Ground Water Engineering

CV0612

INTRODUCTION

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INTRODUCTION

- Groundwater is water that exists in the **pore spaces** and **fractures in rocks** and **sediments** beneath the Earth's surface.
- It originates as **rainfall or snow**, and then moves through the soil and rock into the groundwater system, where it eventually makes its way back to the surface streams, lakes, or oceans.
- Groundwater makes up about 1% of the water on the Earth (most water is in oceans) But, groundwater makes up to 35 times the amount of water in lakes and streams.
- Groundwater occurs everywhere beneath the Earth's surface, but is usually restricted to **depth less than about 750 meters**.
- The volume of groundwater is equivalent to a 55-meter thick layer spread out over the entire surface of the Earth.

To understand the ways in which groundwater occurs, it is needed to think about the ground and the water properties.

- **Porosity**, which is the property of a rock possessing pores or voids.
- **Saturated and unsaturated zones.**
- **Permeability**, which is the ease with which water can flow through the rock.
- **Aquifer**, which is a geologic formation sufficiently porous to store water and permeable enough to allow water to flow through them in economic quantities.
- **Storage coefficient**, which is the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of area normal to surface.

Origin of Groundwater

- Groundwater derived from **rainfall and infiltration** within the normal hydrological cycle. This kind of water is called **meteoric water**. The name implies recent contact with the atmosphere.

- Groundwater encountered at great depths in sedimentary rocks as a result of water having been trapped in marine sediments at the time of their deposition. This type of groundwater is referred to as **connate waters**. These waters are normally saline. It is accepted that connate water is derived mainly or entirely from entrapped sea water as original sea water has moved from its original place. Some trapped water may be brackish.

- **Fossil water** if fresh may be originated from the fact of climate change phenomenon, i.e., some areas used to have wet weather and the aquifers of that area were recharged and then the weather of that area becomes dry.

Groundwater and the Hydrologic Cycle

- The hydrological cycle is the most fundamental principle of groundwater hydrology.
- The driving force of the circulation is derived from the radiant energy received from the sun. Water evaporates and travels into the air and becomes part of a cloud. It falls down to earth as precipitation.
- Then it evaporates again. This happens repeatedly in a never-ending cycle. Water keeps moving and changing from a solid to a liquid to a gas, repeatedly.
- Precipitation creates runoff that travels over the ground surface and helps to fill lakes and rivers. It also percolates or moves downward through openings in the soil and rock to replenish aquifers under the ground.
- As clouds move up and over mountains, the water vapor condenses to form precipitation and freezes.

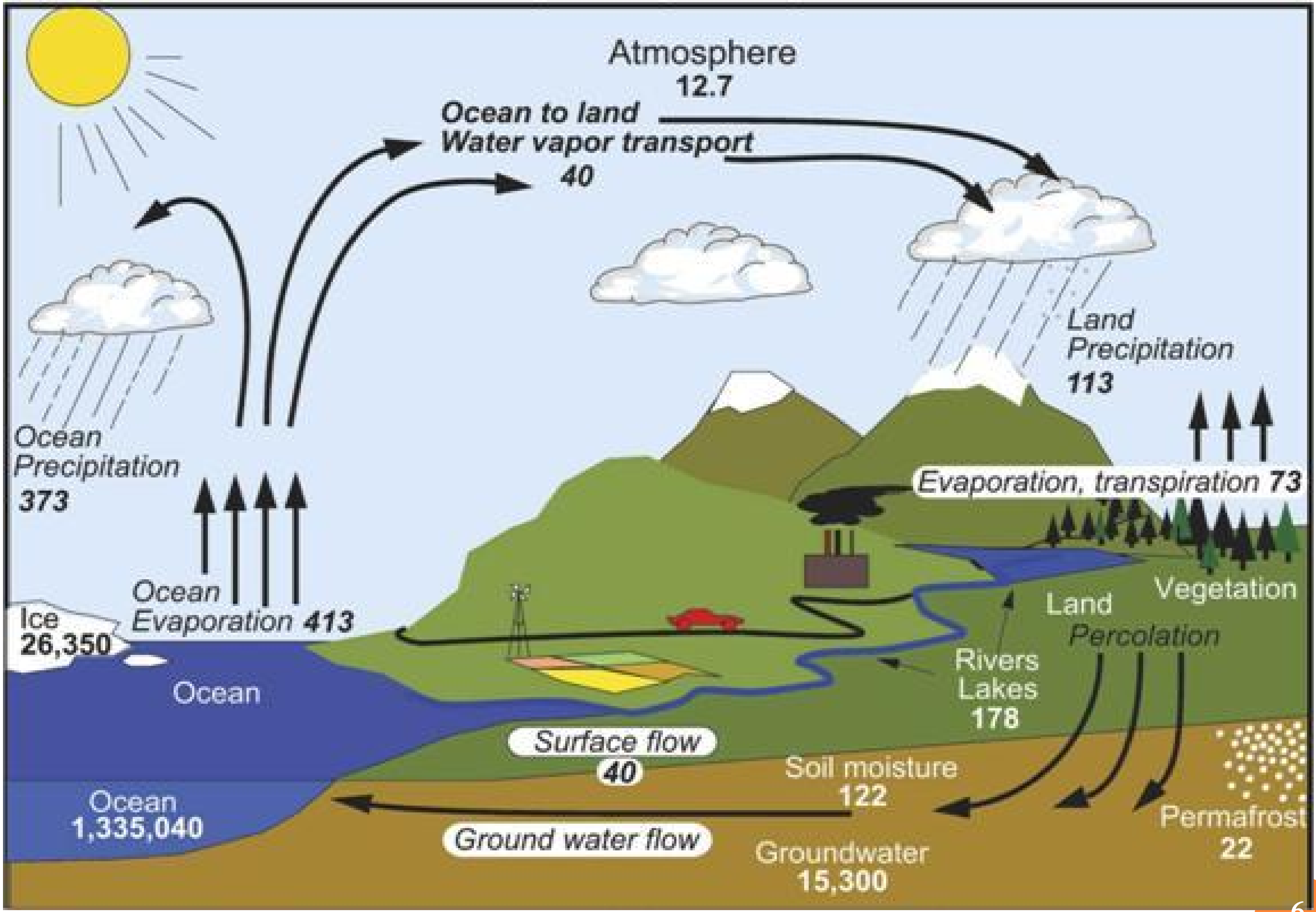


Fig: Hydrological Cycle

Types of Geological Formations and Aquifers

- There are basically four types of geological formations (Aquifers, Aquitard, Aquiclude, and Aquifuge)

1. **Aquifer**

- An aquifer is a ground-water reservoir composed of geologic units that are saturated with water and sufficiently permeable to yield water in a usable quantity to wells and springs.
- Sand and gravel deposits, sandstone, limestone, and fractured, crystalline rocks are examples of geological units that form aquifers. Aquifers provide two important functions:

(1) They transmit ground water from areas of recharge to areas of discharge, and

(2) They provide a storage medium for useable quantities of ground water. The amount of water a material can hold depends upon its porosity.

TYPES OF AQUIFERS

- 1.1 **Unconfined Aquifer**: An unconfined aquifer is one in which a water table varies in undulating form and in slope, depending on areas of recharge and discharge, pumpage from wells, and permeability.
- Rises and falls in the water table correspond to changes in the volume of water in storage within an aquifer.
- Contour maps and profiles of the water table can be prepared from elevations of water in wells that tap the aquifer to determine the quantities of water available and their distribution and movement.
- A special case of an unconfined aquifer involves **perched water bodies**.
- This occurs wherever a groundwater body is separated from the main groundwater by a relatively impermeable stratum of small areal extent and by the zone of aeration above the main body of groundwater.
- Clay lenses in sedimentary deposits often have shallow perched water bodies overlying them. Wells tapping these sources yield only temporary or small quantities of water.

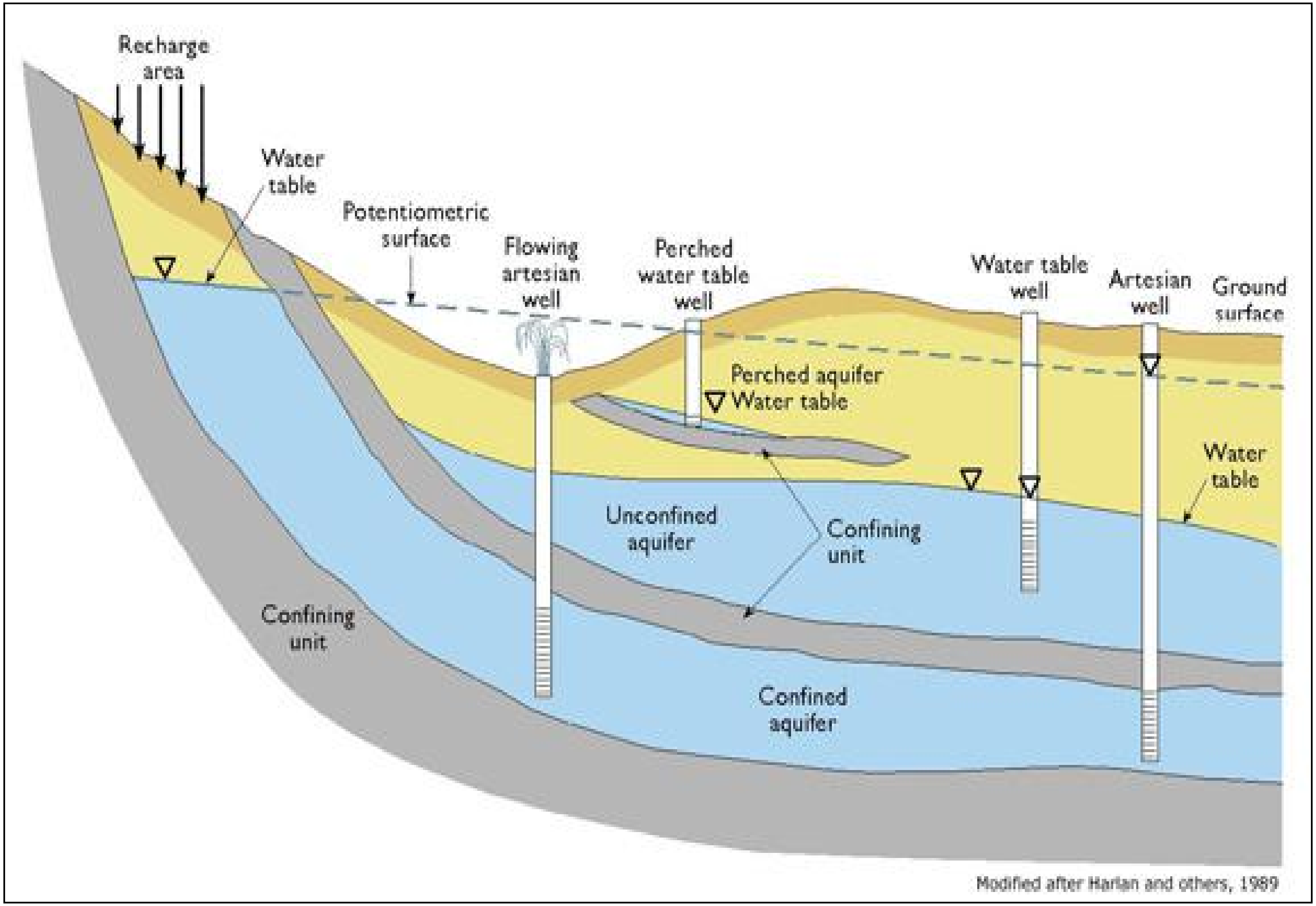


Fig: Schematic Cross-sections of Aquifer Types

- 1.2 **Confined Aquifers**: Confined aquifers, also known as **artesian or pressure aquifers**, occur where groundwater is confined under pressure greater than atmospheric by overlying relatively impermeable strata.
- In a well penetrating such an aquifer, the water level will rise above the bottom of the confining bed.
- Water enters a confined aquifer in an area where the confining bed rises to the surface; where the confining bed ends underground, the aquifer becomes unconfined.
- A region supplying water to a confined area is known as a **recharge area**; water may also enter by leakage through a confining bed.
- Rises and falls of water in wells penetrating confined aquifers result primarily from changes in pressure rather than changes in storage volumes.
- confined aquifers display only small changes in storage and serve primarily as conduits for conveying water from recharge areas to locations of natural or artificial discharge.

- **Leaky Aquifer**: Aquifers that are completely confined or unconfined occur less frequently than do leaky, or semi-confined, aquifers.
- These are a common feature in alluvial valleys, plains, or former lake basins where a permeable stratum is overlain or underlain by a semi–pervious aquitard or semi confining layer.
- Pumping from a well in a leaky aquifer removes water in two ways: by horizontal flow within the aquifer and by vertical flow through the aquitard into the aquifer

1.3 **Aquitard**

- An aquitard is a partly permeable geologic formation.
- Only seepage is possible.
- It transmits water at such a slow rate that the yield is insufficient.
- Pumping by wells is not possible. For example, sand lenses in a clay formation will form an aquitard.

1.4 **Aquiclude**

- An aquiclude is composed of rock or sediment that acts as a barrier to groundwater flow.
- Aquicludes are made up of low porosity and low permeability rock/sediment such as shale or clay.
- Aquicludes have normally good storage capacity but low transmitting capacity.

1.5 **Aquifuge**

- An aquifuge is a geologic formation which doesn’t have interconnected pores.
- It is neither porous nor permeable.
- Thus, it can neither store water nor transmit it.
- Examples of aquifuge are rocks like basalt, granite, etc.

TECHNICAL TERM

- The following properties of the aquifer are required for study of groundwater hydrology:
- 1. Porosity
- 2. Specific Yield
- 3. Specific Retention
- 4. Coefficient of permeability
- 5. Transmissibility
- 6. Specific Storage
- 7. Storage Coefficient

1. Porosity

- **Porosity** (**n**) is the percentage of rock or soil that is void of material. The larger the pore space or the greater their number, the higher the porosity and the larger the water-holding capacity.
- It is defined mathematically by the equation:

$$n = \frac{Vv}{V} * 100\%$$

Where,

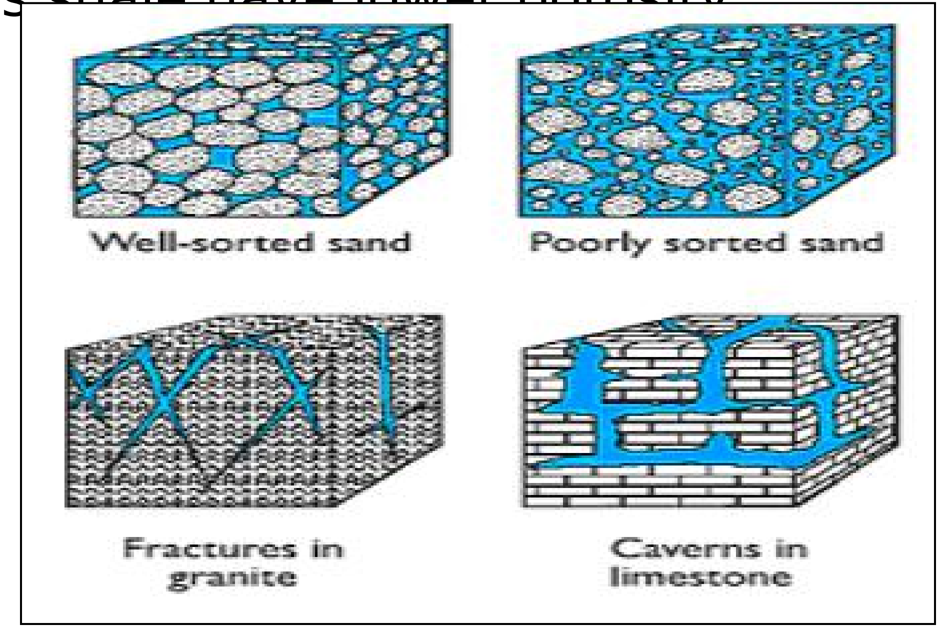
n is the porosity (percentage)

Vv is the volume of void space in a unit volume of earth materials (L3, cm3 or m3)

V is the unit volume of earth material, including both voids and solids (L3, cm3 or m3)

- In sediments or sedimentary rocks the porosity depends on **grain size**, the **shape of the grains**.
- In rocks, the porosity depends upon the **extent, spacing** and **pattern of cracks** and **fractures**.

- Well-rounded coarse-grained sediments usually have higher porosity than fine-grained sediments, because the grains don't fit together well.
- Poorly sorted sediments (sediments contains a mixture of grain sizes) usually have lower porosity because the fine-grained fragments tend to fill the open spaces.
- Porosity can range from zero to more than 60%. Recently deposited sediments have higher porosity. Dense crystalline rock or highly compacted soft rocks such as shale have lower porosity.



- **The kinematic or effective porosity** n_e:

- $n_e = \frac{\text{volume of rock occupied by movable water}}{\text{total volume of rock}}$

It is worth distinguishing between **Intergranular** or **matrix** or **primary porosity** as the latter is the porosity provided by small spaces between adjacent grains of the rock.

secondary porosity of **fractured rocks** is the porosity provided by discrete rock mass discontinuities (faults, joints and fractures).

2. SPECIFIC YIELD (SY)

- **Specific yield (Sy)** is the ratio of the volume of water that drains from a saturated rock owing to the attraction of gravity (or by pumping from wells) to the total volume of the saturated aquifer.
- It is defined mathematically by the equation:

$$s_y = \frac{Vw}{V} * 100\%$$

- where,

Vw is the volume of water in a unit volume of earth materials (L^3, cm^3 or m^3)

V is the unit volume of earth material, including both voids and solids (L^3, cm^3 or m^3)

- The actual volume of water that can be extracted by the force of gravity from a unit volume of aquifer material is known as specific yield.

