2. SOURCES OF WATER SUPPLY

The nature of the water source commonly determines the planning, design and operation of the collection, purification, transmission, and distribution works. It is therefore essential that careful consideration and extensive engineering evaluations, including a water resource development investigation, be conducted as part of source selection. Factors such as quantity, quality, reliability, safety of source, water rights, and environmental impacts, along with capital and operation costs of the project, enter into the decision-making.

2.1. The water cycle

The supply of freshwater on earth is entirely due to the water (hydrologic) cycle. The hydrologic cycle is a continuous natural process which helps the exchange of water between the atmosphere, the land surface, and the ocean (See Fig. 2.1). The solar radiation drives the hydrologic cycle.

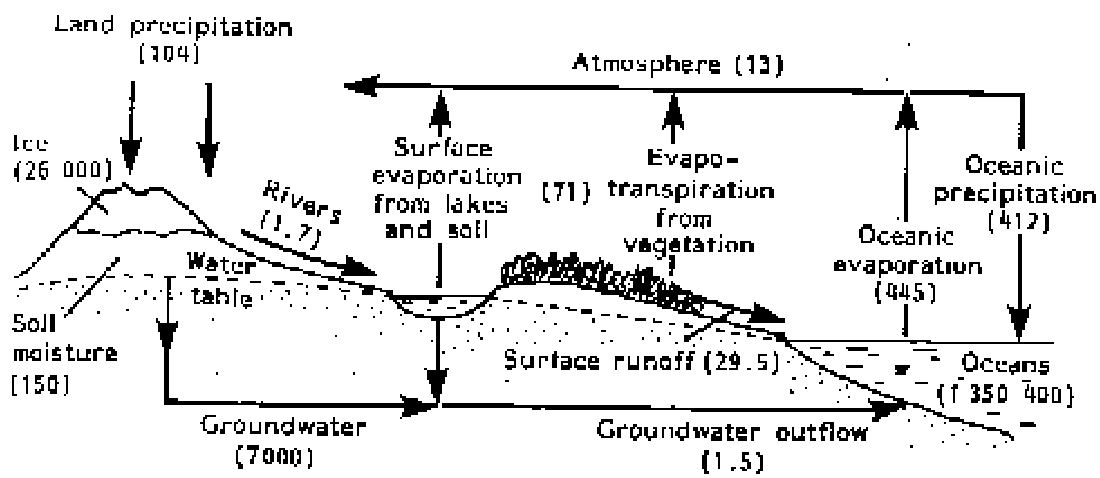

Fig. 2.1 The water cycle
(Numbers indicate volumes of water stored and the amount cycled annually, 10^3 km^3)

The hydrologic cycle has been affected by human activities such as deforestation, and urbanization. Some of the resultant changes in the hydrologic cycle include:

- A large proportion of the rainfall becomes surface runoff and hence the total volume of runoff is increased
- Flood peak magnitudes have increased
- The flow during dry periods, i.e. base flow, is reduced as discharge from groundwater is reduced
- The increased quantity of runoff and velocity of flow increases stream erosion and diffuse pollution load
- Lowering of the general ground water table to the extent that shallow wells run out dry

2.2. Types of water supply sources

Sources of fresh water can be broadly classified as surface water sources such as rivers, lakes and reservoirs and groundwater sources like wells, springs, and infiltration galleries.

SURFACE WATER SOURCES

Surface water is the term used to describe water on the land surface. The water may be flowing, as in streams and rivers, or quiescent, as in lakes, reservoirs, and ponds. Surface water is produced by runoff of precipitation and natural groundwater seepage. Surface water is defined as all water open to the atmosphere and subject to surface runoff. That definition distinguishes surface water from both groundwater and ocean water.

Patterns of surface runoff are described in terms of land areas that drain rainfall and melting snow to a certain point in a river or stream. Those land area may be called drainage areas, drainage basins, catchments, or watersheds. Each watershed is bound by relatively high ground called a divide, which separates it from other watersheds.

Groundwater from springs and seeps also contributes flow to most streams. This is often referred to as base flow. If the adjacent water table is at a level higher than the water surface of the stream, water from the water table flow to the stream (Figure 2-2). If the water table is a level lower than the water surface of the stream, the stream will recharge the groundwater. The pattern of flowing to or from the stream can vary according to seasonal fluctuation of the water table. Many streams would dry up shortly after a rain if it were not for groundwater flow.

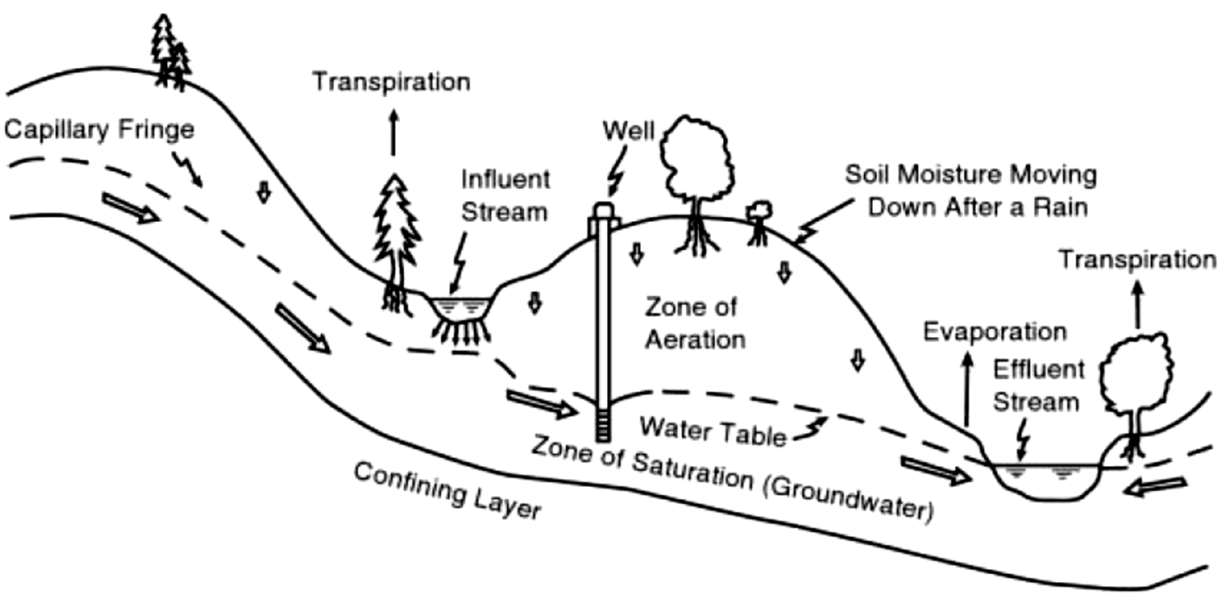

Figure 2-2: Surface water and groundwater interaction

Watercourses

Surface runoff naturally flows along the path of least resistance. All of the water within a watershed flows toward one primary natural watercourse unless it is diverted by a constructed conveyance such as a canal or pipeline or it flows back into the ground to become groundwater.

Natural watercourses. Typical natural watercourses include brooks, creeks, streams, washes, arroyos, and rivers. Watercourses may flow continuously, occasionally, or intermittently, depending on the frequency of rainfall, the availability of snowmelt, and the rate at which groundwater contributes to the base flow of the watercourse. Natural watercourses that flow continuously at all times of the year are called *perennial streams*. Streams that flow only occasionally are called *ephemeral streams*. If the frequency of flow falls somewhere between perennial and ephemeral, the stream is called *intermittent stream*.

Constructed conveyances. These are facilities constructed to hasten the flow of surface water or to divert it in a direction other than the one in which it would flow under natural conditions. Ditches, channels, canals, aqueducts, conduits, tunnels, and pipelines are all examples of constructed conveyances.

Rainwater

The Evaporated water from land and water surfaces, when condenses at high altitude in the form of clouds, starts falling in the form of rain or snow water. During its fall from high altitude to the ground, it absorbs oxygen, carbon dioxide and other gases along with dust, smoke, fumes and bacteria etc. Therefore, rainwater contains large amounts of impurities, the quantity of which is maximum in the first rains and minimum in the last season rains. The quality of rainwater falling on the open land (undisturbed environment) or fields is better than that falling on cities or towns. The quality of rainwater of the last season is good and can be used after little treatment. Rainwater saturated with oxygen is soft, but flat to the taste and corrosive in nature.

Rain is rarely an immediate source of municipal water supplies. Instead the capture of rainwater is confined to farms and rural settlements, usually in semiarid regions devoid of satisfactory ground or surface water. Roofs are mostly obvious choices as catchments for rainwater harvesting and tanks located near or close to homes increase the convenience of this system. Advantages of rainwater collection system over the other water supply sources are:

i. The quality of rainwater is relatively high.
ii. The collection system is independent.
iii. Local materials and craftsmanship can be used in rain water system construction.
iv. No energy costs are needed to run the system.
v. Ease of maintenance by the owner /user.
vi. Convenience and acceptability of water. Valuable time is saved in collecting water

Some disadvantages of rainwater as a source of water supply include:

i. The high initial capital cost may prevent a family from buying the system.
ii. The water available is limited by rainfall and roof area. For long dry seasons, the required storage volume may be too large.
iii. Mineral free water has a flat taste.

Lakes and reservoirs

A lake or reservoir is any standing body of inland water. It is advantageous in that it is usually able to store water in wet periods for use in dry periods. The quality of water is generally poor.

