from 1 to 6 depending on the nature of the rock and the size of the dug well (Michael et al., 2008; Sarma, 2009). Note that dug-cum-bore wells are hydraulically superior to ordinary dug wells and provide higher yields compared to ordinary dug wells. However, their success depends on the availability of a good confined aquifer at a reasonable depth below the bottom of the dug well.

- The depth of the bores from the bottom of the well usually varies from 20 to 30 m in hard rocks. In case of unconsolidated formations, the bored hole is lined by a pipe. In sedimentary formations, boring consists of drilling a small bore of diameter usually ranging from 7.5 to 15 cm.

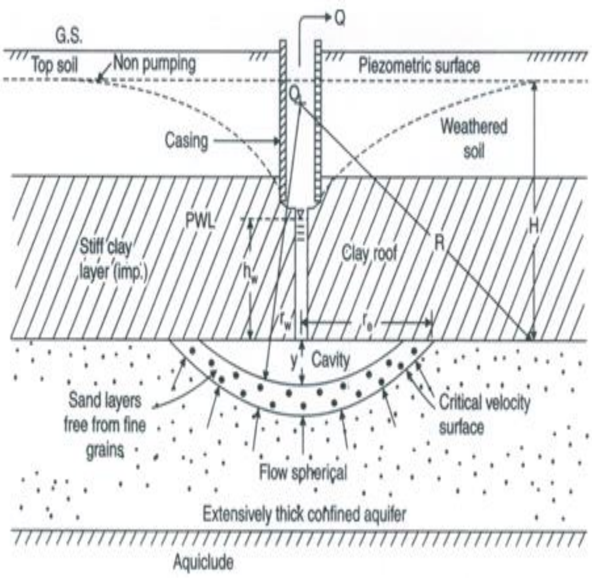
- c) Tube well: Tube wells are wells consisting of pipes ranging in size from 6 to 45 cm in diameter and sunk into an aquifer (Sarma, 2009). Tube wells are constructed by installing a pipe below the ground surface passing through different geological formations comprising water-bearing and non-water-bearing strata. These wells are usually deep penetrating more than one aquifer. Blind pipes are located at the non-water bearing strata and perforated pipes or well screens are placed against the aquifer.

- d) Bore wells: Tube wells in hard rock areas are called bore wells. These wells are not cased since the hole is able to hold on its own except in the top weathered portion.

- e) Cavity wells:

Cavity well is a shallow tube well drilled in an alluvial formation. If a relatively thin impervious formation consisting of stiff clay, conglomerate or stone is encountered at a shallow depth underlain by an extensive thick sandy confined aquifer, then it is an excellent location for constructing 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 as shown in figure.



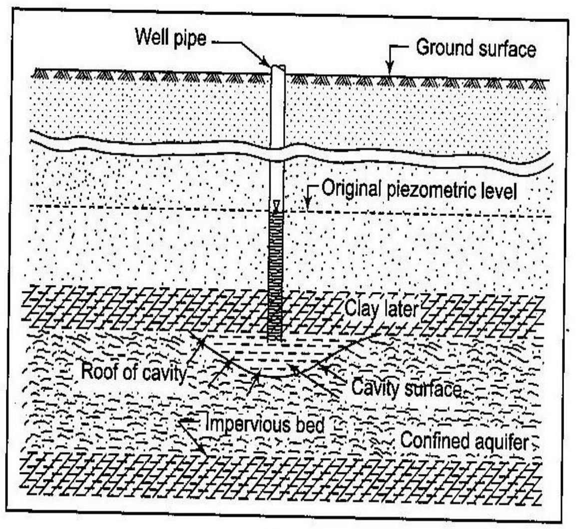


Fig. 4.10 Schematic sketch of a cavity well. (Anjaneyulu, 1972)

Water enters the cavity well through the bottom only and screens are not used in such wells. Thus, the cavity wells do not penetrate the aquifer, and hence they are also known as non-penetrating wells.

The flow of water into the cavity is spherical and the yield is low. Cavity wells have usually a shorter lifespan and the failure is caused mainly due to the collapse of the clay roof. Therefore, an essential requirement for a cavity well is that it should have a strong and reliable roof. Since the depth of the cavity well is usually small, deep well pumps are not necessary. Thus, the capital costs of construction, development and pump set installation for a cavity well are low, and hence cavity wells are very economical compared to other tube wells.

It draws water through the cavity formed at the bottom of the pipe in the water bearing formation. The well casing is made of solid pipes and rests over a confined water bearing formations of sand and gravel. Water enters the well through the bottom only.