3. Specific Retention (Sr)

- **Specific retention** (**Sr**) is the ratio of the volume of water that cannot be drained out to the total volume of the saturated aquifer.
- Since the specific yield represents the volume of water that a rock will yield by gravity drainage, hence the specific retention is the remainder.
- The sum of the two equals porosity.

$$n = s_r + s_y$$

- The specific yield and specific retention depend upon the shape and size of particle, distribution of pores (voids), and compaction of the formation.
- The specific retention increases with decreasing grain size.
- It should be noted that it is not necessary that soil with high porosity will have high specific yield because that soil may have low permeability and the water may not easily drain out.
- For example, clay has a high porosity but low specific yield and its permeability is low.

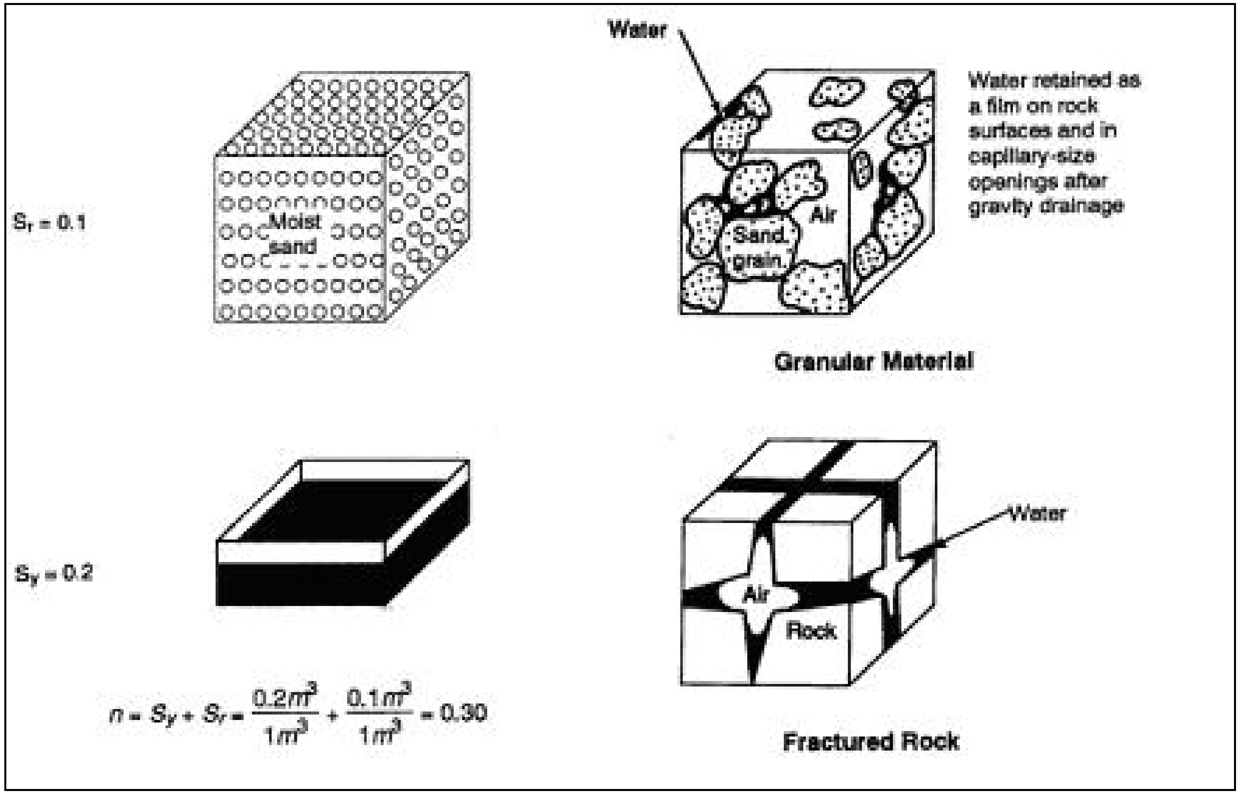


Fig : specific retention

4. Coefficient of Permeability (Hydraulic conductivity) (K)

- **Permeability** is the ease with which water can flow in a soil mass or a rock.
- The **coefficient of permeability** (**K**) is equal to the discharge (m3/s) per unit area (m2) of soil mass under unit hydraulic gradient. Because the discharge per unit area equals to the velocity, the coefficient of permeability has the dimension of the velocity [L/T].
- It is usually expressed as cm/s, m/s, m/day, etc.
- The coefficient of permeability is also called **hydraulic conductivity.**
- It is determined in the laboratory by a permeameter.
- Course grained soils a constant head permeameter is used.
- Hydraulic Conductivity can be determined and expressed as follows:

Formulas

1 **[Hazen method]**. The coefficient of permeability (K) depends on the properties of both porous medium and fluid. It can be expressed as,

$$K = \frac{[Cd_m^2]\rho g}{\mu} \qquad \textbf{(1.9)}$$

where,

- C is the shape factor which depends upon the shape, particle size and packing of the porous media
- d_m is the mean particle size (d_{50}) (L, m)
- ρ is the mass density (M/L^3, kg/m^3)
- g is the acceleration due to gravity (L/T^2, m/s^2)
- μ is the viscosity (M/T.L, kg/s.m)

➤ Another coefficient of permeability, called **intrinsic permeability (k)**, is sometimes used. The intrinsic permeability depends upon the porous medium and is independent of the properties of the fluid. It is usually expressed as,

$$k = Cd_m^2 \qquad \textbf{(1.10)}$$

2 **[Kozeny-Carmen]**

$$K = \frac{\rho g}{\mu} \cdot \left(\frac{n^3}{(1-n)^2} \right) \left(\frac{d_m^2}{180} \right) \qquad \textbf{(1.11)}$$

where, n is porosity,
d_m is representative of grain size (L, m).

3 **[Shepherd] –** Empirically derived

$$K = c\, d^{1.65 \, to \, 1.85} \qquad \textbf{(1.12)}$$

where c and d exponent values vary with material description

5. TRANSMISSIVITY (T)

- **Transmissivity** (**T**) is the discharge rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Thus,

- $T = Kh$ *unconfined aquifer*
- $T = Kb$ *confined aquifer*

where,

b is the saturated thickness of the aquifer.

b is equal to the depth of a confined aquifer.

It is equal to the **average** thickness of the saturated zone of an unconfined aquifer.

- Transmissibility is usually expressed as m2/s, or m3/day/m or l/day/m.

6. Specific Storage (Ss)

Specific Storage (S_s) is the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in head. This is also called the *elastic storage coefficient*. The concept can be applied to both aquifers and confining units.

The specific storage is given by the expression (Jacob 1940, 1950; cooper 1966):

$$S_s = \rho_w g(\alpha + n\beta) \qquad \textbf{(1.14)}$$

where

- ρ_w is the density of the water (M/L^3; Kg/m^3)
- g is the acceleration of gravity (L/T^2; m/s^2)
- α is the compressibility of the aquifer skeleton ($1/(M/LT^2)$; m^2/N)
- n is the porosity
- β is the compressibility of water ($1/(M/LT^2)$; m^2/N)

- Specific storage (Ss) of a confined aquifer is the storage coefficient per unit-saturated thickness of the aquifer. Thus,

$$S_S = \frac{S}{b}$$

- where, **b** is the thickness of aquifer

Table 1.9 Values of Specific Storage Assuming Porosity Equal to 15 % (after Younger, 1993)

Typical Lithologies	Specific Storage (m^{-1})
Clay	9.81×10^{-3}
Silt, fine sand	9.82×10^{-4}
Medium sand, fine	9.87×10^{-5}
Coarse sand, medium gravel, highly fissured	1.05×10^{-5}
Coarse gravel, moderately fissured rock	1.63×10^{-6}
Unfissured rock	7.46×10^{-7}

7. STORAGE COEFFICIENT (S)

- **Storage coefficient** (**S**) is the volume of water released from storage, or taken into storage, per unit of aquifer storage area per unit change in head.
- The storage coefficient is also called **Storativity**.
- The storage coefficient is a **dimensionless** as it is the ratio of the **volume of water released from original unit volume**.
- The water-yielding capacity of an aquifer can be expressed in terms of its storage coefficient.
- In **unconfined aquifers**, **Storativity is the same as the specific yield** of the aquifer.
- In **confined aquifer**, **Storativity is the result of compression of the aquifer and expansion**
- of the confined water when the head (pressure) is reduced during pumping.

GROUND WATER ENGINEERING CV0612

INTRODUCTION TO GROUNDWATER ENGINEERING

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TOPICS

(1)introduction

(2)Groundwater in Hydrologic cycle

(3)groundwater reservoir

(4)water bearing formations

(5)groundwater use, Causes & Effects of changes in ground water quality

(6)conjunctive use of ground

INTRODUCTION

Groundwater engineering, another name for hydrogeology,is a branch of engineering which is concerned with groundwater movement and design of wells, pumps, and drains.

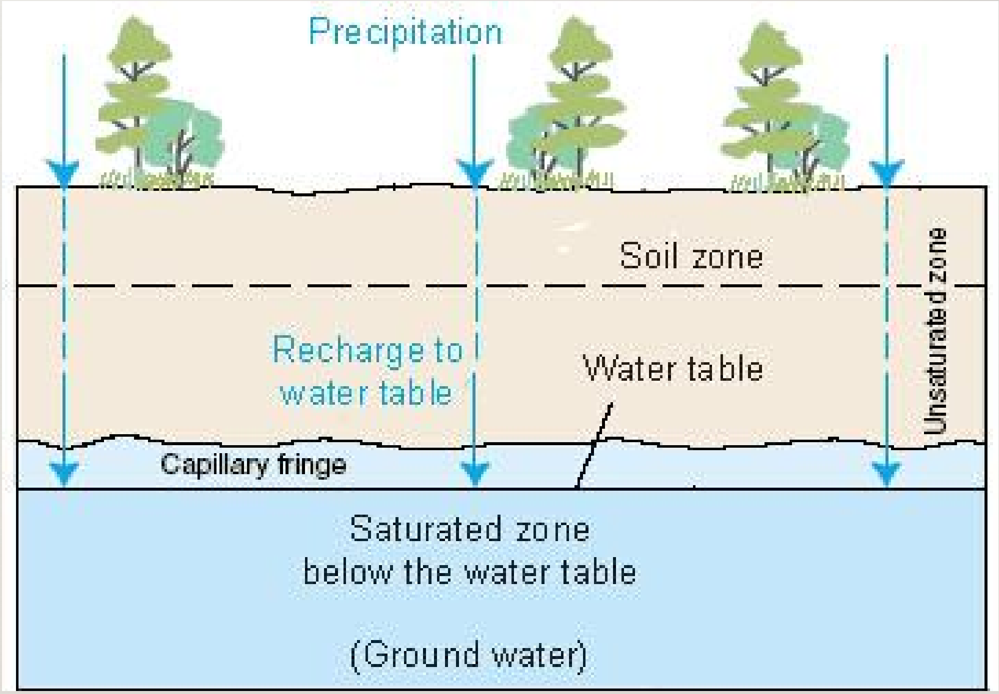

fig:1(ZONES)

GROUND WATER IN HYDROLOGIC CYCLE

- Water cycle, also called hydrologic cycle, cycle that involves the continuous circulation of water in the Earth–atmosphere system. Of the many processes involved in the water cycle, the most important are evaporation, transpiration, condensation, precipitation, and runoff.

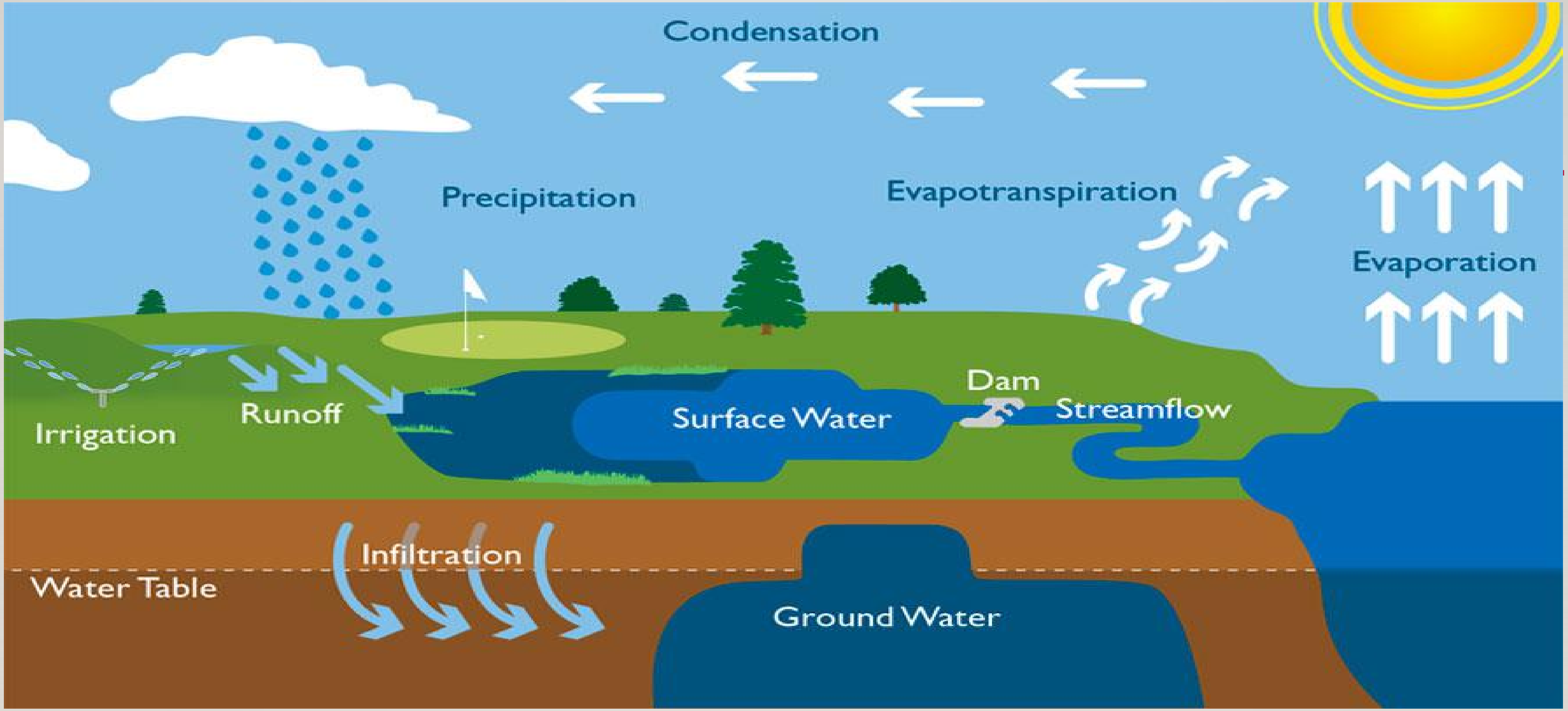

FIG 2 (HYDROLOGICAL CYCLE)

GROUND WATER RESERVOIR

- Groundwater is water that exists in the pore spaces and fractures in rock and sediment beneath the Earth’s surface. ... Groundwater is a long-term reservoir of the natural water cycle, as opposed to short-term water reservoirs like the atmosphere and fresh surface water.

WATER BEARING FORMATION

- The water–bearing formation includes both saturated and unsaturated parts of the formation. ... “Aquifer” means a subsurface water–bearing geologic formation from which significant quantities of water may be extracted.

TYPES OF WATER BEARING UNITS

- The geologic formations are classified in relation to their capacity to store and transmit the water i.e., the porosity and hydraulic conductivity.
- An aquifer is a geologic formation, which contains water and permits significant amount of water to move through it under field conditions.
- An aquiclude is a formation which may contain water but is incapable of transmitting significant quantities under ordinary field conditions . A clay layer is an example of an aquiclude is considered an impervious formation.
- An aquitard is a geologic formation which is of semi-pervious nature it transmits water at a very low rate compared to the aquifer.

AQUIFER

- An aquifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt). Groundwater can be extracted using a water well. The study of water flow in aquifers and the characterization of aquifers is called hydrogeology.

