{-3} \text{ m}^2/\text{s}$$
$$u = \frac{r^2 S}{4 T t} = \frac{(100)^2 \times (0.005)}{4 \times (8.68 \times 10^{-3}) \times (20 \times 60 \times 60)} = 0.02$$

Using Theis method and calculating $W(u)$ to four significant digits,

$$W(u) = -0.5772 - \ln(0.02) + (0.02) - \frac{(0.02)^2}{2.2!} + \frac{(0.02)^3}{3.3!}$$
$$= -0.5772 + 3.9120 + 0.02 - 0.0001 + 4.4 \times 10^{-7} = 3.3547$$

$$S_{100} = \frac{Q}{4 \pi T} W(u)$$
$$= \left(\frac{1.750}{60} \right) \times \frac{1}{4 \pi (8.68 \times 10^{-3})} \times 3.3547 = 0.897 \text{ m}$$

$$(b) \quad r = 50 \text{ m}, u = \frac{(50)^2 \times (0.005)}{4 \times (8.68 \times 10^{-3}) \times (20 \times 60 \times 60)} = 0.005$$

$$W(u) = -0.5772 - \ln 0.005 + 0.005 = 4.726$$

$$S_{50} = \left(\frac{1.750}{60} \right) \times \frac{1}{4 \pi (8.68 \times 10^{-3})} \times 4.726 = 1.264 \text{ m}$$

(Note that for small values of u , i.e. $u < 0.01$, $W(u) \approx -0.5772 - \ln u$).

Unsteady Flow in a Confined Aquifer

Example: A 30-cm well penetrating a confined aquifer is pumped at a rate of a 1200 lpm. The drawdown at an observation well at a radial distance of 30 m is as follows: Calculate the aquifer parameters S and T ?

Time from start (min)	1.0	2.5	5	10	20	50	100	200	500	1000
Drawdown (m)	0.2	0.5	0.8	1.2	1.8	2.5	3.0	3.7	4.4	5.0

Solution: The drawdown is plotted against time on a semi-log plot (Figure above). It is seen that for $t > 10$ min, the drawdown values describe a straight line. A best-fitting straight line is drawn for data points with $t > 10$ min. From this line, when

$$s = 0, t = t_0 = 2.5 \text{ min} = 150 \text{ s}$$

$$s_1 = 3.1 \text{ m at } t_1 = 100 \text{ min}$$

$$s_2 = 5.0 \text{ m at } t_2 = 1000 \text{ min}$$

$$\text{Also, } Q = 1200 \text{ lpm} = 0.02 \text{ m}^3/\text{s}$$

Unsteady Flow in a Confined Aquifer

From equation (D)

$$s_2 - s_1 = \frac{Q}{4\pi T} \ln \frac{t_2}{t_1}$$
$$(5.0 - 3.1) = \frac{0.02}{4 \times \pi \times T} \ln \frac{1000}{100}$$
$$T = \frac{0.02}{4\pi \times 1.9} \ln 10 = 1.929 \times 10^{-3} \text{ m}^3/\text{s}/\text{m} = 1.67 \times 10^5 \text{ lpd}/\text{m}$$

From equation (E)

$$S = \frac{2.25 T t_0}{r^2} = \frac{2.25 \times 1.929 \times 10^{-3} \times 150}{(30)^2}$$
$$S = 7.23 \times 10^{-4}$$

Unsteady Flow in a Confined Aquifer

Example: A well is located in a 25-m confined aquifer of hydraulic conductivity 30 m/day and storativity coefficient 0.005. If the well is being pumped at the rate of 1500 m³/day, calculate the drawdown at a distance of 100 m from the well after 20 h of pumping.

Solution:

$$T = KB = (30/86400) * 25 = 8.68 * 10^{-3}$$

$$u = \frac{r^2 S}{4Tt} = \frac{100^2 * 0.005}{4 * 8.68 * 10^{-3} * 20 * 3600} = 0.08$$

Using This method and calculating $W(u)$ to four significant digits,

$$W(u) = -0.5772 - \ln(0.02) + (0.02) - \frac{(0.02)^2}{2 * 2!} + \frac{(0.02)^3}{3 * 3!} = 3.3547$$

$$s = \frac{Q}{4\pi T} W(u) = \frac{1500 * 3.3547}{4 * \pi * 8.68 * 10^{-3} * 24 * 3600} = 0.32 \text{ m}$$

Aquifer Test Application

- An aquifer test (or a pumping test) is performed to evaluate an aquifer by observing the aquifer's drawdown in observation wells.
- One or more monitoring wells or piezometers are used for aquifer testing as the observation/monitoring wells. Water is not being pumped from the observation well just utilized to monitor the water drawdown.
- While water is being pumped from one well at a steady rate, the water tables are monitored in the observation wells.
- Typically, monitoring and pumping wells are screened across the same aquifers.
- Aquifer testing is based on the data processing to yield valuable qualitative and quantitative features about the subsurface geological composition of the aquifer domain.

Aquifer Test Application

- The test data processing is achieved by matching the data with a suitable type curve.
- An analytical or numerical model of aquifer flow is used to match the data observed in the real world, assuming that the parameters from the idealized model apply to the real-world aquifer.

Most aquifer tests evaluate the aquifer characteristics including:

- Hydraulic conductivity or transmissivity, which shows how permeable the aquifer is and the ability of an aquifer to transmit water.
- Specific storage/specific yield or storativity, which is the measure of the amount of water an aquifer will give up for a certain change in head.
- Boundary determination, which determines the type of boundaries that give up water to the aquifer, providing additional water to reduce drawdown or no-flow boundaries.

Aquifer Test Application

- Three major components for the aquifer tests to the ultimate objectives of quantifying
 - the hydraulic properties,
 - boundary determination,
 - indication of the general type of aquifer, and
 - hypothesis testing include design, field observations, and data analysis.
- In aquifer tests, in addition to knowing the geology of the site and construction of the wells (width, depth, materials used, development), measuring devices such as
 - time,
 - discharge, and
 - water level should be calibrated and verified.

Aquifer Test Application

- Then the observed data during the test are plotted and the best curve is fitted on data.
- Finally, the aquifer characteristics are determined based on the fitted curve.
- Graphical or computer estimation of parameter values using observed drawdown and well-produced rate records can be utilized as the method of analysis of aquifer test data.
- For confined aquifers, there are two graphical methods including the loglog plot of drawdown versus time for the Theis method and the semilog plot for the Cooper–Jacob method.

Aquifer Test Application

Theis Method of Solution

The following equation was adopted by Theis and is used to determine

T and S by expressing $s = \frac{Q}{4\pi T} W(u)$ $u = \frac{r^2 S}{4Tt}$ as

$$\log s = \log \left(\frac{Q}{4\pi T} \right) + \log W(u)$$

$$\log \frac{t}{r^2} = \log \left(\frac{S}{4T} \right) + \log \frac{1}{u}$$

- Because $Q/4\pi T$ and $S/4T$ are constants, the relation between $\log(s)$ and $\log(t/r^2)$ must be similar to the relation between $\log W(u)$ and $\log 1/u$.
- Therefore, drawdown measurements derived from pumping tests are plotted on double-logarithmic paper and $W(u)$ against $1/u$ on the same double-logarithmic paper; the two plotted curves have the same shape, but they are offset by the constants $(Q/4\pi T)$ and $(S/4T)$, vertically and horizontally, respectively, with keeping the coordinate axis parallel.

Aquifer Test Application

- Therefore, if plotting each curve on a separate sheet, match them by placing one graph on top of the other and moving it horizontally and vertically until the curves are matched.
- When superimposed over the type curve, values of $W(u)$, $1/u$, t/r^2 and s may be selected at any desirable point and substituted in the Theis equation.
- This is further illustrated in Figure below.

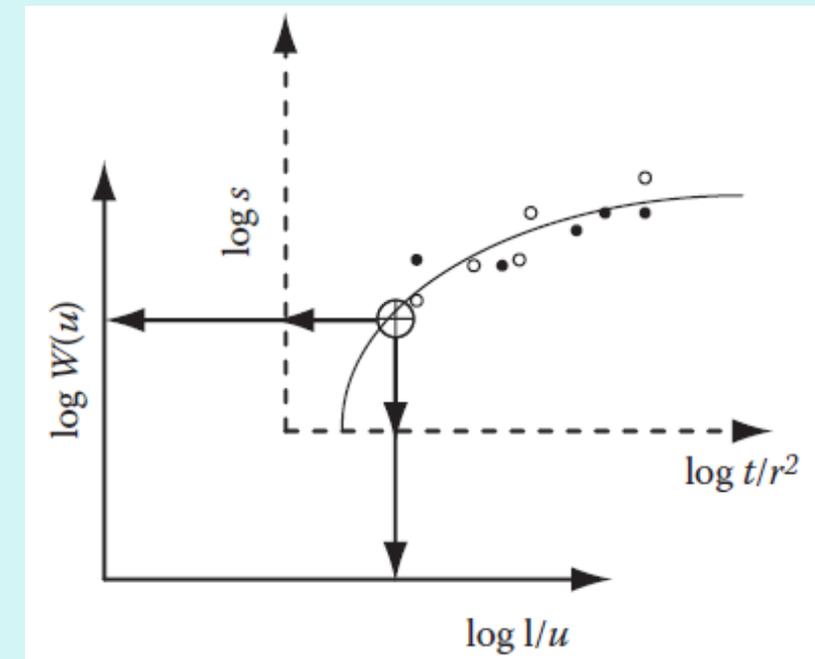
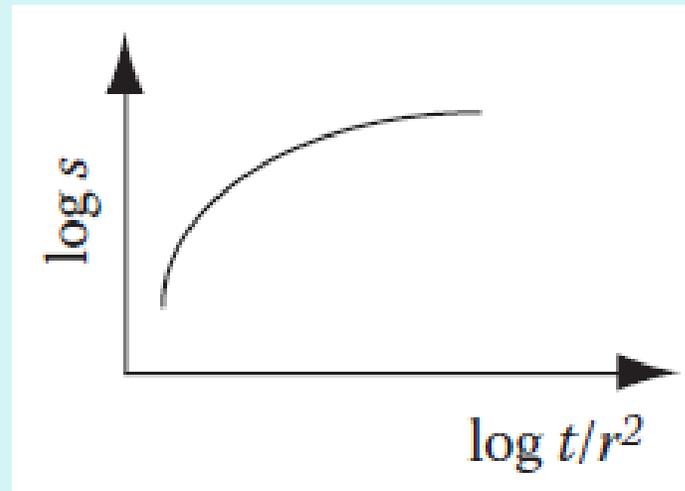
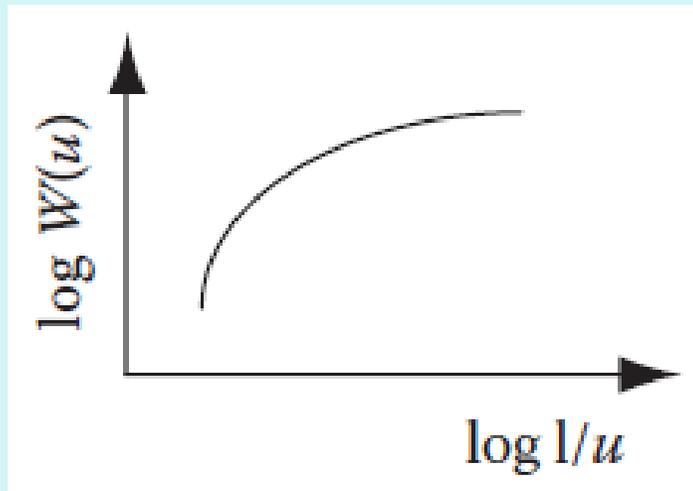


Figure: Graphical procedure to determine t and S from pump test data.

Aquifer Test Application

Example: The drawdown time data recorded at two observation wells situated at a distance of 100 and 200 m from the pumping well are given in Table (a). If the well discharge is 1000 m³/day, calculate the transmissibility and storage coefficient of the aquifer.

