Chapter 7

GROUND WATER

7.1 TYPES OF AQUIFERS AND FORMATIONS

Ground water is widely distributed under the ground and is a replenishable resource unlike other resources of the earth. The problems in Ground Water Investigation are the zones of occurrence and recharge. The modern trends are to create more opportunity for recharge of ground water from natural sources like rain, percolation dams, etc. The ground water is free from pollution and the ground water storage is free from atomic attacks. Ground water can be developed at a small capital cost in least possible time, and intensive irrigation can be practised with double and tripple cropping including commercial crops; ground water can be used for supplemental irrigation during periods of deficient surface supply, for the year-round irrigation practice.

A water bearing geologic formation or stratum capable of transmitting water through its pores at a rate sufficient for economic extraction by wells is called 'aquifer'. Formations that serve as good aquifers are:

- unconsolidated gravels, sands, alluvium
- lake sediments, glacial deposits
- sand stones
- limestones with cavities (caverns) formed by the action of acid waters (solution openings in limestones and dolomites)
- granites and marble with fissures and cracks, weathered gneisses and schists
- heavily shettered quartzites
- vescicular basalts
- slates (better than shales owing to their jointed conditions)

A geologic formation, which can absorb water but can not transmit significant amounts is called an 'aquiclude'. Examples are clays, shales, etc.

A geologic formation with no interconnected pores and hence can neither absorb nor transmit water is called an 'aquifuge'. Examples are basalts, granites, etc.

A geologic formation of rather impervious nature, which transmits water at a slow rate compared to an aquifer (insufficient for pumping from wells) is called an 'aquitard'. Examples are clay lenses interbedded with sand.

Specific yield. While porosity (n) is a measure of the water bearing capacity of the formation, all this water can not be drained by gravity or by pumping from wells as a portion of water is held in the void spaces by molecular and surface tension forces. The volume of water, expressed as a percentage of the total volume of the saturated aquifer, that will drain by gravity when the water table (Ground Water Table (GWT) drops due to pumping or drainage, is called the 'specific yield (S_y)' and that percentage volume of water, which will not drain by gravity is called 'specific retention (S_r)' and corresponds to 'field capacity' *i.e.,* water holding capacity of soil (for use by plants and is an important factor for irrigation of crops). Thus,

$$\text{porosity} = \text{specific yield} + \text{specific retention}$$

$$n = S_y + S_r \qquad ...(7.1)$$

Specific yield depends upon grain size, shape and distribution of pores and compaction of the formation. The values of specific yields for alluvial aquifers are in the range of 10–20% and for uniform sands about 30%.

7.2 CONFINED AND UNCONFINED AQUIFERS

If there is homogeneous porous formation extending from the ground surface up to an impervious bed underneath (Fig. 7.1), rainwater percolating down in the soil saturates the formation and builds up the ground water table (GWT). This aquifer under water table conditions is called an *unconfined aquifer* (water-table aquifer) and well drilled into this aquifer is called a *water table well*.

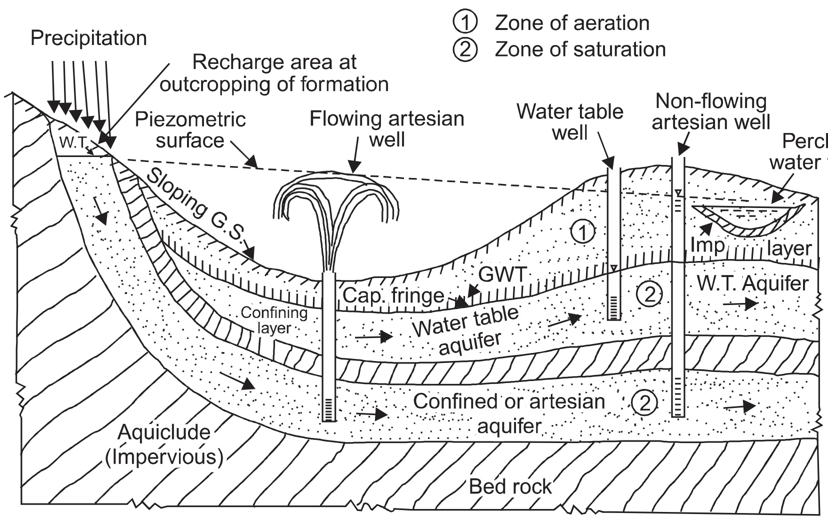

Fig. 7.1 Types of aquifers and location of wells

On the other hand, if a porous formation underneath is sandwiched between two impervious strata (aquicludes) and is recharged by a natural source (by rain water when the formation outcrops at the ground surface—recharge area, or outcrops into a river-bed or bank) at a higher elevation so that the water is under pressure in the aquifer (like pipe flow), *i.e.,* artesian condition. Such an aquifer is called an artesian aquifer or confined aquifer. If a well is drilled into an artesian aquifer, the water level rises in the well to its initial level at the recharge source called the *piezometric surface*. If the piezometric surface is above the ground level at the location of the well, the well is called 'flowing artesian well' since the water flows out of the well like a spring, and if the piezometric surface is below the ground level at the well location, the well is called a non-flowing artesian well. In practice, a well can be drilled through 2-3 artesian aquifers (if multiple artesian aquifers exist at different depths below ground level).

Sometimes a small band of impervious strata lying above the main ground water table (GWT) holds part of the water percolating from above. Such small water bodies of local nature can be exhausted quickly and are deceptive. The water level in them is called 'perched water table'.

Storage coefficient. The volume of water given out by a unit prism of aquifer (*i.e.,* a column of aquifer standing on a unit horizontal area) when the piezometric surface (confined aquifers) or the water table (unconfined aquifers) drops by unit depth is called the *storage coefficient* of the aquifer (S) and is dimensionless (fraction). It is the same as the volume of water taken into storage by a unit prism of the aquifer when the piezometric surface or water table rises by unit depth. In the case of water table (unconfined) aquifer, the storage coefficient is the same of specific yield (S_y).

Since the water is under pressure in an artesian aquifer, the storage coefficient of an artesian aquifer is attributable to the compressibility of the aquifer skeleton and expansibility of the pore water (as it comes out of the aquifer to atmospheric pressure when the well is pumped) and is given by the relation.

$$S = \gamma_w nb \left(\frac{1}{K_w} + \frac{1}{nE_s} \right) \quad \text{...(7.2)}$$

where S = storage coefficient (decimal)

γ_w = specific weight of water

n = porosity of soil (decimal)

b = thickness of the confined aquifer

K_w = bulk modulus of elasticity of water

E_s = modulus of compressibility (elasticity) of the soil grains of the aquifer.