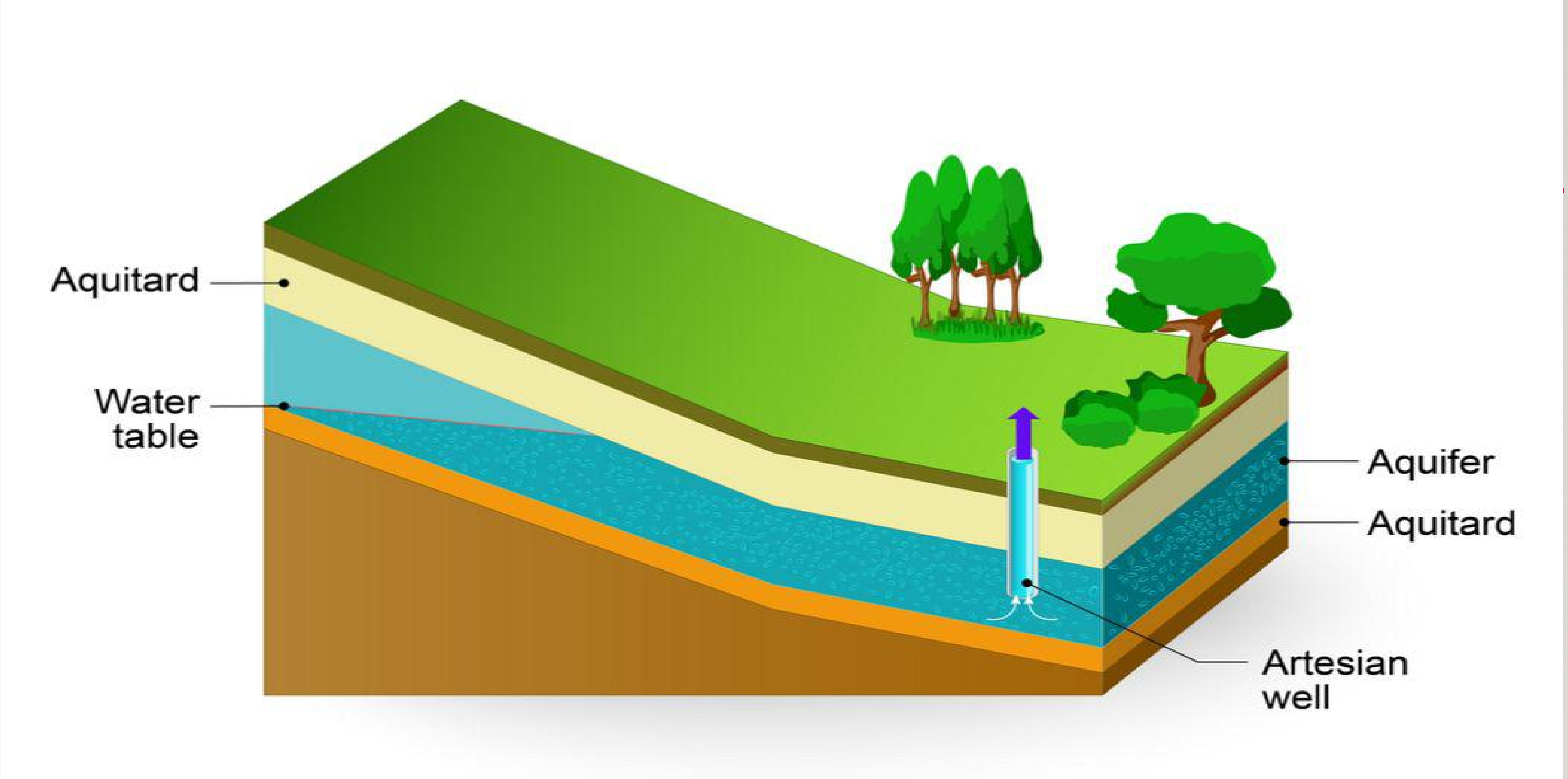

FIG 3 (GEOLOGICAL FORMATIONS)

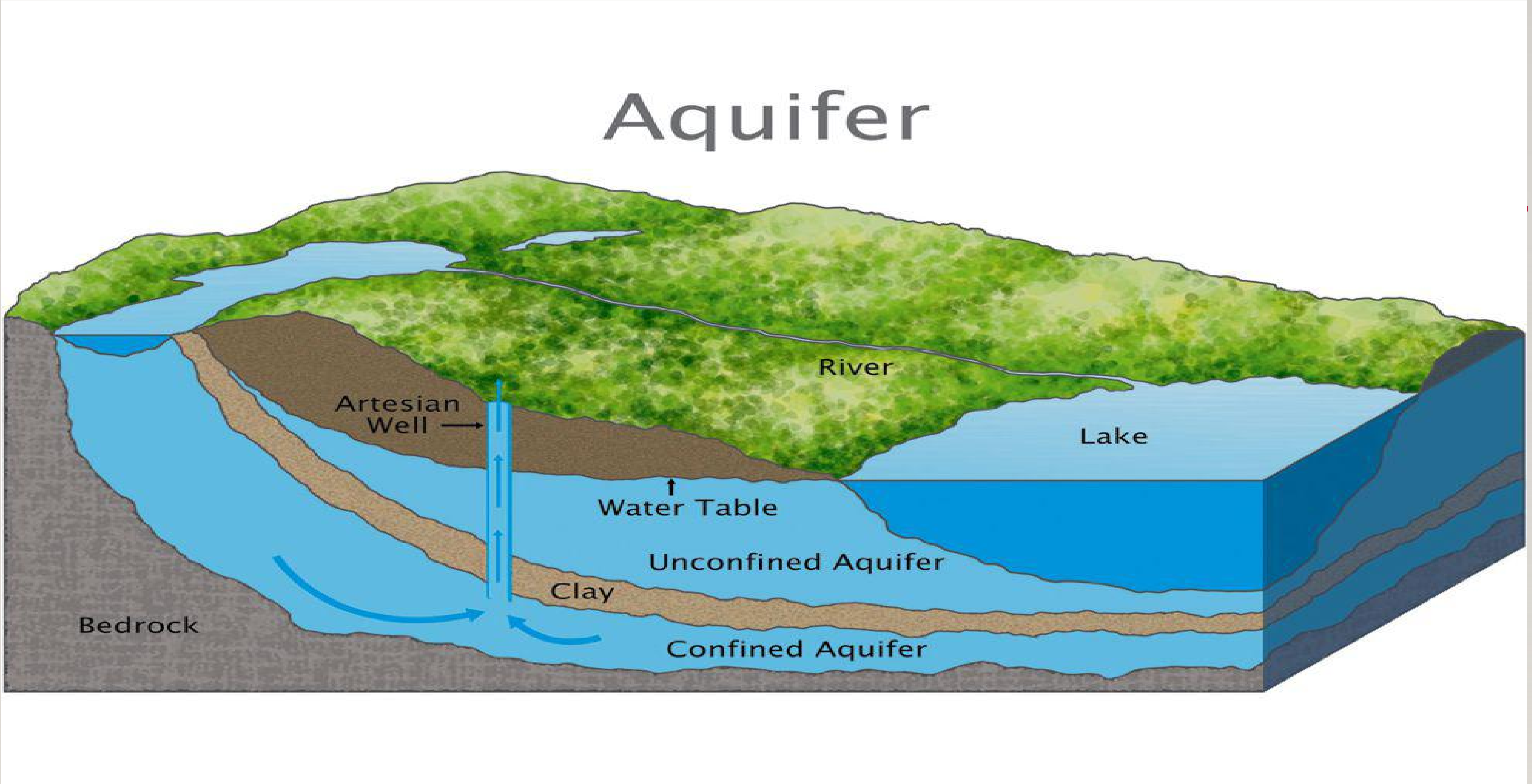

FIG 4 (AQUIFER)

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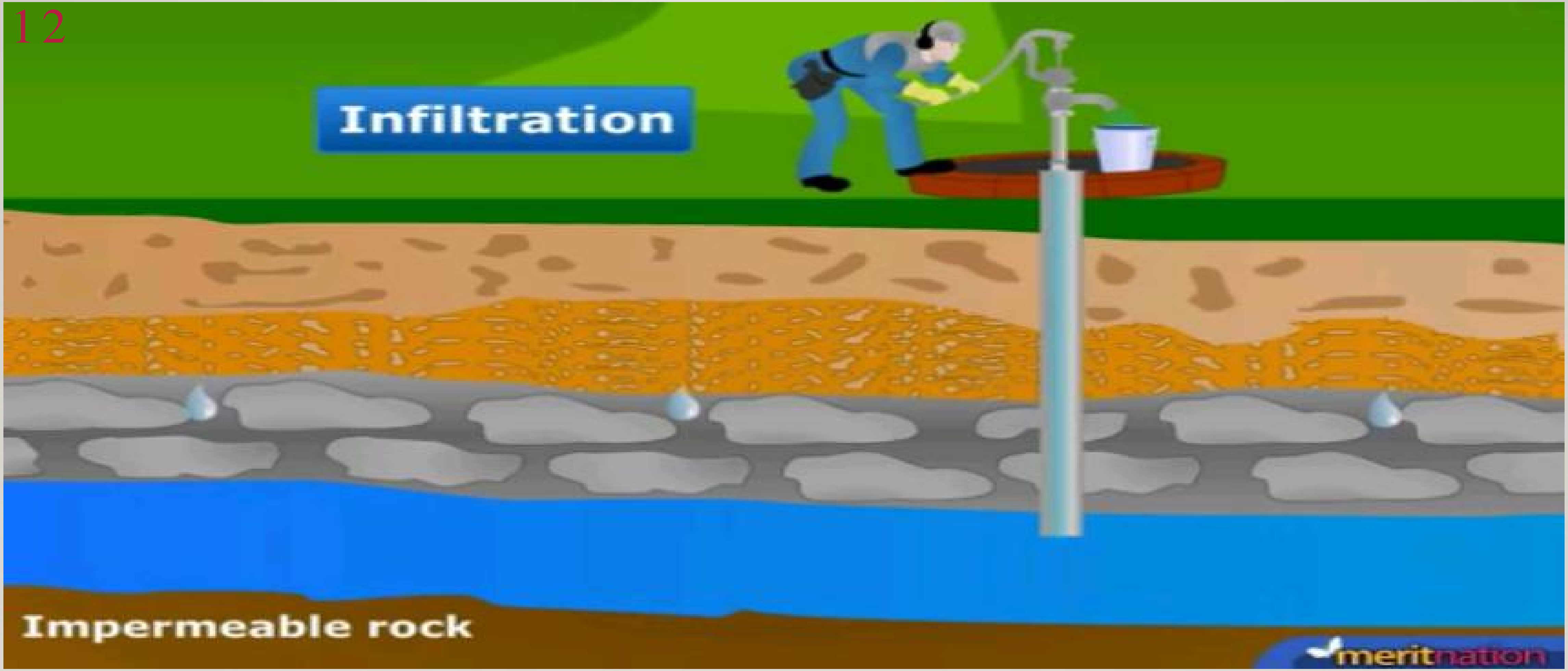


AQUICLUDE

- An aquiclude is a geological formation which is impermeable to the flow of water.
- It contains a large amount of water in it but it does not permit water through it and also does not yield water. It is because of its high porosity.
- Clay is an example of aquiclude.

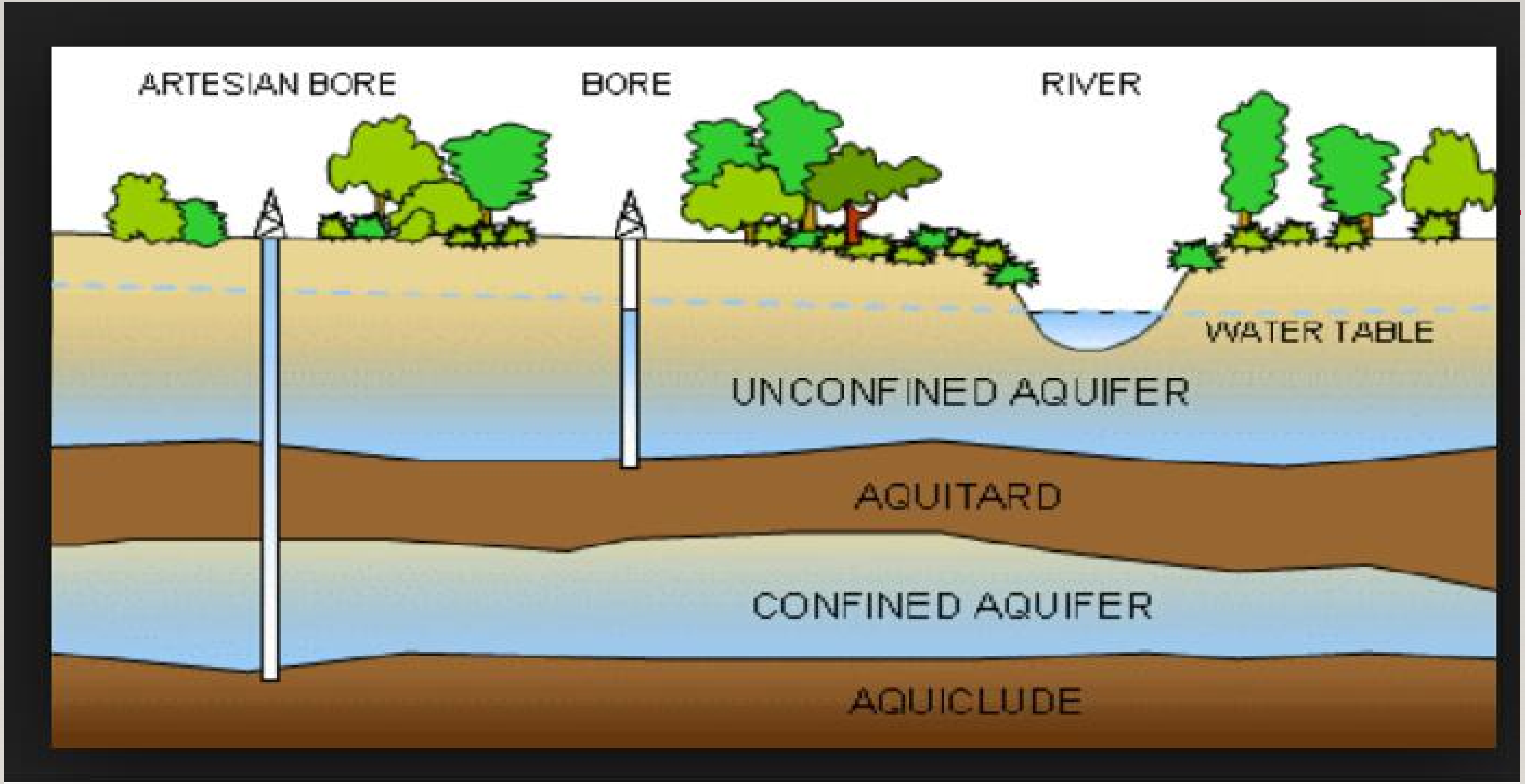


FIG 5 (AQUICLUDE)

AQUITARD

- An aquitard is a zone within the Earth that restricts the flow of groundwater from one aquifer to another.
- A completely impermeable aquitard is called an aquiclude or aquifuge.
- Aquitards comprise layers of either clay or non-porous rock with low hydraulic conductivity.

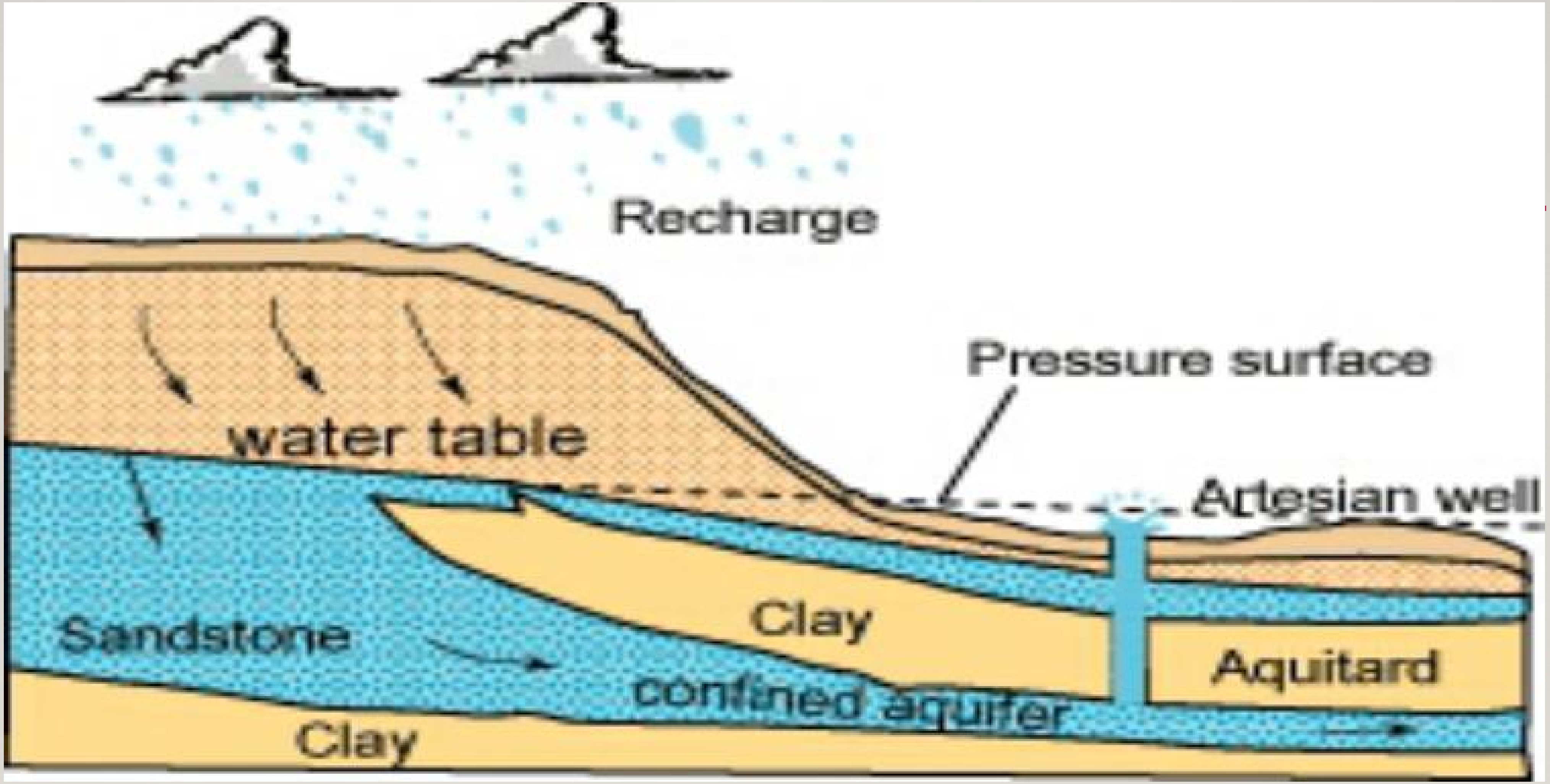


FIG 6 (AQUITARD)

AQUIFUGE

- An aquifuge is an impermeable geological formation which is neither porous nor permeable.
- which means it cannot store water in it and at the same time it cannot permit water through it.
- Compact rock is an example of aquifuge.

TYPES OF AQUIFER

There are two types of Aquifer

(1)Confined Aquifer And

(2) Unconfined Aquifer

(1) CONFINED AQUIFER

- A confined aquifer is an aquifer below the land surface that is saturated with water.
- Layers of impermeable material are both above and below the aquifer, causing it to be under pressure so that when the aquifer is penetrated by a well, the water will rise above the top of the aquifer.

