Instructors: Dr. Yunes Mogheir (ymogheir@iugaza.edu.ps)  
Dr. Ahmed Abu Foul (afoul@iugaza.edu.ps)  

Semester: 2nd/2009-2010
Measurement of Yield of Underground Sources (Aquifers)

1. Estimation of the Yield by Estimation of the Velocity of Ground Water:

\[ Q = n \cdot v_a \cdot A \]

*Where*, \( A \) is the area of the aquifer opening into the well and \( v_a \) is actual flow velocity of groundwater.

- the velocity of the ground water flow \((v_a)\) can be estimated by:
  - using Slichters or Hazen's empirical equations or
  - it can better be measured in the actual field by using **chemical tracers**, such as a dye; or by using **electrical resistivity methods**.
chemical tracers method

The time \((t)\) taken by a chemical tracer to travel a given - known distance \((S)\) between two observation wells will directly indicate the ground flow velocity as

\[ v_a = \frac{S}{t} \]

This method is used to determine \(K\) such as

\[ v = K \cdot I; \quad \text{or} \quad K = \frac{v}{I} = \frac{n \cdot v_a}{I} \quad \text{where} \quad I = \frac{H_L}{S} \]

Where \(H_L\) is the difference of water surface elevations of the two wells

Ex. 16.2
Pumping tests method

1. A well is, first of all, constructed through the aquifer, of which the yield is to be estimated.

2. Huge amount of water is drawn from the well, so as to cause heavy drawdown in its water level.

3. The rate of pumping is changed and so adjusted that the water level in the well becomes constant.

4. In this condition of equilibrium, the rate of pumping will be equal to the rate of yield,

5. and hence, the rate of pumping will directly give us the yield of the well, at a particular drawdown.

Method will be detailed later on
Recuperating or Recovery test methods

1. water is first of all drained from the well at a fast rate, - so as to cause sufficient drawdown.
2. The pumping is then stopped. -
3. The water level in the well will start rising. -
4. The rise is noted at regular intervals of time, till the - initial level is reached.
5. Knowing the area of the well and the rise of the water - level, the volume of the water yielded in that given time interval, can be worked out at different drawdowns.

These methods are also used to determine the characteristics of the aquifer
THOERETICAL APPROACH TO COMPUTATION OF COEFFICIENT OF PERMEABILITY (K) AND 'DISCHARGE CAPACITY;OF AN AQUIFER(Q)

- Dupuit, Thiem, and Theis developed the theoretical analysis of ground water flow, mainly used to compute K and then Q

- We will first of all derive the equations of Thiem, and then switch to the equations of Dupuit,
1. **Thiem's Formula for Unconfined Aquifer case**

   - Let a non-artesian well be driven, and water pumped heavily so as to cause sufficient draw-down.
   - When the water level in the well decreases, the water level in the neighbourhood will also fall down; *(an inverted cone of depression)* all around the well,
   - The base of this cone is a circle of radius $R$, *(the circle of influence)*, and the inclined side is known as the *drawdown curve*. 

![Diagram of Thiem's Equilibrium Formulas](image)
1. Thiem's Formula for Unconfined Aquifer case

- two observation wells lying within the circle of influence of the main pumped well are to be driven.
- Let these wells be numbered as 1 and 2 (Fig. 16.9) and let them be at distances of \( r_1 \) and \( r_2 \) from the main well (centre to centre distance),
- Let \( d \) be the depth of the well or the aquifer, below the static water table.
Thiem's Equilibrium Formulas

Let the main well be pumped at a sufficient rate, so as to cause heavy drawdown.
Then, let the pumping be so adjusted that the equilibrium conditions are reached (the rate of pumping becomes equal to the rate of yield, and thus causing the water level to attain a constant value.)