Normally turbidity and bacteria are the major pollutants. No lake or reservoir water can be considered safe until it has been disinfected. Generally it is also necessary to remove turbidity. It should be used only when ground water sources and controlled catchments are not available or are insufficient or inadequate. Deep lakes and reservoirs may be subjected to thermal stratification which greatly affects the quality of water.

River Water

A stream or river is a body of running water on the surface of the earth, from higher to lower ground. The capacity of rivers to serve as direct source of water supply is controlled by rate of minimum flow per day. Streams generally exhibit marked seasonal variation in flow and they are susceptible to contamination. The chemical nature is partially dependent on bedrock. Physical and bacteriological qualities are highly variable. Development of rivers requires a submerged intake structure and in the case of small streams requires the construction of small diversion dams.

GROUND WATER SOURCES

Groundwater is an important source of water supply through out the world. Its use in irrigation, industries, municipalities, and rural schemes continues to increase. Ground water occurs in many types of geologic formations known as aquifers. An aquifer is a formation that contains sufficient quantities of saturated permeable material to yield significant quantities of water. Groundwater system includes wells, springs, and infiltration galleries.

The advantages of ground water are:

- It is likely to be free of pathogenic bacteria;
- Generally, it may be used without further treatment;
- In many instances it can be found in the close vicinity of rural communities;
- It is often most practical and economical to obtain and distribute;
- The water-bearing stratum from which it is drawn usually provides a natural storage at the point of intake.

The disadvantages are:

- Ground water is often high in mineral content;
- It usually requires pumping.

The quality of groundwater is uniform and is free from turbidity and color. Generally, groundwater contains cations such as calcium, magnesium, iron and manganese as well as anions like bicarbonate, carbonate, and chloride.

Spring Water

Spring water is a groundwater that outcrops from ground due to impervious base that prevents percolation. Spring water is usually fed from sand or gravel water bearings ground formation (aquifer) or fissured rocks. Best places to look for springs are the slopes of hilly sides and river valley sand areas with green vegetation in dry season. If properly protected and well managed, spring water proves to be good for small community water supplies.

Generally, springs are of the gravity or artesian types.

- *Gravity springs*
    - Groundwater flows over an impervious stratum onto the ground surface
    - The yield varies with the position of the water table
    - May dry up during or immediately after a dry season
- *Artesian springs*
    - High quality water due to confinement
    - High discharge due to high pressure in the confinement
    - Yield is likely uniform and nearly constant over the seasons of the year

Infiltration gallery

Infiltration galleries are horizontal wells that collect water over practically their entire lengths. When the stream beds or lake shores are sandy and gravelly, the possibilities of finding a gravel pocket along a bank are excellent. The infiltration gallery is a simple means of obtaining naturally filtered water, and, for this purpose, it should be located 15 m or more from the bank of the river or lake. It is constructed by digging a trench into water-bearing sand, then collecting the water in a perforated pipe or gallery which leads to a central casing from which the water is pumped out.

Recharge of Aquifers

Replenishment of aquifers is known as ***recharge***. Unconfined aquifers are recharged by precipitation percolating down from the land's surface. Confined aquifers are generally recharged where the aquifer materials are exposed at the land's surface —called an outcrop.

Surface waters also provide ground water recharge under certain conditions. When surface water loses water to the adjacent aquifer, the stream is called a ***losing stream***. When the opposite occurs and water flows from the ground water to the stream, it is called a ***gaining stream.***

Properly identifying the recharge area of an aquifer is critical because the introduction of contaminants within the recharge area can cause aquifer contamination.

Knowing if the aquifer is influenced by a gaining or losing stream helps identify periods when biological contaminants from the surface water might reach the well water. Periods of gaining and losing stream flow may change seasonally, depending on the level of the ground water table. Monitoring the surface water level or stream stage and comparing it to the static water level in the well can give an indication of the direction of water flow.

2.3. Water quality considerations

Water quality considerations of sources are required for the following purposes.

- To evaluate and classify raw water quality: Based on levels of physical, chemical, and bacteriological parameters, raw water can be classified as having poor, fair, and good quality.
- To identify sources of pollution: Knowledge of the potential sources of water pollution is the base for devising appropriate mitigation measures. Potential sources of surface and groundwater pollution include- *Surface water*: urban runoff, agricultural runoff, industrial

discharge, and leachate from landfills; *Groundwater*: infiltration from pit-latrines and septic tanks, landfill leachate, and infiltration on areas that accumulate polluting substances.

- To assess the treatment required for beneficial uses: Treatment of the raw water is required to make it safe and wholesome for drinking. The level of treatment and unit process required are dependent on the raw water quality. Typical water treatment processes for different sources are indicated in Fig. 2.3.

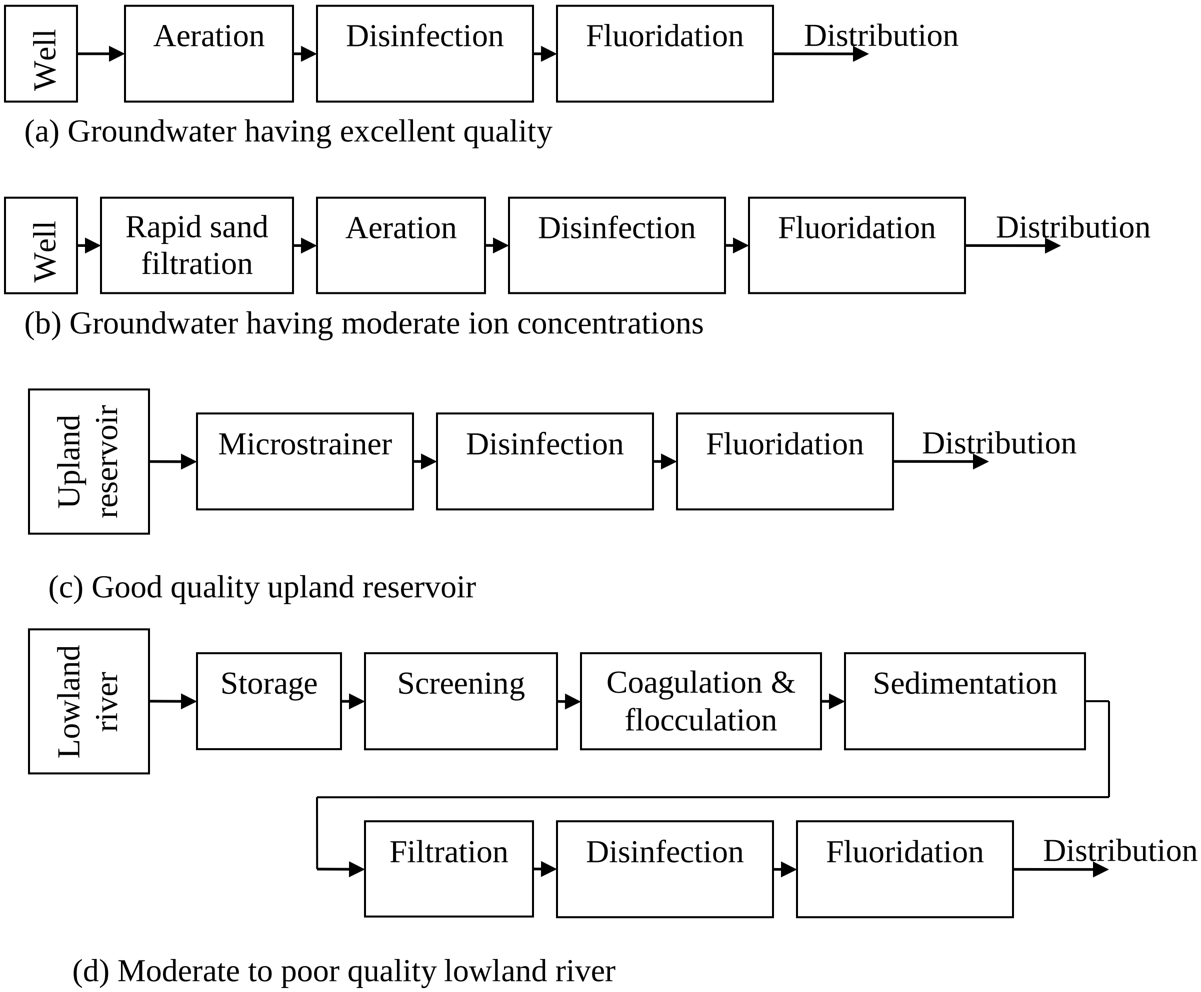

Figure 2-3. Water treatment processes for different sources of supply

2.4. Source Selection

Source selection for water supply purposes requires considerations of factors such as hydrology, water quality, reliability, cost, and environmental and social impacts. Particularly, the following considerations should be included in the study of water supply sources.

Surface water sources

- Safe water yield during the drought years to meet the projected demands
- Urbanization and land development in the watershed
- Proposed impoundments on tributaries
- Water quality
- Assessment of reliability in terms of possible disruptions due to natural and manmade hazards
- Requirements for construction of water supply system components
- Economics of the project
- Environmental impacts of the project
- Water rights

Groundwater:

- Aquifer characteristics
- Safe aquifer yield
- Permissible drawdown
- Water quality
- Sources of contamination
- Saltwater intrusion
- Type and extent of recharge area
- Rate of recharge
- Water rights

2.5. Reservoirs

Reservoir is an artificial lake formed by the construction of a dam across a valley. A storage reservoir contains a dam to hold water, a spillway to allow excess water to flow and a gate chamber containing necessary valves for regulating the flow.