(2) UNCONFINED AQUIFER

- Unconfined aquifers are those into which water seeps from the ground surface directly above the aquifer
- A permeable layer of rock and sediment that contains groundwater. Define unconfined aquifer

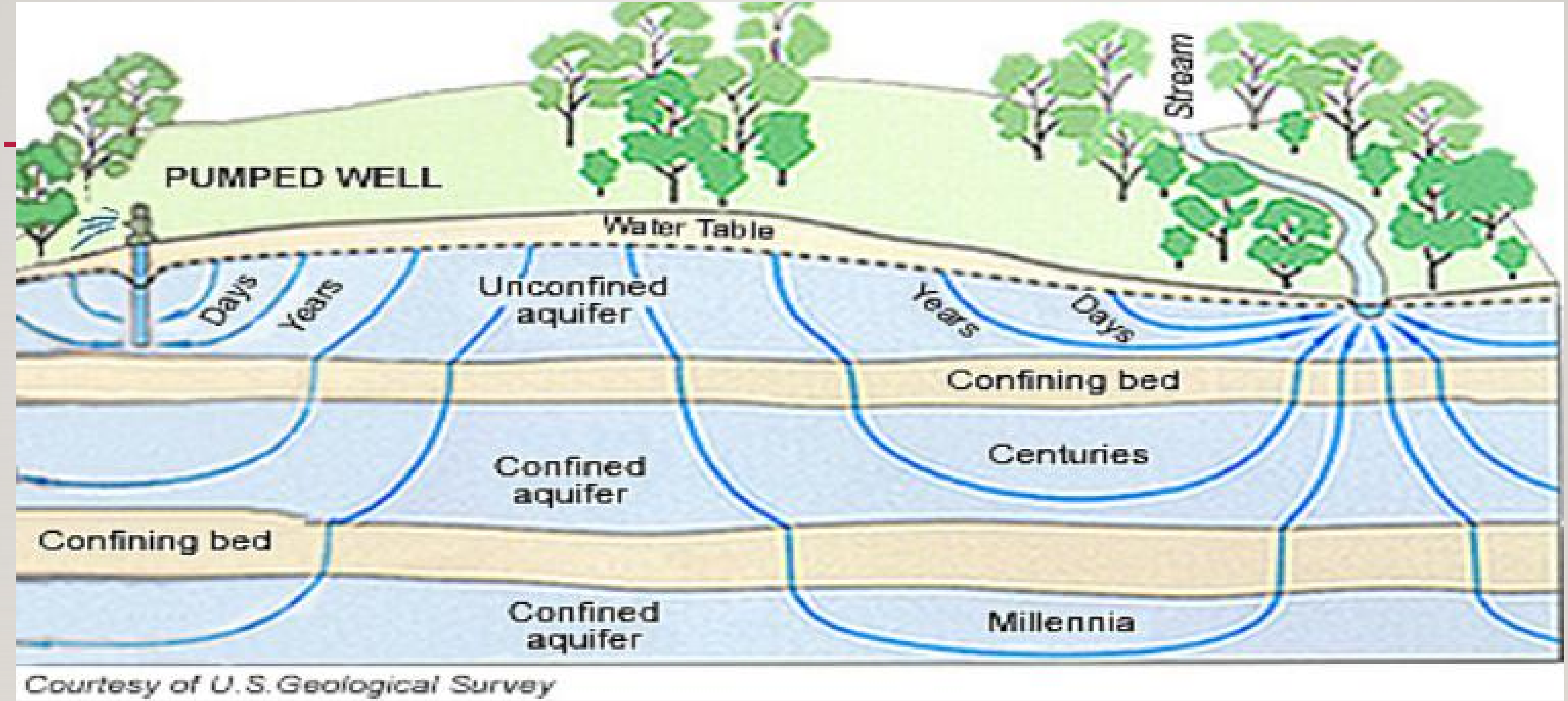


FIG 7 (CONFINED UNCONFINED AQUIFER)

PROPERTIES OF AQUIFER

(1) Porosity,

(2) Specific Yield And Specific Retention,

(3) Darcy’s Law,

(4) Coefficient Of Permeability,

(5) Stratification

(1)POROSITY

- The Amount of Pore space per unit volume of the Aquifer material is called porosity.
- It is Expressed as,

$$n = Vv/Vo$$

- Where,n=Porosity, Vv= Volume of Voids, Vo=Volume of Porous medium

- In Qualitative Terms,(1) Porosity $>20\%$ is considered as Large
- (2) Porosity between $5\text{–}20\%$ is considered as Medium
- (3) Porosity $<5\%$ is considered as Small

(2) SPECIFIC YIELD AND RETENTION

- While porosity gives a measure of the water storage capability of a formation,not all the water held in the pores is available for extraction by Pumping or Draining by Gravity.
- The Pores hold back some water by molecular attraction and surface tension.

- The actual volume of water that can be extracted by the force of gravity from a unit volume of aquifer material is known as Specific Yield(Sy).
- The Fraction of water held back in the Aquifer is known as Specific Retention(Sr).

DARCY'S LAW

- The darcy's law is,
- "For the laminar flow which is passed through the saturated soil mass, the discharge per unit time is proportional to the hydraulic gradient."

$q=k.i.A$

$q/A=k.i$ (but $q/A=V$)

- $V = k.i$ ……..Darcy's Law .

  Where, q= discharge part time

- A= total cross section area of soil
- i= hydraulic gradient
- k= darcy's coefficient of permeability
- V= velocity of flow

COEFFICIENT OF PERMEABILITY

- Coefficient Of Permeability. It is the measure of capacity of the soil with which the water can easily flow through it. It is also termed as Darcy coefficient of permeability. ... With the use of the permeameter device, the coefficient of permeability is found in the laboratory.

$$k = \frac{qL}{Ah}$$

where k = coefficien t of permeabili ty in cm/sec

q = Discharge cm^3/sec

L = Length of specimen in cm.

A = Cross -sectional area of specimen in cm^2

H = Constant head causing flow in cm.

STRATIFICATION

(i) When the flow is parallel to the stratification as in Fig. 9.5(a) equivalent permeability K_e of the entire aquifer of thickness $B = \sum_1^n B_i$ is

$$K_e = \frac{\sum_1^n K_i B_i}{\sum_1^n B_i} \tag{9.10}$$

The transmissibility of the formation is

$$T = K_e \Sigma B_i = \sum_1^n K_i B_i$$

(ii) When the flow is normal to the stratification as in Fig. 9.5(b), the equivalent permeability K_e of the aquifer of length

$$L = \sum_1^n L_i \quad \text{is}$$

$$K_e = \frac{\sum_1^n L_i}{\sum_1^n (L_i / K_i)} \tag{9.11}$$

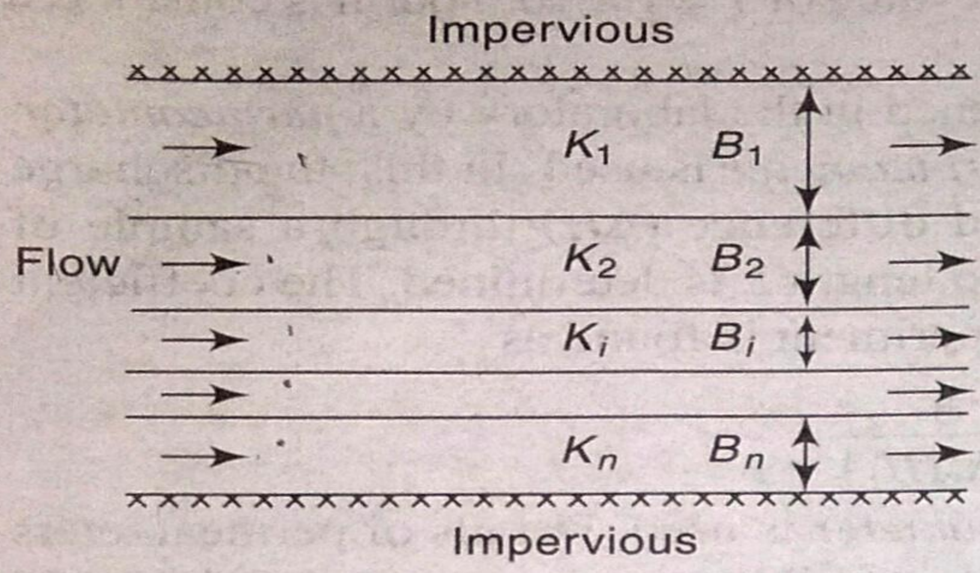


Fig. 9.5(a) ***Flow Parallel to Stratification***

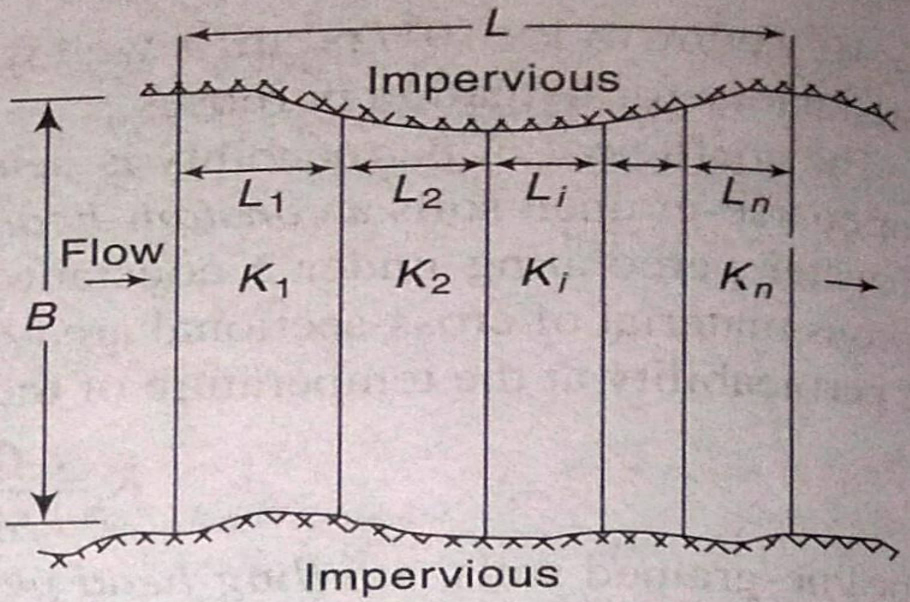


Fig. 9.5(b) ***Flow Normal to Stratification***

(Note that in this case L is the length of seepage and the thickness B of the aquifer does not come into picture in calculating the equivalent permeability)

The transmissibility of the aquifer is $T = K_e \cdot B$

GROUND WATER USE

- Groundwater is recharged from the surface; it may discharge from the surface naturally at springs and seeps, and can form oases or wetlands. Groundwater is also often withdrawn for agricultural, municipal, and industrial use by constructing and operating extraction wells. ... Groundwater may not be confined only to Earth.

- Groundwater is the world’s most extracted raw material with withdrawal rates currently in the estimated range of 982 km3 /year.
  About 70% of groundwater withdrawn worldwide is used for agriculture.

- Groundwater provides almost half of all drinking water worldwide.
  Globally, about 38% of irrigated lands are equipped for irrigation with groundwater.
  The volume of modern groundwater is equivalent to a body of water with a depth of about 3 m spread over the continents.

PRESENT WATER ON EARTH

- The total volume of water on Earth is estimated at 1.386 billion km^3 (333 million cubic miles), with 97.5% being salt water and 2.5% being fresh water.

Table 1.1 *Estimated World Water Quantities*

Item	Area (M km^2)	Volume (M km^3)	Percent total water	Percent fresh water
1. Oceans	361.3	1338.0	96.5	—
2. Groundwater				
(a) fresh	134.8	10.530	0.76	30.1
(b) saline	134.8	12.870	0.93	—
3. Soil moisture	82.0	0.0165	0.0012	0.05
4. Ice caps and glaciers	16.0	24.0235	1.7	68.6
5. Other ice and snow	0.3	0.3406	0.025	1.0
6. Lakes				
(a) fresh	1.2	0.0910	0.007	0.26
(b) saline	0.8	0.0854	0.006	—
7. Wetlands	2.7	0.01147	0.0008	0.03
8. Rivers	148.8	0.00212	0.0002	0.006
9. Biological water	510.0	0.00112	0.0001	0.003
10. Atmospheric water	510.0	0.01290	0.001	0.04
Total: (a) All kinds of water	510.0	1386.0	100.0	
(b) Fresh water	148.8	35.0	2.5	100.0

Table from WORLD WATER BALANCE AND WATER RESOURCES OF THE EARTH, © UNESCO, 1975. Reproduced by the permission of UNESCO.

The global annual water balance is shown in Table 1.2.

Table 1.2 *Global Annual Water Balance*

Item	Ocean	Land
1. Area (M km^2)	361.30	148.8
2. Precipitation (km^3/year)	458,000	119,000
(mm/year)	1270	800
3. Evaporation (km^3/year)	505,000	72,000
(mm/year)	1400	484
4. Runoff to ocean		
(i) Rivers (km^3/year)		44,700
(ii) Groundwater (km^3/year)		2,200
Total runoff (km^3/year)		47,000
(mm/year)		316

Table from WORLD WATER BALANCE AND WATER RESOURCES OF THE EARTH, © UNESCO, 1975. Reproduced by the permission of UNESCO.

TABLE 1

CAUSES & EFFECTS OF CHANGES IN GROUND WATER QUALITY

- Groundwater pollution occurs as a result of release of pollutants into the ground to natural underground water reservoirs known as aquifers. Once the pollutants released find their way into groundwater, they cause contamination.

- It is a type of water pollution that is mainly caused by release of substances either intentionally or accidentally through anthropogenic activities or natural causes

CAUSES OF GROUNDWATER POLLUTION

1. Natural Sources
2. Hazardous waste Disposal
3. Solid Waste
4. Agricultural Chemicals
5. Injection wells

EFFECTS OF GROUNDWATER POLLUTION

1. Health Issues
2. Affects economic growth
3. Can lead to damaging impacts on the environment such as aquatic systems and the overall ecosystem

SOLUTIONS OF GROUNDWATER POLLUTION

1. The use of water cleaning systems
2. Proper management of the sources of pollution
3. Recycling

CONJUCTIVE USE OF GROUND

- In active conjunctive use, surface water is directly injected into aquifers and wells to be used as needed as part of groundwater banking. ... Storing groundwater below ground through conjunctive use is also seen as a way to lessen its evaporation and avoid building reservoirs and dams.

CONJUCTIVE USE

- This technique involves the usage of two or more sources of irrigation to get a sustained irrigation system and to meet the crop demand.
- In agriculture the irrigating the field has become the major problem.
- To mitigate this problem the conjuctive use of water is made.
- In conjuctive use the ground water and other surface flow like river,canal water can be used.

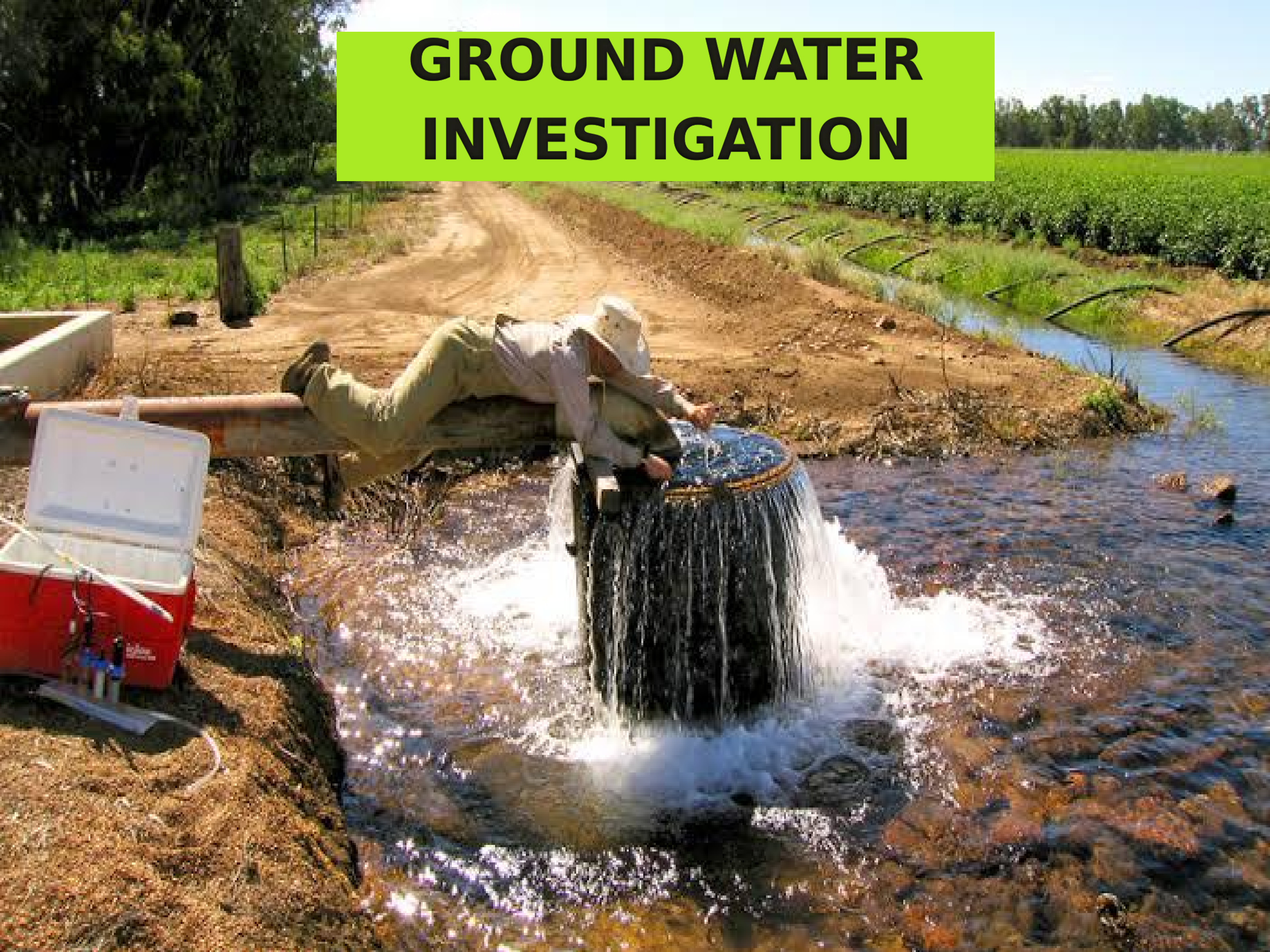
45 EFFECT FOR USING THIS METHOD

- Much greater water supply security– by taking advantage of natural groundwater storage in aquifers.
- Larger net water–supply yield –than would generally be possible using only one source alone.
- Better timing of irrigation–water delivery– since groundwater can be rapidly deployed to compensate for any shortfall in canal–water availability at critical times in the crop –growth cycle.
- Reduced environmental impact – by counteracting land waterlogging and salinization ,and excessive riverflow depletion or aquifer overexploitation.

