in which,

b = thickness of the horizontal pervious stratum confined between two horizontal impervious strata, m

The other variables are the same as defined in Eq. (2.9). Equation (2.12) can be used to evaluate the hydraulic properties of an aquifer, based on the measurements made during a pumping test. This equation is also known as Dupuit-Thiem equation. Thiem (1870), who worked independently of Dupuit, derived Eq. (2.9) and (2.12), based on the following assumptions which were more precisely defined than those of Dupuit:

1. The aquifer has a seemingly infinite areal extent.
2. The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test.
3. The pumped well penetrates the entire thickness of the aquifer and receives water from its entire thickness by horizontal flow.
4. Flow to the well is in steady state.

Evaluation of Hydraulic Properties

To determine the hydraulic properties of the water-bearing formations, in case of wells in a confined aquifer, any one of the following two procedures can be used:

Procedure 1. On a semi-logarithmic paper, the observed drawdown in each piezometer or observation well is plotted against the corresponding time, with drawdown on the vertical axis, on a linear scale and with time on the logarithmic scale. The time drawdown curve of each piezometer, that best fits the points is drawn. It will be observed that the curves of the different piezometers run parallel for the later time data and thus, the mutual distance is constant. This implies that the hydraulic gradient is constant and the flow in the aquifer can be considered to be in a steady state. The values of the steady state drawdown of two piezometers are substituted in Eq. (2.12) together with the corresponding values of r and the known value Q to solve for the transmissibility $T = Kb$.

$$Q = \frac{2\pi T(s_1 - s_2)}{\ln (r_2 / r_1)} \tag{2.13}$$

where, s_1 and s_2 are the values of drawdown of the piezometers and r_1 and r_2 distances from the centre of the well, respectively.

The same process should be repeated for all possible combinations of piezometers to get a more precise value of T. Theoretically the results should show a close agreement. However, an average value can be used as the results usually give slightly different values of T.

Procedure 2. The observed steady state drawdown s of each observation well is plotted against the distance r between the pumped well and the piezometer on a semi-logarithmic paper. The distance is plotted on the horizontal axis on a logarithmic scale, and the drawdown on the vertical axis on a linear scale. The best-fitting straight line is drawn through the plotted points, which is the distance-drawdown curve (Fig. 2.6). The slope of the distance-drawdown curve for logarithmic cycle of distance, Δs, is determined. The value of Δs, when substituted in Eq. (2.13), gives the following relationship:

$$Q = \frac{2\pi T \Delta s}{2.30} \tag{2.14}$$

UNSTEADY STATE FLOW

Unsteady state flow: The flow is said to be steady when the flow conditions at any instant are not constant.

dv / dt # 0

Where v = velocity of flow and t = time.

Unsteady state flow to wells in unconfined aquifers

In unsteady state flow in an unconfined aquifer with a declining water table, dewatering of the pore space is not instantaneous, but continuous for some time after drawdown. The region above the water table, through unsaturated, goes on supplying water to the receding water table. Thus, the specific yield increases at a diminishing rate with the duration of pumping. Hence, the saturated thickness of the unconfined aquifer is variable in magnitude. Assuming that the change in drawdown is negligible and almost constant in the evaluated by the procedure adopted for unsteady state flow in confined aquifer by assuming $s' = s - s^2 / 2H$ m., in which s' is the drawdown component for the decrease in saturated thickness of the unconfined aquifer.

2.4.2 Unsteady State Flow to Wells in Confined Aquifers

The solution for the determination of aquifer properties under unsteady state flow conditions was developed by Theis (1935), by introducing the time factor and storage coefficient. Theis noted that, when a well penetrating an extensive confined aquifer is pumped at a constant rate, the influence of the discharge extends outward with time. The rate of decline of the head times the storage coefficient summed over the area of influence equals the discharge. Since the water must come from a reduction of storage within the aquifer, the head will continue to decline as long as the aquifer is effectively infinite. Therefore, unsteady flow exists. However, the rate of decline decreases continuously, as the area of influence expands.