Let $S_1$ and $S_2$ be the drawdowns in the two corresponding observation wells, at this equilibrium stage.
Thiem's Equilibrium Formulas

By Darcy's law

\[ Q = KIA \]

where \( I = \) Hydraulic gradient

Using cylindrical co-ordinates, we take \( r \) as the radius of any cylinder, and \( h \) as the height of the cone of depression at a distance \( r \) from the main well.

\[ I = \frac{dh}{dl} \approx \frac{dh}{dr}. \]

\[ I = \frac{dh}{dr} \]

the area of flow (\( A \)) is equal to \( 2\pi rh \)

\[ Q = KIA = K \cdot \frac{dh}{dr} \cdot 2\pi r \cdot h \]

\[ Q = 2\pi Khr \cdot \frac{dh}{dr} \]

\[ \frac{dr}{r} = \frac{2\pi Khdr}{Q} \]

\[ \int_{r_1}^{r_2} \frac{dr}{r} = \int_{h_1}^{h_2} \frac{2\pi K}{Q} \cdot h dh \]
Thiem's Equilibrium Formulas

\[ K = \text{Permeability of soil, which is assumed to be constant at all places and at all times i.e. (homogeneous soil), and in all directions, i.e. (isotropic soil), by assuming the soil to be homogeneous and isotropic.} \]

Therefore

\[ \int_1^2 \frac{dr}{r} = \frac{2\pi K}{Q} \int_1^2 h dh \]

or

\[ \log_e \frac{r_2}{r_1} = \frac{2\pi K}{Q} \cdot \frac{h_2}{2} \]

or

\[ \log_e \frac{r_2}{r_1} = \frac{2\pi K}{Q} \left[ \frac{(h_2^2 - h_1^2)}{2} \right] \]

\[ = \frac{\pi K}{Q} \left[ h_2^2 - h_1^2 \right] \]

\[ (h_2^2 - h_1^2) = (h_2 + h_1) \cdot (h_2 - h_1) \]

\[ h_2 - h_1 = s_1 - s_2 \]
Thiem's Equilibrium Formulas

In the case of the amount of drawdown is small compared to the saturated thickness of the water layer:

\[ h_1 + h_2 \approx d + d = 2d \]

\[ (h_2^2 - h_1^2) \approx (s_1 - s_2) \cdot 2d = 2d \cdot (s_1 - s_2) \]

\[ Q \approx \frac{2\pi \cdot Kd \cdot (s_1 - s_2)}{2.3 \log_{10} \frac{r_2}{r_1}} \]

\[ Q \approx \frac{2\pi \cdot T \cdot (s_1 - s_2)}{2.3 \log_{10} \frac{r_2}{r_1}} \]

T is the transmissibility
Thiem's Equilibrium Formulas

The assumptions are as follows:
1. The aquifer is homogeneous, isotropic and of infinite and areal extent, so that its coefficient of transmissibility or permeability is constant everywhere.
2. The well has been sunk through the full depth of the aquifer and it receives water from the entire thickness of the aquifer.
3. Pumping has continued for a sufficient time at a uniform rate, so that the equilibrium stage or steady flow conditions have reached.
4. Flow lines are radial and horizontal, and flow is laminar.
5. The inclination of the water surface is small so that its tangent can be used in place of sine for the hydraulic gradient in Darcy's equation.
Thiem's Equilibrium Formulas

2. Thiem's Formula for Confined Aquifer case

-The formula used for the case of the unconfined aquifer has to be slightly modified in the case of an artesian aquifer,
-the flow is actually radial and horizontal.
-Rest of the assumptions remain the same and hold good in this case also

\[
Q = \frac{2\pi KH (h_2 - h_1)}{2.3 \log_{10} \frac{r_2}{r_1}}
\]

But \( h_2 - h_1 = s_1 - s_2 \)

Therefore, \[
Q = \frac{2\pi KH (s_1 - s_2)}{2.3 \log_{10} \frac{r_2}{r_1}}
\]

Also \[
Q = \frac{2\pi T (s_1 - s_2)}{2.3 \log_{10} \frac{r_2}{r_1}}
\]
Limitations of Thiem's Equilibrium Formulas

in actual practice,

-an aquifer is not fully homogeneous, or
-the well might have been dug half way through the aquifer, or
-permeability may not be uniform, or
-the ground water table may be inclined and thus, the base of the cone may not be a circle, or
-the equilibrium conditions might have not fully reached.

However, it is very difficult to assess the effects of these factors, and despite the various limiting assumptions,

Thiem's formula is widely used in ground water problems and many of its limitations are removed by appropriate adjustments.
Dupuit's Original Equilibrium Formulas

-no observation wells (as constructed in Thiem's formula) are constructed.

-The main well is pumped out so as to get sufficient drawdown,

-and then the rate of pumping is so adjusted as to establish equilibrium conditions (the water level in the well becomes constant).