NEED FOR THIS METHOD

- To prevent water scarcity that occurred on the region that are remote to the river or other similar water source.
- To create equal distribution of water to all regions
- To reduce sea water intrusion
- To meet the crop demand in a sustained manner
- To get reliable yield in places where we have saline water


Thank You


GROUND WATER
INVESTIGATION

1.

INDEX

- <u>Introduction</u>

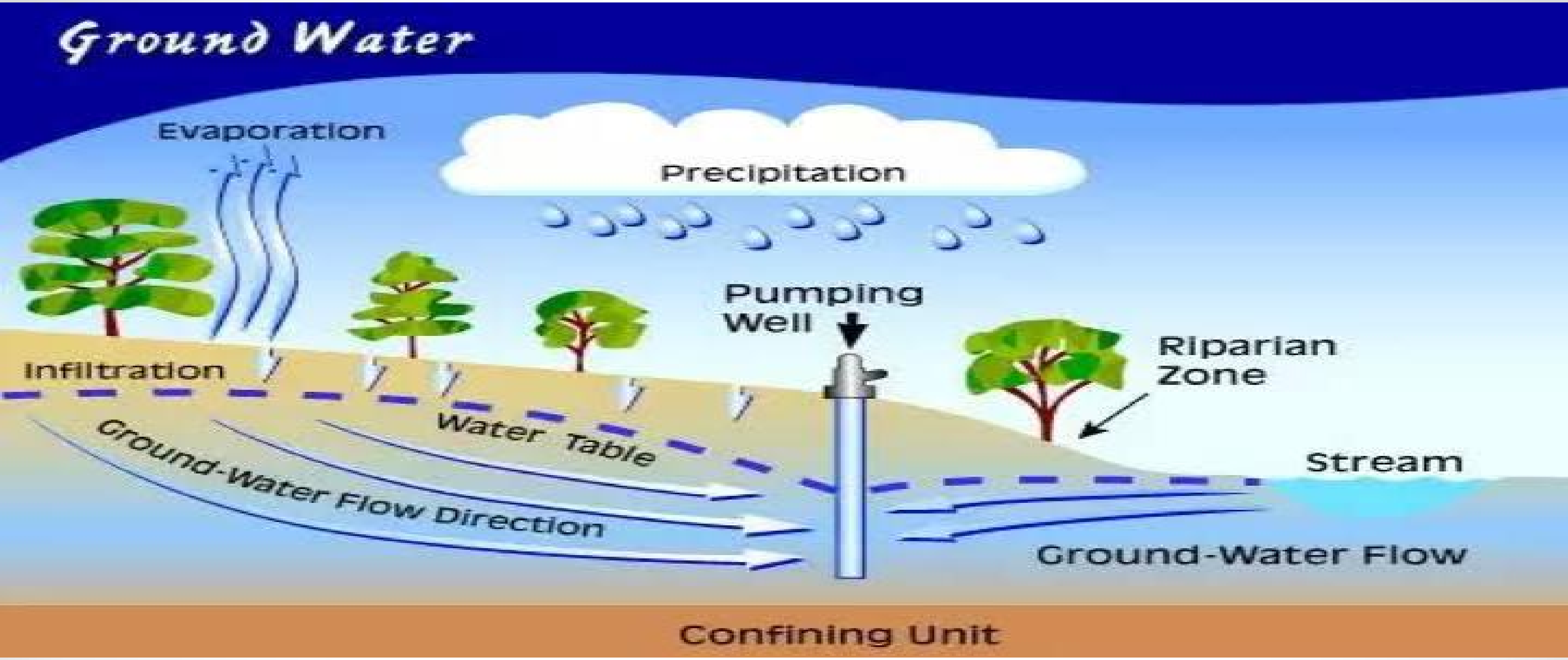
1. What is ground water
2. What is ground water exploration

- <u>Types of ground water exploration</u>

1. Surface
2. Subsurface

2.

INTRODUCTION



What is Ground water ?

- When rain falls to the ground, the water does not stop moving. The top of the water in the soil, sand, or rocks is called the water table and the water that fills the empty spaces and cracks is called ground water.

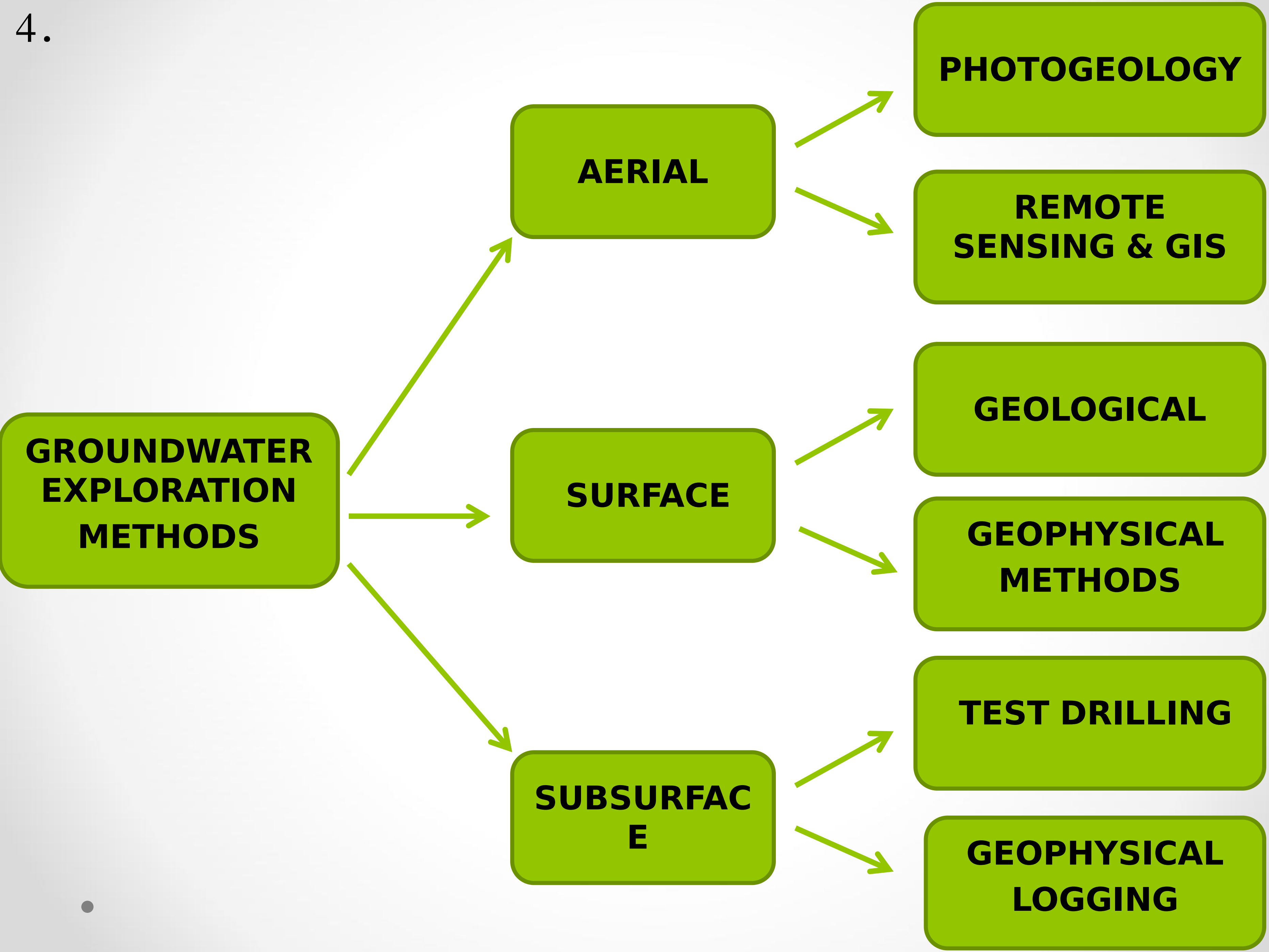
3.

What is Ground water investigation ?

- Groundwater exploration is the investigation of underground formations to understand the hydrologic cycle, know the groundwater quality, and identify the nature, number and type of aquifers.

- OBJECTIVE – To create the ground water mapping of the area which will help in overall water resource development , planning and management.

4.


GROUNDWATER EXPLORATION METHODS
AERIAL
SURFACE
SUBSURFAC E
PHOTOGEOLOGY
REMOTE SENSING & GIS
GEOLOGICAL
GEOPHYSICAL METHODS
TEST DRILLING
GEOPHYSICAL LOGGING

5.

Surface Method Of Groundwater

- The exploration of groundwater can be done from the earth’s surface or above surface locations which is known as surface investigation.

- Advantage– Less expensive and less time consuming than the subsurface investigations.

- Disadvantage– Do not provide quantitative information concerning aquifers or groundwater as obtained from subsurface investigation.

Types Of Surface Method

(a) **Geologic methods ('reconnaissance methods').**

- involves collection, analysis and hydrogeologic interpretation of existing geologic data, topographic maps and aerial photographs.

(b) **Geophysical methods.**

- Geophysical methods are scientific measurements of differences or anomalies of physical properties within the earth's crust.

7.

Geologic Methods

- The occurrence and movement of groundwater is mainly dependent on the geology of an area, so it is essential to study the geology as a preliminary step.

- The geologic methods enable to evaluate large areas for groundwater development rapidly and economically.

- The geologic investigation involves the collection, analysis and hydrogeological interpretation of existing topographic maps, aerial photographs, geologic maps, well logs and other relevant data/information.

8.

GEOLOGIC METHODS

- Test pits and trenches’
- Adits
- Continuous cone penetrometer
- Auger

- This should be supplemented by geologic field reconnaissance and hydrologic data such as streamflow, springs, well yield, groundwater levels, groundwater recharge and discharge, and water quality.

- These field data and information indirectly/directly indicate the possibility of water-bearing formations (aquifers), their extent and continuity, interconnection of aquifers, aquifer boundaries, nature and thickness of overlying strata, presence of faults, etc.

10.

Test Pits and Trenches

- Test pits and trenches are excavations on the ground surface for in situ examinations of near surface soil, rocks or any other geologic formations.

- These excavations can be done by hand tools or by power equipment like backhoes, bulldozers, scrapers, etc.

- The depth of the excavation depends on the field conditions, type of equipment used and the budget available.

- Test pits are usually square or circular in shape with 1–3 m length or diameter, respectively.

- These are deeper than trenches which are about 1 to 2 m wide and may extend to any lengths.

11.

12.

Adits

- Adits are horizontal or nearly horizontal excavations mainly used to drain water from mines and also serve as an entrance and ventilation.
- Typical dimensions of adits are 1 m × 1.5 m or 2 m × 2.5 m.
- They are mainly used for the exploration of rocks, their structural features such as joints, fractures, faults and shear zones.
- The main limitation to this method is that it is costly for small projects; generally it is not used in the soil.

13.

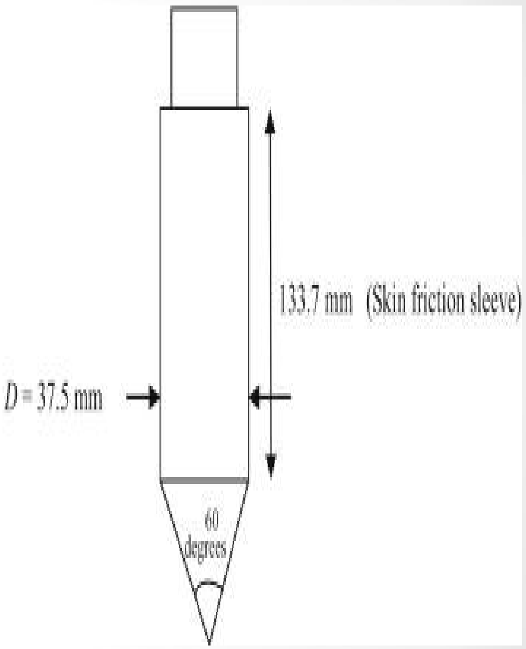
14.

Continuous Cone Penetrometer

- Continuous cone penetrometer is a device consisting of a cylindrical probe with a cone shaped tip with different sensors in it.

- The cylindrical probe is 3 to 5 cm in diameter with its cone tip having a cross sectional area of 10 to 15 cm^2 and apex angle of 60°.

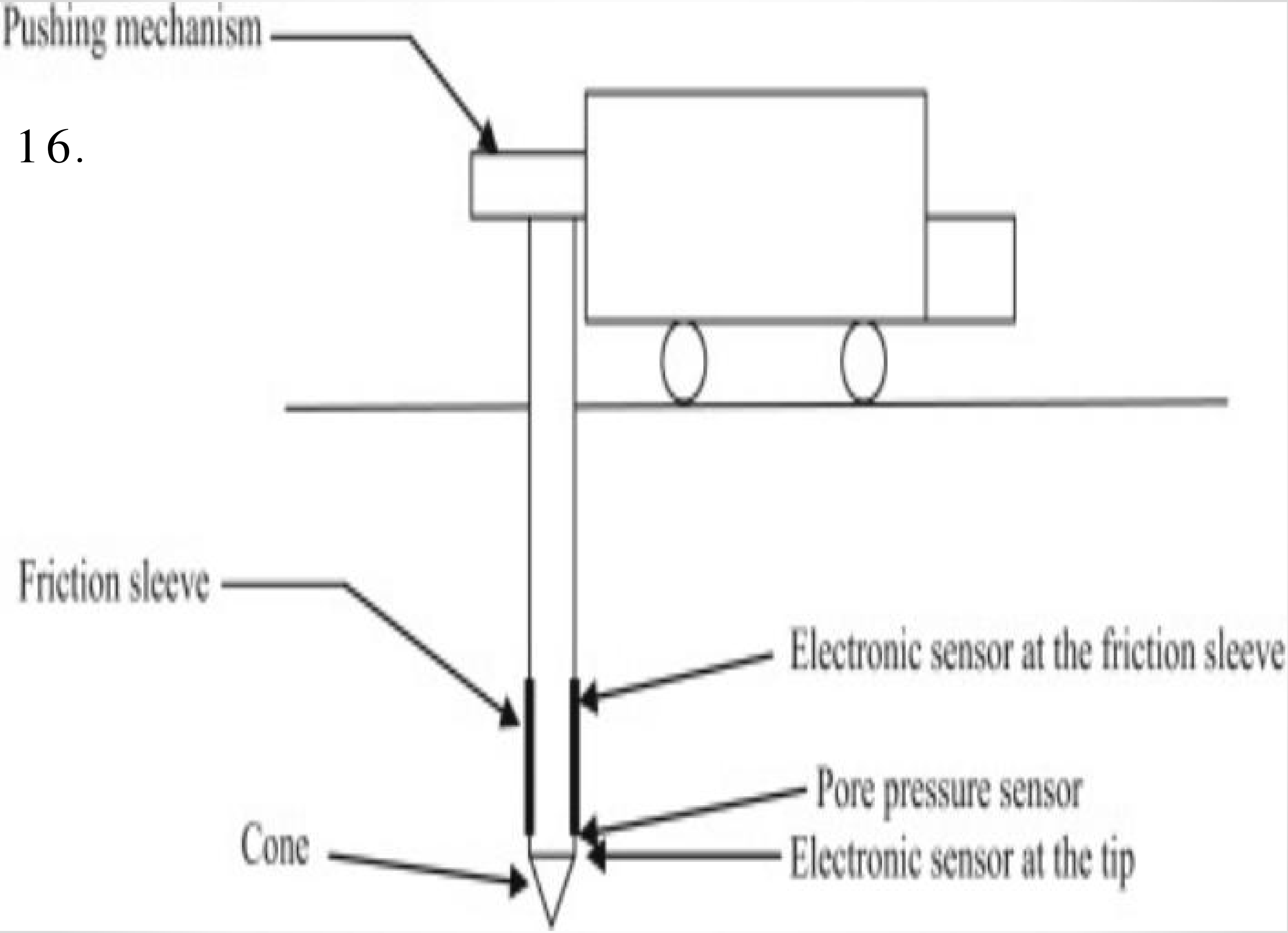
- A porous filter element is present above this cone tip used to measure the pore water pressure.



15.

- The device is pushed into the ground with its tip facing the surface at a controlled rate of 1.5 to 2.5 cm/s.
- The data is recorded by a field computer through a cable connected to the device.
- This is used to measure stress, sleeve friction and pore water pressure.
- It provides a continuous record of penetration resistance and friction.

16.



Pushing mechanism
Friction sleeve
Electronic sensor at the friction sleeve
Pore pressure sensor
Cone
Electronic sensor at the tip

17.

Auger

- Auger is a drilling device consisting of a rotating helical blade with an extendable steel rod and a handle.

- The auger is driven into the ground to remove the drilled materials.

- It is a cheap and fast method, but restricted only to soft unconsolidated formations.

- Depending on the geology, augers can be used up to a depth of 15 to 25 m.

- Many types of augers can be used based on the type of geologic formations available in a particular region.

- Hand augers are used in sand, silt and soft clay, while bucket augers are used in relatively hard grounds.