Solution

The first step is to calculate r^2/t from the given data. The calculated values are presented in Table (b). Then the measured drawdown versus r^2/t is plotted on log paper as shown in Figure (a). The data plotted are superimposed on the $W(u)$ versus u plot as presented in Figure b. An arbitrary match point is selected as

Table (a): The Drawdown Time Data Recorded at the Distance of 100 and 200 m

t (Day)	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10
s1 (m)	0.083	0.196	0.249	0.379	0.431	0.559	0.614	0.742	0.797
s2 (m)	0.017	0.097	0.145	0.267	0.322	0.449	0.504	0.632	0.687

Aquifer Test Application

Table (b): The Drawdown Time Data Recorded at the Distance of 100 and 200 m

t (Day)	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10
$t/r^2, d = 100\text{m}$ (m^3/day)	10^{-7}	5×10^{-7}	10^{-6}	5×10^{-6}	10^{-5}	5×10^{-5}	10^{-4}	5×10^{-5}	10^{-3}
$t/r^2, d = 200\text{m}$ (m^3/day)	0.25×10^7	0.13×10^6	0.25×10^6	0.13×10^5	0.25×10^5	0.13×10^4	0.25×10^4	0.13×10^3	0.25×10^3

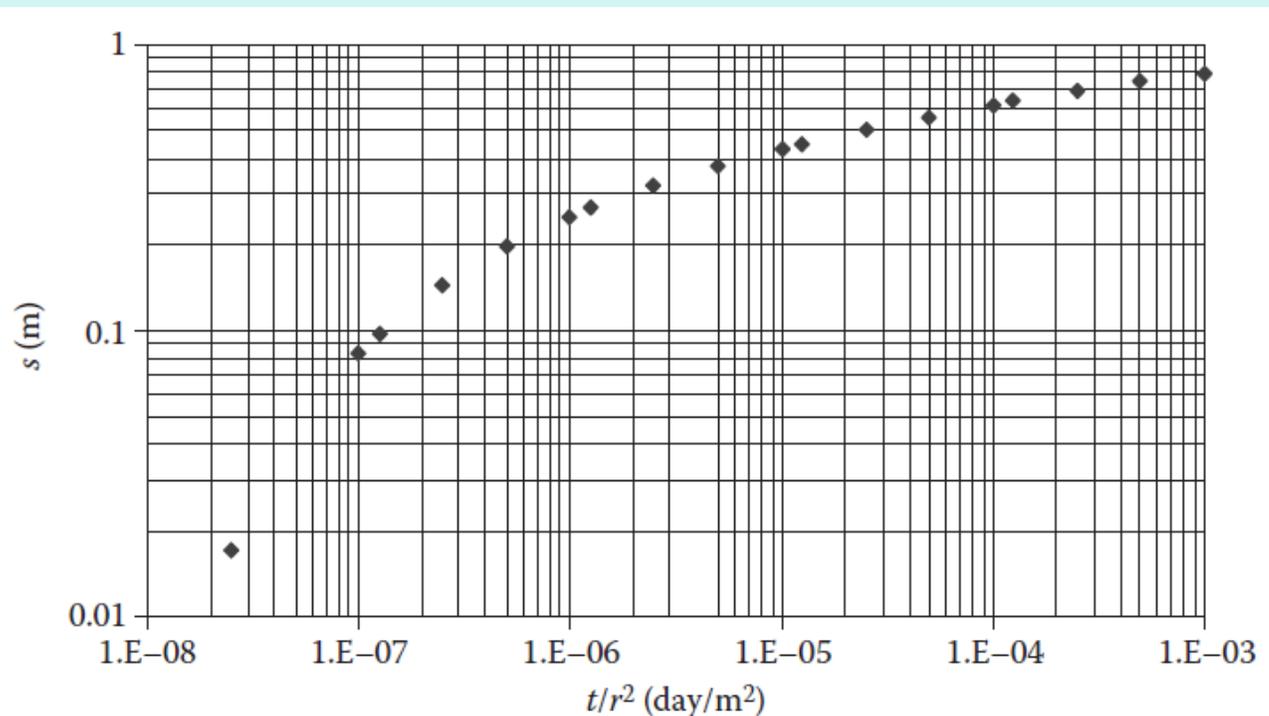


Figure a. The drawdown versus t/r^2 for Example above

Aquifer Test Application

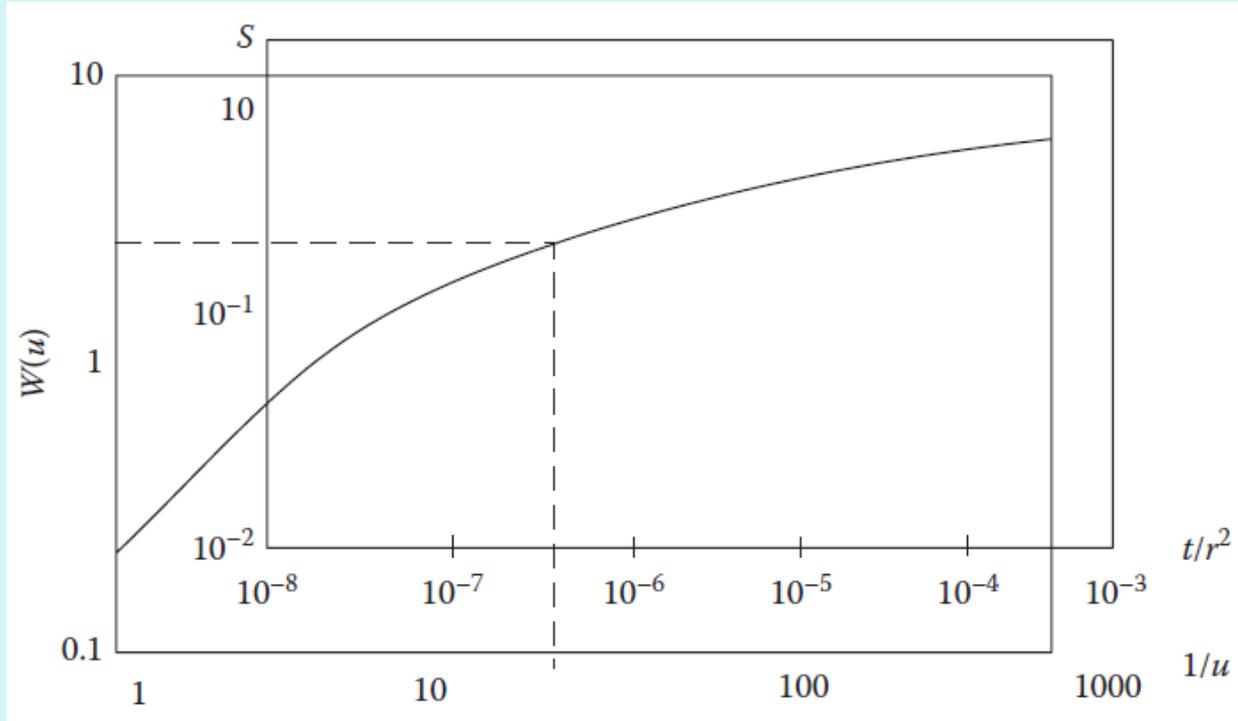


Figure b: Matching the type curve with drawdown data.

$$s = 0.167 \text{ m}, \quad \frac{t}{r^2} = 3 * 10^{-7} \frac{\text{m}^2}{\text{day}}, \quad W(u) = 2.1, \quad \frac{1}{u} = 12.5$$

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

$$T = \frac{Q}{4\pi s} * W(u) = \frac{1000}{4\pi * 0.167} * 2.1 = 1000.7 \frac{\text{m}^2}{\text{day}}$$

$$S = \frac{4 * 1000.7}{12.5 * 3 * 10^{-7}} = 0.000107 \text{ m}^2 / \text{day}$$

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

Aquifer Test Application

Cooper–Jacob Method

- Cooper and Jacob noted that for small values of r and large values of t , the parameter $u = r^2S/4T$ becomes very small and the infinite series can be approximated by
- $W(u) = -0.5772 - \ln u$
- Thus $s' = \frac{Q}{4\pi T} \left(-0.5772 - \ln \left(\frac{r^2S}{4Tt} \right) \right)$

Rearranging and conversing to decimal logs yield

$$s' = \frac{2.3Q}{4\pi T} \log \left(\frac{2.25Tt}{r^2S} \right) \quad \text{Equation (i)}$$

A plot of drawdown s via log of t forms a straight line. A projection of the line back to $s = 0$, where $t = t_o$ yields the following relation:

$$S = \left(\frac{2.25Tt_o}{r^2} \right) \text{Equation (ii)} \quad \text{and} \quad T = \left(\frac{2.3Q}{4\pi s'} \right) \text{Equation (iii)}$$

- The Cooper–Jacob method first solves for T and then for S and is only applicable for small values of $u < 0.01$.

Aquifer Test Application

Example: A well penetrating a confined aquifer is pumped at a rate of a 2500 m³/s. The drawdown at an observation well at a radial distance of 30 m is presented in Table below.

Calculate the transmissibility and storage coefficient of the aquifer.

Table: The drawdown time data recorded at the distance of 30 m.

Time (min)	0	1	1.5	2	2.5	3	4	5	6	8	10	12	14
Drawdown (m)	0	0.2	0.27	0.3	0.34	0.37	0.41	0.45	0.48	0.53	0.57	0.6	0.63
Time (min)	18	24	30	40	50	60	80	100	120	150	180	210	240
Drawdown (m)	0.67	0.72	0.76	0.81	0.85	0.9	0.93	0.96	1	1.04	1.07	1.1	1.12

Solution

The drawdown is plotted against time on a semilog plot (Figure below). From the fitted line,