-All the assumptions which have been made in the Theim's formulas hold good for the Dupuit's formulas also.
Dupuit's Original Equilibrium Formulas

-The only difference is that the integration which was done between the limits of \( r_1 \) and \( r_2 \) (radii of two observation wells) in Theim's formulas is changed,

-the integration is done between the limits \( r_w \) and \( R \), where

\( r_w \) : is the radius of the main pumped well and
\( R \) : is the radius of influence.

The radius of influence: is the distance from the centre of the pumped well to the point, where the drawdown is zero or is inappreciable.
Dupuit's Original Equilibrium Formulas

-Dupuit's Formula for Gravity Well or Unconfined Aquifer Case

\[ Q = K \cdot I.A. \]
\[ Q = K \cdot \frac{dh}{dr} \cdot 2\pi rh. \]

where \( K = \) Coefficient of permeability

\[ \frac{dr}{r} = \frac{2\pi K}{Q} \cdot h \cdot dh. \]

Integrating between the limits \( r_w \) and \( R \), we get

\[ \int_{r_w}^{R} \frac{dr}{r} = \frac{2\pi K}{Q} \int_{h_w}^{h_d} h \cdot dh \]

\[ \log_e \frac{R}{r_w} = \frac{2\pi K}{Q} \left( \frac{h^2}{2} \right)_{h_w}^{h_d} \]

\[ \log_e \frac{R}{r_w} = \frac{\pi K}{Q} \cdot [d^2 - h_w^2] \]

\[ 2.3 \log_{10} \frac{R}{r_w} = \frac{\pi K}{Q} \cdot [d^2 - h_w^2] \]

\[ Q = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \frac{R}{r_w}} \]
- Dupuit's Formula for Gravity Well or Unconfined Aquifer Case

- *R value* is not easily assessable, various arbitrary values have been assigned to *R* by various investigators. Slitcher gives it as 150m and Tolman calls it as 300 m.

- when \( R = CQ \), where, \( C = \) is a constant and \( Q = \) is the discharge

\[
Q = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \left(\frac{CQ}{r_w}\right)}
\]

*Q can be determined by trial and error method*
Dupuit's Original Equilibrium Formulas

- Dupuit's Formula for Confined Aquifer Case

\[ Q = KIA \]

or
\[ Q = K \cdot \frac{dH}{dr} \cdot \frac{2\pi \cdot rH}{2\pi} \]

or
\[ \frac{dr}{r} = \frac{2\pi KH}{Q} \cdot dh \]

Integrating between \( r_w \) and \( R \), we get

\[ \int_{r_w}^{R} \frac{dr}{r} = \frac{2\pi K}{Q} \cdot H \int_{h_w}^{h} dh \]

or
\[ \log_e r \bigg|_{r=r_w}^{r=R} = \frac{2\pi K}{Q} \cdot H \bigg|_{h=h_w}^{h=D} \]

or
\[ 2.3 \log_{10} \frac{R}{r_w} = \frac{2\pi KH}{Q} \left[(D - h_w)\right] \]

\[ K = \frac{2.3 Q \log_{10} \frac{R}{r_w}}{2\pi H (D - h_w)} \]

\[ Q = \frac{2\pi KH (D - h_w)}{2.3 \log_{10} \frac{R}{r_w}} \]
Dupuit's Original Equilibrium Formulas

- Dupuit's Formula for Confined Aquifer Case

\[ Q = KIA \]

or
\[ Q = K \cdot \frac{dH}{dr} \cdot \frac{2\pi \cdot rH}{Q} \]

or
\[ \frac{dr}{r} = \frac{2\pi KH}{Q} \cdot dh \]

Integrating between \( r_w \) and \( R \), we get

\[ \int_{r_w}^{R} \frac{dr}{r} = \frac{2\pi K}{Q} \cdot H \int_{h_w}^{D} dh \]

or
\[ \left| \log_e r \right|_{r = R}^{r = r_w} = \frac{2\pi K}{Q} \cdot H \left| h \right|_{h = h_w}^{h = D} \]

or
\[ 2.3 \log_{10} \frac{R}{r_w} = \frac{2\pi KH}{Q} \left[ (D - h_w) \right] \]
Dupuit's Original Equilibrium Formulas

- Dupuit's Formula for Confined Aquifer Case

\[
Q = KIA
\]
\[
Q = K \cdot \frac{dh}{dr} \cdot 2\pi \cdot rH
\]

\[
\frac{dr}{r} = \frac{2\pi KH}{Q} \cdot dh
\]