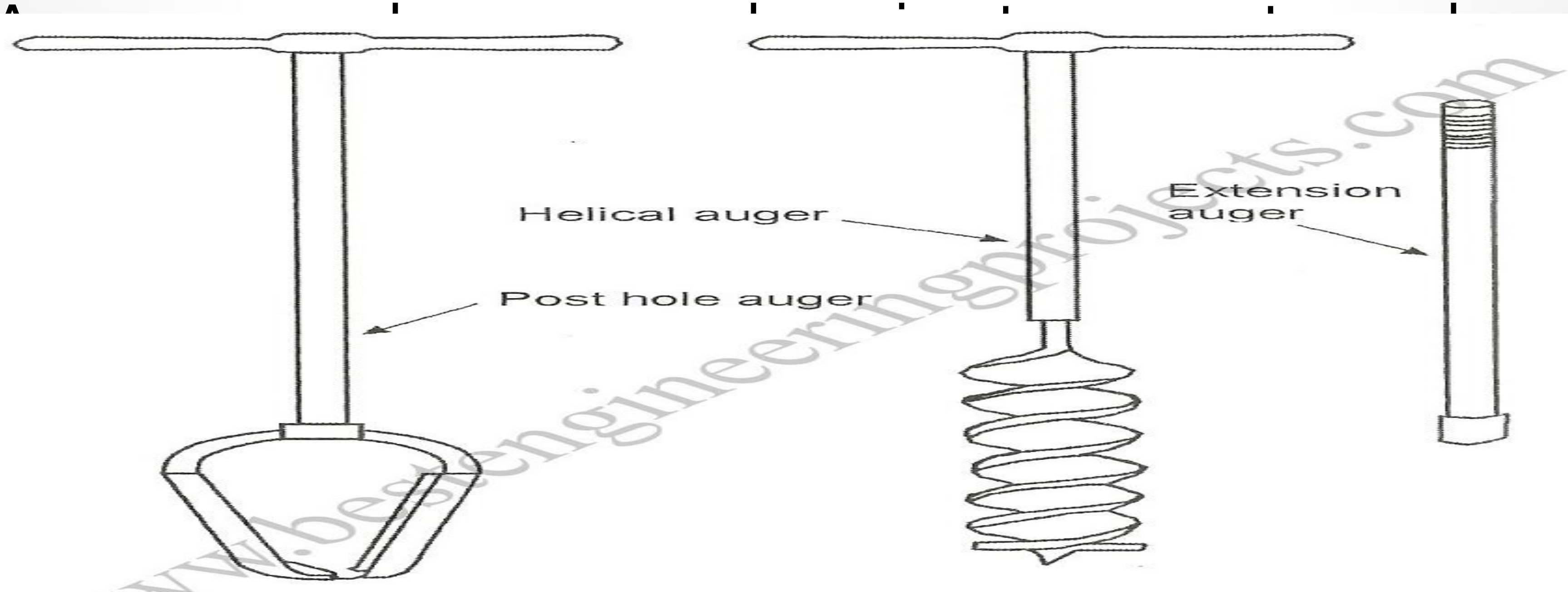


Fig 1: Hand Augers

20.

21.

GEOPHYSICAL METHODS

- Electric resistivity method’
- Seismic methods
- Gravity method’
- Magnetic method’
- Remote sensing techniques

2 Geophysical Methods

- Electric resistivity, density, magnetism, and elasticity are the most commonly measured properties by different geophysical methods (Todd, 1980).
- Some of the geophysical methods are briefly described in subsequent sub-sections.

23.

Electric Resistivity Method

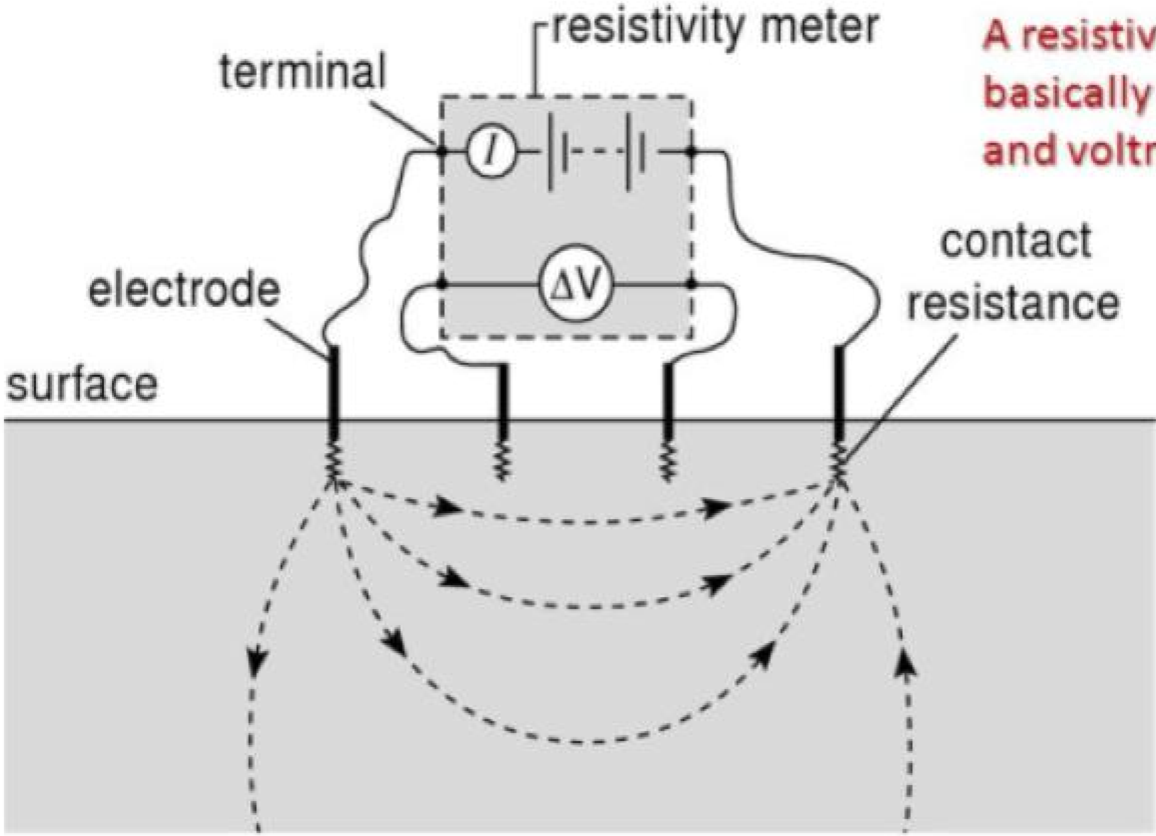
- Among all surface geophysical methods of groundwater exploration, the electric resistivity method has been applied most widely for groundwater investigations, even these days.

- Electric resistivity of a rock formation limits the amount of current passing through the formation when an electric potential is applied.

- If a material of resistance R has a cross–sectional area A and length L, then its resistivity can be expressed as

$$\rho = \frac{RA}{L}$$

24.


resistivity meter
terminal
electrode
surface
contact
resistance
A resistivity meter is basically a current meter and voltmeter all in one

25. • **Advantages of the electric resistivity method are**:

I. its portable equipment and the ease of operation facilitate rapid measurements;

II. it frequently aids in planning efficient and economic test-drilling or well-drilling programs;

III. it is especially well adapted for locating subsurface saltwater boundaries, because the decrease in resistance due to the presence of saltwater becomes apparent on a resistivity-spacing curve;

IV. it can be used for delineating geothermal areas and estimating aquifer permeability; and

V. it can also be used for defining areas and magnitudes of polluted groundwater.

26.

Seismic Methods

- Seismic techniques involve the measurement of seismic waves travelling through the subsurface.
- seismic techniques require special equipment and trained persons for operation and data interpretation,
- They have been applied to a relatively limited extent for groundwater investigations. Three most commonly used seismic methods are:

I. Seismic refraction,

II. Seismic reflection, and

III. Seismic surface wave analysis.

Gravity Method

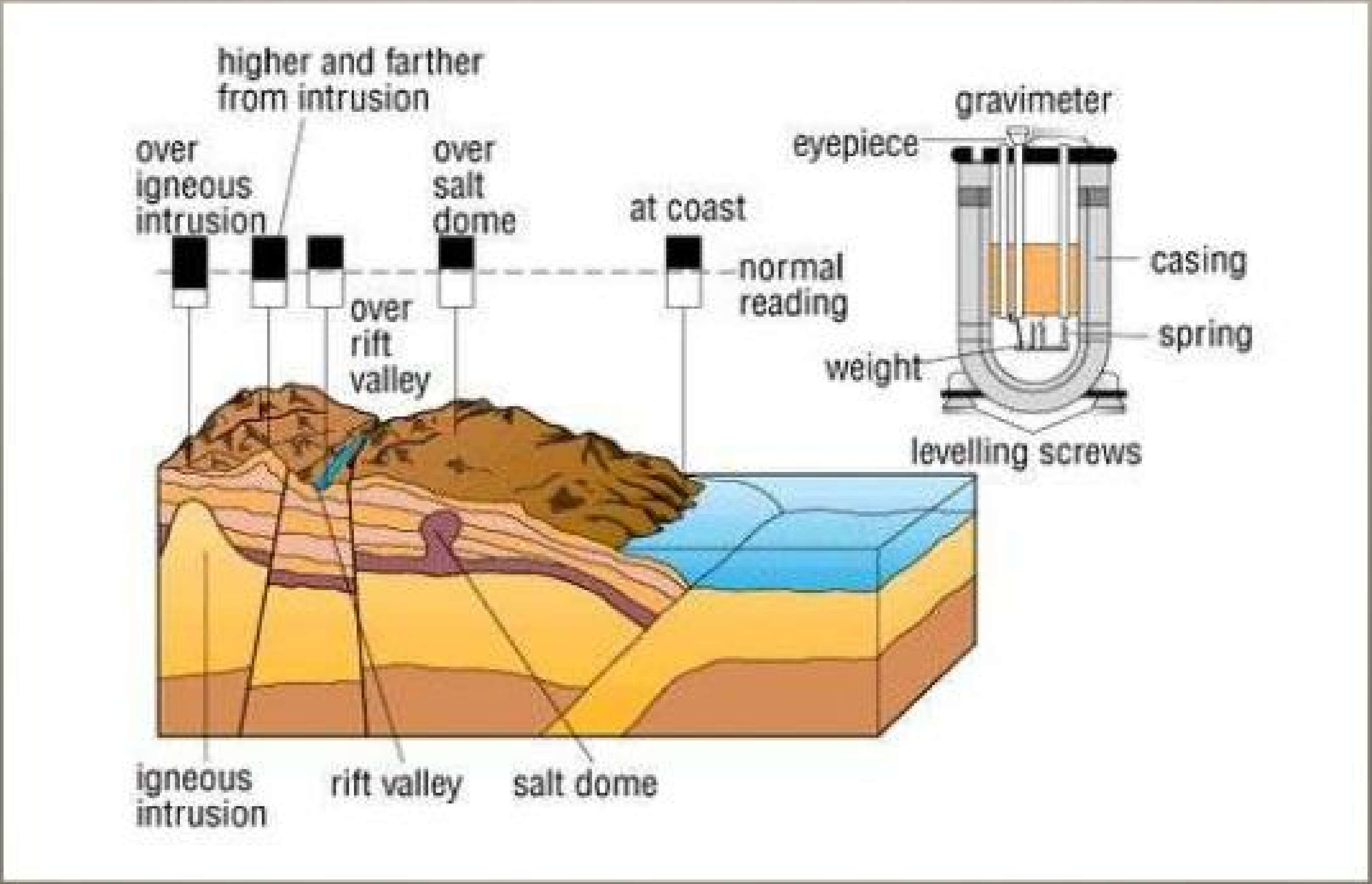
- The gravity method measures the difference between the gravitational fields at two points in a series of different locations on the earth's surface and the variation is associated to the type of rock (i.e., geologic structure).

- This method is expensive and the differences in water content in subsurface strata seldom involve measurable differences in specific gravity at the surface.

- it has little application to groundwater exploration.

28.

Gravity Methods



29.

Magnetic Method

- Measurement of direction, gradient or intensity of earth's magnetic field and the interpretation of variations in these quantities over an area.

- It uses a simple principle of balancing the force exerted by the vertical component of the earth's magnetic field on a magnet against the force of gravity.

- The distortion of magnetic field produced by a magnetic material in the earth's crust is called magnetic anomaly which is measured by the magnetic method and is indicative of type of rock producing it.

- This method can provide indirect information related to groundwater studies such as dikes that form aquifer boundaries or limits of a basaltic flow.

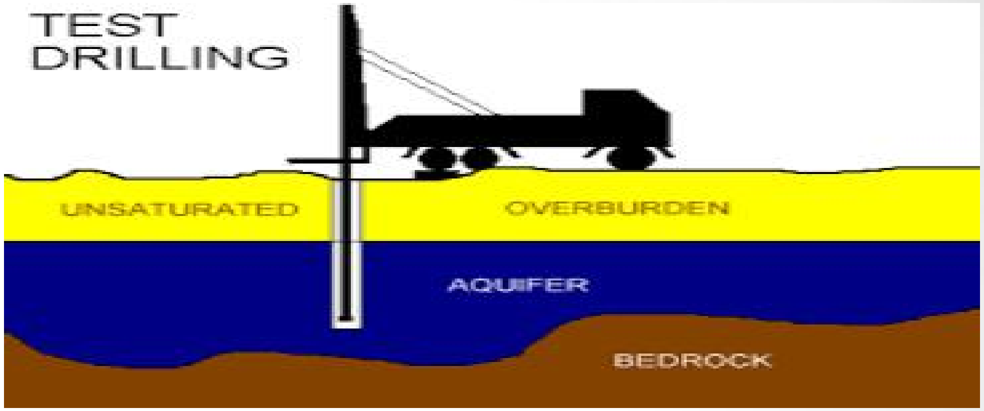
30.

Subsurface Method Of Groundwater Investigation

- Subsurface investigations are conducted by a person or a group of persons on the earth’s surface who operate the instruments extending underground through a borehole which provides direct access to subsurface formations and groundwater.
- The Subsurface methods are expensive than the surface methods but more accurate method as it helps in direct observations of features from hole dig into ground.
- Mainly done for the government based projects where large scale investigations are carried out.

31. Various Subsurface Methods Of Groundwater Explorations.

- **Test drilling**



- **Borehole sensing**
- (**'television logging'**)

- **Geophysical logging.**

32.

- **Test drilling** provides information regarding subsurface formations in a vertical line from the ground surface.

- **Borehole sensing** provides more detailed information about the borehole, geologic strata, and well casing and screen.

- **Geophysical logging** techniques provide information on physical properties of subsurface formations, groundwater quality, and well construction.

33.

Test Drilling

- Drilling a small-diameter (usually 1” or 1.5” diameter) hole to ascertain geologic and groundwater conditions at a particular location/site is known as test drilling.

- Test drilling is the most reliable method to obtain information about subsurface formations at different depths, which is very useful in verifying the results of other investigation methods as well as to obtain assurance of underground conditions before well drilling.

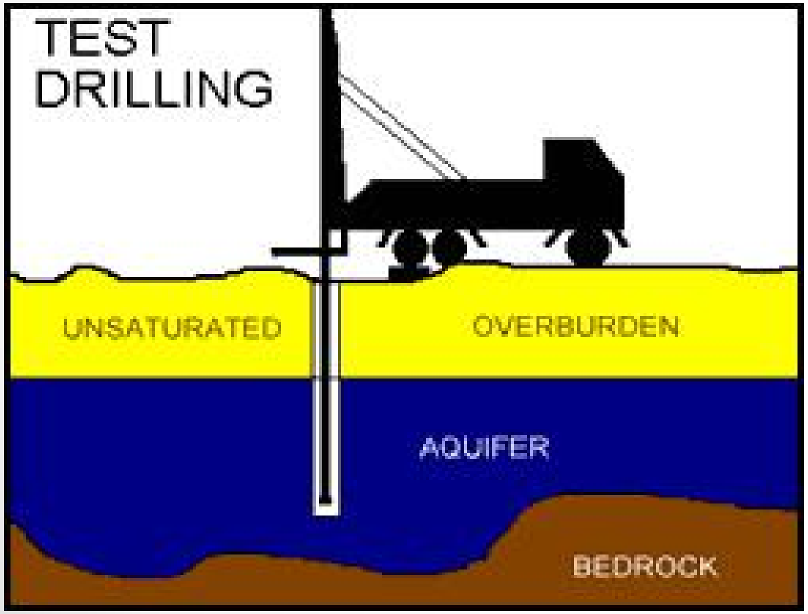
During test drilling-

- geologic samples are collected at regular depth intervals
- the air-dried samples are subject to sieve analysis for determining the proportion of sand, silt, clay and gravel in a given geologic sample.

- If such information is presented in a graphical or physical manner as a function of depth at a given site/location, it is known as a 'well log', 'borehole log' or 'geologic log' of that site/location provide reliable information about subsurface conditions (i.e., variation of subsurface materials and their thickness, availability and type of aquifers, type of other layers, etc.

- If the test drilling proves fruitful, it is re-drilled to a larger diameter to form a pumping well (also called '**production well**').

- The test holes created by test drilling also serve as observation wells (also called '**monitoring wells**') for measuring groundwater levels, taking groundwater samples, or for conducting pumping tests



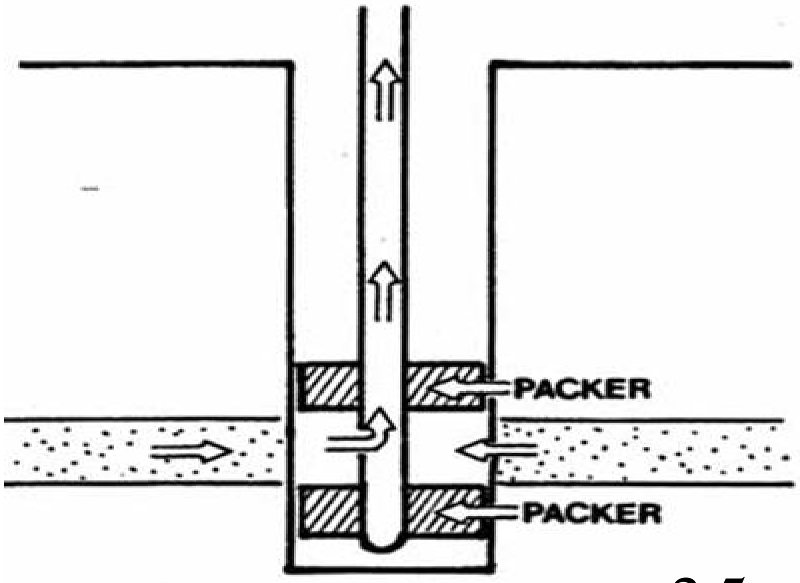


Figure 18-2 A drill stem test.