Since water is practically incompressible, expansibility of water as it comes out of the pores has a very little contribution to the value of the storage coefficient.

The storage coefficient of an artesian aquifer ranges from 0.00005 to 0.005, while for a water table aquifer $S = S_y$ = 0.05–0.30. The specific yield (unconfined aquifers) and storage coefficient (confined aquifers), values have to be determined for the aquifers in order to make estimates of the changes in the ground water storage due to fluctuation in the GWT or piezometric surface (ps) from the relation.

$$\Delta GWS = A_{aq} \times \Delta GWT \text{ or } ps \times S \text{ or } S_y \quad \text{...(7.3)}$$

where ΔGWS = change in ground water storage

A_{aq} = involved area of the aquifer

ΔGWT or ps = fluctuation in GWT or ps

S or S_y = storage coefficient (confined aquifer) or specific yield (unconfined aquifer).

Example 7.1 *In a certain alluvial basin of 100 km², 90 Mm³ of ground water was pumped in a year and the ground water table dropped by about 5 m during the year. Assuming no replenishment, estimate the specific yield of the aquifer. If the specific retention is 12%, what is the porosity of the soil?*

Solution (i) Change in ground water storage

$$\Delta GWS = A_{aq} \times \Delta GWT \times S_y$$

$$90 \times 10^6 = (100 \times 10^6) \times 5 \times S_y$$

$$\therefore \qquad S_y = \mathbf{0.18}$$

(*ii*) Porosity $n = S_y + S_r = 0.18 + 0.12 = 0.30$. or **30%**

Example 7.2 *An artesian aquifer, 30 m thick has a porosity of 25% and bulk modulus of compression 2000 kg/cm². Estimate the storage coefficient of the aquifer. What fraction of this is attributable to the expansibility of water?*

Bulk modulus of elasticity of water = 2.4 × 10⁴ kg/cm².

Solution $S = \gamma_w \, nb \left(\dfrac{1}{K_w} + \dfrac{1}{nK_s}\right) = 1000 \times 0.25 \times 30 \left(\dfrac{1}{2.14 \times 10^8} + \dfrac{1}{0.25 \times 2 \times 10^7}\right)$

$$= 7500\,(0.467 \times 10^{-8} + 20 \times 10^{-8}) = \mathbf{1.54 \times 10^{-3}}$$

Storage coefficient due to the expansibility of water as a percentage of S above

$$= \frac{7500 \times 0.467 \times 10^{-8}}{7500 \times 20.467 \times 10^{-8}} \times 100 = \mathbf{2.28\%}, \quad \text{which is negligibe}$$

Note In less compressible formations like limestones for which $E_s \approx 2 \times 10^5$ kg/cm², $S = 5 \times 10^{-5}$ and the fractions of this attributable to water and aquifer skeleton are 70% and 30%, respectively.

7.3 DARCY'S LAW

Flow of ground water except through coarse gravels and rockfills is laminar and the velocity of flow is given by Darcy's law (1856), which states that 'the velocity of flow in a porous medium is proportional to the hydraulic gradient', Fig. 7.2, *i.e.,*

$$V = Ki, \qquad \text{...(7.4)}$$

$$i = \frac{\Delta h}{L} \qquad \text{...(7.4 a)}$$

$$Q = AV = AKi, \quad A = Wb, \quad T = Kb \qquad \text{...(7.4 b)}$$

$$\therefore \qquad Q = WbKi \qquad \text{...(7.4 c)}$$

$$\therefore \qquad Q = T\,iw \qquad \text{...(7.5)}$$

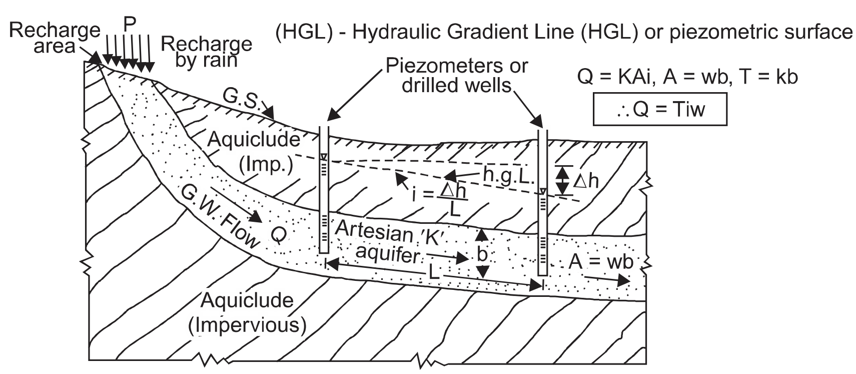

Fig. 7.2 Flow of ground water

where V = velocity of flow through the aquifer

K = coefficient of permeability of aquifer soil

i = hydraulic gradient

$= \frac{\Delta h}{L}$, Δh = head lost in a length of flow path L

A = cross-sectional area of the aquifer (= wb)

w = width of aquifer

b = thickness of aquifer

T = coefficient of transmissibility of the aquifer

Q = volume rate of flow of ground water (discharge or yield)

Darcy's law is valid for laminar flow, *i.e.,* the Reynolds number (R_e) varies from 1 to 10, though most commonly it is less than 1

$$R_e = \frac{\rho V d}{\mu} \leq 1 \qquad \text{...(7.6)}$$

where ρ = mass density of water

μ = dynamic viscosity of water

d = mean grain size of the aquifer soil

In aquifers containing large diameter solution openings, coarse gravels, rockfills and also in the immediate vicinity of a gravel packed well, flow is no longer laminar due to high gradients and exhibit non linear relationship between the velocity and hydraulic gradient. For example, in a gravel-packed well (mean size of gravel ≈ 5 mm) $R_e \approx 45$ and the flow would be transitional at a distance of about 5 to 10 times the well radius.

7.4 TRANSMISSIBILITY

It can be seen from Eq. (7.5) that $T = Q$, when $i = 1$ and $w = 1$; *i.e.,* the transmissibility is the flow capacity of an aquifer per unit width under unit hydraulic gradient and is equal to the product of permeability times the saturated thickness of the aquifer. In a confined aquifer, $T = Kb$ and is independent of the piezometric surface. In a water table aquifer, $T = KH$, where H is the saturated thickness. As the water table drops, H decreases and the transmissibility is reduced. Thus, the transmissibility of an unconfined aquifer depends upon the depth of GWT.

7.5 WELL HYDRAULICS

Steady radial flow into a well (Dupuit 1863, Thiem 1906)

(a) Water table conditions (unconfined aquifer)

Assuming that the well is pumped at a constant rate Q for a long time and the water levels in the observation wells have stabilised, *i.e.,* equilibrium conditions have been reached, Fig. 7.3 (a).