Integrating between \( r_w \) and \( R \), we get

\[
\int_{r_w}^{R} \frac{dr}{r} = \frac{2\pi K}{Q} \cdot H \int_{h_w}^{D} dh
\]

\[
\left| \log_e r \right|_{r=r_w}^{r=R} = \frac{2\pi K}{Q} \cdot H \left| h \right|_{h=h_w}^{h=D}
\]

\[
2.3 \log_{10} \frac{R}{r_w} = \frac{2\pi KH}{Q} \left[ (D - h_w) \right]
\]

\[
K = \frac{2.3 Q \log_{10} \frac{R}{r_w}}{2\pi H \cdot (D - h_w)}
\]

\[
Q = \frac{2\pi KH \cdot (D - h_w)}{2.3 \log_{10} \frac{R}{r_w}}
\]
Partial Penetration of an Aquifer by a Well

\[ Q = \frac{2\pi KH (D - h_w)}{2.3 \log_{10} \left( \frac{R}{r_w} \right)} \]
(for confined wells)

\[ Q = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \left( \frac{R}{r_w} \right)} \]
(for unconfined wells)

If a well does not penetrate up to the bottom of the aquifer, these formulas will not be applicable, as the nature of the flow will become three-dimensional.
Partial Penetration of an Aquifer by a Well

Kozeny has given a correction factor, and according to him the discharge $Q_p$ through such a well is given as follows:

\[
Q_p = \frac{\pi \cdot K \cdot (d_1^2 - h_w^2)}{2.3 \log_{10} \left( \frac{R}{r_w} \right)} \cdot \left[ 1 + 7 \cdot \sqrt{\frac{r_w}{2d_1}} \cdot \cos \left( \frac{\pi d_1}{2d} \right) \right]
\]

\[
Q_p = \frac{2\pi \cdot KH_1 (D - h_w)}{2.3 \log_{10} \left( \frac{R}{r_w} \right)} \cdot \left[ 1 + 7 \cdot \sqrt{\frac{r_w}{2H_1}} \cdot \cos \left( \frac{\pi H_1}{2H} \right) \right]
\]
Spherical Flow in a Well

The yield in a spherical flow is much less than that in a radial flow. Hence, the spherical flow is much less efficient than the radial flow.

\[
Q_s = \frac{2\pi K r_w \cdot (D - h_w)}{2\pi K H (D - h_w) + 2.3 \log_{10} \left( \frac{R}{r_w} \right)}
\]
Interference Among Wells

• If two or more wells are constructed near to each other and their cones of depressions interact (interfere).
• Interference of wells decreases the discharges of such interfering wells.
• Muskat has proposed the following formulas for computation of discharges from such interfering wells

(1) For two artesian identical wells at a distance $B$ apart

$$Q_1 = Q_2 = \frac{2\pi KH \cdot (D - h_w)}{2.3 \log_{10} \left( \frac{R^2}{r_w \cdot B} \right)}$$

(2) For three artesian identical wells at a distance $B$ apart, in a pattern of equilateral triangle

$$Q_1 = Q_2 = Q_3 = \frac{2\pi KH \cdot (D - h_w)}{2.3 \log_{10} \left( \frac{R^3}{r_w \cdot B^2} \right)}$$
(3) For three artesian identical wells at a distance $B$ apart in a straight line

\[
Q_1 = Q_3 = \frac{2 \pi K H}{2.3} \frac{(D - h_w)}{B} \log_{10} \left( \frac{B}{R_w} \right) \left[ \log_{10} \left( \frac{R}{B} \right) \cdot \log_{10} \left( \frac{B}{r_w} \right) + \log_{10} \left( \frac{B}{2r_w} \right) \cdot \log_{10} \left( \frac{R}{r_w} \right) \right]
\]

\[
Q_2 = \frac{2 \pi K H}{2.3} \frac{(D - h_w)}{B} \log_{10} \left( \frac{B}{2r_w} \right) \left[ 2 \cdot \log_{10} \left( \frac{R}{B} \right) \cdot \log_{10} \left( \frac{B}{r_w} \right) + \log_{10} \left( \frac{B}{2r_w} \right) \cdot \log_{10} \left( \frac{R}{r_w} \right) \right]
\]
Interference Among Wells

(3) For two identical unconfined wells at a distance $B$

\[ Q_1 = Q_2 = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \left( \frac{R^2}{r_w \cdot B} \right)} \]

(2) For three artesian gravity wells at a distance $B$ apart, in a pattern of equilateral triangle

\[ Q_1 = Q_2 = Q = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \left( \frac{R^3}{r_w \cdot B^2} \right)} \]
- The difference between the actual free surface and the Dupuit's base pressure curve, in a gravity well, arises due to the Dupuit's assumption of 'horizontal and radial flow'.