HYDRAULICS OF WELLS

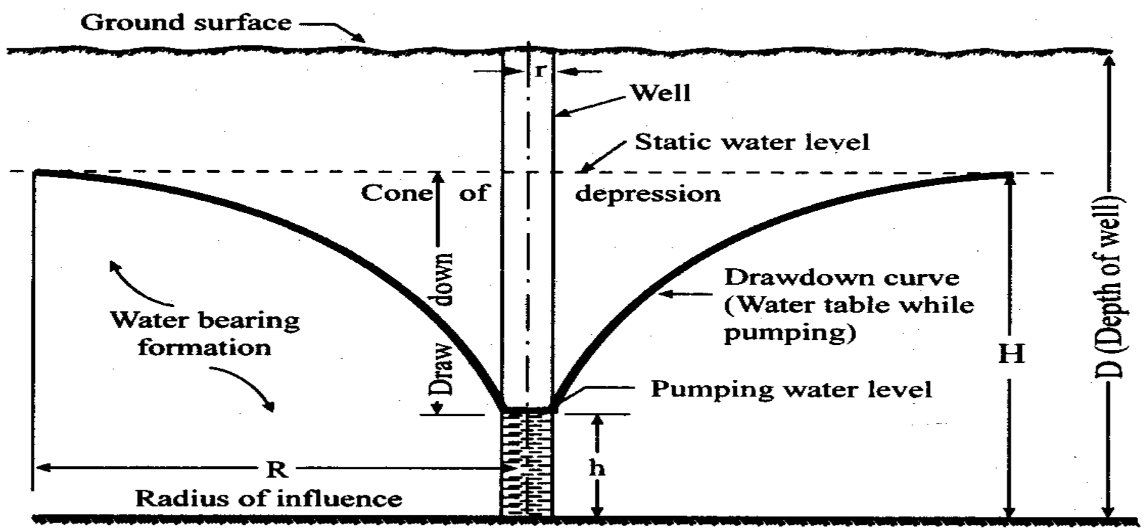


Fig. 2.12. Definition sketch illustrating the hydraulics of flow into a well penetrating an unconfined aquifer.

Irrigation wells operate according to certain fundamental hydraulic principles. Water flows into the well from surrounding aquifer because the pumping of the well creates a difference in pressure.

Before pumping, the water in the well stands at a height equal to the static water level in the saturated sand around the well. When pumping starts, the water in the well is pulled down and the water starts to flow into the well from the water bearing formation because the water level or pressure inside the well during pumping is lower than it is in the aquifer outside the well.

This pressure difference is the 'drive' that cause the water to move through the pores of the sand towards the well. The closer the water gets to the well, the faster it has to move because the area through which it has to travel is continuously decreasing.

DEFINATION OF TERMS

1) Static water level

Def.^{n}: The level at which the water stands in a well before pumping starts is called static water level.

The pressure of water at static water level is atmospheric pressure. It is generally the level of the watertable in case of unconfined aquifer and it may be piezometric level in case of confined aquifer. It is generally expressed as the distance from the ground surface to the water level in the well.

2) Pumping water level

Def^n: This is the level at which water stands in a well when pumped at any time. This level is variable and changes with quantity of water being pumped.

3) Drawdown

Def^n: Drawdown at any instant time is the difference between the static water level and the pumping water level at that instant time.

Drawdown affects the yield of well. The maximum practical drawdown in a tube well is limited to the pumping water level reaching the top of well screen.

4) Piezometric Surface

The piezometric surface is height at which water will stand in a piezometer or pipe open at the end which extend into aquifer. The height *h* to which the water will rise in the pipe from the base equal to the pressure p at the bottom of the pipe divided by the unit weight *w* of water.

$$h = p / w$$

4) Area of Influence / Cone of Depression

Def^n: As water is pumped out of the well, it gets the supply of water from the surrounding formations. There is thus an imaginary inverted cone formed around the well having static water level as base and pumping water level as apex. This inverted cone is called cone of depression. The area which gets affected by the pumping of the well is called the area of influence.

As more and more water pumped out of the well, it takes more water from storage and as a result, the radius of influence gets extended till a position is reached when the rate of discharge from the well become equal to the rate recuperation from storage of the well. It is at that instance when cone of depression gets stabilized.

5) Well Yield

Def^n: It is the volume of water pumped out per unit of time from the well. It is commonly expressed in litres per second or litres per minute.

The rate at which water can penetrate through an aquifer depend on the slope of the watertable (unconfined aquifer) or piezometric surface (confined & semi-confined aquifer) and the permeability of the material constituting the aquifer.

6) Specific Capacity of Well
Def^{n}: It may be defined as well yield per unit of drawdown. It is commonly expressed in litres per minute per metre of drawdown.

7) Filter Points
In deltaic regions, where the aquifer formations are of course sand and gravel, the tube wells are shallow and consist of a well screen and a short length of casing pipe. Such wells are called filter points.