Aquifer Test Application

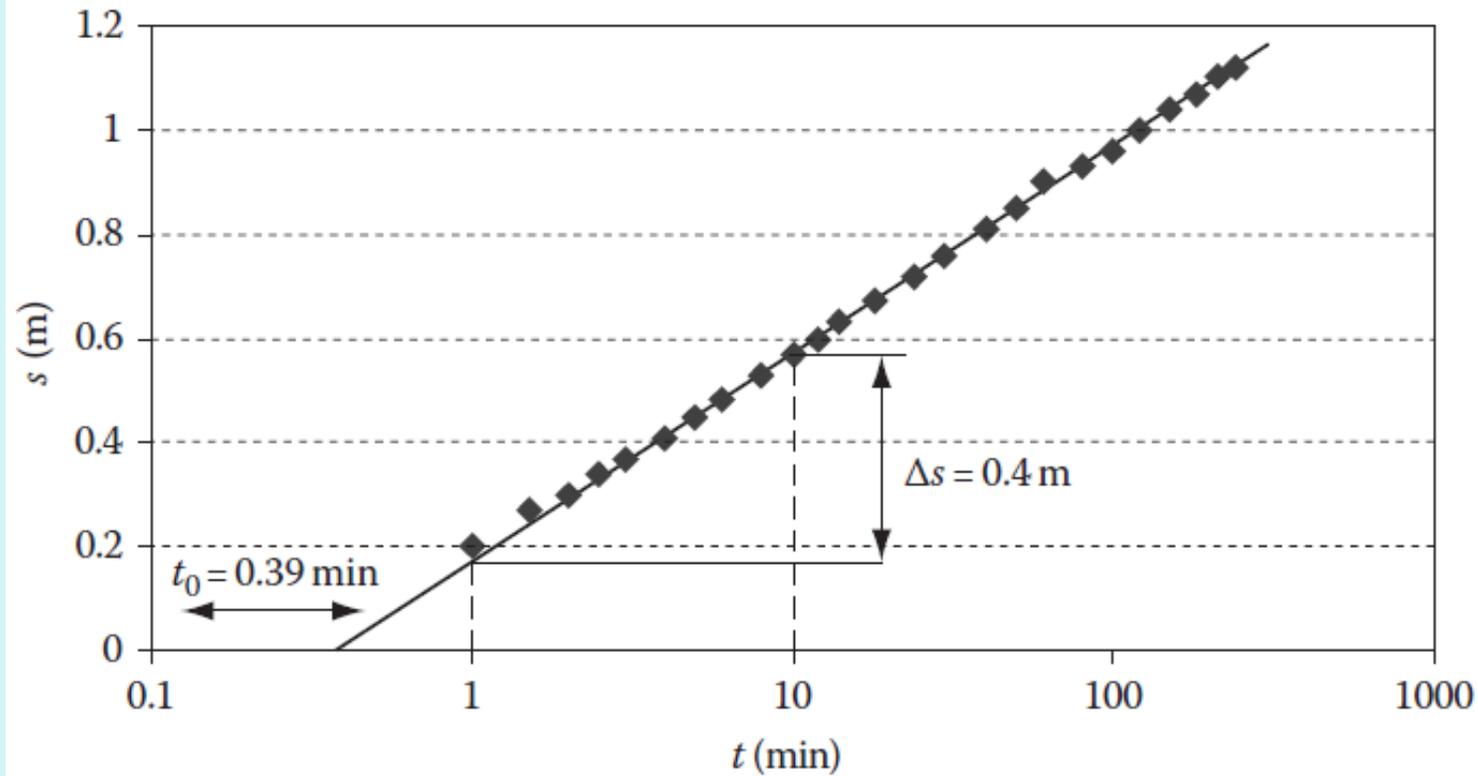


Figure: Time-drawdown plot for Example above

$$t_0 = 0.39 \text{ min} = 2.7 * 10^{-4} \text{ day}$$

$$T = \left(\frac{2.3Q}{4\pi s'} \right) = \frac{2.3 * 2500}{4 * \pi * 0.4}$$

$$= 1144.5 \frac{\text{m}^2}{\text{day}}$$

$$S = \left(\frac{2.25Tt_0}{r^2} \right)$$

$$= \frac{2.25 * 1144.5 * 2.7 * 10^{-4}}{60^2}$$

$$= 0.000193$$

Effective Conditions on Time Drawdown

- In order to apply the Theis equation, basic assumptions are made in developing the equations for groundwater flow.
- However, geologic or hydrologic conditions do not conform fully in real aquifers.
- One of these assumptions is that aquifers have an infinite areal extent and clearly it is necessary in order to solve many groundwater problems.
- It is obvious that this type of aquifer cannot exist in reality and the aquifers have some boundaries.
- A hydrologic boundary could be the edge of the aquifer, a region of the recharge to a fully confined artesian aquifer, or the source of the recharge such as a stream or lake.
- The boundary conditions can be divided into two categories: recharge ones and impermeable ones.
- Another assumption for applying the developed formula is the fully penetrated well that leads to change in the flow pattern.

Recharge Boundary

- Equilibrium conditions that stabilize the cone of depression around a pumping well may develop in several general situations.
- One of these is when an aquifer is recharged from a river or lake.
- A recharge boundary is a region in which the aquifer is replenished.

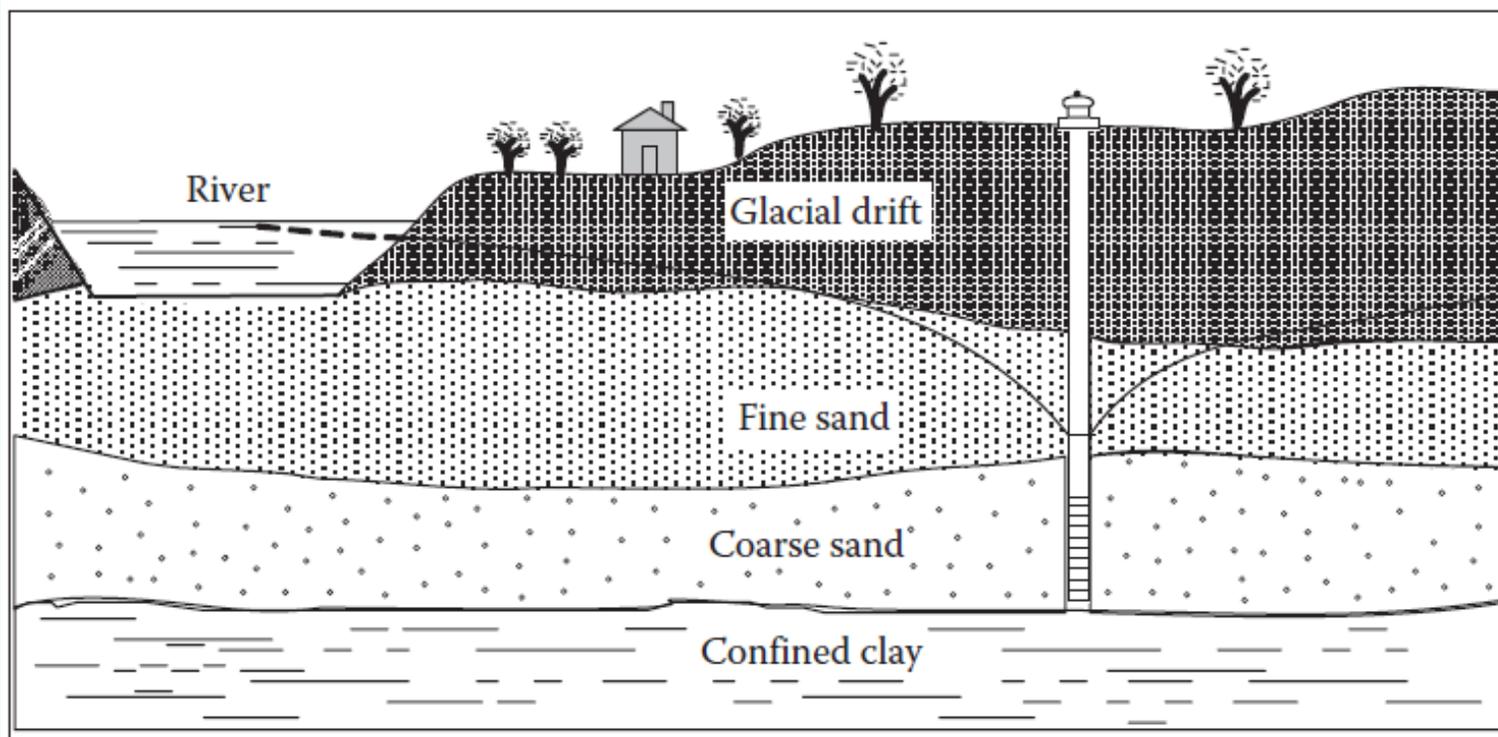


Figure: shows a recharge boundary after equilibrium has been reached

Recharge Boundary

- The drawdown data due to water pumping show that the cone of depression does not extend to the river and no recharge is evident.
- By keeping on pumping, the water table in the well decreases.
- A hydraulic gradient develops between the groundwater in the aquifer and the water in the river when the cone of depression intersects a river channel.
- If the stream bed is hydraulically connected with the aquifer, river water will percolate downward through the pervious stream bed under the influence of the hydraulic gradient.
- Thus, the river recharges the aquifer at an increasing rate as the cone of depression enlarges.
- When the rate of recharge to the aquifer equals the rate of discharge from the well, the cone of depression and the pumping level become stable.

Recharge Boundary

- In order to predict aquifer behavior in the presence of boundaries, introduce imaginary wells such that the response at the boundary is made true.
- Image well method is widely used in heat-flow theory and has been adapted for application in the groundwater milieu, in order to predict the decreased drawdowns that occur in a confined aquifer in the vicinity of a constant-head boundary, such as would be produced by the slightly unrealistic case of a fully penetrating stream (Figure 1a).
- For this case, the imaginary infinite stream (Figure 1b) is introduced in order to set up a hydraulic flow system which will be equivalent to the effects of a known physical boundary.
- The recharge boundary can be simulated by a recharging image well duplicated in an equal and opposite side from the real well (Figure 1c).

Recharge Boundary

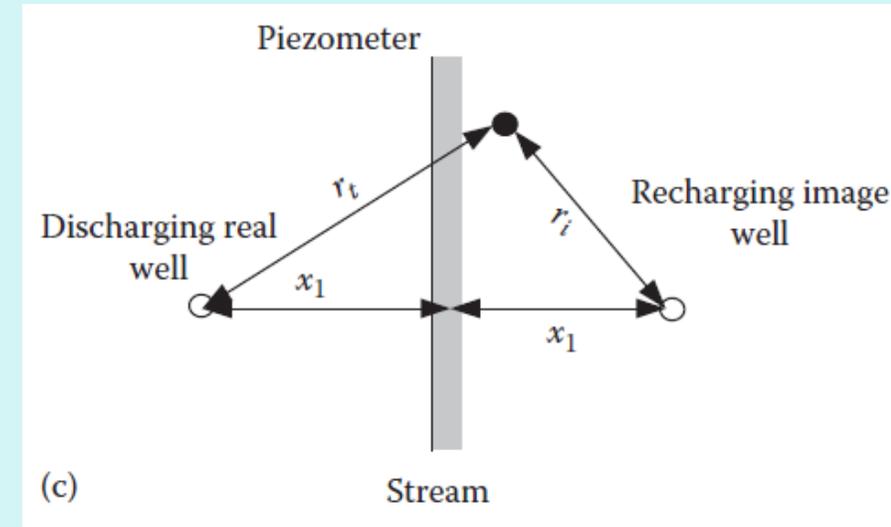
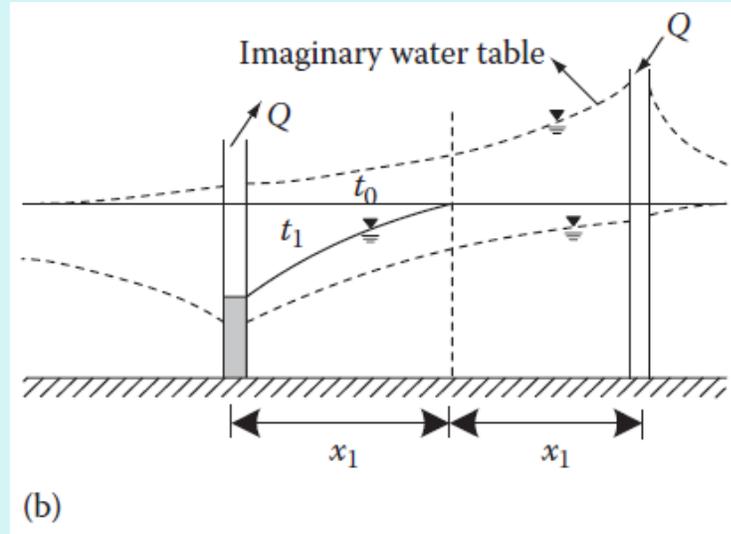
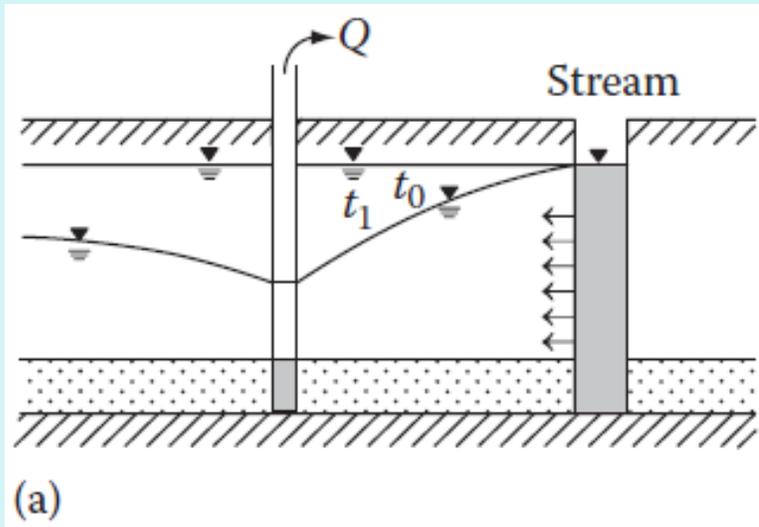


Figure 1: Drawdown in an aquifer bounded on one side by a stream.