Theis' equation for unsteady state flow in aquifers, derived from the analogy between the flow of ground water and conduction of heat, is based on the following assumptions which are in addition to the assumptions mentioned for the Thiem-Dupuit Eqs. (2.9) and (2.12):

1. The aquifer is confined.
2. The flow to a well is in the unsteady state, i.e. neither the drawdown difference with time is negligible nor is the hydraulic gradient constant with time.
3. The water removed from storage is discharged instantaneously with the decline of head.
4. The well diameter is very small, i.e., the storage in the well can be neglected.

The differential equation governing the unsteady state radial flow in a non-leaky confined aquifer, in polar coordinate notations is:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \quad (2.24)$$

in which,

T = transmissibility of the aquifer, m^2/s
S = storage coefficient, dimensionless
h = hydraulic head at (r, t)
r = radial distance of the piezometer from the centre of the pumped well, m
t = elapsed time after pumping is started, s

Theis (1935) obtained the solution of Eq. (2.24), based on the analogy between ground water flow and heat conduction, and for boundary conditions $h = h_o$ before pumping and $h \to h_o$ as $r \to \infty$ as pumping begins $(t > 0)$, which may be written as

$$h_0 - h = \frac{Q}{4\pi T}\int_{r^2 s/4tT}^{\infty} \frac{e^{-u}}{u}\,du \quad (2.25)$$

in which

$$u = \frac{r^2 S}{4Tt} \quad (2.26)$$

and Q = constant discharge rate, m^3/s

The exponential integral is written symbolically as $W(u)$ which in this usage, is generally read 'well function of u' or 'Theis well function'.

The above equation in term of Theis' well function may be written as,

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

Where s = Unsteady state drawdown.

DESIGN OF IRRIGATION WELLS

The performance of irrigation well is influenced by the elements of well design, method of construction and aquifer characteristics.

Irrigation wells can be designed based on.....

1) Purpose of uses i. e. irrigation, drainage, domestic and industrial uses.
2) Hydraulic characteristics such as rainfall, runoff and recharge.
3) Hydro-geological characteristics of the aquifers.

Two general principles influencing the design of both the open wells and tube wells are the water requirement of crops to be irrigated and the location of well.

1) Water requirement: The yield potential of a well is evaluated on the basis of hydrological conditions of the area such as rainfall, runoff and recharge. When the yield potential of an area is not a limiting factor, a properly designed irrigation well should be provide the required quantity of water to irrigate the entire area owned by the farmer, keeping in view the area to be irrigated, cropping pattern and other needs such as domestic and livestock requirements.

2) Location of the well: The main factors to be considered in deciding the location of the well are the topography of the farm, type of water conveyance system (surface channel /underground pipeline), the method of irrigation to be used (Furrow/border/check-basin/sprinkler/drip), recharge possibilities of the area and safety of pumping set.

If the general slope of the farm does not exceed 1 % and the surface methods of water conveyance are used, the well should be constructed at higher elevation. But if underground pipeline water conveyance methods or sprinkler or drip systems is to be used, it is not necessary to locate the well at a high point because the location at a lower point of the farm usually facilities better yield.

Design of irrigation wells may be broadly divided into two parts:

A) Design of open wells B) Design of tube wells

Proper design of water wells (tube wells and open wells) is essential in order to obtain optimum quantity of groundwater economically from a given aquifer system. The choice of open wells or bore wells (tube wells) mainly depends on the economic condition of users, depth to groundwater availability and the quantity of water required. A majority of irrigation wells in India are open wells, drawing their water mostly from shallow unconfined aquifers.

A) DESIGN OF OPEN WELLS

A properly designed open well supplies water at the required rate and remains relatively trouble free in operation for a longer period of time. The design of an open well includes the selection of its diameter & depth and designing of well lining, its thickness, reinforcement and design of well curb. The two common types of open wells are those located in hard rock areas (consolidated formation) and those in unconsolidated formations.