From Darcy's law, $Q = K\, i\, A$

$$Q = K \frac{dy}{dx} (2\pi\, xy)$$

$$Q \int_{r_1}^{r_2} \frac{dx}{x} = 2\,\pi\, K \int_{h_1}^{h_2} y\, dy$$

$$\therefore \qquad Q = \frac{\pi\, K(h_2^2 - h_1^2)}{2.303 \log_{10} \left(\frac{r_2}{r_1}\right)} \qquad \text{...(7.7)}$$

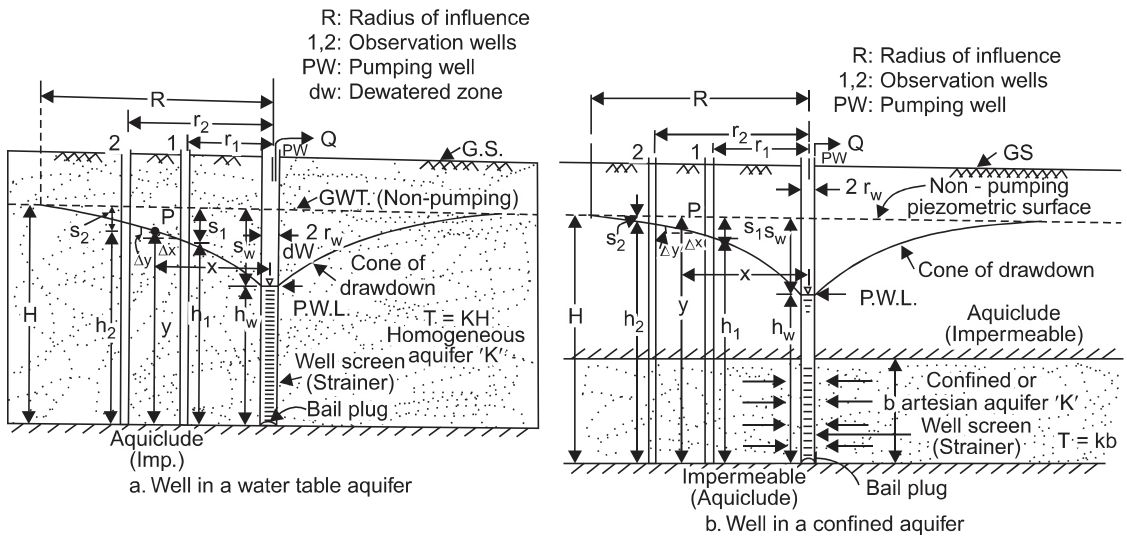

Fig. 7.3 Steady radial flow into a well

Applying the Eq. (7.7) between the face of the well ($r = r_w$, $h = h_w$) and the point of zero-drawdown ($r = R$, $h = H$)

$$Q = \frac{\pi K(H^2 - h^2)}{2.303 \log_{10}\left(\frac{R}{r_w}\right)} \qquad \text{...(7.7 } a\text{)}$$

If the drawdown in the pumped well ($s_w = H - h_w$) is small

$$H^2 - h_w^2 = (H + h_w)(H - h_w), \quad H + h_w \approx 2H$$
$$= 2H\,(H - h_w)$$

Then,
$$Q = \frac{2\pi KH\,(H - h_w)}{2.303 \log_{10}\left(\frac{R}{r_w}\right)}, \quad KH = T$$

$\therefore$
$$Q = \frac{2.72\,T\,(H - h_w)}{\log_{10}\left(\frac{R}{r_w}\right)} \qquad \text{...(7.8)}$$

(b) Artesian conditions (confined aquifer)

If the well is pumped at constant pumping rate Q for a long time and the equilibrium conditions have reached, Fig. 7.3 (b).

From Darcy's law, $Q = K\,i\,A$

$$Q = K\,\frac{dy}{dx}\,(2\pi\, xb)$$

$$Q\int_{r_1}^{r_2}\frac{dx}{x} = 2\pi\,Kb\int_{h_1}^{h_2} dy$$

$\therefore$
$$Q = \frac{2\pi\,(kb)\,(h_2 - h_1)}{2.303 \log_{10}\left(\frac{r_2}{r_1}\right)} \qquad \text{...(7.9)}$$

Applying Eq. (7.9) between the face of the well ($r = r_w$, $h = h_w$) and the point of zero-drawdown ($r = R$, $h = H$), simplifying and putting $T = Kb$,

$$Q = \frac{2.72\, T\,(H - h_w)}{\log_{10}\left(\dfrac{R}{r_w}\right)} \qquad \text{...(7.10)}$$

which is the same as Eq. (7.8) (for water table conditions under small drawdown).

Note The length of screen provided will be usually half to three-fourth's of the thickness of the aquifer for obtaining a suitable entrance velocity (≈ 2.5 cm/sec) through the slots to avoid incrustation and corrosion at the openings; the percentage open area provided in the screen will be usually 15 to 18%.

Dupuit's Equations Assumptions

The following assumptions are made in the derivation of the Dupuit Thiem equations:

(*i*) Stabilised drawdown—*i.e.,* the pumping has been continued for a sufficiently long time at a constant rate, so that the equilibrium stage of steady flow conditions have been reached.

(*ii*) The aquifer is homogeneous, isotropic, of infinite areal extent and of constant thickness, *i.e.,* constant permeability.

(*iii*) Complete penetration of the well (with complete screening of the aquifer thickness) with 100% well efficiency.

(*iv*) Flow lines are radial and horizontal and the flow is laminar, *i.e.,* Darcy's law is applicable.

(*v*) The well is infinitely small with negligible storage and all the pumped water comes from the aquifer.

The above assumptions may not be true under actual field conditions; for example, if there is no natural source of recharge nearby into the aquifer, all the pumped water comes from storage in the aquifer resulting in increased drawdowns in the well with prolonged pumping and thus the flow becomes unsteady (transient flow conditions). There may be even leakage through the overlying confining layer (say, from a water table aquifer above the confining layer) of an artesian aquifer (leaky artesian aquifer). The hydraulics of wells with steady and unsteady flow under such conditions as developed from time to time by various investigators like Theis, Jacob, Chow, De Glee, Hantush, Walton, Boulton etc. have been dealt in detail in the author's companion volume 'Ground Water' published by M/s Wiley Eastern Limited New Delhi and the reader is advised to refer the book for a detailed practical study of Ground Water dealing with Hydrogeology, Ground Water Survey and Pumping Tests, Rural Water Supply and Irrigation Systems. For example, in the Theis equation for unsteady radial flow into a well it is assumed that the water pumped out is immediately released from storage of the aquifer (no recharge) as the piezometric surface or the water table drops. But in unconfined aquifers and leaky artesian aquifers (that receive water from upper confining layer with a free water table), the rate of fall of the water table may be faster than the rate at which pore water is released; this is called 'delayed yield' as suggested by Boulton.