Borehole Sensing

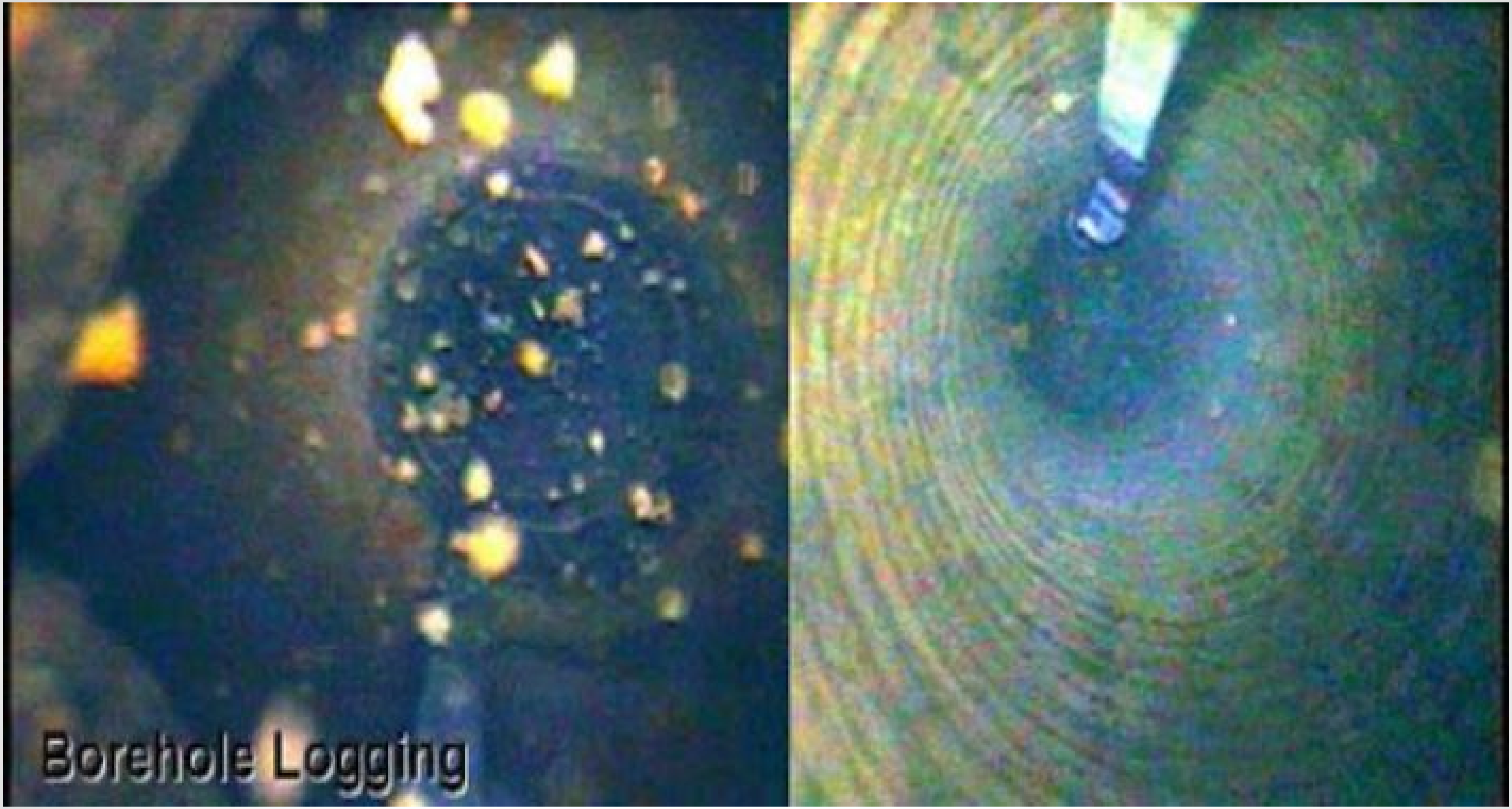
- A borehole sensing or television logging is a convenient technique with increasing use for investigating boreholes (uncased or cased).

- Specially designed wide-angle cameras, typically less than 7 cm in diameter are equipped with lights and when lowered into a borehole (uncased or cased) provide continuous visual inspection of the borehole which can be preserved in electronic storage devices.

- Borehole sensing has a variety of applications such as locating changes in geologic strata, pinpointing large pore spaces, inspecting the condition of well casing and screen, checking for debris in wells, locating zones of sand entrance, and searching for lost drilling tools.

standard 63mm Dual view camera.

- 360º infinite rotation
- Real time video viewing, depth, speed, comments, title, useful software controllable functions (editing, zoom, BLC, camera control…),
- variable high and low intensity lighting as well as focusing and rotation speed control is included.
- Can attach compass for orientation.


Borehole Logging

37.

Geophysical Logging

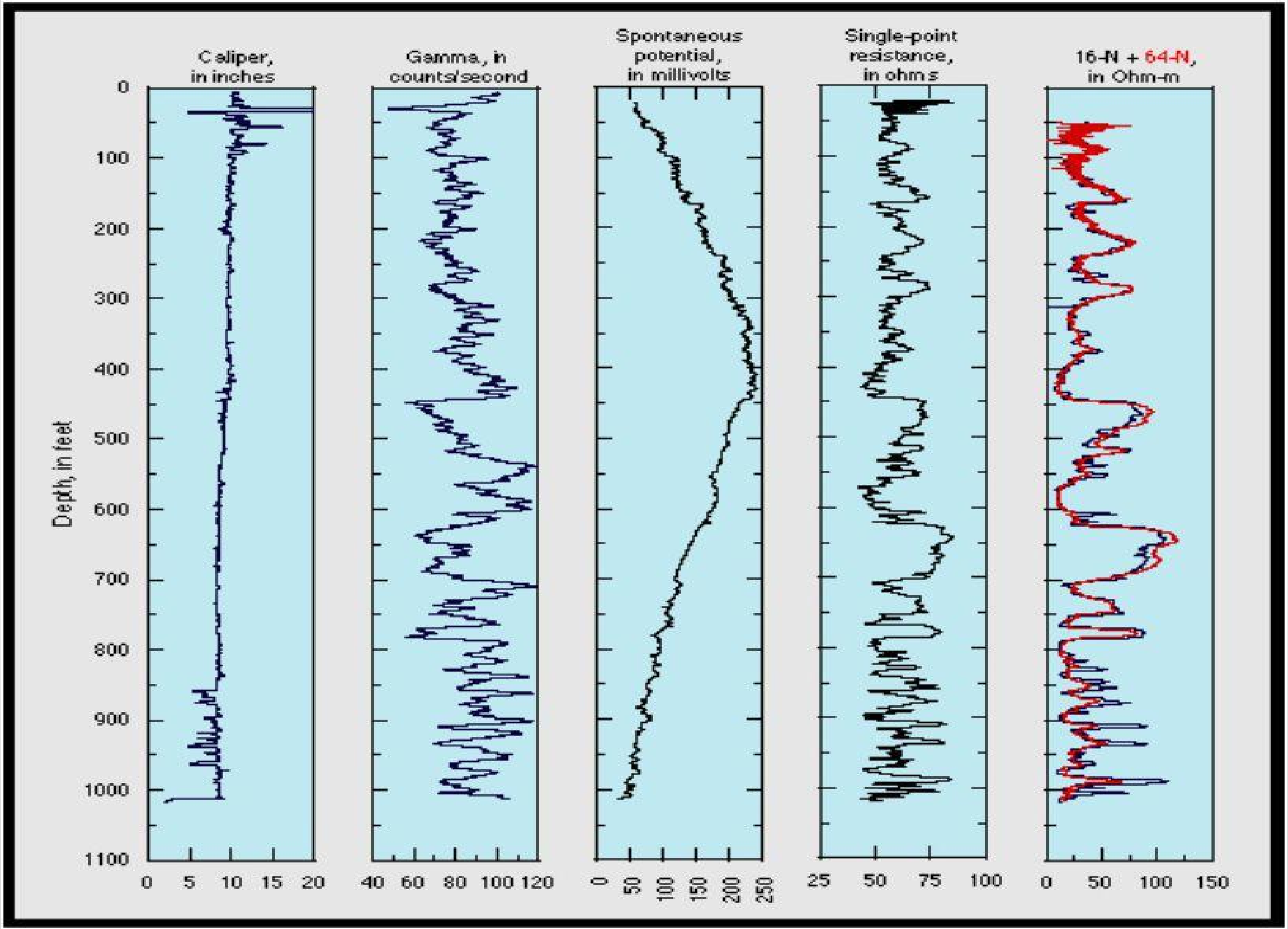
- This involves lowering sensing devices in a borehole (cased or uncased) and recording a physical parameter that may be interpreted in terms of :

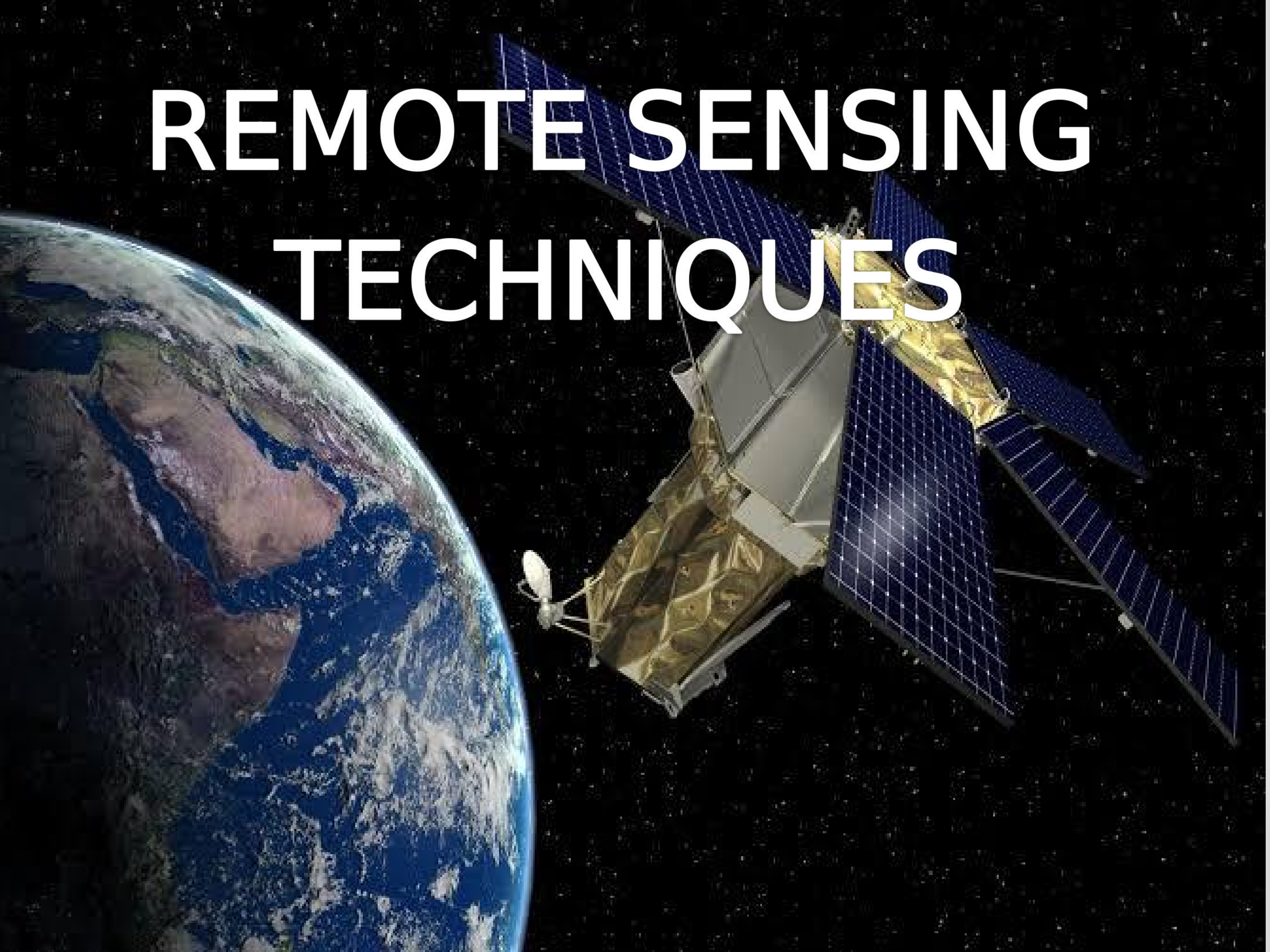
I. subsurface formation characteristics;
II. groundwater quantity,
III. quality and movement; or
IV. physical structure of the borehole.

- Mainly used for petroleum exploration.

- Includes mechanical method, nuclear methods, active electrical methods

Suite of geophysical logs in an alluvial-basin aquifer, southern California




REMOTE SENSING
TECHNIQUES

Application of RS and GIS in Groundwater

- It is the process of detecting and monitoring the physical characteristics of an area, by measuring its reflected and emitted radiation at a distance from the targeted area.

- Remote Sensing (RS) and Geographic Information System (GIS) techniques have emerged as handy, complementary tools in assessing, monitoring and conserving ground water resources.

- Ground prospects zonation means identifying and mapping the prospective groundwater zones in an area by qualitative assessment of the controlling and indicative parameters.

- The data for the development of numerical groundwater flow model includes time-constant parameters and time-variant parameters.

40.

Time-constant parameters	Time-variant parameters.
• **Aquifer geometry** (areal and vertical distribution of subsurface strata, aquifer thickness etc.). It also requires river network, land cover, soil, surface and subsurface hydrological data input . • **Hydraulic parameters** (surface water bodies, surface and ground water irrigated areas, depth to water table.)	• Hydro-meteorological data • Water level monitoring data • Number, distribution and pumpage from irrigation/drainage tube wells • River and canal flows and hydraulic features

OBJECTIVE

Identifying the groundwater availability for agriculture in a part

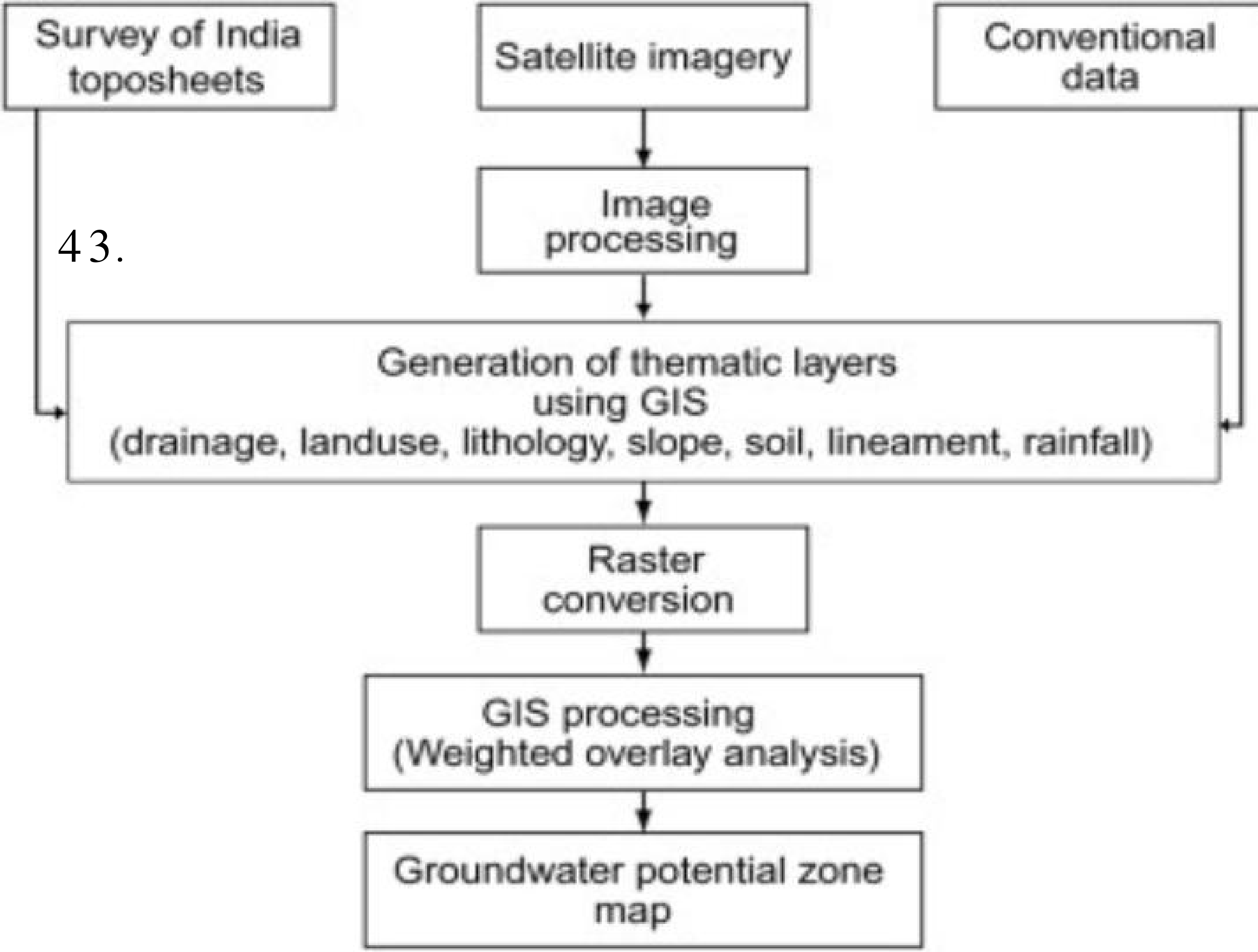
- RS data and Geographic Information System (GIS) are used to locate potential zones for groundwater in the part.
- Various maps are prepared.
- It determines the influence of each parameter on the potentiality.
- Each category of a particular map is assigned ranks according to their suitability and each parametric map is given certain weightage based on its influence on the ground water availability.
- Higher ranks are given to most suitable category and ranks decrease as per the decrease in suitability.