1) Open wells in hard rock areas:

These wells are not cased since the hole is able to hold on its own except in the top weathered portion. A major part of geographical area of India, comprising of vast areas of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamilnadu is covered by consolidated underground formations usually known as hard rock areas. Important criteria for designing open wells are the pattern, density and the fabric of joints in these rocks.

2) Open wells in unconsolidated formations:

Open wells in unconsolidated formations are dug down about 7 to 10 m below the static water level in the dry season. The open excavation is usually circular in shape, diameter varying from 1.5 to 4.5 m. The wells, in general, derive their water from unconfined aquifers. When the wells are dug through unconsolidated formations, the wells are provided with lining to prevent cave-in the wells. The common materials used for lining are brick or stones laid in cement mortar or R.C.C. The portion of the curb (lining) surrounded by the aquifer should be perforated to permit entry of water into the well. The curb must be firmly seated at the bottom of the well. The space between the curb and sides of excavation should be filled with clean sand and gravel up to the top of the water bearing strata.

1) Well Diameter

The diameter of well should be selected on the basis of a compromise between economical and practical considerations. It has been observed in case of masonry wells, the diameter is the main factor influencing the cost of construction. From the point of view of the yield of a well, its diameter is decided on the basis of the concept of specific yield. Specific yield is defined as the volume of water released or store per unit surface area of aquifer per unit change in component of head, normal to the surface.
Specific yield is determined by the following relationship

$$K = 2.303\ (A/T) \log (H1/H2)$$

Where, K = Specific yield of a well (m^3/hr) under a depression head of 1 m.

A = Cross-sectional area of well (m^2)

H1 = Difference between water level in well at the time of stoppage of pumping and the static water level (m)

H2 = Difference between water level in well at the time T after stoppage of pumping and the static water level (m)

Let the discharge of an open well be proportional to the depression head H,

$$Q \alpha H$$

$$Q = K' H$$

Where, K' = Proportionality constant, which is the same as specific yield of the well.
Let a = Static water level (m)
b= water level when pumping is stopped (m)
c= water level at the time T' after stoppage of pumping (m).
d= Water level at any time t after stoppage of pumping (m)
e= Water level at time t+dt after stoppage of pumping (m)

The quantity of water percolating into the well in a short time dt is given by,

$$q = A \times dH$$

in which dH is the rise in water level in a short time dt

$$q = Q \times dt$$

$$Q \times dt = A \times dH$$

Substituting the value of Q from above eauation,

$$K' \times H \times dt = A \times dH$$

Separating the variables,

$$(K'/A)\, dt = (1/H)\, dH$$

Integrating the above equation for boundary conditions, $H = H_1$ at $t = 0$ and $H = H_2$ at $t = T'$

$$\int_0^{T'} \frac{K'}{A} dt = -\int_{H1}^{H2} \frac{dH}{H}$$

As the time increase, the depression head decrease, hence the negative sign is used for the limits of H.

$$\left(\frac{K'}{A}\right) T' = \ln\left(\frac{H1}{H2}\right)$$

$$2.303 \log \frac{H1}{H2} = \frac{K'}{A}\ T'$$

$$K' = 2.303 \left(\frac{A}{T'}\right) \log \frac{H1}{H2}$$

$$\left(\frac{K'}{A}\right) = \frac{2.303}{T'} \log \frac{H1}{H2}$$

in which, K'/A Specific yield per unit area of the well.

Specific yield may be assumed to be constant for a well when the limit of critical velocity is not exceeded. Critical velocity may be defined as the velocity of entry of water into the well at which sand particles start moving with the water. In case of open wells, the critical velocity is usually assumed as 7.5 cm/minute. The following table presents the values of specific yield for different sub-soil formations.