2.5.1. Catchment areas and reservoir sites

Dams are constructed across rivers and streams to create reservoir behind them. The area of land draining to the dam site is called a catchment or watershed. Conscientious planning, design and operation of dams and reservoirs are necessary to minimize the overall cost of the project. The following investigations are required for reservoir planning:

- ***Topographic surveying-*** to produce a topo map which will be used as a base for
  - preparing water surface area vs. elevation curve
  - plotting storage volume vs. elevation
  - indicating man-made and natural features that may be affected

- ***Geologic investigations-*** required to give detailed information about the following items
  - Water tightness of the reservoir basin
  - Suitability of foundations for the dam
  - Geological and structural features, such as faults, fissures, etc
  - Type and depth of overburden
  - Location of permeable and soluble rocks if any
  - Ground water conditions in the region

- Location and quantity of materials for the dam construction

- ***Hydrological investigations***- involve determination of rainfall, runoff, seepage, and evaporation in the reservoir catchment from long years of data. These information are essential for estimating the reservoir capacity and design of spill way.

Criteria for selection of reservoir sites

- Catchment geology- minimum percolation losses and high runoff potential
- Dam site- strong foundation with minimum seepage loss under the dam
- Narrow valley- sites that resulting lesser dam length
- Topography- should be such that large area and valuable properties are not submerged
- Site that creates deep reservoirs- this has the advantages of minimizing the evaporation loss and submerged area when compared to shallow reservoirs
- Sites that ensure good water quality- avoid sites that are downstream of waste discharges and tributaries with high silt loads

2.5.2. Volume of reservoirs

Reservoirs should have a storage capacity such that the safe yield exceeds the maximum day demand. *Yield* is the amount of water that can be supplied from a reservoir in a specified interval of time (e.g. day, month or year). *Safe yield* or *firm yield* represents the maximum quantity of water that can be guarantied during a critical dry period. The storage capacity of reservoirs can be determined using two methods- mass curve method and analytical method.

Mass curve method

In this method reservoir capacity is determined from accumulated mass inflow and accumulated demand curves. The inflow represents net flows into the reservoir and can be obtained by subtracting outflows (e.g. evaporation, seepage loss, and downstream flow requirements) from total inflows (e.g rainfall, and stream flow). The procedure is as follows (see Fig. 2.4):

- Prepare accumulated mass inflow curve from the stream hydrograph
- Prepare the accumulated demand curve on the same scale
- Draw tangent lines that are parallel to the accumulated demand curve at the high points of the accumulated mass curve (P_1, P_2, P_3, etc)
- Measure the vertical distances between the tangent lines and the mass inflow curve (V_1, V_2, V_3, etc.)
- Determine the required reservoir storage capacity as the ***largest of the vertical distances*** (V_1, V_2, V_3, etc.)

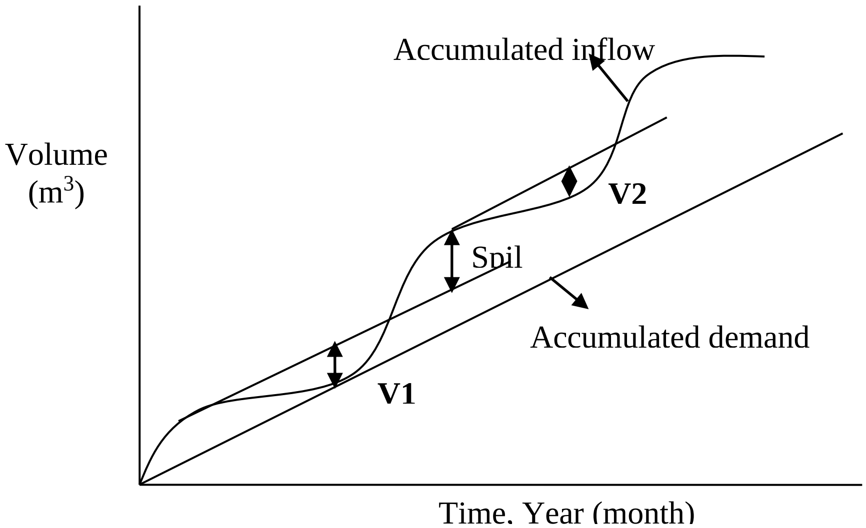

Figure. 2.4 Mass curve method

Analytic method

The analytic method involves tabular computations and the procedure is as follows (Table 2.1).

- Calculate the net inflow from the given hydrological data
- Calculate the deficiency (demand – net inflow)
- Compute the cumulative deficiency. If the cumulative deficiency is negative, take the cumulative deficiency as zero
- Determine the required reservoir capacity as the ***maximum cumulative deficiency***

Table 2.1

(1)	**(2)**	**(3)= (2)-(1)**	**(4) if CF is –ve, take 0**
Net inflow (m^3)	Demand (m^3)	Deficiency (m^3)	Cumulative deficiency (m^3)
I1	D1	F1	CF1 = F1
I2	D2	F2	CF2 = CF1 + F2
I3	D3	F3	CF3 = CF2 + F3

2.5.3. Determination of safe yield from a given reservoir capacity

The following is the procedure of determining the safe yield from a reservoir of a given storage capacity, with the help of a mass inflow curve:

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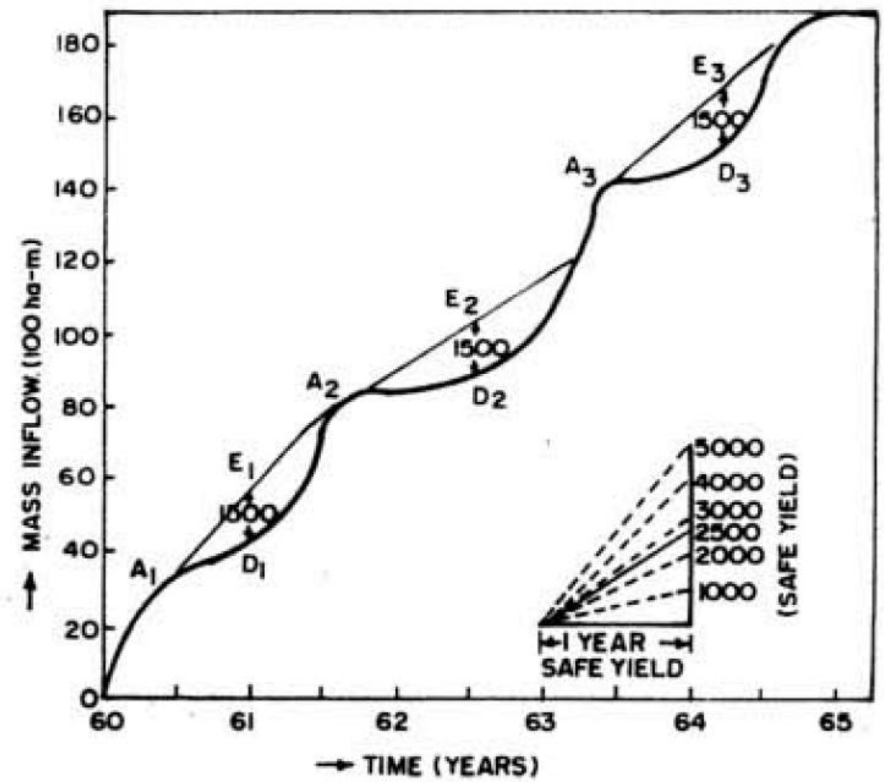

Figure 2-5. Determination of firm yield

1) Prepare the mass inflow curve. On the same diagram, draw straight lines, from a common origin, representing demands at various rates, say varying from 0 to 5000 ha.m per year.
2) From the apices A_1, A_2, A_3, etc. of the mass curve, draw tangents in such a way that their maximum departure from the mass curve does not exceed the specified reservoir capacity. Thus, in Fig., the ordinates E_1D_1, E_2D_2, E_3D_3, etc. are all equal to the reservoir capacity (say 1500 ha.m).
3) Measure the slopes of each of these tangents. The slopes indicate the yield which can be attained in each year from the reservoir of given capacity. The slope of the flattest demand line is the firm yield.

2.5.4. Impoundments

Some of the commonly used impoundments include embankment dams and concrete dams.

- Embankment dam- a dam constructed from natural materials excavated or obtained nearby. The natural fill materials are placed and compacted without the addition of any binding agent. Two types- *Earthfill dam (*if compacted soil constitutes over 50% of the dam volume) and *Rockfill dam* (over 50% of the material is coarse-grained material or crushed rock with impervious membrane). Some advantages of embankment dams include:
  - Suitability to sites in wide valleys and relatively steep-sided gorges alike
  - Adaptability to a broad range of foundation conditions
  - Use of locally available natural materials

The major disadvantages of embankment dam are

  - o Its susceptibility to damage or destruction by overflow, with a consequent need to ensure adequate flood relief
  - o Vulnerability to leakage and internal erosion

- Concrete dams- type include gravity dam, arch dam, buttress dam, etc.
  - o Gravity dam
  - Dependent upon its own mass for stability. All external pressures (e.g. water pressure, wave pressure, silt pressure, uplift pressure, etc.) are counterbalanced by the weight of the dam
  - Particularly, suitable across gorges with very steep side slopes
  - Masonry can also be an alternative construction material
  - Shape: straight or curved
  - Dam height: can be very high if sound foundation is obtained

  - o Arch dam
  - Functions structurally as a horizontal arch, transmitting the major portion of the water load to the abutments or valley sides rather than to the floor of the valley.
  - It is structurally more efficient and requires less concrete volume

  - o Buttress dam- consists of a continuous upstream face supported at regular intervals by downstream buttresses.