- The summation of the cone of depression from the pumping well and the cone of impression from the recharge well leads to an expression for the drawdown in an aquifer bounded by a constant-head boundary:

$$h_0 - h = \frac{Q}{4\pi T} [W(u_r) - W(u_i)]$$

$$u_r = \frac{r_r^2 S}{4Tt} \quad \text{and} \quad u_i = \frac{r_i^2 S}{4Tt}$$

Impermeable Boundary

- In many localities, definite geologic and hydraulic boundaries limit aquifers to areas.
- An impermeable boundary is an edge of the aquifer, where it terminates by thinning or abutting a low-permeability formation or has been eroded away
- Assuming that there is no groundwater flow across this layer, it is called a zero-flux boundary.
- The effects of an impermeable boundary on the time-drawdown data is opposite to the effects of recharge boundary.
- When an aquifer is bounded on one side by a straight-line impermeable boundary, drawdowns due to pumping will be greater near the boundary (Figure 2a).
- The effect of the impermeable boundary to flow in some region of the aquifer is to accelerate the drawdown (Figure 2b).

Impermeable Boundary

- In order to simulate an impermeable boundary, a discharging image well is duplicated in an equal and opposite side from the real well (Figure 2c).
- The summation of the cone of depression from the pumping well and the cone of impression from the discharge well leads to an expression of the drawdown in an aquifer bounded by a constant-head boundary:

$$h_0 - h = \frac{Q}{4\pi T} [W(u_r) + W(u_i)]$$

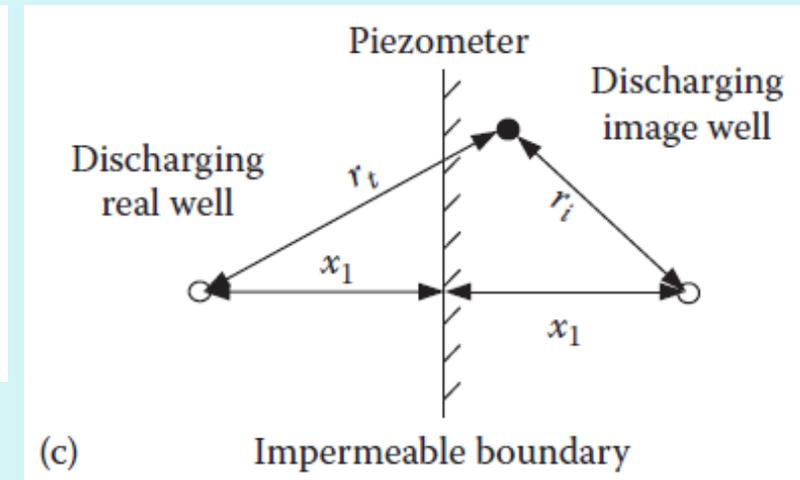
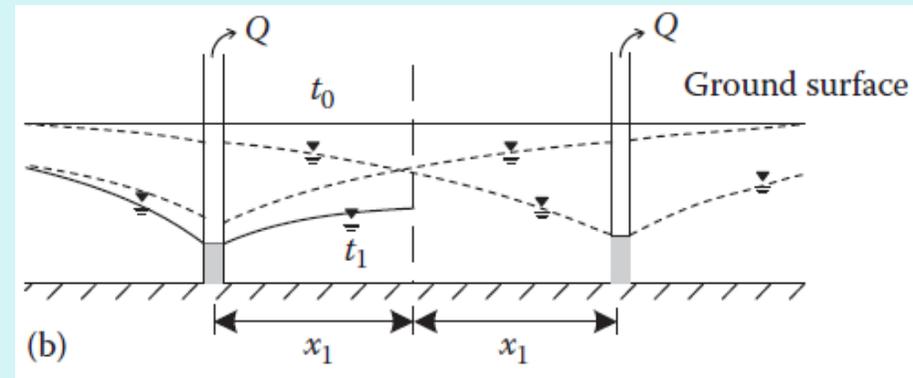
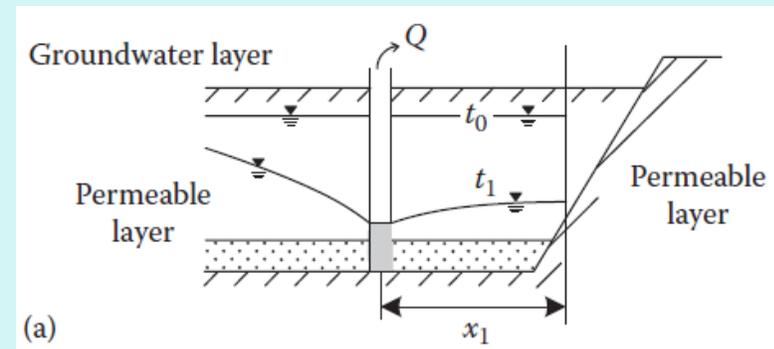


Figure 2: Drawdown in an aquifer bounded on one side by an impermeable boundary.

Partially Penetrating Wells

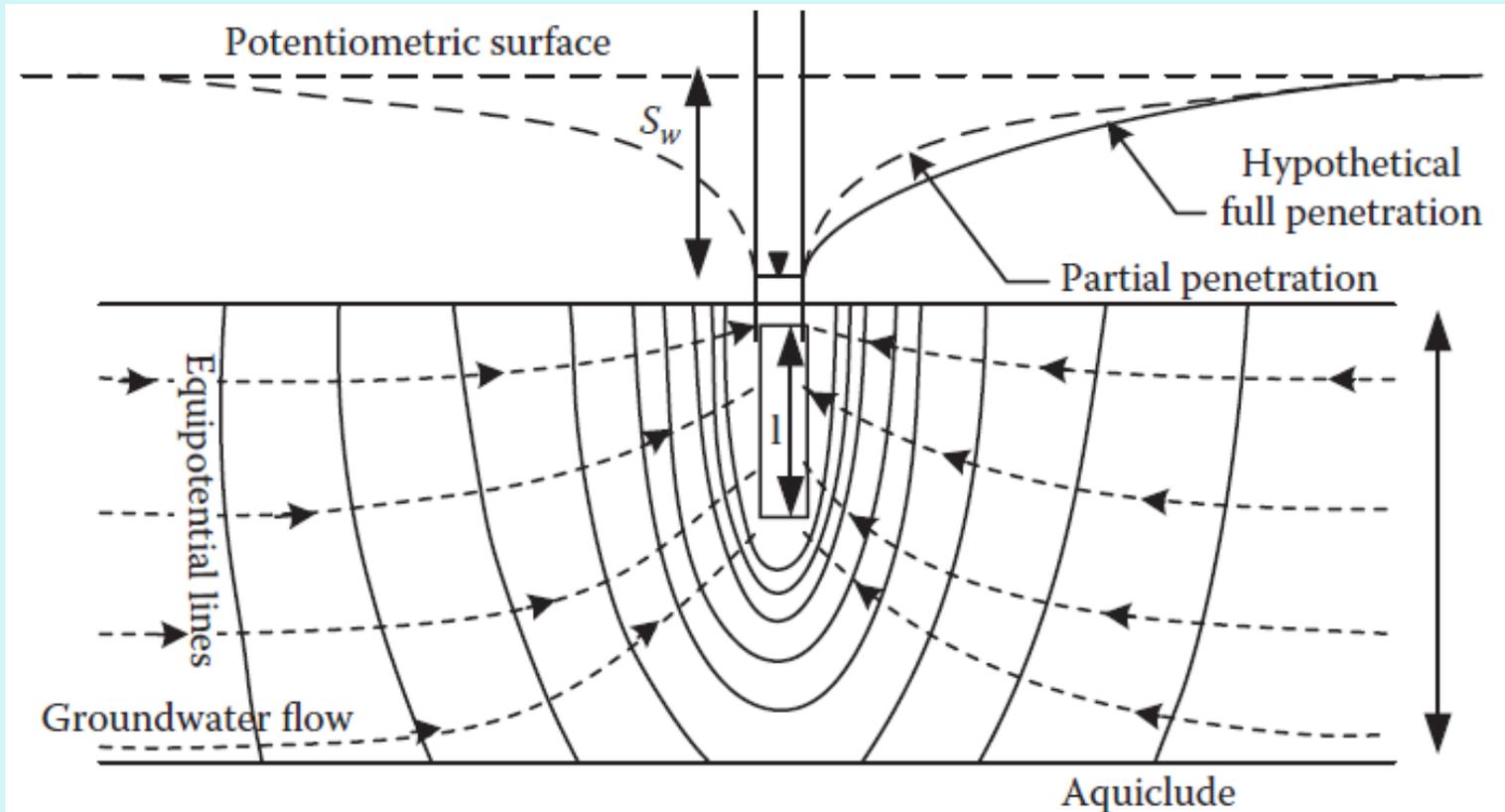
- In practice and well construction, it happens that water enters the well bore over a length which is less than the aquifer thickness.
- This is called a partially penetrating well.
- The flow pattern will differ from the radial flow which is thought to exist around wells which fully penetrate.
- Flow toward a partially penetrating well experiences convergence that is in addition to the convergence in flow toward a fully penetrating well.
- By changing the flow pattern, the presented equations can not be used to estimate the drawdowns because flow is not strictly radial.
- Partial penetration causes the flow to have a vertical component in the vicinity of the well as shown in Figure 3.

Partially Penetrating Wells

- Some typical flow lines or paths of water particles are presented by the arrows as they move through the formation toward the intake portion of the well.
- Water in the lower part of the aquifer moves upward along the curved lines to reach the well screen.
- Therefore, the path that water must take is longer than radial flow lines.
- Also, the flow must converge through a smaller cross-sectional area while approaching the short screen.
- The result of the longer flow paths and the smaller cross-sectional area is an increase in head loss.
- For a given yield, therefore, the drawdown in a pumping well is greater if the aquifer thickness is only partially screened.
- For a given drawdown, the yield from a well partially penetrating the aquifer is less than the yield from one completely penetrating the aquifer.

Partially Penetrating Wells

- It is assumed that for distances from the well that exceed about $1.5b\sqrt{Kh/Kv}$ the vertical components of flow are negligible and developed equations can be applied for the partially penetrating case, provided that $r > 1.5b\sqrt{Kh/Kv}$.
- Kh/Kv are the horizontal and vertical conductivity, respectively, in an anisotropic aquifer.



Partially Penetrating Wells

- In case $r < 1.5b\sqrt{Kh/Kv}$, the discharge per unit of drawdown is smaller than if the well is fully penetrating.
- One of the basic equations for the partially penetrating case utilizes a continuous superposition of sinks to represent the partially penetrating well to derive an approximate relationship between the discharge of a partially penetrating well and that for a fully penetrating well (Musket, 1946).

- The discharge per unit drawdown is called specific capacity and is widely used to characterize the discharge capacity of pumped wells.
where

$$\left(\frac{Q}{s_w}\right)_p = \left(\frac{Q}{s_w}\right) \left[\frac{l}{b} \left\{ 1 + 7 \left(\frac{r_w}{2l}\right)^{1/2} \cos \frac{\pi l}{2b} \right\} \right]$$

- l is the length of well bore over which water enters the well Subscript p denotes the partially penetrating case

Partially Penetrating Wells

Example: A well with an effective well radius of 0.15 m exhibits a specific capacity of 0.032 m³/s in an aquifer for which b is 35 m. The length of screened well bore is 10 m. If the length of well screen is increased to 20 m, estimate the increase in specific capacity.