7.6 SPECIFIC CAPACITY

The specific capacity $\frac{Q}{S_w}$ of a well is the discharge per unit drawdown in the well and is usually expressed as lpm/m. The specific capacity is a measure of the effectiveness of the well; it decreases with the increase in the pumping rate (Q) and prolonged pumping (time, t).

In Eq. (7.8) by putting r_w = 15 cm, R = 300 m, $H–h_w = S_w$, the specific capacity

$$\frac{Q}{S_w} \approx \frac{T}{1.2}\text{, in consistent units} \quad \text{...(7.11)}$$

Example 7.3 *A 20-cm well penetrates 30 m below static water level (GWT). After a long period of pumping at a rate of 1800 lpm, the drawdowns in the observation wells at 12 m and 36 m from the pumped well are 1.2 m and 0.5 m, respectively.*

Determine: (i) the transmissibility of the aquifer.

(ii) the drawdown in the pumped well assuming R = 300 m.

(iii) the specific capacity of the well.

Solution Dupuit's Eq. (7.7): $Q = \frac{\pi K(h_2^2 - h_1^2)}{2.303 \log_{10} r_2/r_1}$

$$h_2 = H - s_2 = 30 - 0.5 = 29.5 \text{ m}; \; h_1 = H - s_1 = 30 - 1.2 = 28.8 \text{ m}$$

$$\frac{1.800}{60} = \frac{\pi K(29.5^2 - 28.8^2)}{2.303 \log_{10} 36/12}$$

$\therefore$ $K = 2.62 \times 10^{-4}$ m/sec or **22.7 m/day**

(i) Transmissibility $T = KH = (2.62 \times 10^{-4})\, 30 = 78.6 \times 10^{-4}$ m²/sec,

or $= 22.7 \times 30 =$ **681 m²/day**

(ii) Eq. (7.8): $Q = \frac{2.72\, T\, (H - h_w)}{\log_{10} R/r_w}$

$$\frac{1.800}{60} \equiv \frac{2.72(78.6 \times 10^{-4})\, S_w}{\log_{10} 300/0.10}$$

$\therefore$ drawdown in the well, S_w = **4.88 m**

(iii) The specific capacity of the well

$$= \frac{Q}{S_w} = \frac{1.800}{60 \times 4.88} = 0.0062 \text{ (m}^3\text{ sec}^{-1}\text{/m)}$$

or **372 Ipm/m**

$$\frac{Q}{S_w} \approx \frac{T}{1.2} = \frac{78.6 \times 10^{-4}}{1.2} = 0.00655 \text{ (m}^2\text{ sec}^{-1}\text{/m)}$$

or **393 lpm/m**

Example 7.4 *A tube well taps an artesian aquifer. Find its yield in litres per hour for a drawdown of 3 m when the diameter of the well is 20 cm and the thickness of the aquifer is 30 m. Assume the coefficient of permeability to be 35 m/day.*

If the diameter of the well is doubled find the percentage increase in the yield, the other conditions remaining the same. Assume the radius of influence as 300 m in both cases.

Solution Dupuit's Eq. (7.10): $Q = \dfrac{2.72\, T\,(H - h_w)}{\log_{10} R/r_w}$

$$= \frac{2.72\,\{(35/24) \times 30\}3}{\log_{10}(300/0.10)} = 102.7 \text{ m}^3\text{/hr}$$

or $= \mathbf{102700\ lph}$

The yield $$Q \propto \frac{1}{\log (R/r_w)} \quad \text{...(7.12)}$$

other things remaining same.

If the yield is Q' after doubling the diameter, *i.e.*,

$$r_w' = 0.10 \times 2 = 0.20 \text{ m}$$

$$\frac{Q}{Q'} = \frac{\log R/r_w}{\log R/r_w}$$

$$\log \frac{300}{0.10} = 3.4771, \qquad \log \frac{300}{0.20} = 3.1761$$

$$\frac{102.7}{Q'} = \frac{3.1761}{3.4771} \quad \therefore \quad Q' = 112.4 \text{ m}^3\text{/hr}$$

percentage increase in yield $= \dfrac{Q' - Q}{Q} \times 100 = \dfrac{112.4 - 102.7}{102.4} \times 100 = \mathbf{9.45\%}$

Thus, by doubling the diameter the percentage in yield is only about 10%, which is uneconomical. Large diameter wells necessarily do not mean proportionately large yields. The diameter of a tube well usually ranges from 20 to 30 cm so that the bowl assembly of a deep well or a submersible pump can easily go inside with a minimum clearance.

Refer Appendix-D for Unsteady Groundwater Flow.

7.7 CAVITY WELLS

If a relatively thin impervious formation or a stiff clay layer is encountered at a shallow depth underlain by a thick alluvial stratum, then it is an excellent location for a cavity well. A hole is drilled using the hand boring set and casing pipe is lowered to rest firmly on the stiff clay layer, Fig. 7.4. A hole of small cross-section area is drilled into the sand formation and is developed into a big hollow cavity by pumping at a high rate or by operating a plunger giving a large yield. The depth of the cavity at the centre varies from 15-30 cm with 6-8 m radius of the cavity. The flow of water into the cavity is spherical and the yield is low. The failure of a cavity well is usually due to caving of the clay roof. Since the depth is usually small, deep well pumps are not necessary and thus the capital costs of construction, development and installation of pumpset of a cavity well are low.