2.5.5. Catchment protection

Activities that take place within the reservoir catchment have impacts on the quality and quantity of water stored behind the dam. Catchment protection primarily focuses on maintaining the water quality and capacity of the reservoir. It involves activities that include:

- Minimization of diffuse pollution from urban runoff (e.g. improving waste management, street cleaning, decreasing directly connected impervious surfaces, etc.)
- Minimization of agricultural diffuse pollution (use of best agricultural management practices- rate, time and method of application of agro-chemicals, i.e. fertilizers and pesticides, should be environmentally friendly
- Controlling discharges from point sources such as wastewater treatment plant, industries, etc
- Limitation of soil erosion through soil conservation measures, such as afforestation, etc.
- Providing corridors along tributary streams, rivers, and the reservoir

Catchment protection requires identification of critical problem areas so that the limited available fund is effectively used. GIS is an invaluable tool in the formulation of catchment plans and strategies.

2.6. Groundwater

Groundwater is an important source of water supply for municipalities, agriculture and industry. At a global scale the percentage of groundwater is estimated to be 0.62 % of the total amount of water stored in the hydrosphere (of 0. 31% has a depth less than 800 m). Groundwater is characterized according to its vertical distribution shown in Fig. 2.6. It is the water that is found in the saturation zone that can be tapped for different purposes.

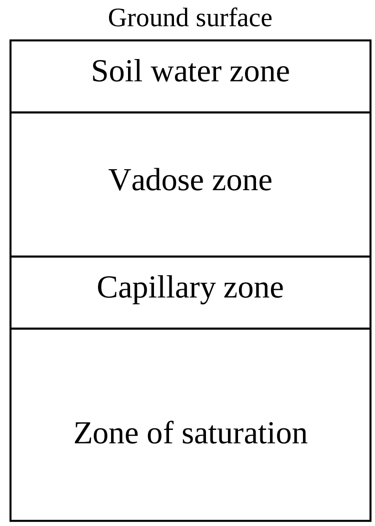

Figure 2-6. Vertical zones of groundwater distribution

Groundwater occurs in geologic formations called aquifers. Aquifer is a water-bearing formation that is saturated and that transmits large quantities of water. The water yield capacity of aquifers depends on different parameters that include particle size, porosity, specific yield, storage coefficient, hydraulic gradient, hydraulic conductivity, and transmissivity. Definitions of these terms are presented below.

Porosity: ratio of volume of voids to total volume

Specific yield: the amount of aquifer water expressed as a percentage that is free to drain under the influence of gravity. By definition it is less than the porosity since some water is not free to drain due to attractive and bonding forces such as surface tension.

Storage coefficient (S): volume of water that an aquifer releases from or takes into storage per unit surface area per unit change in piezometric head. For confined aquifers S = 0.00005-0.001 and for unconfined aquifers S = 0.01-0.35.

Hydraulic gradient (dh/dx): the slope of the piezometric surface or water table line in m/m. the magnitude of the head determines the pressure on the groundwater to move and its velocity.

Hydraulic conductivity: ratio of velocity to hydraulic gradient, indicating permeability of porous media.

Transmissivity: measure of how easily water in a confined aquifer can flow through the porous media.

Geologic formations that are considered to be good aquifers include sand, gravel, and sandstones. Limestone and shale that have caverns, fissures or faults can also be considered as good aquifers. Although clay is highly porous, its ability to transmit water is very poor due to the very small particle sizes (< 0.0004 mm).

Aquifers are classified as unconfined and confined aquifers (see Fig. 2.7). An unconfined aquifer does not have confining unit and is defined by water-table. Confined aquifer is overlain by a confining unit that has a lower hydraulic conductivity.

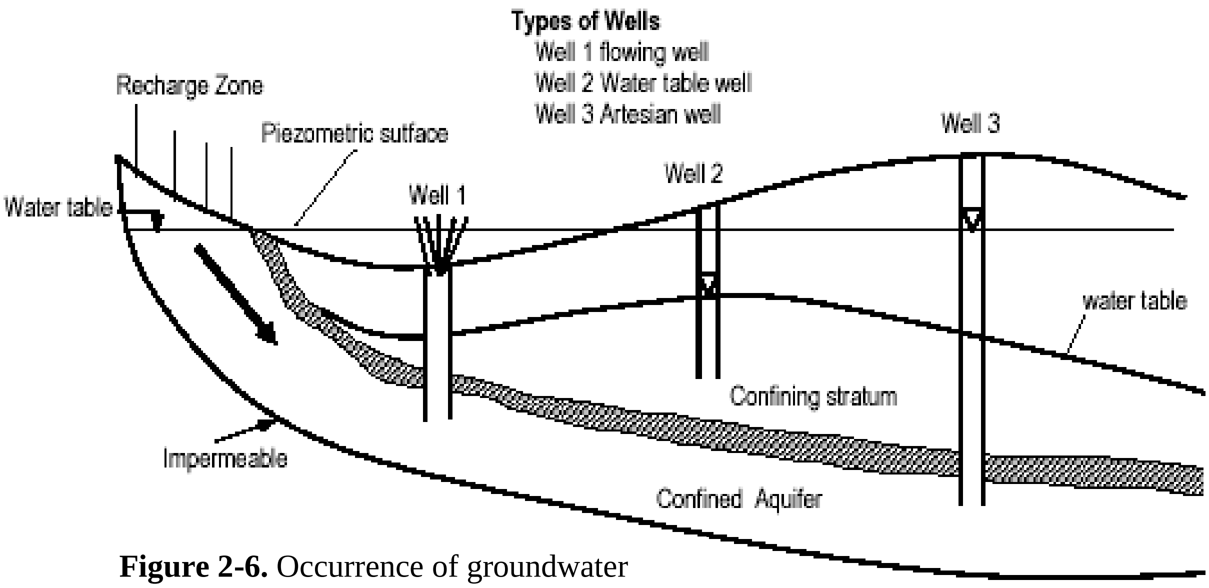

Figure 2-6. Occurrence of groundwater

2.6.1. Groundwater flow

Groundwater flows in the direction of decreasing head. Graphically the flow direction can be represented by drawing lines that are orthogonal to equipotential lines (Fig. 2.7). Equipotential lines are lines of equal piezometric head for confined aquifers or equal water-table for unconfined aquifers.

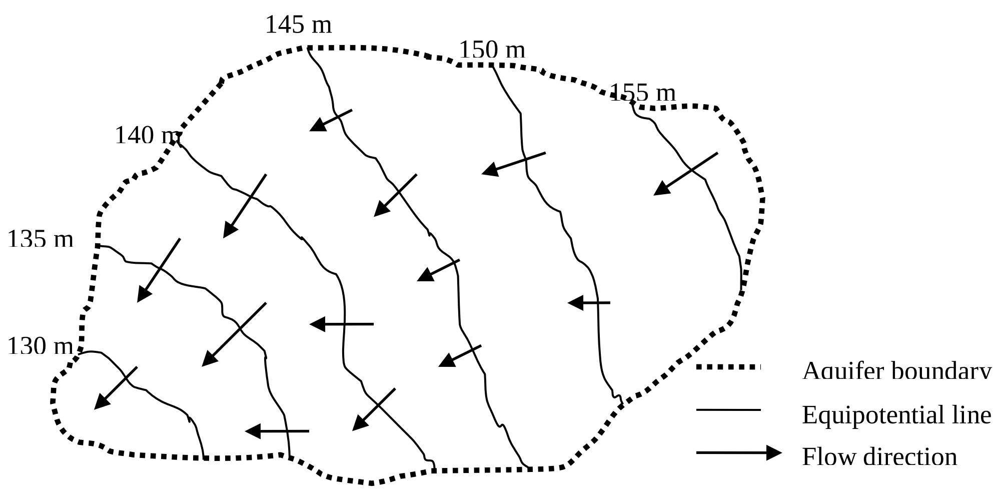

Figure 2-7. Groundwater flow direction

The velocity of groundwater flow can be estimated from Dracy's Law. Darcy law states that the flow rate through porous media is proportional to the head loss and inversely proportional to the length of the flow path. Its applicability is limited to laminar flow which is the case for most groundwater flows in aquifers.

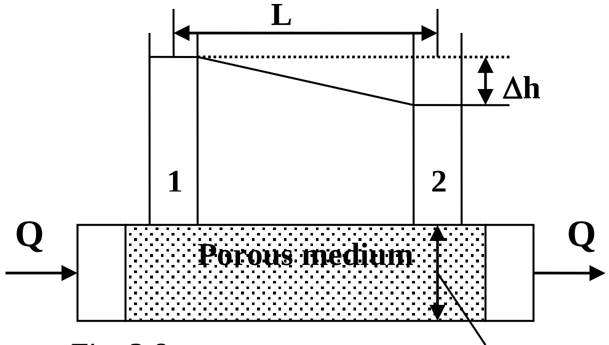

Fig. 2.8

$$V = \frac{Q}{A} = -K\frac{\Delta h}{L}$$

or

$$V = -K\frac{dh}{dL}\text{; for very small element}$$

The negative sign indicates that flow is in the direction of falling head.