- In other words, in an unconfined aquifer, the velocity distribution will not be horizontal near the well but Dupuit assumed it to be so.
Free Surface Curve

Equation of free surface curve:

\[ Q = \left[ \frac{\pi K}{2C} \right] \left[ \frac{(d - h) d}{\log_{10} \left( \frac{R}{0.1d} \right)} \right] \]

Where:
- \((r, h)\) is any point on the curve.
- \(R\) = Radius of influence.
- \(K\) = Permeability coefficient.
- \(C\) = a constant, the value of which depends upon the value of \(r/R\)
Well Loss and Specific Capacity

Well loss, is a certain drawdown caused by the flow of water through the well screen and axial movement within the well.

Total drawdown = aquifer loss or formation loss + Well loss,

\[ s_w = C_1 Q + C_2 \cdot Q^2 \]

\[ s = \frac{2.3 Q \log_{10} \frac{R}{r_w}}{2\pi KH} \]

\[ = C_1 \cdot Q \]
Specific Capacity

The specific capacity of a well is defined as the well yield per unit of drawdown.

\[
\text{Sp. Capacity} = \frac{\text{discharge of the well}}{\text{Drawdown}} = \frac{Q}{C_1Q + C_2Q^2} = \left[\frac{1}{C_1 + C_2Q}\right]
\]
Efficiency of a Well

- The specific capacity will be different for different well design.

- Yield draw down curve can be used to determine the best drawdown discharge conditions for a well.

- This curve can be developed by chaining the discharge will under vary the drawdown values.

- The optimum and efficient limit of the well is generally found to be 70% of the maximum drawdown.

Fig. 16.23. Yield drawdown curve.
Examples

Example 16.4. A well penetrates into an unconfined aquifer having a saturated depth of 100 metres. The discharge is 250 litres per minute at 12 metres drawdown. Assuming equilibrium flow conditions and a homogeneous aquifer, estimate the discharge at 18 metres drawdown. The distance from the well where the draw-down influences are not appreciable may be taken to be equal for both the cases.

\[ d = 100 \text{ m} \quad S1 = 12 \text{ m} \quad S2 = 18 \text{ m} \]
\[ Q1 = 250 \text{ litres/minute} \quad Q2 = ? \]

Dupuit's formula for unconfined aquifers

\[ Q = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \left( \frac{R}{r_w} \right)} \]

1. \[ h_w = (100 \text{ m} - 12 \text{ m}) = 88 \text{ m} \]
2. \[ h_w = 100 - 18 = 82 \text{ m} \]

\[ 250 \text{ litres/minute} = \pi K \left[ (100)^2 - (88)^2 \right] \]
\[ 2.3 \log_{10} \left( \frac{R}{r_w} \right) \]
\[ \pi K \left[ (100)^2 - (82)^2 \right] \]
\[ 2.3 \log_{10} \left( \frac{R}{r_w} \right) \]

\[ Q2 = \frac{250}{188 \times 12} \left[ (100)^2 - (82)^2 \right] \]
\[ Q2 = 363 \text{ litres/minute.} \]
Examples

Example 16.6. 60 cm diameter well is being pumped at a rate of 1360 litres/minute. Measurements in a nearby test well were made at the same time as follows. At a distance of 6 m from the well being pumped, the drawdown was 6 m, and at 15 m the drawdown was 1.5 m. The bottom of the well is 90 m below the ground water table.

(a) Find out the coefficient of permeability.
(b) If all the observed points were on the Dupuit curve, what was the drawdown in the well during pumping?
(c) What is the sp. capacity of the well?
(d) What is the rate at which water can be drawn from this well?