Yield of Cavity Well

For the unsteady flow condition, the pumping rate Q of a cavity well is given by

$$s = \frac{Q\sqrt{S_s}}{6K\sqrt{\pi t}} + \frac{Q}{2\pi k r} \quad \text{...(7.13)}$$

where s = drawdown in the observation well at a distance r from the cavity well

Q = constant pumping rate

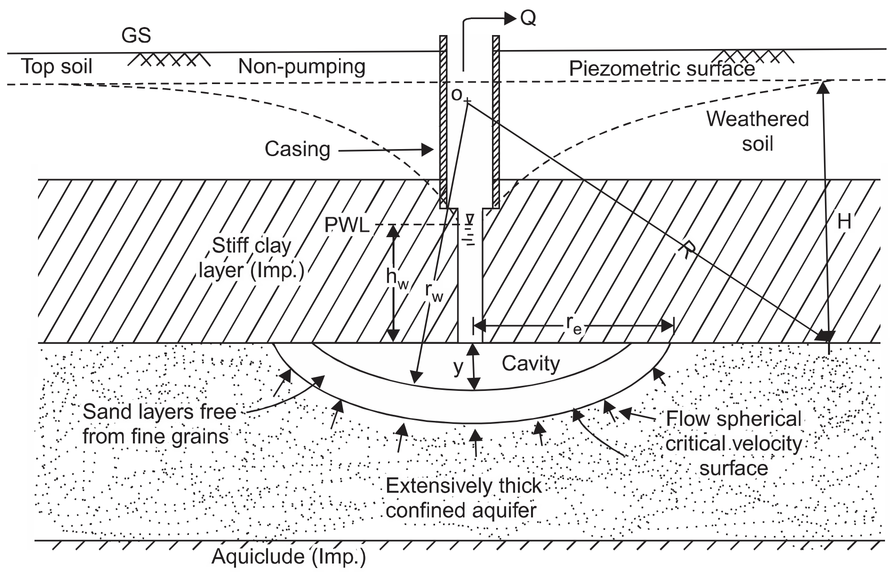

Fig. 7.4 Flow into a cavity well

S_s = specific storage coefficient (*i.e.,* for unit aquifer thickness)

K = permeability of the aquifer

t = time since pumping began

For steady state flow condition, the well yield is given by

$$Q = \frac{2\pi Ky\,(H - h_w)}{1 - r_w/R} \qquad ...(7.14)$$

and the width of the cavity, Fig. 7.4

$$r_e = \sqrt{(2r_w - y)y} \qquad ...(7.15)$$

where y = depth of cavity (at the centre)

r_w = radius of cavity

R = radius of influence

Example 7.5 *The following data are obtained from a cavity tube well:*

Discharge	*30 lps*
Drawdown	*4 m*
Permeability of the aquifer	*50 m/day*
Depth of cavity	*20 cm*
Radius of influence	*150 m*

Determine the radius and width of cavity.

Solution Well yield $Q = \dfrac{2\pi Ky\,(H - h_w)}{1 - \dfrac{r_w}{R}}$

$$\frac{30}{1000} = 2\pi \times \frac{50}{24 \times 60 \times 60} \times \frac{0.20 \times 4}{1 - \dfrac{r_w}{150}}$$

∴ Radius of cavity, r_w = **135.5 m**

Width of cavity, $r_e = \sqrt{(2r_w - y)y} = \sqrt{(2 \times 4.5 - 0.2)\,0.2}$ = **7.36 m**

7.8 HYDRAULICS OF OPEN WELLS

Theis equation does not apply for shallow dug open wells since there is no instantaneous release of water from the aquifer, most of the water being pumped only from storage inside the well (Fig. 7.5).

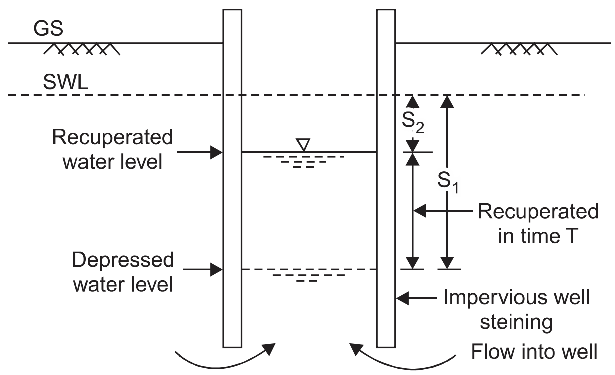

Fig. 7.5 Recuperation test in open wells

In alluvial soil, if the water is pumped at a high rate the depression head (static water level–water level inside the well during pumping) will increase, which may cause excess gradients resulting in loosening of sand particles (quick sand phenomenon). This limiting head is called 'critical depression head'. The 'safe working depression head' is usually one-third of the critical head and the yield under this head is called the *maximum safe yield* of the well.

Yield Tests

The following tests may be performed to get an idea of the probable yield of the well:

(*a*) Pumping test

(*b*) Recuperation test

(*a*) *Pumping Test.* In the pumping test, the water level in the well is depressed to an amount equal to the safe working head for the sub-soil. Then the water level is kept constant by making the pumping rate equal to the percolation into the well. The quantity of water pumped in a known time gives an idea of the probable yield of the well of the given diameter. The test may be carried out in an existing open well.

In hard-rock areas,

if D = diameter of the well

d = depth of water column

Q = pumping rate

t = time required for emptying the well

then,

Rate of seepage into the well

$$= \frac{\text{Volume of water pumped out} - \text{Volume of water stored in the well}}{\text{Time of pumping}}$$

$$= \frac{Qt - \dfrac{\pi D^2}{4} \times d}{t} \quad \text{...(7.16)}$$

(*b*) *Recuperation Test*. In the recuperation test, the water level in the well is depressed by an amount less than the safe working head for the subsoil. The pumping is stopped and the water level is allowed to rise or recuperate. The depth of recuperation in a known time is noted from which the yield of the well may be calculated as follows (Fig. 7.5).

Let the water level inside the well rise from s_1 to s_2 (measured below static water level, *swl*) in time T. If s is the head at any time t, from Darcy's law

$$Q = KAi$$

if a head s is lost in a length L of seepage path

$$Q = KA \frac{s}{L}$$

$$Q = CAs$$

where the constant $C = \dfrac{K}{L}$ and has dimensions of T^{-1}.

If in a time dt, the water level rises by an amount ds

$$Q\,dt = -A\,ds$$

the –ve sign indicates that the head decreases as the time increases.

Putting $Q = CAs$

$$CAs\,dt = -A\,ds$$

$$C \int_0^T dt = \int_{s_1}^{s_2} -\frac{ds}{s}$$

$$\therefore \qquad C = \frac{2.303}{T} \log_{10} \frac{s_1}{s_2} \quad \text{...(7.17)}$$

Assuming the flow is entirely from the bottom (impervious steining of masonry), the yield of the well

$$Q = CAH \quad \text{...(7.17}a\text{)}$$

where Q = safe yield of the well

A = area of cross section of the well

H = safe working depression head

C = specific yield of the soil

From Eq. (7.17*a*) $Q = C$ when $A = 1$, $H = 1$, *i.e.*, the specific yield of the soil is the discharge per unit area under a unit depression head and has dimension of T^{-1} (1/time) and the usual values are

$C = 0.25$ hr^{-1} for clayey soil

$C = 0.50$ hr^{-1} for fine sand

$C = 1.00$ hr^{-1} for coarse sand

The value of C is usually determined from a recuperation test, (Eq. (7.17)).