K = hydraulic conductivity
dh = is head loss which can be determined by using Bernoulli's equation.

Determination of K

The hydraulic conductivity in saturated zones can be determined by laboratory or field methods. Constant head and variable falling head permeameter are used in the laboratory. In the field pump tests, slug tests and tracer tests are available for determination of K. Field methods generally yield significantly different values of K than corresponding laboratory tests performed on cores removed from the aquifer. Thus, field tests are preferable for the accurate determination of aquifer parameters.

In the laboratory the K values are determined by the following equations.

Constant head permeameter, $K = \frac{VL}{Ath}$

V = volume water flowing in time t through of area A, length L, and with constant head h.

Falling head permeameter, $K = \frac{r^2 L}{r_c^2 t}\ln\left(\frac{h_1}{h_2}\right)$

Where, r = radius of the column in which the water level drops
r_c = radius of the sample
h_1, h_2 are heads at times t_1 and t_2, respectively
$t = t_2 - t_1$

Field pumping tests result in accurate K value. The test involves a constant removal of water from a single well and observations of water level declines at several adjacent wells. In this way, an integral K value for portion of the aquifer is obtained.

Representative values of hydraulic conductivities for different materials are given in Table 2.2.

Table 2.2 Hydraulic conductivity of various formations

Material	K (cm/s)
Gravel	$3 – 3 \times 10^{-2}$
Coarse sand	$6 \times 10^{-1} – 9 \times 10^{-5}$
Medium sand	$5 \times 10^{-2} – 9 \times 10^{-5}$
Fine sand	$2 \times 10^{-2} – 2 \times 10^{-5}$
Silt	$2 \times 10^{-3} – 1 \times 10^{-7}$
Clay	$5 \times 10^{-7} – 1 \times 10^{-9}$
Limestone and dolomite	$6 \times 10^{-4} – 1 \times 10^{-7}$
Sandstone	$6 \times 10^{-4} – 3 \times 10^{-8}$
Shale	$2 \times 10^{-7} – 1 \times 10^{-11}$
Permeable basalt	$2 – 4 \times 10^{-5}$
Basalt	$4 \times 10^{-5} – 2 \times 10^{-9}$
Fractured igneous and metamorphic rocks	$3 \times 10^{-2} – 8 \times 10^{-7}$
Unfractured igneous and metamorphic rocks	$2 \times 10^{-8} – 3 \times 10^{-12}$
Weathered granite	$3 \times 10^{-4} – 5 \times 10^{-3}$

For anisotropic aquifers that comprise different layers, the combined hydraulic conductivity in the horizontal direction can be determined as follows.

$$K = \frac{\sum K_i Z_i}{\sum Z_i}$$

Where, K_i = K in layer i; Z_i = thickness of layer i

2.6.2. Hydraulics of water wells

Water flow to a well situated in a confined or unconfined aquifer under steady or transient conditions can be estimated by applying Darcy's law. When water is pumped out the water-table or piezometric surface declines and forms a cone of depression or drawdown curve.

1. Steady state condition

Assumptions:

- Cone of depression remains in equilibrium
- The water table is only slightly inclined
- Flow direction is horizontal
- Slopes of the water table and the hydraulic gradient are equal
- Aquifer: isotropic, homogeneous and infinite extent
- Well fully penetrating the aquifer

The equations for steady radial flow to a well in confined and unconfined aquifers are given below.

Steady Radial Flow to a Well-Confined

In a confined aquifer, the drawdown curve or cone of depression varies with distance from a pumping well (Fig. 2.9).

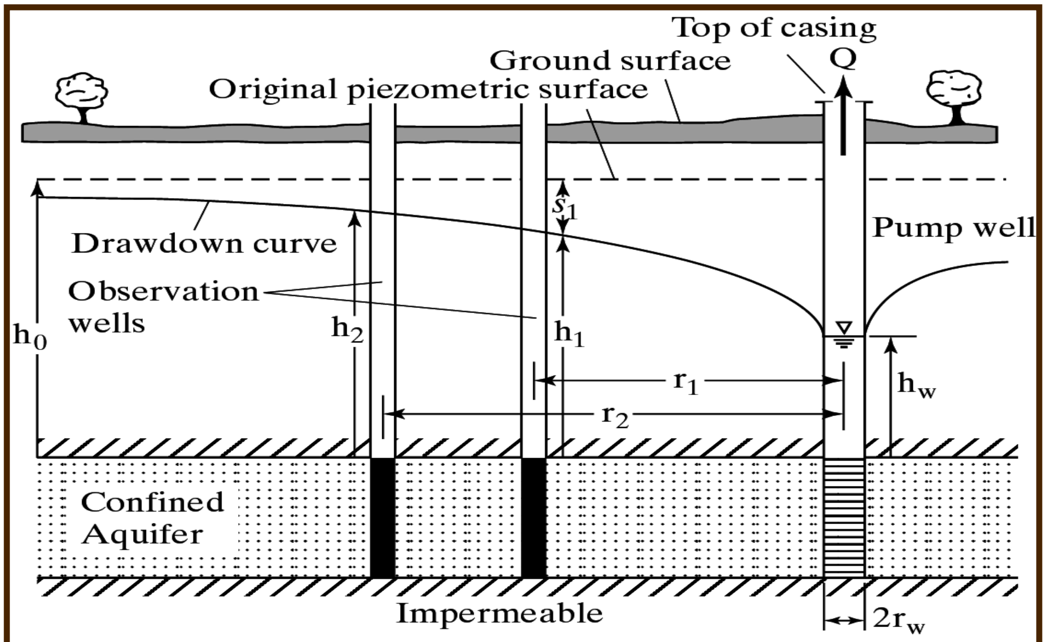

Figure 2.9

Radial flow to a well penetrating an extensive confined aquifer.

For horizontal flow, Q at any radius r equals, from Darcy's law,

$$Q = -2\Pi rbK\frac{dh}{dr} = -2\Pi rT\frac{dh}{dr}$$

Integrating after separation of variables, with $h = h_w$ at $r = r_w$ at the well, yields Thiem Equation.

$$Q = 2\Pi T\frac{h - h_w}{\ln\frac{r}{r_w}}$$

Near the well, transmissivity, T, may be estimated by observing heads h_1 and h_2 at two adjacent observation wells located at r_1 and r_2, respectively, from the pumping well.

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

Steady Radial Flow to a Well-Unconfined

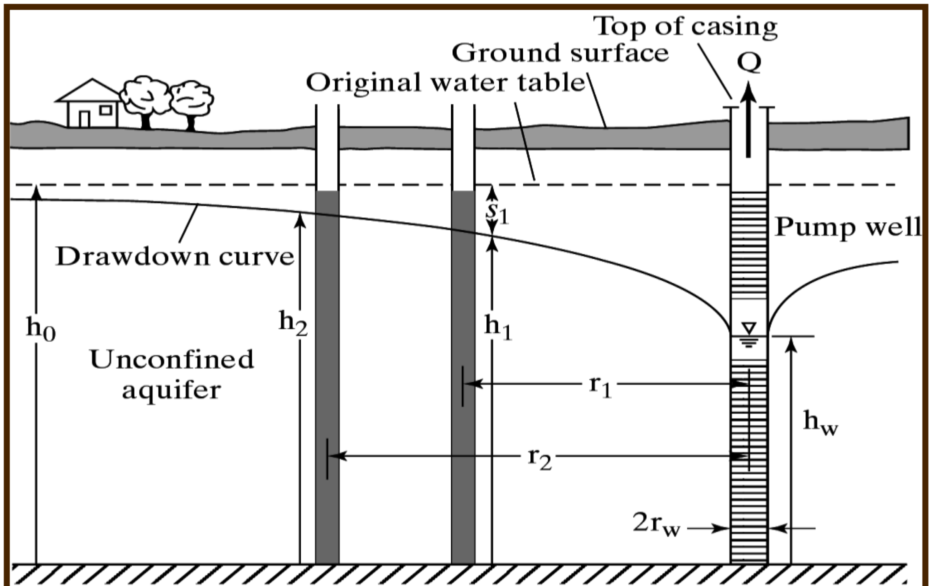

Fig. 2.10

Radial flow to a well penetrating an unconfined aquifer.

Using Dupuit's assumptions and applying Darcy's law for radial flow in an unconfined, homogeneous, isotropic, and horizontal aquifer yields:

$$Q = -2\Pi rhK\frac{dh}{dr}$$

Integrating,

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

Solving for K,

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

Where heads h_1 and h_2 are observed at adjacent wells located distances r_1 and r_2 from the pumping well respectively.

2. Transient or unsteady state condition

The transient condition conforms to the reality where the drawdown curve changes with time.
Assumptions:

- The aquifer is homogenous, isotropic, uniformly thick, and of infinite areal extent
- Prior to pumping the piezometric surface is horizontal
- The fully penetrating well is pumped at constant rate

- Flow is horizontal within the aquifer
- Storage within the well can be neglected
- Water removed from storage responds instantaneously with a declining head

The governing equation in plane polar coordinates is:

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

Where, h = head
r = radial distance
S = storage coefficient
T = transmissivity

Solution methods for the governing equation:

Two methods are given- Theis and Cooper-Jacob methods.