Solution: By applying equation above for partially penetrating case, the specific capacity for full penetration

$$\text{is } \left(\frac{Q}{s_w}\right) = \frac{\left(\frac{Q}{s_w}\right)_p}{\left[\left(\frac{l}{b}\right)\left\{1 + 7\left(\left(\frac{r_w}{2l}\right)^{\frac{1}{2}}\right)\cos\frac{\pi l}{2b}\right\}\right]}$$
$$\left(\frac{Q}{s_w}\right) = \frac{0.032}{\left[\left(\frac{10}{35}\right)\left\{1 + 7\left(\left(\frac{0.15}{20}\right)^{\frac{1}{2}}\right)\cos\frac{10\pi}{70}\right\}\right]} = 0.072 \text{ m}^2/\text{s}$$

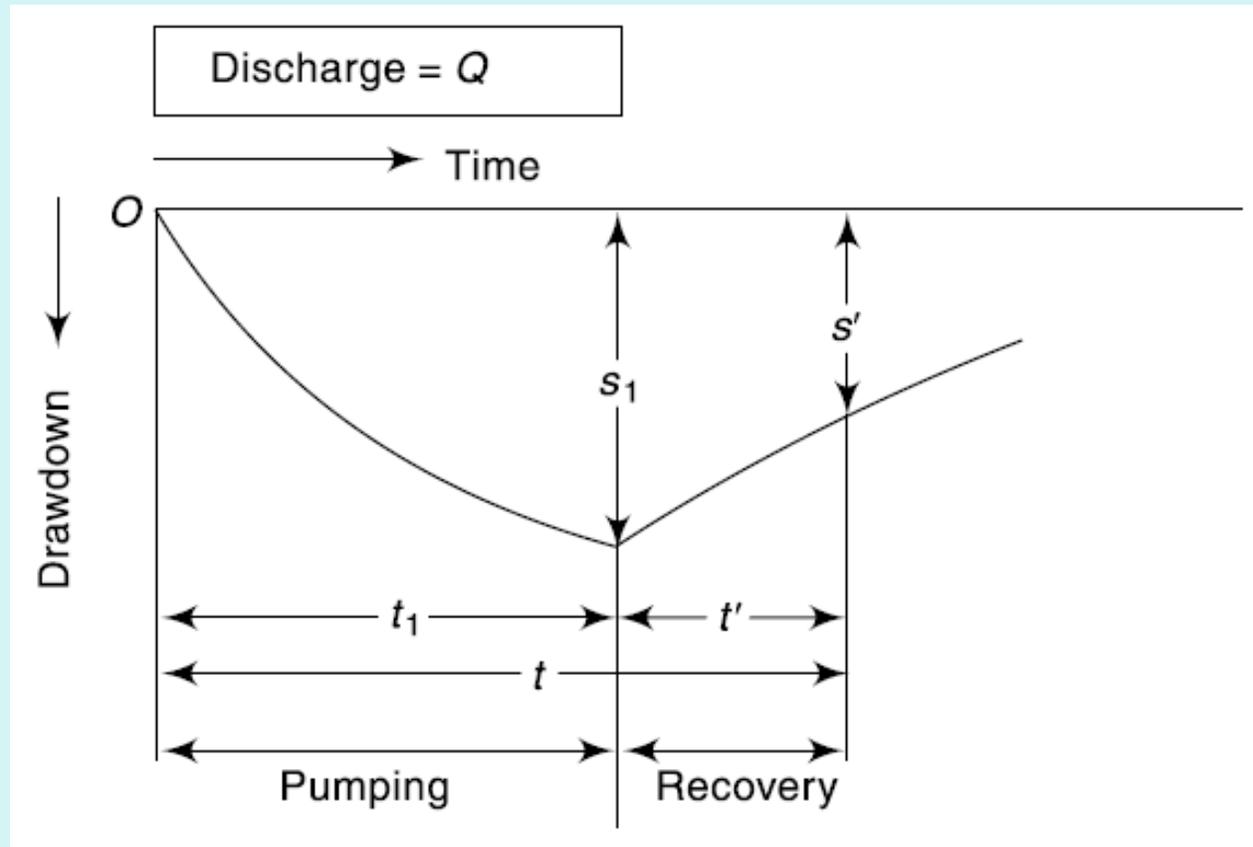
The specific capacity with $l = 20$ m is

$$\left(\frac{Q}{s_w}\right)_p = 0.072 \left[\frac{20}{35}\left(1 + 7\left(\left(\frac{0.15}{40}\right)^{\frac{1}{2}}\right)\cos\frac{20\pi}{70}\right)\right] = 0.052 \frac{\text{m}^2}{\text{s}}$$

Increasing the length of the well screen to 20 m will change the specific capacity from 0.032 to 0.052 m²/s, an increase of 63%.

Recovery of Piezometric Head

- Consider a well pumped at constant rate of Q .
- Let s_1 be the drawdown at an observation well near the well in time t_1 .
- If the pumping is stopped at the instant when the time is t_1 , the groundwater flow into the cone of depression will continue at the same rate Q .
- Since there is not withdrawn now, the water level in the observation well will begin to rise and the drawdown will begin to decrease.



Recovery of Piezometric Head

- This is known as the recovery of the cone of depression.
- The variation of the water level with time during pumping and in the recovery phase is shown in Figure.
- The drawdown at the observation well at any time t' after the cessation of the pumping is known as residual drawdown and can be calculated as:

$$s' = \frac{Q}{4\pi T} [W(u) - W(u')]$$

where $u = \frac{r^2 S}{4\pi T t}$ and $u' = \frac{r^2 S}{4\pi T t'}$

(i)

$t = t_1 + t' =$ time from start of pump and $t' =$ time since stoppage of pumping (start of recovery).

Unsteady Flow in a Confined Aquifer

For small value of r and large values of t' Equation (i) can be approximated as

$$s' = \frac{Q}{4\pi T} \cdot \ln \frac{t}{t'} = \frac{2.302}{4\pi} \cdot \frac{Q}{T} \cdot \log \frac{t}{t'} \quad (\text{ii})$$

The plot of residual drawdown s' vs (t/t') on semi-log paper represents a straight line with

its slope as

$$\left[\frac{2.302 Q}{4\pi T} \right]$$

Recovery Test

The relationship of the residual recovery given by Equation (ii) is used as a method of assessing the transmissivity T of the aquifer.

The procedure is known as *Recovery test*.

In this test, the pump is run at constant discharge rate for a sufficiently long time t_1 , and then stopped.

The value of t_1 depends on the type of aquifer and aquifer characteristics and may range from 12 to 24 hours.

The recovery of the water level s' in an observation well situated at a distance r from the production well is noted down at various times (t').

Recovery Test

In view of the logarithmic nature of the variation of residual drawdown with the time ratio (t/t'), the time intervals between successive readings could progressively increase.

When observational wells are not available, the recovery water levels can be observed in the production well itself and this is a positive advantage of this test.

The value of *transmissivity* T is calculated from plot of s' against (t/t') on semi-log axis.

It is to be noted that the recovery test data does not enable the determination of the storage coefficient S .

Recovery Test

Example: *Recovery test on a well in a confined aquifer yielded the following data: Pumping was at a uniform rate of 1200 m³/day and was stopped after 210 minutes of pumping.*

Recovery data was as shown below:

Time since stoppage of pump (min)	2	5	10	20	40	90	150	210
Residual drawdown (m)	0.70	0.55	0.45	0.30	0.25	0.19	0.15	0.10

Solution: Here since $t_1 = 210$ min, $t = t_1 + t' = 210 + t'$

The time ratio t/t' is calculated (as shown in the table below) and a semi-log plot of s' vs t/t'

is plotted (Figure)

t'	2	5	10	20	40	90	150	210
t	212	215	220	240	250	300	360	420
t/t'	106	43	22	11.5	6.25	3.33	2.40	2.0
s'	0.70	0.55	0.45	0.30	0.25	0.19	0.15	0.10

Recovery Test

A best fitting straight line through the plotted points is given by the equation

$$s' = 0.1461 \ln(t/t') - 0.0027$$

By equation (ii), slope of best fit

$$\text{slope} = 0.1461 = \frac{Q}{4\pi T}$$

$$T = \frac{1200}{0.1461 * 4 * \pi} = 654 \text{ m}^2 /$$

day

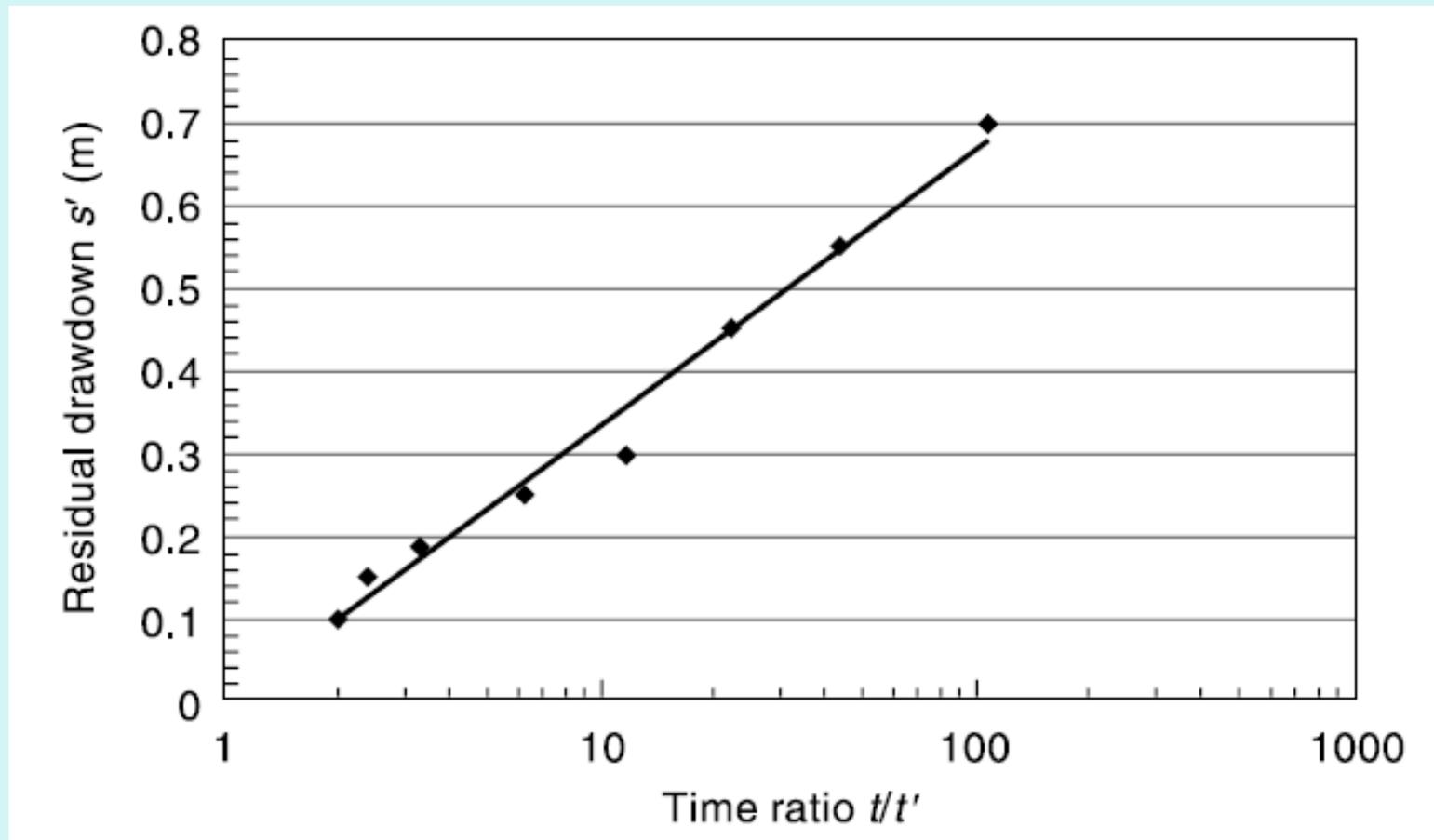


Figure. Plot of residual drawdown against time ratio (t/t')

Well Loss

In a pumping artesian well, the total drawdown at the well s_w , can be considered to be made up of three parts:

1. Head drop required to cause to cause laminar porous media flow, calculated formation loss, s_{wL} .
1. Drop of piezometric head required to sustain turbulent flow in the region nearest to the well where the Reynolds number may be larger than unity, s_{wt}' and
2. Head loss through the well screen and casing, s_{wc}