Example 7.6 *A well of size 7.70 × 4.65 m and depth 6.15 m in lateritic soil has its normal water level 5.08 m below ground level (bgl). By pumping for* $1\frac{1}{2}$ *hours, the water level was* *depressed to 5.93 m bgl and the pumping was stopped. The recuperation rates of the well during 4 hours after the pumping stopped are given below. The total volume of water pumped during $1\frac{1}{2}$ hours of pumping was 32.22 m^3. (no well steining is provided)*

Recuperation rates

Time since pumping stopped (min)	*Water level bgl (m)*
0	5.930
15	5.890
30	5.875
45	5.855
60	5.840
90	5.820
120	5.780
180	5.715
240	5.680

Determine

(*i*) *Rate of seepage into the well during pumping.*

(*ii*) *Specific yield of the soil and specific capacity of the well.*

(*iii*) *Yield of the well under a safe working depression head of 0.85 m.*

(*iv*) *The area of crop that can be irrigated under the well (assume a peak consumptive use of 4 mm and irrigation efficiency of 75%).*

(*v*) *Diameter of the well in such a soil to get an yield of 3000 lph under a safe working depression head of 0.8 m.*

Solution (*i*) Seepage into the well—from pumping data:

Volume of water pumped out = 32.22 m^3

Volume of water stored in the well (that was pumped out)

$$= (7.70 \times 4.65)\,(5.93 - 5.08) = 30.5 \text{ m}^3$$

Rate of seepage into the well

$$= \frac{32.22 - 30.5}{1.5} = \mathbf{1.15\ m^3/hr}$$

(*ii*) Specific yield of the soil

$$C = \frac{2.303}{T} \log_{10} \frac{s_1}{s_2} = \frac{2.303}{4} \log_{10} \frac{5.93 - 5.08}{5.68 - 5.08}$$

$$= 0.09 \text{ hr}^{-1} \text{ (or m}^3\text{/hr per m drawdown)}$$

Specific capacity of the well is its yield per unit drawdown

$$Q = CAH$$

∴ Specific capacity = $Q/H = CA$ = 0.09 (7.70 × 4.65)

= **3.58 m^3 hr^{-1}/m** (or m^2/hr)

(*iii*) Safe yield of the well

$$Q = CAH = 0.09\ (7.70 \times 4.65)\ 0.85 = 3.04\ \text{m}^3/\text{hr}$$

which is more than twice the seepage into the well during pumping.

(*iv*) Area of crop that can be irrigated under the well:

Data to draw the curve s_1/s_2 vs. t (s_1 = total drawdown, s_2 = residual drawdown): SWL = 5.08 m, s_1 = 5.93 – 5.08 = 0.85 m

Time since pumping stopped t (min)	*Water level bgl (m)*	*Residual drawdown $s_2 = wL - SWL$ (m)*	*Ratio (s_1/s_2)*
0	5.930	0.850 (= s_1)	1.00
15	5.890	0.810	1.05
30	5.875	0.795	1.07
45	5.855	0.775	1.09
60	5.840	0.760	1.11
90	5.820	0.740	1.15
120	5.780	0.700	1.21
180	5.715	0.635	1.33
240	5.680	0.600	1.41

From the plot of 's_1/s_2 vs. time' on a semi-log paper (Fig. 7.6), it is seen that s_1/s_2 = 9.5 after 24 hours of recovery (by extending the straight line plot), and the residual drawdown after 24 hours, $s_{24} = \frac{0.85}{9.5} \approx 0.09$ m; hence the depth of recuperation per day = 0.85 – 0.09 = 0.76 m and the volume of water available per day ≈ (7.70 × 4.65) ≈ 27.2 m^3. With an average peak consumptive use of 4 mm for the type of crops grown and irrigation efficiency of 75%, the area of crop (A_{crop}) that can be irrigated under one well in lateritic soils is

$$\frac{4}{1000 \times 0.75} \times A_{crop} = 27.2$$

∴ A_{crop} = 5100 m^2 or **0.5 ha**

(*v*) Diameter of the well to yield 3000 lph:

$$Q = CAH$$

$$\frac{3000}{1000} = 0.09 \times \pi \times \frac{D^2}{4} \times 0.8$$

∴ D = 7.3 m, which is too big

It may be noted that it is not advisable to go deeper in these areas otherwise salt water instrusion takes place.

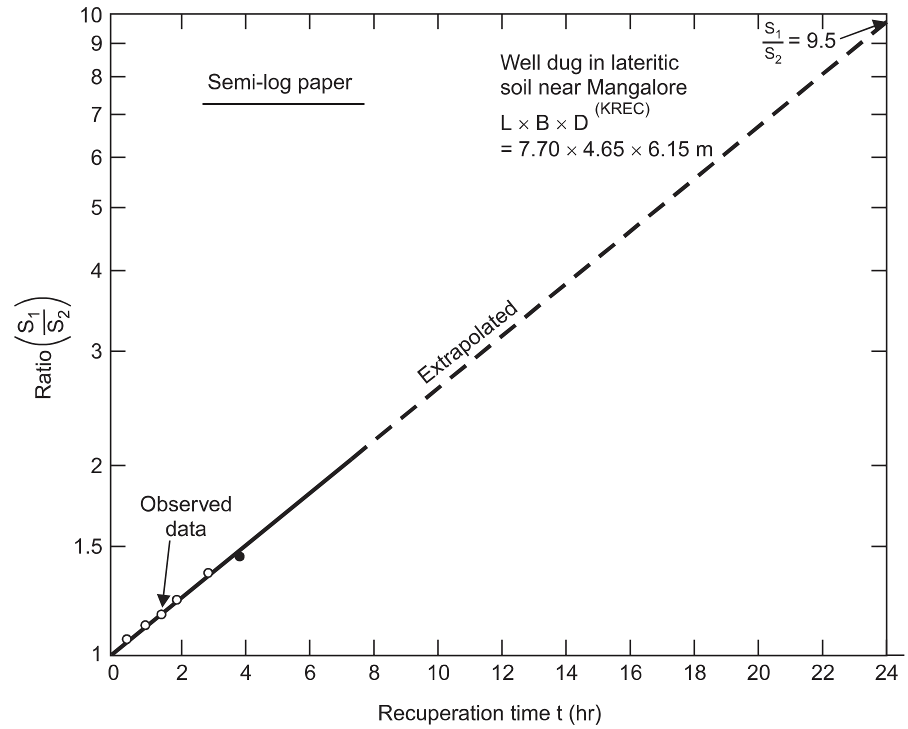

Fig. 7.6 Plot of recuperation test data (Example 7.6)

7.9 CONSTRUCTION OF OPEN WELLS

In alluvial soil, where an impervious vertical steining is provided to support the soil, percolation into the well is entirely from the bottom and depends on the area of cross-section of the well. Bigger diameter wells are recommended in such soil to give larger yields. In case of wells in rocky substrata with fissures and cracks, the lower portion of the steining may be provided with alternate bands of masonry laid dry (*i.e.,* without cement mortar) (Fig. 7.7), and the percolation into the well is mostly from the sides through fissures and cracks in the weathered rock. In such wells, higher yields are obtained by going deeper, as long as the weathering and fractures are evident rather than making the wells wider or larger diameter. Larger diameter wells also involve large volume of excavation in rocks and the mounds of excavated rock deposited on the ground surface occupy considerable area of cultivable land. Sometimes, it is proposed to widen when it is felt that such widening will, include some well-defined fissures and fractures.