Predicting Well Yield
Darcy's theory established the fundamentals of groundwater movement. Dupuit, a French hydraulic engineer established the analysis of seepage phenomenon and derived well equations based on the following assumptions
1) The hydraulic gradient is the same at all points in a vertical section of an aquifer.
2) The hydraulic gradient at the water table is equal to the slope of water surface at that point.

Pumping Tests of Wells
Pumping tests are conducted to obtain information on the characteristics of the water bearing formations of the well. Such tests are provide information on the hydro-geological properties of the well site such as types of aquifer and its areal extent, thickness of aquifer, water table gradients and recharge boundaries. The hydraulic properties of aquifer such as hydraulic conductivity, transmissibility, storage coefficient, specific yield, leakage factor and hydraulic resistance could be obtained from pumping tests data. A pumping test will also provide information about drawdown and yield capacity of well. This will help in selecting pump.

Steps of pumping tests
1) Selection of test site.
2) Installation of observation wells
   a) Number of observation well
   b) Spacing of observation well
   c) Type of aquifer
   d) Hydraulic conductivity
   e) Length of well screen
   f) Stratification

g) Depth of the observation well
h) Diameter of observation well
i) Length of perforated portion of the observation well
j) Size of perforations of observation well
k) Installation of observation well

3) Duration of pumping tests.
   a) Water level measurement.

STEADY STATE FLOW TO WELLS IN UNCONFINED AQUIFER

Steady state flow: The flow is said to be steady when the flow conditions at any instant are constant.

$$dv / dt = 0$$

Where v = velocity of flow and t = time.

Dupuit distinguished between unconfined and confined aquifer. To derive an equation of flow into an unconfined or gravity well, he considered the case of a cylindrical island of pervious sand surrounded by water at constant level and underlain by a horizontal impervious base.

Applying eq. Q = *K*ia to an arbitrary cylindrical surface surrounding a unconfined well located at the centre of the island and penetrating the horizontal base, using plane polar coordinates with the well as the origin, the well discharge Q at any distance r equals,

$$Q = K\ i\ a = 2\ \pi\ r\ h\ K\ (dh/dr)$$

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

Integrating for boundary conditions at the well, h = h_w ar r = r_w and h = H at r = R

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

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

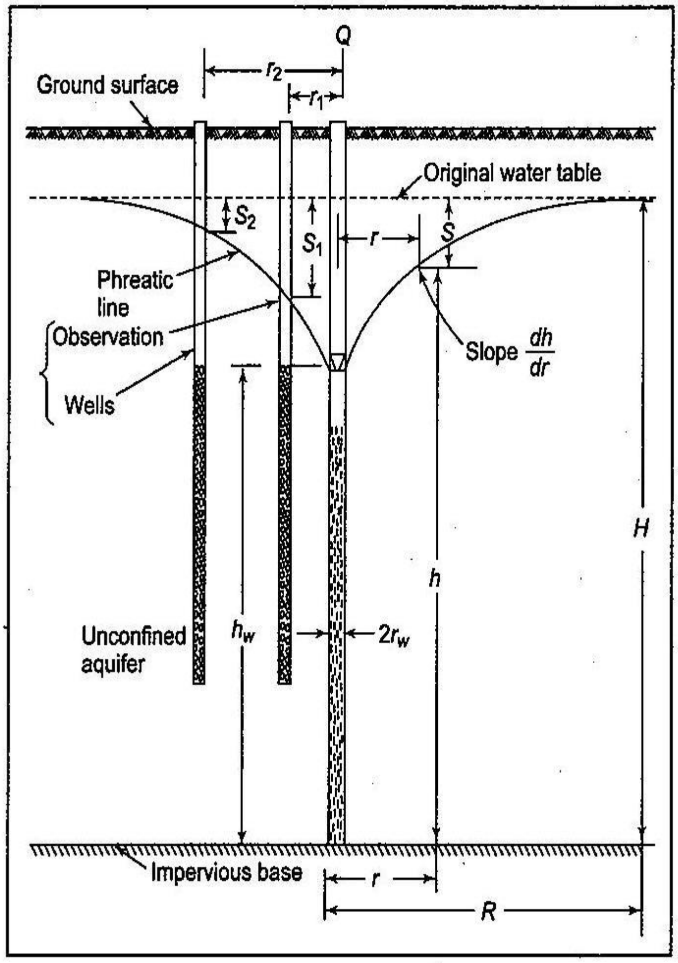


Fig. 2.4 Definition sketch illustrating steady state flow into a fully penetrating well in an unconfined aquifer

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

$$= \frac{\pi K(H + h_w)(H - h_w)}{\ln (R/r_w)} \quad (2.9)$$

in which,

Q = constant discharge rate, m^3/s

H = original elevation of the water surface, measured from the impervious base, m

h_w = depth of water in the well, measured from the impervious base, m

R = radius of influence of the well field, m

K = hydraulic conductivity of the aquifer, m/s

r_w = radius of the well, m

Thiem (1870) established the practicability of Eq. (2.9). He showed that beyond a certain distance from the well, the drawdown of the phreatic surface from the original ground water table became negligible. The Dupuit-Thiem theory, stated above, is of paramount importance in well hydraulics.