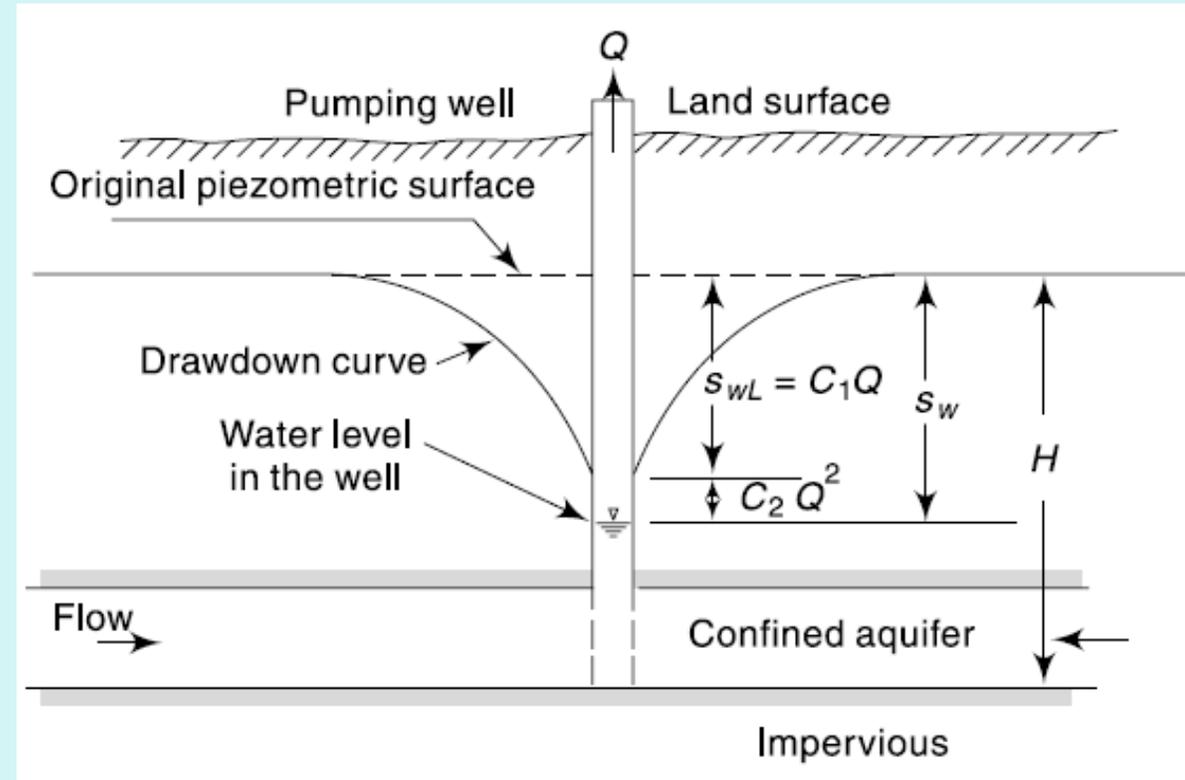


Figure. Definition sketch for well loss

Well Loss

Of these three, $s_{wL} \propto Q$ and $(s_{wt} \text{ and } s_{wc}) \propto Q^2$

Thus $s_w = C_1 Q + C_2 Q^2$

Where C_1 and C_2 are constants for the given well.

- While the first term $C_1 Q$ is the formation loss the second term $C_2 Q^2$ is termed well loss.
- The magnitude of a well loss has an important bearing on the pump efficiency.
- Abnormally high value of well loss indicates clogging of well screen, etc, and requires immediate remedial action. The coefficients C_1 and C_2 are determined by pump test data of drawdown for various discharges.

Specific Capacity

- The discharge per unit drawdown at the well (Q/s_w) is known as specific capacity of a well and is a measure of the performance of the well.
- For a well in a confined aquifer under equilibrium conditions and neglecting well losses, by Equation (9.48).

$$\frac{Q}{s_w} = \frac{2\pi}{\ln R/r_w} T \quad \text{i.e.} \quad Q/s_w \propto T$$

- However, for common case of a well discharging at a constant rate Q under unsteady drawdown conditions, the specific capacity is given by

$$\frac{Q}{s_w} = \frac{1}{\frac{1}{4\pi T} \ln \frac{2.25 T t}{r_w^2 \cdot S} + C_2 Q} \quad (9.62)$$

Recharge

- Where t = time after the start of pumping. The term C_2Q is to account for well loss. It can be seen that the specific capacity depends upon T, s, t, r_w and Q . Further, for a given well it is not a constant but decreases with increases in Q and t .

Recharge:

- Addition of surface water to zone of saturation is known as *recharge*. Recharge taking place naturally as a part of hydrologic cycle is called *natural recharge* while the process of increasing infiltration of surface water to groundwater systems by altering natural conditions is known as *artificial recharge*.

Natural Recharge:

The amount of precipitation that infiltrates into the soil and reaches the zone of saturation is an important component of natural recharge. Seepage from irrigated lands is another important component of recharge of groundwater. In this process the infiltration phase is natural while the supply of water to the irrigated lands is through artificial means and as such it is sometimes called as *incidental recharge*. Other means of natural recharge are seepage from reservoirs; rivers, streams and canals; and other water bodies. Estimation of recharge rates of aquifers is an important component of groundwater resource estimation and in proper utilization of groundwater.

Recharge

Artificial Recharge:

The process of artificially enhancing the amount of water recharging the aquifer in a given location is known as artificial recharge. In the face of present-day large demands for groundwater artificial recharge is restored to

- ✓ Conserve runoff
- ✓ Improve quantity of available groundwater
- ✓ Reduce or correct saltwater intrusion

Various recharging methods commonly adopted are

- ✓ Spreading (flooding, Basin, Ditch, Pit & Channel)
- ✓ Through injection wells
- ✓ Induced recharge from surface water bodies

Estimation of Recharge

GEC-97 committee recommends two approaches to assessment of recharge to groundwater. These are (i) Groundwater level fluctuation method, and (ii) Rainfall infiltration factor method.

1. Groundwater level fluctuation and specific yield method

In this method the groundwater level fluctuations over a period (usually a rainy season) is used along with the specific yield to calculate the increase in storage in the water balance equation.

Thus for a given area of extent A (usually a watershed), for a water level fluctuation of h during a rainy season,

Estimation of Recharge

$$h S_y A = R_G - D_G - B + I_s + I \quad (9.63)$$

where

S_y = specific yield

R_G = gross recharge due to rainfall and other sources

D_G = gross water draft

B = base flow into the stream from the area

I_s = recharge from the stream into the ground water body

I = net ground water flow into the area across the boundary (i.e. inflow – outflow)

Writing $R = R_G - B + I + I_s$

$$\text{Eq. 9.63 would be } R = h S_y A - D_G \quad (9.64)$$

where R = possible recharge, which is gross recharge minus the natural recharge of the area, and would consist of other recharge factors as

Estimation of Recharge

Computations, using Eq. (9.63) through (9.65) are usually based on the rainfall season rainfall and corresponding groundwater fluctuation covering a span of 30 to 50 years to obtain normal recharge due to rainfall.

The recharge in non-rainy months is taken as zero if rainfall in dry months is less than 10% of normal annual rainfall.

The computation for calculating the total annual recharge is carried out for both rainy and non-rainy months and the total annual recharge is obtained as a sum of these two.

Estimation of Recharge

Rainfall Infiltration Method:

- In areas where ground water level monitoring is not adequate in space and time, rainfall infiltration method may be used.
- The recharge from rainfall in rainy season is taken as a percentage of normal rainfall in the area.
- Thus $R_{rf} = f A P_{nm}$

Where R_{rf} = recharge from rainfall in rainy season.

f = rainfall infiltration factor

P_{nm} = normal rainfall in rainy season

A = area of computation for recharge

Design of Wells

- A well is an intake structure dug in the ground to remove water from groundwater resources.
- Exploitation wells are drilled for the supply of municipal, industrial, and irrigation water demands, and for water table control for drainage purposes.
- The wells can be made as open, dug wells, or tube wells; tapping an unconfined aquifer;
- or penetrating the ground to tap a confined aquifer.
- The design of tube wells, a typical installation, is given in Figure.

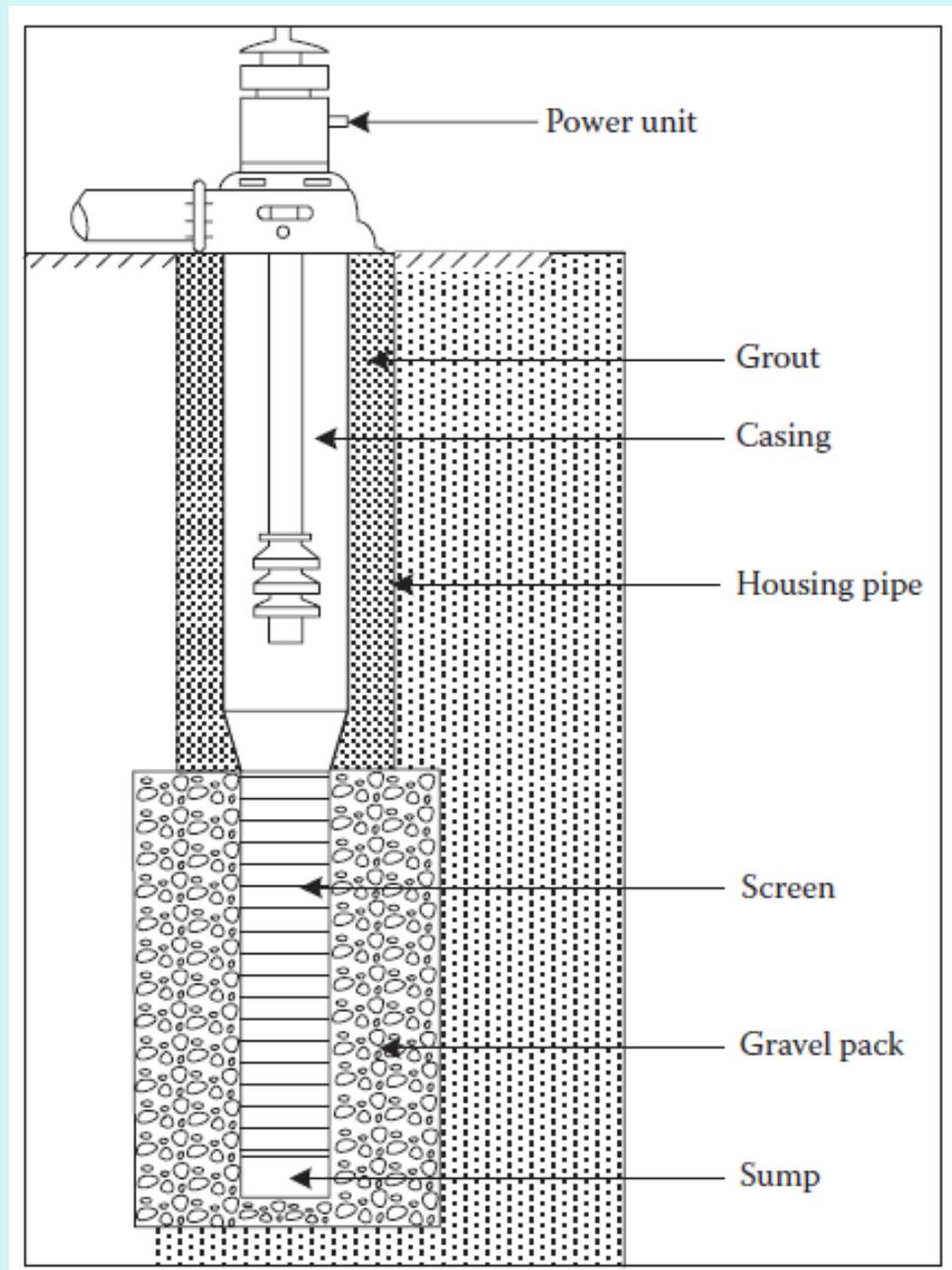


Figure: Typical installation of tube wells.

Design of Wells

- The design of a well is the process of selecting appropriate dimensions of various components and determining the physical materials for a well construction.
- Dimensional factors, strength requirements, and construction/maintenance cost play an important role in establishing the design parameters.
- A good design of a well minimizes economic costs including capital and maintenance costs and the possibility of collapse of service in large water-supply developments and also increases the life of the well.
- A well is composed of two main elements, which include the casing and the screen.
- Casing is used to maintain an open access in the earth and to avoid any entrance or leakage into the well.