Some of the existing wells may be revitalised by deepening by blasting; vertical bores may be drilled at the bottom of the well when it is felt it will tap some layer under pressure, *i.e.,* a dug-cum-borewell (Fig. 7.8), with a centrifugal pump kept at the bottom of the open well and the suction pipe lowered inside the bore, thus reducing the suction lift and saving the costs involved in deep well turbine pump or submersible pump installations in drilled deep wells from the ground surface. Lateral bores horizontal or inclined, may be drilled in the direction of certain well-defined fractures yielding water.

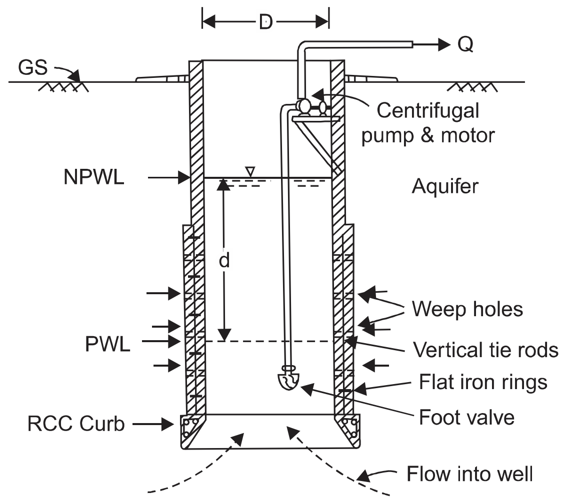

Fig. 7.7 Open well construction

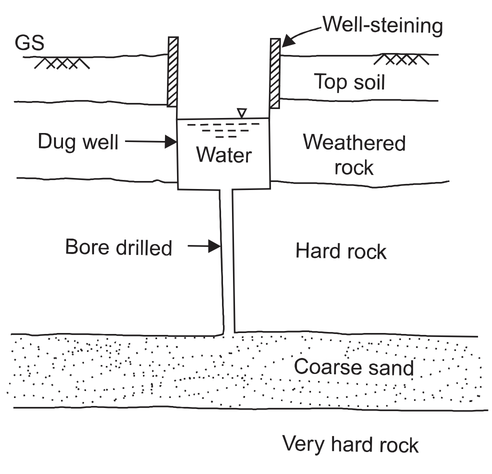

Fig. 7.8 Dug-cum-borewell

7.10 SPACING OF WELLS

Pumping wells should be spaced far apart so that their cones of depression will not overlap over each other resulting in the reduction of their yields and/or increased drawdowns (Fig.7.9), *i.e.,* to avoid 'well interference', the wells should be spaced beyond their radii of influence. This is roughly estimated to be around 600–1000 m in alluvial area and around 100–200 m in hard rock areas.

An open dug well should be located beyond the cone of depression of the tubewell; otherwise when the tubewell is pumping, it will dewater the open well. The open well can get water only when the tubewell pumping is stopped and fast recuperation takes place.

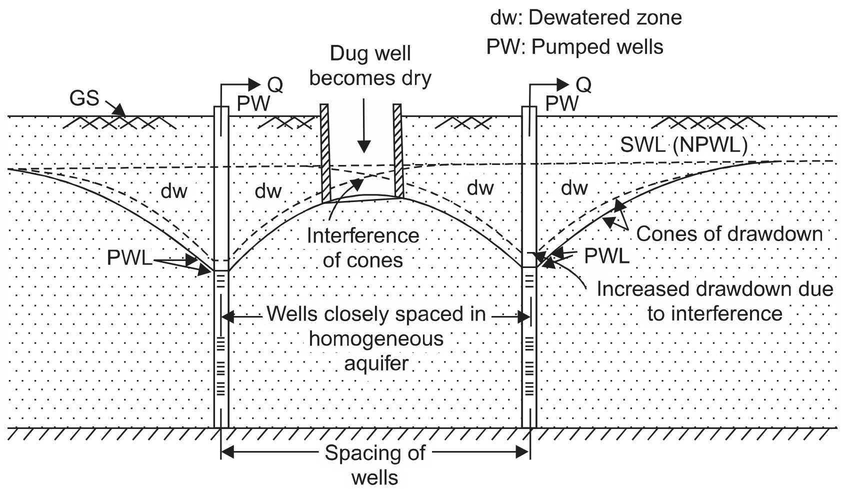

Fig. 7.9 Well interference

QUIZ VII

I Choose the correct statement/s in the following:

1 The underground formations, which serve as good aquifers are in the order:

(*i*) consolidated formations of clays and shales
(*ii*) rock with no signs of weathering or fractures
(*iii*) rock with fissures and cracks
(*iv*) cavernous lime stones
(*v*) sand stones
(*vi*) vescicular basalts
(*vii*) unconsolidated gravels, sands and alluvium

2 The soil properties characteristic of good water yield are:

(*i*) porosity
(*ii*) permeability
(*iii*) specific yield
(*iv*) storage coefficient
(*v*) transmissibility
(*vi*) uniformity coefficient > 3
(*vii*) uniformity coefficient < 2
(*viii*) effective size > 0.1 mm
(*ix*) Reynolds number > 10
(*x*) specific capacity of the well > 30 lpm/m
(*xi*) all the above characteristics

(1-except *i, ii,* 2 *ii, iii, iv, v, viii, x*)

II Match the items in 'A' with the items in 'B':

A	B
(*i*) Ground water flow	(*a*) Recuperation test
(*ii*) Unconsolidated alluvium	(*b*) Bore at the bottom of open well
(*iii*) Aquiclude	(*c*) Lateral or vertical bores
(*iv*) Specific yield (S_y)	(*d*) Well spacing
(*v*) Confined aquifer	(*e*) $n - S_r$
(*vi*) Storage coefficient	(*f*) Artesian
(*vii*) Transmissibility (T)	(*g*) $f(K_w, E_s)$

(*viii*) Rate of ground water flow (Q)	(*h*) KH or Kb
(*ix*) Reynolds number (R_e)	(*i*) $T\ iW$
(*x*) Dupuit's equation	(*j*) $\rho vd/\mu$
(*xi*) Specific capacity	(*k*) $\dfrac{Q}{sw} \approx \dfrac{T}{1.2}$
(*xii*) Open well	(*l*) Stabilised drawdown
(*xiii*) Well revitalisation	(*m*) Clay
(*xiv*) Dug-cum-borewell	(*n*) Aquifer
(*xv*) Well interference	(*o*) Darcy's law

III Say 'true' or 'false'; if false, give the correct statement:

(*i*) The transmissibility of a confined aquifer depends upon the depth of the water table while that of the water table aquifer does not.