Theis Method

Theis obtained a solution to the governing equation by assuming that the well (pumping Q) is a sink of constant strength and by using boundary conditions:

$$h = h_0 \text{ at } t = 0 \text{ and } h \rightarrow h_0 \text{ as } r \rightarrow \infty \text{ for } t \geq 0$$

Theis solution is written as:

$$s' = \frac{Q}{4\Pi T}\int_u^\infty \frac{e^{-u}}{u} du$$

The integral in the Theis equation is written as *W(u)* and is known as the exponential integral, or well function, which can be expanded as infinite series:

W(u) = – 0.5772 – ln(u) + u – u2/2·2! + u3/3·3! – u4/4·4! + …

Therefore,

$$s' = \frac{Q}{4\Pi T} W(u)$$

Where, s' = drawdown; *Q* = discharge at the well, $u = \frac{r^2 S}{4Tt}$; t = time; *W(u)* = well function; S = storage coefficient; T = transmissivity

The Theis equation can be used to obtain aquifer constants *S* and *T* by means of pumping tests at fully penetrating wells. The solution procedure uses graphical method as presented in Fig. 2.11.

- Plot the type curve, i.e., W(u) vs u and on a log-log paper
- Plot the observed data, i.e., s' vs r^2/t on a transparent log-log paper
- Superimpose the observed plot on the type curve
- Adjust the observed plot in such a way that most of the points lie on the type curve. This is done because the relationship between *W(u)* and *u* is the same as that between *s* and r^2/t because all other terms are constants.

- Select one matching point and take the corresponding readings for W(u), u, s and r^2/t.
- Compute T from the Theis equation

$$T = \frac{Q}{4\Pi s'} W(u)$$

- Determine S from the equation for u

$$S = 4Tu \frac{1}{r^2/t}$$

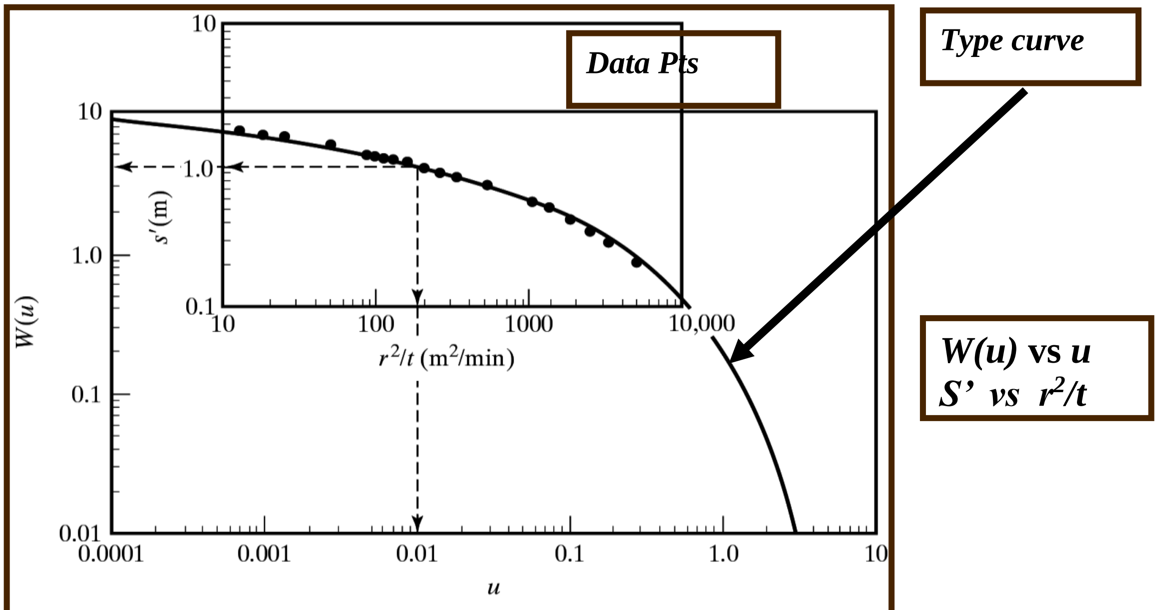

Fig. 2.11

Theis method of superposition for solution of the nonequilibrium equation.

For a known S and T, one can use Theis to compute ***s*** directly at a given ***r*** from the well as a function of time:

- First compute $u = r^2S / (4T\,t)$
- Then, read W(u) from a table
- Finally

$$s' = \frac{Q}{4\Pi T} W(u)$$

Cooper-Jacob Method of Solution

Cooper and Jacob noted that for small values of ***r*** and large values of ***t***, the parameter $\boldsymbol{u = r^2S/4Tt}$ becomes very small so that the infinite series can be approximated by:
W(u) = – 0.5772 – ln(u) *(neglecting higher terms)*

$$s' = \frac{Q}{4\Pi T}\left(-0.5772 - \ln u\right)$$

Further rearrangement and conversion to decimal logs yields:

A plot of s vs. log (t) forms a straight line as seen in Fig 2.12.
A projection of the line back to s' = 0, where t = t_0 yields the following relation:

$$s' = \frac{2.3Q}{4\Pi T}\log\left(\frac{2.25Tt}{r^2 S}\right)$$

$$0 = \frac{2.3Q}{4\Pi T}\log\left(\frac{2.25Tt_0}{r^2 S}\right)$$

So, since *log(1) = 0,* rearrangement yields

$$S = \frac{2.25Tt_0}{r^2}$$

$$T = \frac{2.3Q}{4\Pi\Delta s'}$$

Replacing *s* by *Δs*, where *Δs* is the drawdown difference per unit log cycle of *t*:

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

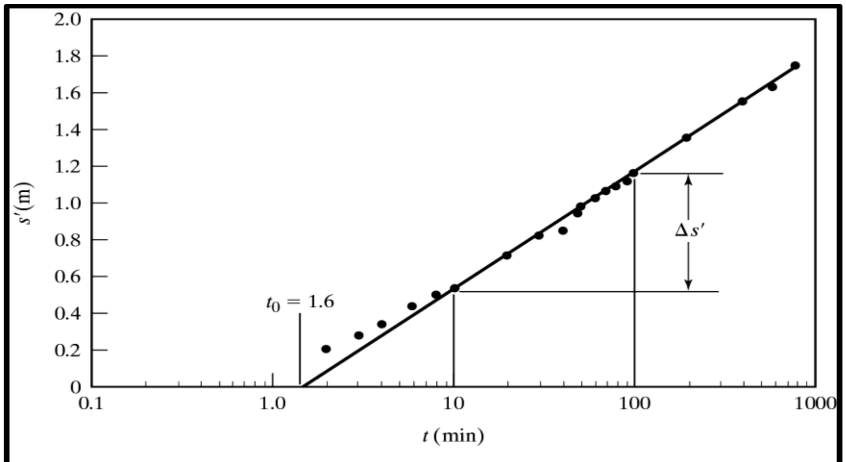

Fig. 2.12 Cooper-Jacob method of analysis

Example

For the data given in the Fig. 2.12 t_0 = 1.6 min and *Δs'* = 0.65 *m*, *Q* = 0.2 m^3/sec and *r* = 100 *m*. Thus,

$T = 2.3Q/4\pi\Delta s'$ = 5.63 x 10^{-2} m^2/sec

$S = 2.25Tt_0/r^2$

From which, $S = 1.22 \times 10^{-3}$

Interference of wells

Operation of multiple wells may result in interference of drawdown curves. The combined drawdown at a point is equal to the sum of the drawdowns caused by individual wells (Fig. 2.13). Well interference reduces the water available to each of the wells.

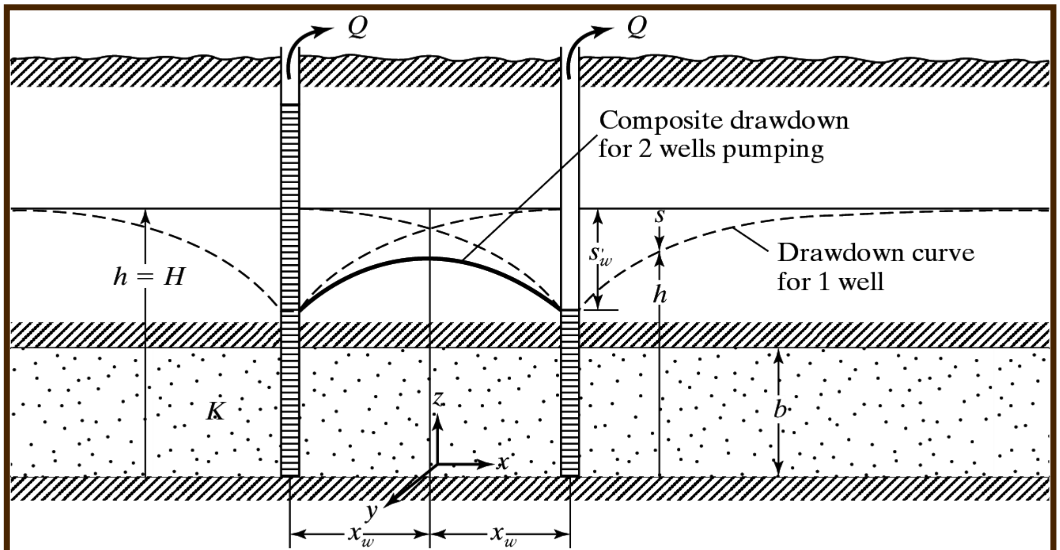

Fig. 2.13

Individual and composite drawdown curves for two wells in a line.