Design of Wells

- Housing for the pumping equipment and as a vertical conduit for water flowing upward from the aquifer to the pump intake is accommodated in the casing.
- The pump housing is the upper section of blind casing which supports the well against collapse.
- The pump housing diameter should be such that the pump accommodates with enough clearance for installation.
- It is recommended that the casing diameter be two pipe sizes larger than the nominal diameter of the pump.
- The length of the pump housing should be tall enough so that the pump remain below the water level in the well during the lifetime of the well.

Design of Wells

- Thus, the maximum expected drawdown determines the length of the pump casing for the water-supply well and the water table should be used instead for drainage purposes.
- The casing material is chosen based on water quality, well depth, diameter, drilling procedure, construction cost, and well regulations.
- The most popular materials used for casing are black steel, galvanized steel, PVC pipe, and concrete pipe.
- The space around the outside of the well is filled by grout to prevent the intrusion of contaminants.
- A mix of cement, bentonite, or concrete can be used as grout.
- The intake portion of wells is generally screened to prevent sand and fine material from entering the well during pumping and to minimize the head loss and entrance velocity.

Design of Wells

- The screen keeps sand and gravel out of the well while allowing groundwater and water from formations to enter into the well.
- The wall of the well is supported from the loose formation material and the aquifer materials in many consolidated formations, especially sandstone and limestone, are established, and chemical and physical corrosion by the pumped water is resisted.
- The optimum length of the well screen is based on the thickness of the aquifer and the total cost for water discharge or drainage.
- The total cost includes capital cost and pumping cost. In thick aquifers, while a fully penetrating well has high construction cost, it reduces the pumping cost since it reduces head loss.

Design of Wells

- For confined aquifers, about 80%–90% of the depth at the center of the aquifer is advised to be screened.
- For unconfined aquifers, it is recommended to provide screen in the lower one-third thickness.
- The screen length can be chosen to keep the actual screen entrance velocity in the allowable ranges.
- The minimum length of the well screen can be calculated using the relationship between different screen parameters (AWWA, 1998):

Design of Wells

$$l_{min} = \frac{Q}{86400 A_e V_e}$$

where

l_{min} is the minimum screen length (m)

Q is the discharge of the well (m³/day)

A_e is the effective open area per meter screen length (m²/m)

V_e is the screen entrance velocity (m/s)

- The entrance velocity near the well screen does not exceed 0.03 m/s (Walton, 1962).
- The size of screen slot openings depends on the grain-size-distribution curve for the aquifer materials.

Design of Wells

- The size is selected to limit the moving of the finer formation materials near the borehole into the screen and pumped from the well during development.
- The typical approach to determine the slot openings size for nonhomogeneous sediments is to select a slot through which 60% of the material will pass and 40% will be retained.
- With corrosive water, the 50%-retained size should be chosen, because even a small enlargement of the slot openings due to corrosion could cause sand to be pumped (Driscoll, 1986).

Design of Wells

- The screen materials' strength should withstand the physical forces acting upon them during and following their installation, and during their use,
 - ✓ including forces due to suspension in the borehole, grouting, development, purging, pumping, and sampling, and
 - ✓ forces exerted on them by the surrounding geologic materials.
- Screens are available in many materials, the most popular being stainless steel and slotted PVC pipe.
- They should be resistant to incrustation and corrosion and should maintain their structural integrity and durability in the environment in which they are used over their operating life.

Design of Wells

- Also the quality of groundwater, diameter, and depth of the well and type of strata encountered are important factors in selecting screen material.
- In order to minimize the passage of formation materials into the well and to stabilize the well assembly, the annular space between the borehole wall and the screen or slotted casing should be filled.
- To make the zones around the well screen more permeable, some formation materials around the well are removed and replaced with graded material.
- A filter pack is selected to retain about 90% of the gravel pack after development.
- A filter pack is appropriate when the natural formation is a uniform fine sand, silt, or clay.

Construction of wells

- Well construction usually includes drilling, installing the casing, placing a well screen and filter pack, grouting, and developing the well.
- There are various well drilling and installation methods depending on the size of the tube well, depth and formation to be drilled, and available facility and technical proficiency.
- The cable-tool and rotary drilling methods are the most common methods for drilling deep wells.

Cable-Tool Drilling

- Cable tool drilling machines or percussion rigs operate by repeatedly lifting and dropping a heavy string of drilling tools into the borehole (Delluer, 1999).
- The consolidated rock is crushed into small fragments by impacts of the drill bit on the lower end with a relatively sharp tool.
- The cutting tool for breaking the rock is suspended from a cable and by up-and-down movement of the sharp tool, the drilling is accomplished.
- During the drilling, water is injected to the well and the slurry is made after mixing with crushed or loosened particles. Its use increases as drilling proceeds.
- Slurry is removed from the borehole by a sand pump when the penetration rate decreases.

Cable-Tool Drilling

- A rig consists of a mast, lines of hoist for operating the drilling tool, and a sand pump as shown in Figure 4.28.
- A full string of drilling tool as shown in the figure consists of drill bit, drill stem, drilling jars, and rope socket.
- The drill stem is a long steel bar that adds weight and length to the drill so it will cut rapidly, and vertically fixed above the bit it provides additional tools in order to maintain a straight line.
- The drilling jars consist of a pair of linked steel bars and can be moved in vertical direction relative to each other. Its purpose is only to loosen the tools should they stick in the hole. The rope socket connects the string of tools to the cable (Todd and Mays, 2008).

Rotary Drilling Method

- In this method, a rotating bit drills the hole and circulation of a drilling fluid removes the crushed or loosened particles.
- Drilling mud, which consists of a suspension of water, bentonite, clay, and various organic additives, is entered into the hollow to loosen and to lubricate the rotating bit hole.
- Then the mud is removed from the hole.
- In this method, the walls of the well are sealed and the holes of the walls are filled.
- The method operates continuously with a hollow rotating bit through which a mixture of clay and water, or drilling mud, is forced.

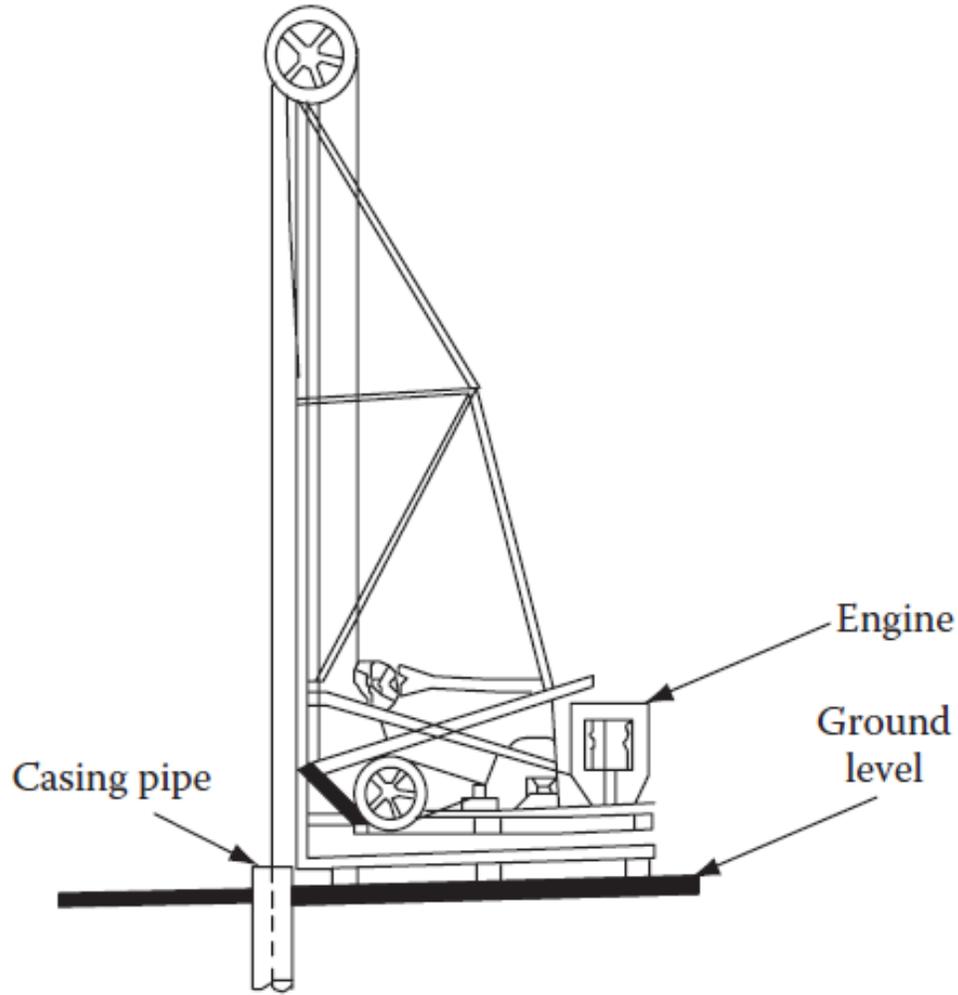
Rotary Drilling Method

- Material loosened by the bit is carried upward in the hole by the rising mud.
- No casing is ordinarily required during drilling because the mud forms a clay lining, or mud cake, on the wall of the well by filtration.
- This seals the walls, thereby preventing caving, entry of groundwater, and loss of drilling mud.
- For the rotary method of drilling without casing, screens are lowered into place as drilling mud is diluted and again are sealed by a lead packer to an upper permanent casing.
- Direct rotary and reverse rotary methods are two primary types of rotary drilling methods.

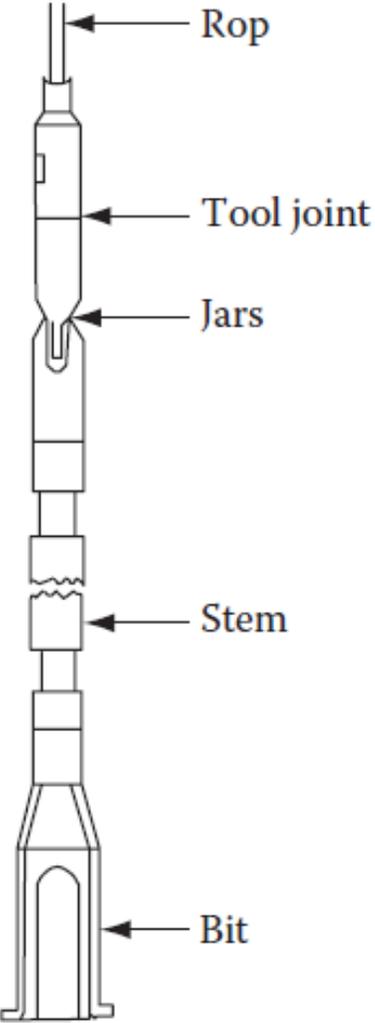
Rotary Drilling Method

- Direct rotary and reverse rotary methods are two primary types of rotary drilling methods.
- In the direct rotary method, the drilling mud is picked up from the annular space between the hole and drill pipe to ground surface by the pump.
- The fluid is cleaned in a settling pit and then a storage pit from where it is pumped back into the hole and it is recirculated.
- The schematic of the direct rotary is shown in Figure 4.29.
- The major difference between the two methods as shown in this figure is in the direction of the flowing fluid.

Rotary Drilling Method



(a) Drill machine



(b) Drill machine

FIGURE 4.28 Cable-tool percussion drilling.

Well Development

- During well construction, unconsolidated aquifer materials and packed artificial gravel are placed around the well screens and the permeability around the borehole is reduced.
- Well development is used to increase well-specific capacity, prevent sanding, and maximize economical well life.
- Well development also removes smaller grains initially present in the formation immediately surrounding the well screen to create a more permeable and stable zone adjacent to the well screen.
- The development procedures are varied and include pumping, surging, use of compressed air, hydraulic jetting, addition of chemicals, and use of explosives.
- The simplest method of removing finer material from the borehole is pumping at a higher rate than the well will be pumped during exploitation or over pumping.

Skin Effect, Aquifer Loss and Other Well Losses

- In any well the drawdown is composed of aquifer and well loss components corresponding
- to energy losses (see Figure 3.1).
- Aquifer loss appears as a result of porous medium resistance against groundwater flow, and as the pump discharge increases so does the aquifer loss.
- The well loss can be considered in two parts as linear and nonlinear losses.