(*ii*) The available yield of a tube well can be doubled by doubling the diameter.

(*iii*) The specific yield of an aquifer may be more than its porosity.

(*iv*) Storage coefficient is the same as specific yield for a water table aquifer.

(*v*) Flow in a medium sand aquifer is entirely laminar.

(*vi*) Plants usually extract water from the capillary zone (the intermediate belt or vadose zone).

(false: *i, ii, iii*)

QUESTIONS

1 (*a*) Define 'transmissibility' and 'storage coefficient' of an aquifer.

(*b*) Calculate the discharge from a tubewell of 20-cm diameter penetrating fully into a confined aquifer of 20-m thick and having a permeability of 40 m/day. The drawdown in the well is 3 m and zero drawdown at 300 m from the well.

If the diameter of the well is doubled, find the percentage increase in the yield, the other conditions remaining the same.

State the assumptions in the formula you use. (1303.7 lpm)

2 A tubwell penetrates fully an unconfined aquifer. Calculate the discharge from the well in lpm from the following data:

Diameter of the well	30 cm
Drawdown in the well	3 m
Effective length of the strainer under the above drawdown	10 m
Coefficient of permeability of the aquifer	40 m/day
Radius of zero drawdown	300 m

3 A 20-cm well penetrates 25 m below the static water table. After 24 hours of pumping out at the rate of 800 lpm, the water level in a test well at 80 m from the pumping well is lowered by 0.53 m and in a test well 20 m away 2.11 m. Find the coefficient of transmissibility of the aquifer.

4 (*a*) What is the nature of ground water flow? State the law governing the flow with limitations, if any.

(*b*) In an area of 100 ha, the water table dropped by 4.5 m due to continuous ground water pumping. If the porosity of the aquifer soil is 26% and the specific retention is 10 per cent, determine:

(*i*) the specific yield of the aquifer.

(*ii*) the decrease in the ground water storage. (16%, 72 *ham*)

5 In a certain alluvial basin of 120 km^2, 100 Mm^3 of ground water was pumped in a year and the ground water table dropped by 5 m during the year. Assuming no replenishment, estimate the specific yield of the aquifer. If the specific retention is 12%, what is the porosity of the soil? (16.7%, 28.7%)

6 An artesian aquifer 25-m thick has a porosity of 17% and bulk modulus of compression 2400 kg/cm^2. Estimate the storage coefficient of the aquifer. What fraction of this is attributable to the expansibility of water ?

Bulk modulus of elasticity of water = 2.14×10^4 kg/cm^2. (0.00106, 1.87%)

7 A well penetrates into an unconfined aquifer having a saturated depth of 50 m. The discharge is 250 1pm at 8 m drawdown. What would be the discharge at 10 m drawdown. The radius of influence in both the cases may be taken as same.

8 (*a*) Explain: 'the water balance of a catchment'.

(*b*) In a given year over 60 km^2 catchment, 120 cm of rainfall was received and 1000 ha-m was discharged through the outlet. The ground water table rose by 30 cm and the average specific yield of the soil was 18%. The soil moisture increased by 5 cm on an average. Estimate the evapotranspiration during the year. (93 cm)

9 (*a*) Describe the method of construction of open wells

(*i*) in a soil where a clayey stratum is encountered.

(*ii*) in rocky sub-strata.

(*b*) A well of size 6.60 × 4.05 m and depth 4.7 m in the lateritic soil near Mangalore (west coast of India) has its normal water level at 3.825 m below ground level (bgl). By pumping for $1\frac{1}{2}$ hours, the water level (bgl) was depressed to 4.525 m and the pumping was stopped. The recuperation rates of the well during $2\frac{1}{2}$ hours after the pumping stopped are given below. The total volume of water pumped during $1\frac{1}{2}$ hours of pumping was 28.87 m^3 (no well steining is provided)

Recuperation rates	
Time since pumping stopped (min)	*Water level, bgl (m)*
0	4.525
10	4.365
20	4.245
30	4.135
40	4.075
50	4.015
60	3.985
70	3.960
80	3.950
90	3.935
120	3.920
150	3.902

Determine

(*i*) Rate of seepage into the well during pumping

(*ii*) Specific yield of the soil and specific capacity of the well

(*iii*) Yield of the well under a safe working depression head of 0.7 m

(*iv*) The area of crop that can be irrigated under the well, assuming a peak consumptive use of 4 mm and irrigation efficiency of 75%.

(*v*) Diameter of the well in such a soil to get an yield of 3000 lph under a safe working depression head of 0.7 m (note that it is not advisable to go deeper in these areas lest salt water intrusion may not take place).

10 In a recuperation test, the static water level in an open well was depressed by pumping by 3 m and it recuperated 1.5 m in 1 hour. If the diameter of the well is 3 m and the safe working depression head is 2.4 m, find the average yield of the well in lpm. What area of crop can come under this well assuming a peak consumptive use of 5 mm and irrigation efficiency of 75%?

11 Determine the diameter of an open well in coarse sand to give an average yield of 200 lpm under a safe working depression head of 2.5 m (Hint: for coarse sand $C \approx 1\ \text{hr}^{-1}$).

12 Distinguish between:

(*i*) Specific capacity of a well and specific yield of an aquifer

(*ii*) Aquifer and acuiclude

(*iii*) Open wells and tube wells

(*iv*) Water table and artesian aquifers

(*v*) Drainage divide and ground water divide

13 Write short notes on:

(*i*) Well development

(*ii*) Well spacing

(*iii*) Radius of influence

(*iv*) Validity of Darcy's law

(*v*) Dug-cum-borewell

(*vi*) Well revitalisation

(*vii*) Well interference

(*viii*) Recuperation test for open well