For water supply purposes it is recommended that interference be avoided by spacing wells far apart. On some occasions it may be more economical to allow some interference to offset other costs, such as those of land and connecting pipelines and electric equipment.

2.6.3. Well construction and maintenance

A variety of methods exist for constructing wells, depending on the flow rate, depth to groundwater, geologic condition, casing material, and economic factors. Prior to drilling a well in a new area, a test hole is normally drilled and a record, or log, is kept of various geologic formations and the depth at which they are encountered. Sample cuttings are often collected at selected depths and later studied and analyzed for grain size distribution.

Shallow well construction

Shallow wells are less than 30 m deep and are constructed by digging, boring, driving, or jetting methods. They all are used in unconsolidated formations.

Dug wells are generally excavated by hand using pick and shovel, and they are vertical wells in the ground that intersect the water table. Generally they have diameter > 0.5 m and depth < 15 m.

Lining and casing materials are usually concrete or brick. Figure 2-14 shows a typical construction of dug well.

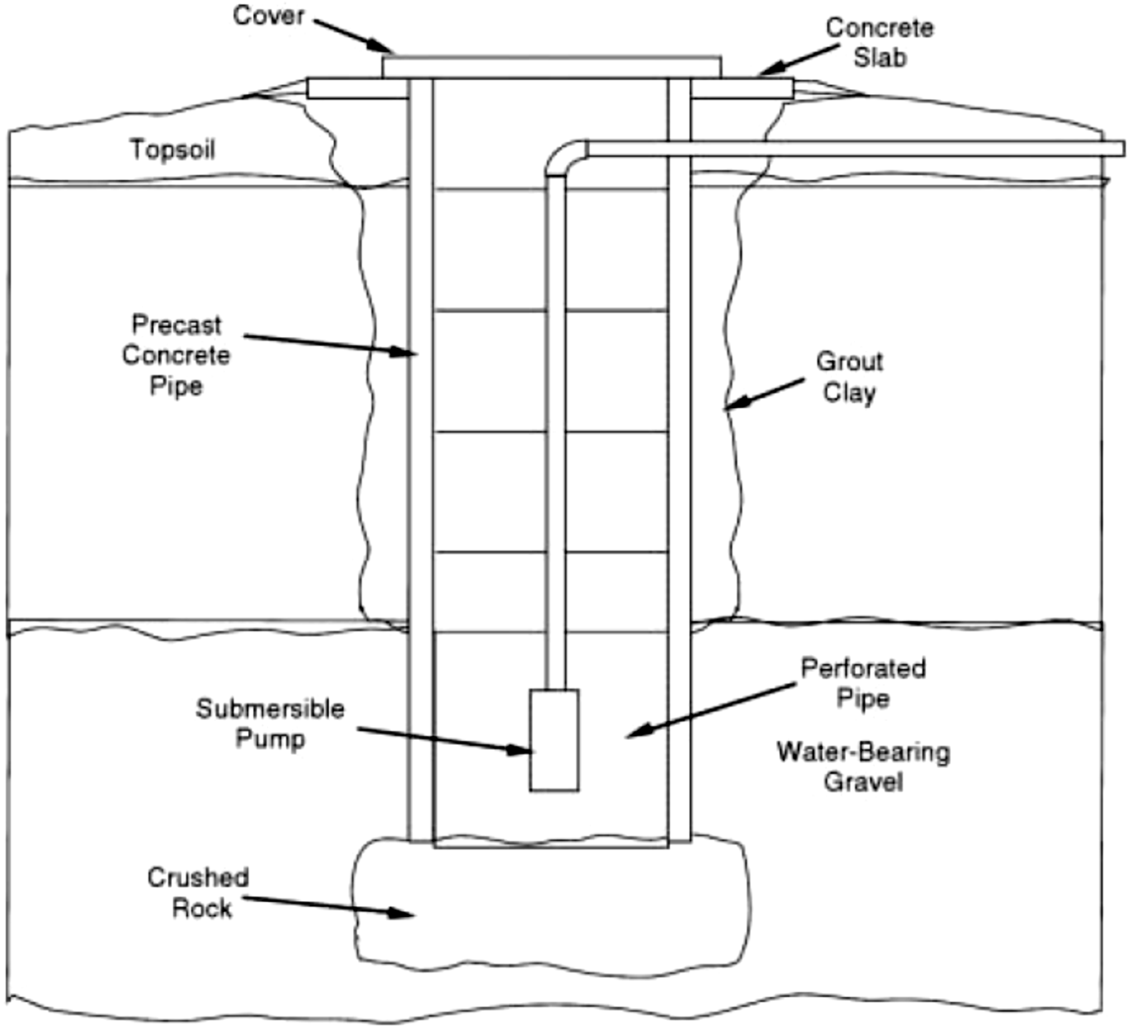

Figure 2-14 Construction of dug well

Driven wells consist of a series of pipe lengths driven vertically downward by repeated impacts into the ground. Water enters the wells through a drive point at the lower end, which consists of a screened, cylindrical section, protected by a steel cone (Figure 2-15). Driven wells usually have diameters 25 – 75 mm and length generally below 15 m.

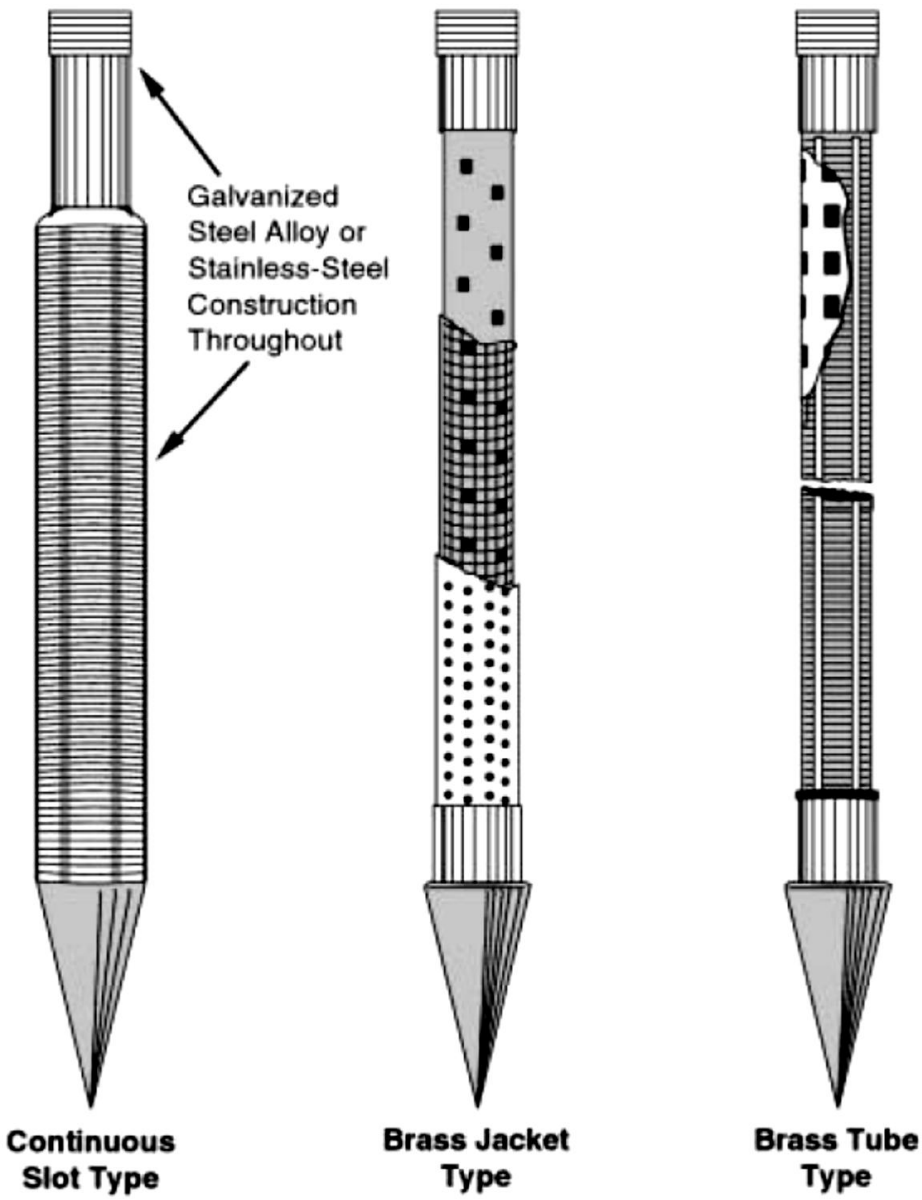

Figure 2-15 Different types of driven well points

Bored wells are constructed with hand-operated or power-driven augers. Diameters of 25 to 900 mm and depths up to 30 m, under favorable conditions, can be attained.

Jetted wells are constructed with a high-velocity stream of water directed vertically downward, while the casing that is lowered into the hole conducts the water and cuttings to the surface. Small-diameter holes, up to 10 cm, with depths up to 15 m, can be installed in unconsolidated formations. Because of the speed of installation, jetted wells are useful for observation wells and well-point systems for dewatering purposes.