Thiem's formula for unconfined aquifers:

\[ Q = \frac{\pi K (h_2^2 - h_1^2)}{2.3 \log_{10} \frac{r_2}{r_1}} \]

For (a)

\[ Q = \frac{\pi K (h_2^2 - h_w^2)}{2.3 \log_{10} \frac{r_2}{r_w}} \]

For (b)

Dupuit's formula for unconfined aquifers:

\[ Q = \frac{\pi K (d^2 - h_w^2)}{2.3 \log_{10} \left(\frac{R}{r_w}\right)} \]

For (c) and (d)
Example 16.7. Two rivers A and B are separated by an aquifer formation of 5 km length. Compute the seepage flow per unit length of river, if the coefficient of permeability of aquifer material is 16 m l day.
Non-Equilibrium Formula for Aquifers (Unsteady Radial Flows)

- The main assumption of the equilibrium formulas given by Thiem and Dupuit, was the problem to attain equilibrium conditions,
- A major advancement in this field was made by Thies when he developed his non equilibrium formula by introducing the time factor $t$
- Later, Jacob derived the same formula by directly using the hydraulic concept.

\[ s = \frac{Q}{4\pi T} \left[ \log e \frac{4Tt}{r^2 \cdot A} - 0.5772 \right] \]

Where
- $s =$ Drawdown in the observation well after a time $t$, from the start of pumping in the main well
- $T =$ Coefficient of transmissibility of the aquifer
- $Q =$ Constant discharge pumped out from the main pumped well.
- $A =$ Coefficient of storage of the measured drawdown.
- $r =$ Radial distance of the observation well from the main pumped well.
Non-Equilibrium Formula for Aquifers (Unsteady Radial Flows)

\[ A = \frac{2.25 T t_0}{r^2} \]

\( A \) = Coefficient of storage of the measured drawdown, which can be determined in pumping test.
Example

Example 16.10. A well is located in a 30 m thick confined aquifer of permeability 3,5 m/day and storage coefficient of 0.004. If the well is pumped at the rate of 1500 litres per minute, calculate the drawdown at a distance of 40 m from the well after 20 hours of pumping.

Using Jacob’s eqn. (16.35), we have

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

where \( s = \) drawdown = ?

- \( H = \) depth of aquifer = 30 m
- \( K = \) 35 m/day
- \( A = \) storage coeff = 0.004
- \( Q = \) 1500 l/min = \( \frac{1.5}{60} \) cum/sec
  \( = 0.025 \text{ m}^3/\text{s} \)
- \( r = 40 \text{ m} \)
- \( t = 20 \text{ hr} = 20 \times 3600 \text{ secs} \)
  \( = 72000 \text{ secs} \)

\[ T = K \cdot H = 35 \times 30 \text{ m}^2/\text{day} \]
\[ = \frac{1050}{60 \times 60 \times 24} \text{ m}^2/\text{sec} \]
\[ = 0.012153 \text{ m}^2/\text{s} \]

\[ s = \frac{0.025}{4 \times 3.14 \times 0.012153} \left[ \log_e \frac{4 \times 0.012153 \times 72000}{(40)^2 \times 0.004} - 0.5772 \right] \]

\[ = 0.163 \left( 6.3042 - 0.5772 \right) \]
\[ = 0.163 \times 5.724 \]
\[ = 0.94 \text{ m. Ans.} \]
Exercise 1

1. A 30 cm dia well penetrates 20 m below the static watertable. After 24 hours of pumping at 5000 litres per minute, the water level in a test well at 100 m away is lowered by 0.5m, and in a well at 30 m away, the drawdown is 1 m. What is the transmissibility of the aquifer?

2. A well penetrating an aquifer which is underlain and overlain by impermeable layers was tested with a uniform discharge of 1000 litres/min. The steady state drawdown measured in two observation wells which were at 1 m and 10 m radial distances from the centre of the pumped well were 13.40 m and 4.2m, respectively. Determine the hydraulic properties of the aquifer, if its saturated thickness is 10 m.

3. In an artesian aquifer, the drawdown is 1.5 m at a radial distance of 8 metres from a well after two hours of pumping. On the basis of Theis' non-equilibrium equation, determine the pumping time for the same draw-down (1.5 metre) radial distance of 20 metres from the well.

4. A 10 cm diameter well was pumped at it uniform rate of 500 litres/min, while observations of draw down were made in an observation well located at a distance of 50 m from the well. The original head of water, measured from the top of the impervious layer was 25 m. The hydraulic conductivity of the aquifer was 1.83 x 10-3 m/min. Determine the drawdown at the face of the well, using Dupuit- Thiem equation, and assuming that the flow to the uncon-fined aquifer is under steady state.