Evaluation of Hydraulic Properties

The hydraulic properties of the aquifer can be evaluated by using Eq. (2.9) for steady state conditions.

Let the steady state drawdown at the observation wells be s_1 and s_2 and r_1 and r_2 the distances of the observation wells from the centre of the test well (Fig. 2.4).

Since $$h = H - s$$

Eq. (2.9) can be transformed as

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

which can be expanded into

$$Q = \frac{\pi K[(H-s_2)^2 - (H-s_1)^2]\,2H/2H}{\ln(r_2/r_1)}$$

in which h_1 and h_2 are elevations of water surface, measured from impervious base at observation wells 1 and 2.

Replacing $s - s^2/2H$ by s' = the corrected drawdown, yields

$$Q = \frac{2\pi KH(s_1' - s_2')}{\ln(r_2/r_1)} \tag{2.10}$$

in which,

$$s_1' = s_1 - s_1^2/2H$$

$$s_2' = s_2 - s_2^2/2H$$

s_1' and s_2' are corrected steady-state drawdowns at points 1 and 2, respectively,

or $$Q = \frac{2\pi T(s_1' - s_2')}{\ln(r_2/r_1)}$$

in which,

$T = KH$ = assumed transmissibility of the aquifer, m^2/s.

or $$T = \frac{Q\ln(r_2/r_1)}{2\pi(s_1' - s_2')} \tag{2.11}$$

The values of transmissibility and hydraulic conductivity can be estimated using Eq. (2.11) only when the drawdown in the aquifer is small in relation to the thickness of the saturated portion of the aquifer.

2.3.2 Steady State Flow to Wells in Confined Aquifer

To derive the radial flow equation for a well completely penetrating a confined aquifer (Fig. 2.5), Dupuit used Eq. (2.4). The flow is assumed two-dimensional to a well centred on a circular island and penetrating a homogeneous and isotropic aquifer. Since the flow is horizontal everywhere, the Dupuit assumptions apply without error. Using plane polar coordinates, with the well as the origin, the well discharge Q, at any distance r, when the thickness of the aquifer is b, is determined as follows:

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

or

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

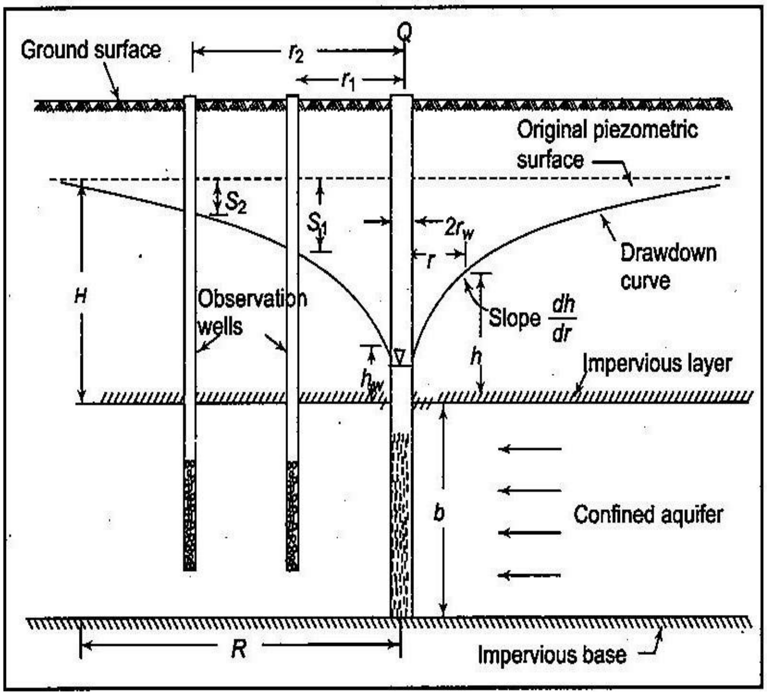


Fig. 2.5 Definition sketch illustrating the hydraulics of flow in a fully penetrating well in a confined aquifer

Integrating for the boundary conditions at the well, $h = h_w$ at $r = r_w$ and $h = H$ at $r = R$ at the extremity of the area of influence,

$$\int_{h_w}^{h} dh = \frac{Q}{2\pi Kb}\frac{dr}{r}\int_{r_w}^{h}\frac{dr}{r}$$

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

After rearranging,

$$Q = \frac{2\pi Kb(H - h_w)}{\ln(R/r_w)} \tag{2.12}$$