Deep well construction

Deep and extensive aquifers with adequate yield can be tapped by constructing deep wells by *percussion (cable tool) drilling* or *rotary drilling methods.*

Percussion drilling is accomplished by regular lifting and dropping of a string of tools, with a sharp bit on the lower end to break rock by impact. The method is most useful for consolidated rock materials to depths of 600 m. After drilling the well to the maximum desired depth, a screen is lowered inside the casing and held in place while the casing is pulled back to expose the screen. (Figure 2-16)

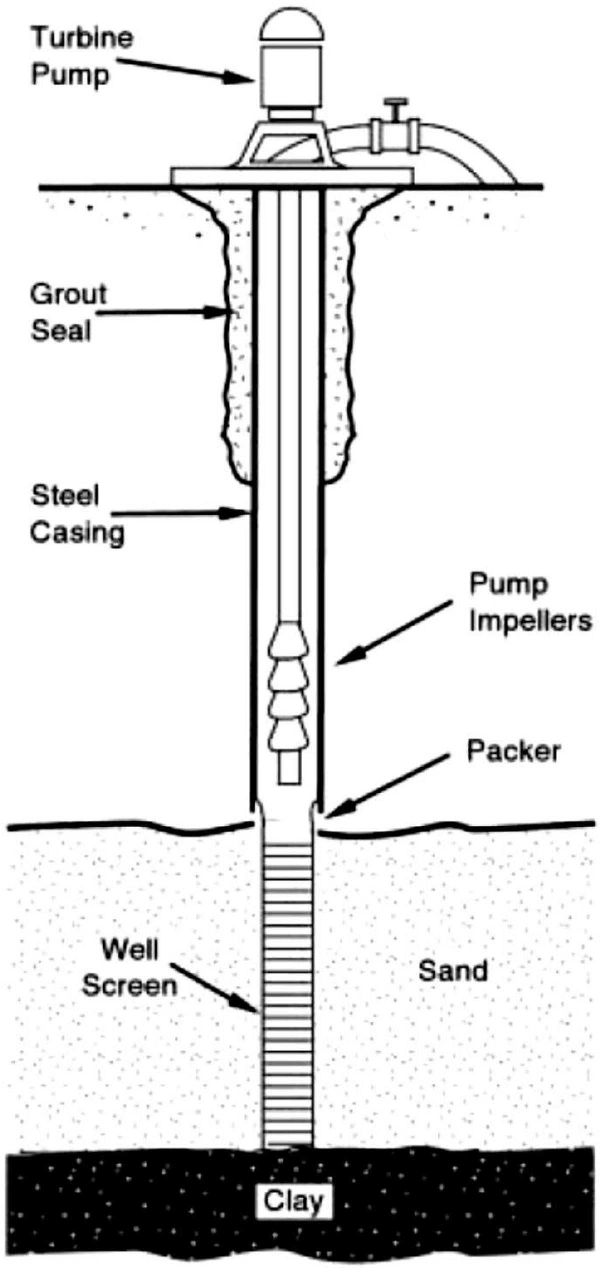

Figure 2-16 Exposed well screen

A rapid method for drilling in unconsolidated formations is the rotary method, which consists of drilling with a hollow, rotating bit, with drilling mud or water used to increase efficiency. No casing is required with drilling mud because the mud forms a clay lining on the wall of the well. Drilling mud consists of a suspension of water, bentonite clay, and various organic additives (Figure 2-17). Air rotary methods use compressed air in place of drilling mud and are convenient for consolidated formations. Drilling depths can exceed 150 m under favorable conditions.

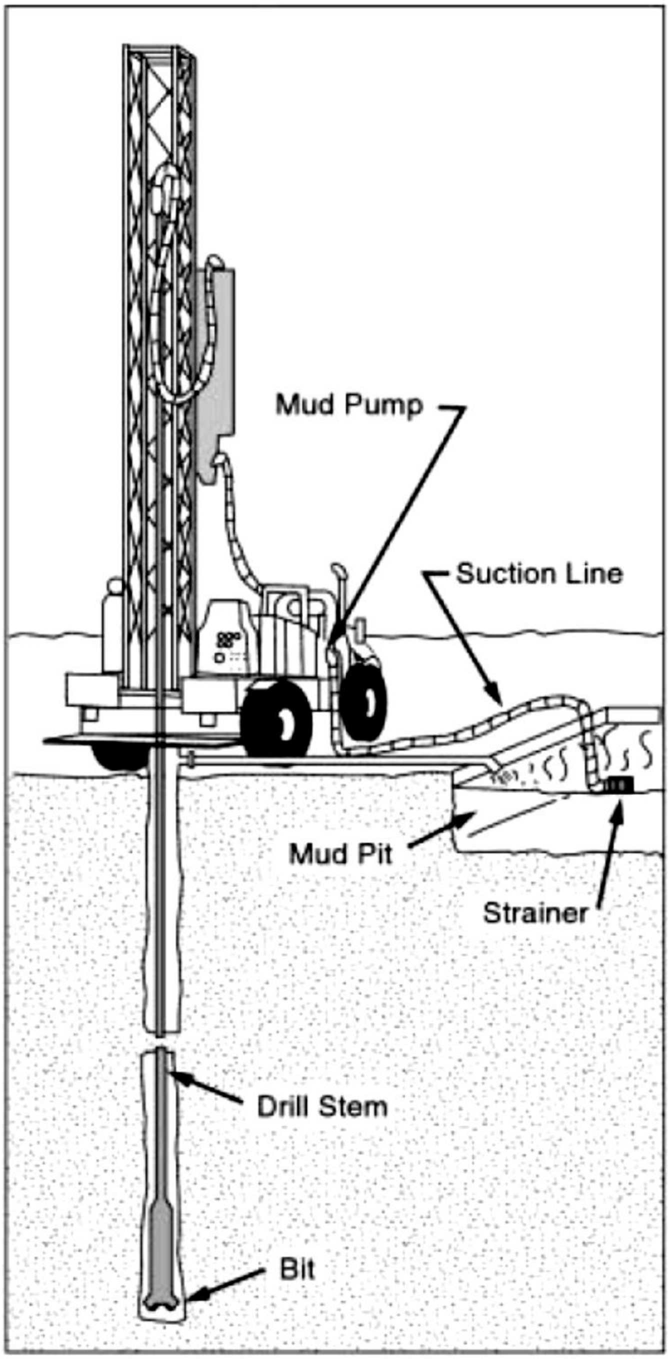

Figure 2-17 Circulation of drilling fluid in a direct rotary drilling rig

The reverse-circulation rotary method can attain of a hole up to 125 m deep in unconsolidated formations. Water is pumped up through the drill pipe, using a large capacity pump, and after cuttings settle out in a large pit, water is recycled into the hole. Velocities must be kept low, and hole diameters must be greater than 40 cm.

2.6.4. Well completion and development

Once a well has been drilled, it must be completed in such a way that it remains an efficient producer of water. This may involve installation of casing, cementing, placement of well screens, and gravel packing.

Well casings serve as a lining to maintain an open hole up to the ground surface. They provide structural support against caving materials and seal out surface water. Casing materials include wrought iron, steel, and PVC pipe. Application of cement grout in the annular space around the casing is required to prevent entrance of water of unsatisfactory quality.

Well screens, typically used for unconsolidated formations, are perforated sections of pipe of variable length that allow groundwater to flow into the well. Their main purpose is to prevent aquifer material, such as sand or gravel, from entering the well and to minimize hydraulic resistance to flow. Screens materials should be corrosion-resistant and can be of metals and metal alloys, PVC, or wood. The size of the screen hole should be such that 20 – 30 % of the surrounding materials are larger in size. The total net area of the screen openings should result in a water flow velocity (50 – 100 mm/s) that doesn't allow transport of sand particles into the well. The drawdown at the well should not be below the top of the screen to prevent corrosion.

A gravel pack that envelops a well screen is designed to stabilize the aquifer and provide an annular zone of high permeability material. The thickness of the gravel pack should be 25- 225 mm. fine gravel with low uniformity coefficient is desirable.

Well development follows completion and is designed to increase the hydraulic efficiency by removing the finer material from the formation surrounding the screen. The importance of well development is often overlooked but is required to produce full-potential yields. Development procedures include pumping, surging, use of compressed air, hydraulic jetting, chemical addition, and use of explosives.

2.6.5. Well protection and maintenance

Whenever groundwater is pumped and is to be used for human consumption, proper sanitary precautions must be taken to protect water quality. Surface pollution can enter wells through the annular space or through the top of the well itself. Cement grout outside the casing and a watertight cover of concrete should be installed for protection. Samples of well water should be evaluated for quality after development and after periods of excessive flooding if contamination is suspected. Wells should have adequate distance from polluting activities and facilities such as septic tank systems.

To maintain the yield of wells for a longer duration regular and timely maintenance services should be provided. Common well troubles and the corresponding remedial measures are presented in Table 2.3.

Table 2-3 Major water well troubles and remedial measures

Trouble	Measure
Water extraction greater than recharge	• Lower the pump into the well- temporary solution • Reduce the pumpage- desirable solution
Corrosion or collapse of casing/screen	• Replace the casing/screen for consolidated materials • Abandon the well if is in unconsolidated formations
Incrustation of screens (due to precipitation of $CaCO_3$, formation of insoluble Fe and Mn compounds, and other causes)	• Acid treatment by HCl inhibited by addition of gelatin • Pressurizing the well with dry ice • Chlorination • Use of polyphosphates