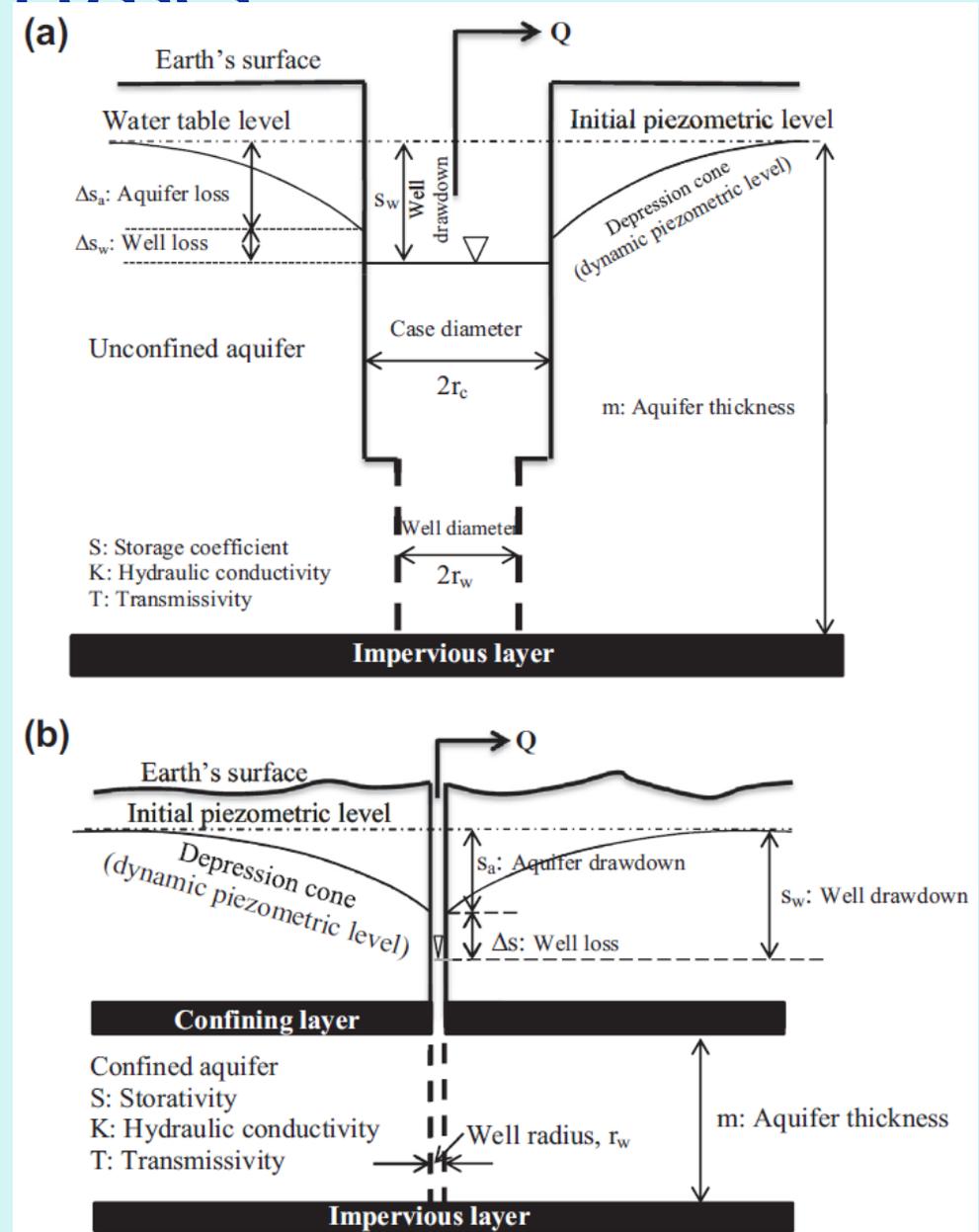


FIGURE 3.1 a) Large diameter, (b) small diameter wells.

Skin Effect, Aquifer Loss and Other Well Losses

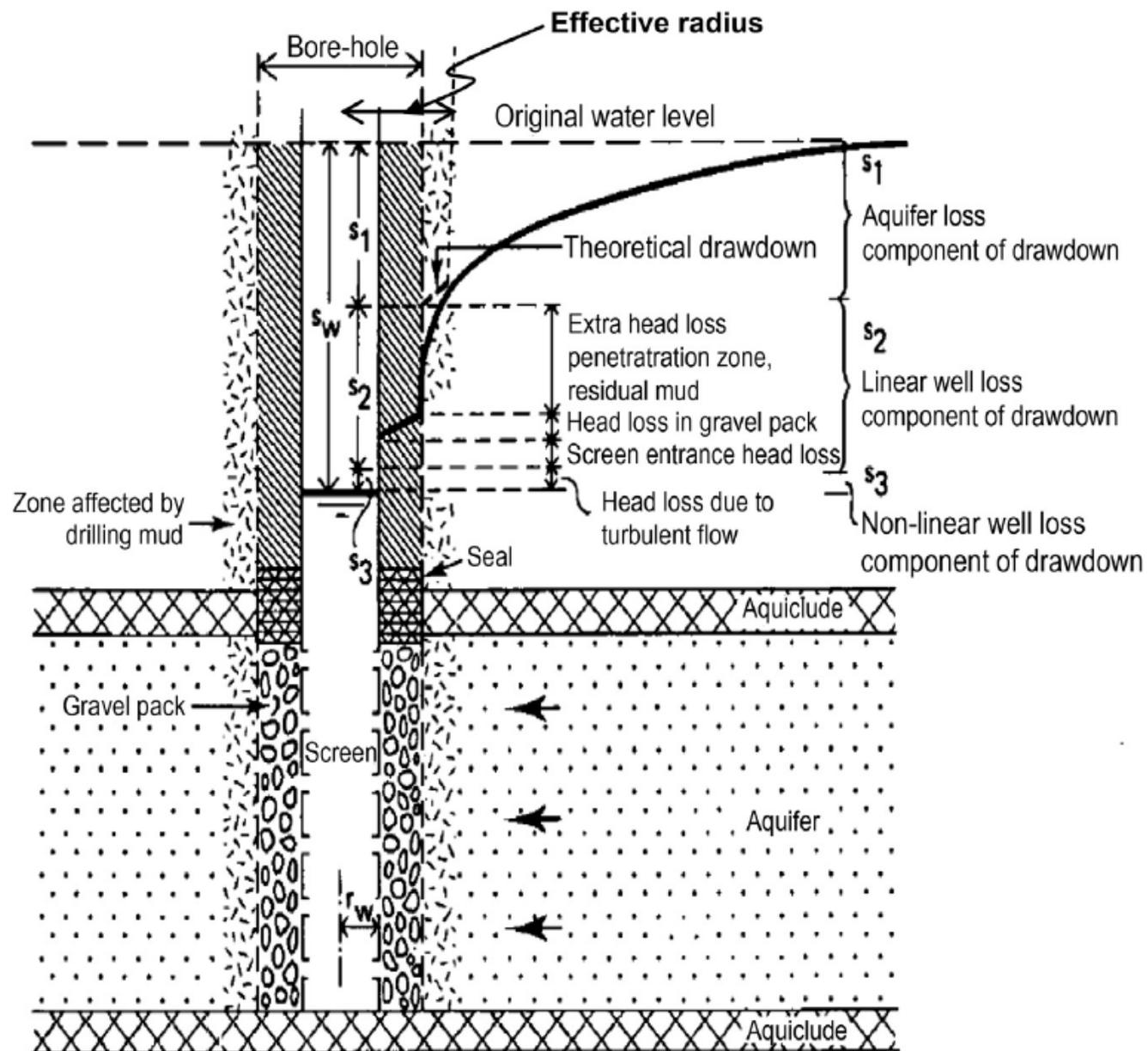


Figure: Skin effect and losses.

Skin Effect, Aquifer Loss and Other Well Losses

- The linear part consists of hydraulic head losses due to
 - ✓ compaction of the aquifer material during drilling,
 - ✓ head losses due to plugging of the aquifer with drilling mud, which reduces the permeability near the bore hole;
 - ✓ head losses in the gravel pack; and
 - ✓ head losses due to the screen resistance against water entrance into the well.
- The nonlinear well loss includes the friction losses that occur inside the well screen and in the suction pipe where the flow is turbulent and the head losses that occur in the zone adjacent to the well.
- The collective effect of these well losses appears in an additive manner within the well drawdown.

Skin Effect, Aquifer Loss and Other Well Losses

- As a result of these nonlinear losses, the drawdown, especially in the small diameter MW is always greater than the loss due to the groundwater flow in the aquifer.
- Petroleum engineers recognize the concept of “skin effect” to account for the head losses in the vicinity of a well.
- The theory behind this concept is that the aquifer is assumed to be homogeneous up to the wall of the bore hole, while all head losses are assumed to be concentrated in a thin, resistant “skin” against the wall of the bore hole.
- Gravel pack is necessary for aquifer stabilization in the vicinity of wells against fine sand and silt entrance.
- For this purpose, a gravel belt is constructed artificially between the screen and aquifer.
- The gravel pack should have larger particles than the surrounding formation.

Skin Effect, Aquifer Loss and Other Well Losses

- This supports the development of larger void formation closer to the screen, which allows water entrance almost free of head loss.
- The gravel pack supports the following points:
 1. Sand free water entrance into the well during pumping operation,
 2. Highest permeability generation in the well vicinity,
 3. Low water entrance velocity.
- Aquifer loss is due to Darcy flow through the aquifer material, which causes steady energy loss as water flow approaches the main well.
- The coarser (finer) the medium, the smaller (bigger) is the aquifer loss.
- Linear well loss consists of the head losses in the transitional zone between the aquifer and the gravel pack, and screen losses.

Skin Effect, Aquifer Loss and Other Well Losses

- Turbulent flow loss is due to the very high gradients next to the well lateral surface, where energy losses are proportional nonlinearly with groundwater velocity, which is the greatest at the well surface.
- As obvious from Figure 3.11, the total drawdown, s_w , in the main well is equal to the difference between the static (initial) and the dynamic (final) water levels.
- This drawdown is the summation of aquifer, s_1 , the linear well, s_2 and the turbulent flow, s_3 , losses.
$$s_w = s_1 + s_2 + s_3 \quad (3.10)$$
- Well screen and the gravel pack together help to provide open access after well development so that there will not be clogging due to fine grains and the well is not impeded by sand.

Skin Effect, Aquifer Loss and Other Well Losses

- Groundwater flow toward the well carries unconsolidated sand and gravel in addition to friable materials.

A proper well design should provide the following features:

- Minimum entrance velocity, Maximum open area of screen, Minimization of the blockages, Corrosion resistance screen material.

Prior to water abstraction for supply purposes, well development stage must be performed with high abstraction rates.

After the well development the gravel pack should have the following features:

1. Sand free well-aquifer operation,
2. Low entrance velocity,
3. Resistance to chemicals.

Skin Effect, Aquifer Loss and Other Well Losses

- Screen area should provide entrance velocity that is less than that required to move the finest particles of the surrounding formation into the well.
- The screen should also retain physically the required proportion of the formation with adequate strength to prevent collapse of the well.
- The head loss through a well screen is a function of the
 - ✓ screen length,
 - ✓ screen diameter,
 - ✓ percentage screen opening area,
 - ✓ opening contraction coefficient,
 - ✓ roughness,
 - ✓ water velocity in the screen, and discharge.

Skin Effect, Aquifer Loss and Other Well Losses

- In order to protect side collapse of the wells they must be reinforced by solid materials, which can be iron, steel, concrete pipes, or stone masonry.
- The well losses comprise the turbulent losses about the well screen and frictional losses in the casing.
- One can seek to minimize the well losses so as to increase the efficiency, but the length of the casing is governed by the aquifer depth.
- In general, the preliminary field work includes well inventory, topographic and surface geological assessments, identification and drilling locations in order to obtain direct subsurface data.
- It is also possible to use geophysical prospecting techniques for the subsurface exploration.