42.

METHODOLOGY

- **Base map** – Topographical map of the area
- **Drainage map** – scanned from the SOI Survey of India top sheets and digitalized in GIS.
- **The rainfall map** – prepared using the data obtained from the Indian Meteorological Department (IMD) gauge stations.

43.

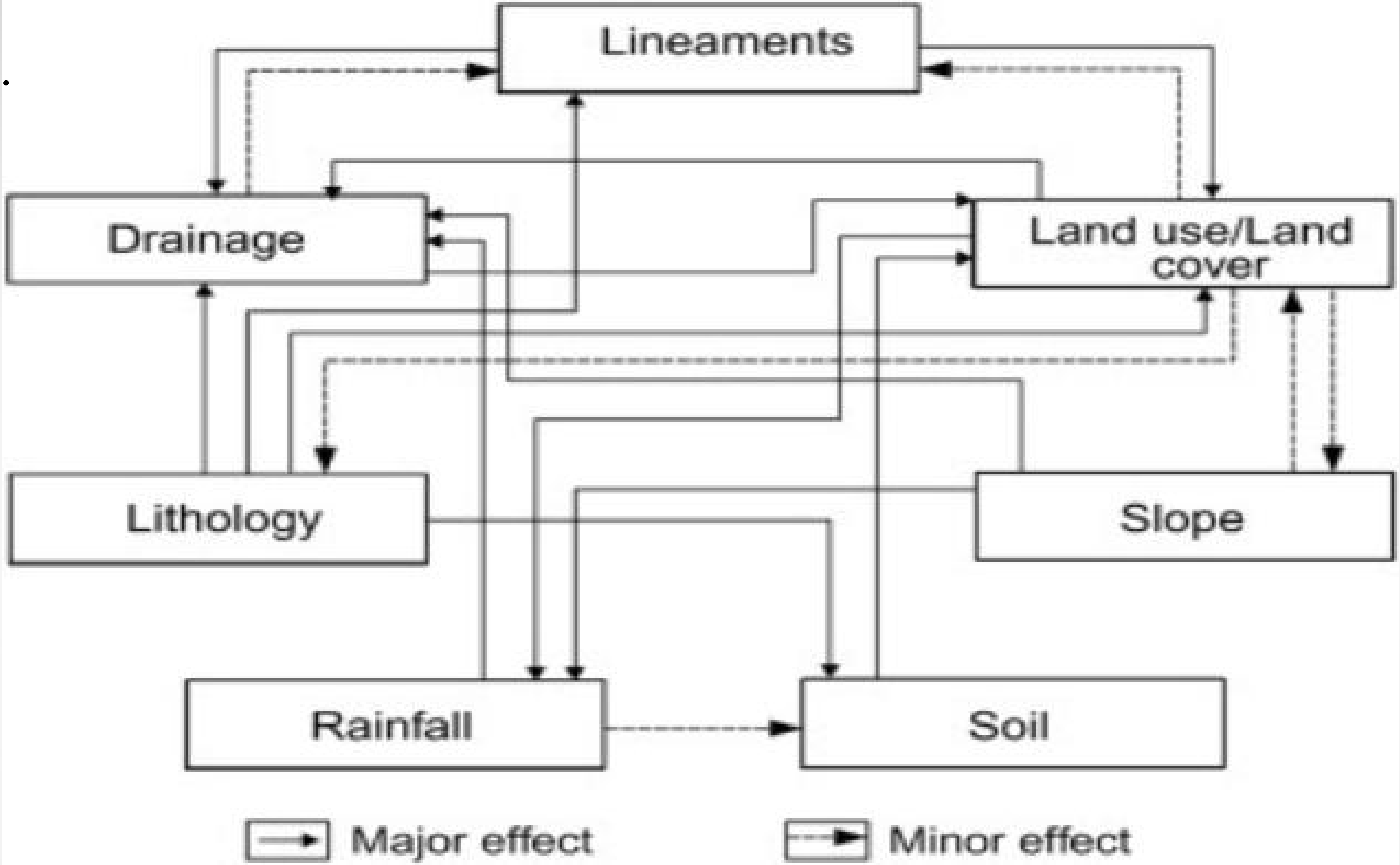


Survey of India toposheets
Satellite imagery
Conventional data
Image processing
Generation of thematic layers using GIS (drainage, landuse, lithology, slope, soil, lineament, rainfall)
Raster conversion
GIS processing (Weighted overlay analysis)
Groundwater potential zone map

44.

- Satellite images have been used for allocation of thematic layers such as land-use, lithology, and soil types.
- These thematic layers were converted into a raster format (30 m resolution) before they were brought into GIS environment.
- The groundwater potential zones were obtained by overlaying all the thematic maps in terms of weighted overlay methods

45.



- Seven influencing factors have been identified to decide the groundwater potential zones.

- Interrelationship between these factors and their effect is shown in Fig. Each relationship is weighted according to its strength.

- The representative weight of a factor of the potential zone is the sum of all weights from each factor.

- Integration of these factors with their potential weights is computed through weighted overlay analysis in ArcGIS.

47.

ADVANTAGES

- This technique is an important tool for groundwater management.
- Effects of exploitation of aquifer can be simulated.
- Gives information about flow rates, flow distribution , water pressure distribution.
- Easy method of acquiring up–to–date information of large geographical area.
- Informations are easy to manipulate with computers and combine with other geological data.

- Speed of operation
- Survey of inaccessible places
- Possibility of repetitive coverage of changing landform, land use , vegetative cover , water in reservoir etc.


THANK YOU

GROUND WATER ENGINEERING
CV0612

GROUND WATER INVESTIGATION

Prepared By:
Prof. Nirali Padhiyar

Scale of Groundwater Investigation

- Groundwater investigations can be carried out at a regional scale, local scale or site scale

i) **Regional scale** investigation is the largest scale for groundwater investigations, which typically encompasses **hundreds or thousands of square kilometers.** It provides somewhat an **overall evaluation** of groundwater conditions.

ii) **Local scale** investigation covers an area of a **few tens or hundreds of square kilometers**. This type of study provides more detailed information about **geology, groundwater dynamics, aquifer characteristics and water quality.**

I. **site-scale** investigation is the **smallest scale** for groundwater investigations, wherein a particular site is involved such as a **well field, mining site, waste disposal site, industrial site,** etc. Site-scale groundwater investigation provides in-depth field investigations at the site under study.

Surface Methods of Groundwater Exploration

- Introduction
- The exploration of groundwater can be done from the earth's surface or above-surface locations, which is known as surface investigation.
- Groundwater exploration can also be done using equipment/instruments extending underground, which is known as subsurface investigation.
- Surface investigations of groundwater usually do not provide quantitative data/information concerning aquifers or groundwater as obtained from subsurface investigations.
- Correct interpretation requires supplemental data from subsurface investigations to verify the findings of surface investigations.

- surface investigations of groundwater provide an incomplete picture or qualitative information of hydrogeological conditions below the ground.
- They are usually less expensive and less time consuming than the subsurface investigations.
- The surface methods of groundwater exploration can be classified into two major groups :
- (a) geologic methods (‘reconnaissance methods’), and
- (b) geophysical methods.

GEOLOGIC METHODS

- Test pits and trenches’
- Adits
- Continuous cone penetrometer
- Auger

GEOPHYSICAL METHODS

- Electric resistivity method’
- Seismic methods
- Gravity method’
- Magnetic method’
- Remote sensing techniques

1.Geologic Methods

- The occurrence and movement of groundwater is mainly dependent on the geology of an area, so it is essential to study the geology as a preliminary step.
- The geologic methods enable to evaluate large areas for groundwater development rapidly and economically.
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1.1 Test Pits and Trenches

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- These excavations can be done by hand tools or by power equipment like backhoes, bulldozers, scrapers, etc.

- The depth of the excavation depends on the field conditions, type of equipment used and the budget available.

- Test pits are usually square or circular in shape with 1-3 m length or diameter, respectively.

- These are deeper than trenches which are about 1 to 2 m wide and may extend to any lengths.

- Some of the advantages of test pits and trenches are:

(i) They are cost effective,

(ii) Information can be obtained on lateral and vertical extent of subsurface features,

(iii) In situ examination is possible, and

(iv) They facilitate sample collection.

1.2 ADITS

- Adits are horizontal or nearly horizontal excavations mainly used to drain water from mines and also serve as an entrance and ventilation.

- Typical dimensions of adits are 1 m × 1.5 m or 2 m × 2.5 m.

- They are mainly used for the exploration of rocks, their structural features such as joints, fractures, faults and shear zones.

- The main limitation to this method is that it is costly for small projects; generally it is not used in the soil.

1.3 Continuous Cone Penetrometer

- Continuous cone penetrometer is a device consisting of a cylindrical probe with a cone shaped tip with different sensors in it.
- The cylindrical probe is 3 to 5 cm in diameter with its cone tip having a cross sectional area of 10 to 15 cm^2 and apex angle of 60°.
- A porous filter element is present above this cone tip used to measure the pore water pressure.
- The device is pushed into the ground with its tip facing the surface at a controlled rate of 1.5 to 2.5 cm/s.
- The data is recorded by a field computer through a cable connected to the device.
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1.4 Auger

- Auger is a drilling device consisting of a rotating helical blade with an extendable steel rod and a handle.
- The auger is driven into the ground to remove the drilled materials.
- It is a cheap and fast method, but restricted only to soft unconsolidated formations.
- Depending on the geology, augers can be used up to a depth of 15 to 25 m.
- Many types of augers can be used based on the type of geologic formations available in a particular region.
- Hand augers are used in sand, silt and soft clay, while bucket augers are used in relatively hard grounds.
- Augers are cheaper, and easier to operate and maintain.

2 Geophysical Methods

- Geophysical methods are scientific measurements of differences or anomalies of physical properties within the earth's crust.
- Electric resistivity, density, magnetism, and elasticity are the most commonly measured properties by different geophysical methods (Todd, 1980).
- Some of the geophysical methods are briefly described in subsequent sub-sections.

2.1 Electric Resistivity Method

- Among all surface geophysical methods of groundwater exploration, the electric resistivity method has been applied most widely for groundwater investigations, even these days.
- Electric resistivity of a rock formation limits the amount of current passing through the formation when an electric potential is applied.
- If a material of resistance R has a cross-sectional area A and length L, then its resistivity can be expressed as: $\rho = \frac{RA}{L}$

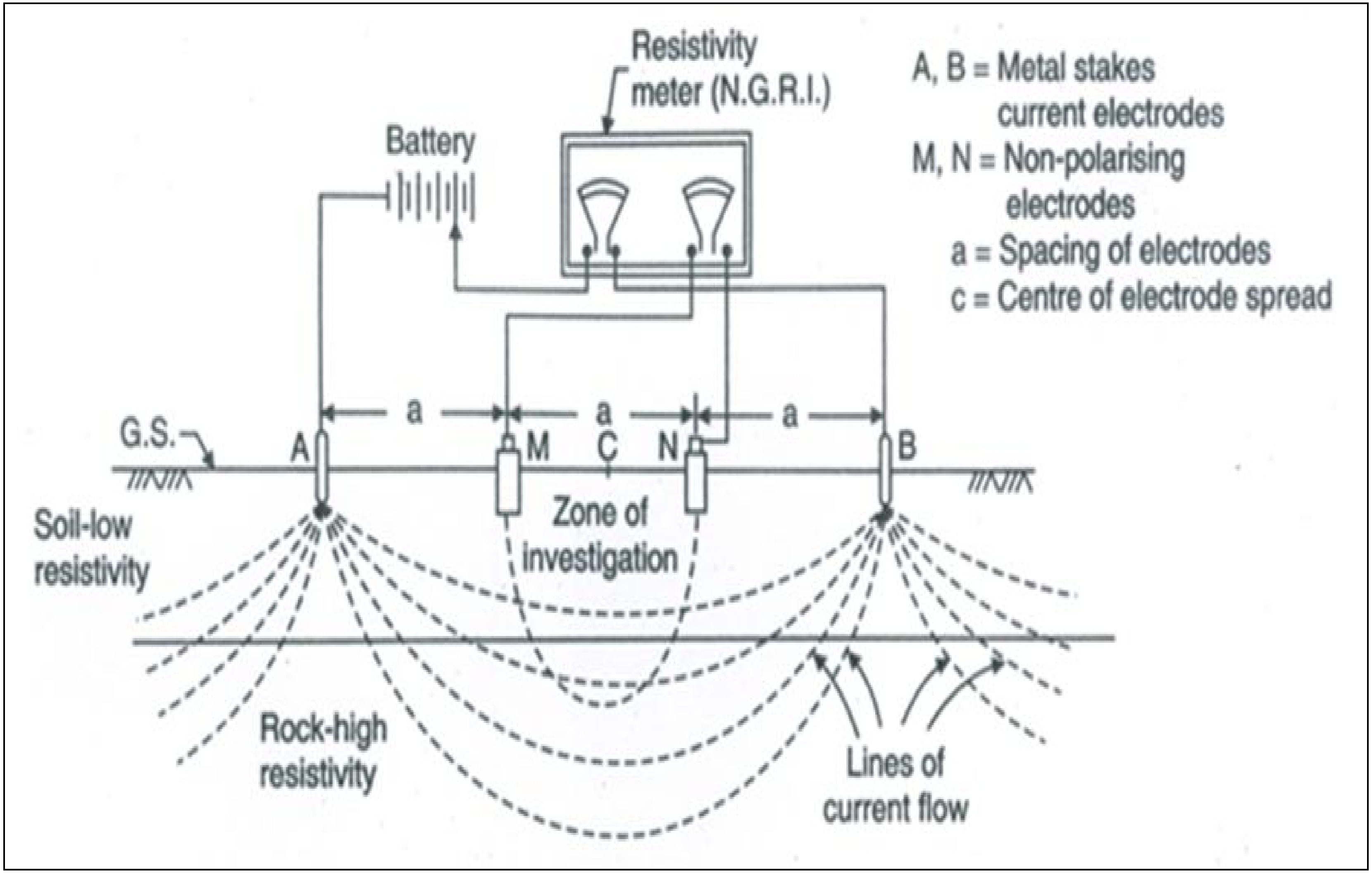


Fig. Schematic view of the Wenner electrode arrangement.

- In the Wenner electrode arrangement (Fig. 7.1), A and B are current electrodes, M and N are potential electrodes, and ‘a’ (distance between adjacent electrodes) is called spacing or separation of the electrodes; the value of ‘a’ is taken as the approximate depth of resistivity measurement. In this case, the apparent resistivity (ρ_a) is given as:

$$\rho_a = 2\pi a \frac{\Delta V}{I}$$

Where, ΔV = potential difference between the potential electrodes M and N on the earth’s surface (volts), and I = direct current introduced into the earth by means of two current electrodes A and B (amperes).

- The unit of resistivity is Ohm-meter (W-m). Resistivity of rock formations varies depending on the material density, porosity, pore size and shape, water content, water quality and temperature (Todd, 1980).
- Electric resistivity methods are based on the response of the earth to the flow of electrical current.
- In these methods, an electric current is introduced into the ground by two current electrodes, and the potential difference is measured between two points using potential electrodes suitably placed with respect to the current electrodes. The potential difference for unit current sent through the ground is a measure of the electrical resistance of the ground between the probes.
- The measured resistance is a function of the geometrical configuration of the electrodes and the electrical parameter of the ground.

Advantages of the electric resistivity method are:

I. its portable equipment and the ease of operation facilitate rapid measurements;
II. it frequently aids in planning efficient and economic test-drilling or well-drilling programs;
III. it is especially well adapted for locating subsurface saltwater boundaries, because the decrease in resistance due to the presence of saltwater becomes apparent on a resistivity-spacing curve;
IV. it can be used for delineating geothermal areas and estimating aquifer permeability; and
V. it can also be used for defining areas and magnitudes of polluted groundwater.

limitation of the resistivity method

limitation of the resistivity method is that the factors like

I. lateral geologic heterogeneities,
II. buried pipelines, cables,
III. wire fences can disturb the electric field close to the electrodes,
IV. it is not effective for determining actual resistivity's below a few hundred meters, as the change in resistivity at large depths has only a slight effect on the apparent resistivity compared to that at shallow depths.

2.2 Gravity Method

- The gravity method measures the difference between the gravitational fields at two points in a series of different locations on the earth's surface and the variation is associated to the type of rock (i.e., geologic structure).

- This method is expensive and the differences in water content in subsurface strata seldom involve measurable differences in specific gravity at the surface.

- it has little application to groundwater exploration.

2.3 Magnetic Method

- This method involves the measurement of direction, gradient or intensity of earth's magnetic field and the interpretation of variations in these quantities over an area.
- It uses a simple principle of balancing the force exerted by the vertical component of the earth's magnetic field on a magnet against the force of gravity.
- The distortion of magnetic field produced by a magnetic material in the earth's crust is called magnetic anomaly
- which is measured by the magnetic method and is indicative of type of rock producing it.
- This method can provide indirect information related to groundwater studies such as dikes that form aquifer boundaries or limits of a basaltic flow.

2.4 Remote Sensing Techniques

- Remote sensing from aircraft or satellite has become an increasing valuable tool for understanding subsurface water conditions.
- Remote sensing techniques offer many types of investigations about an area without causing any damage to the sites.
- Satellite images and aerial photographs are the most commonly used remote sensing techniques.
- Aerial photographs and satellite images taken at various electromagnetic wavelength ranges can provide useful information about groundwater conditions.
- Other non-visible portions of the electromagnetic spectrum (e.g., infrared imagery, near-infrared imagery, radar imagery, and low-frequency electromagnetic aerial survey) hold promise for a whole array of imaging techniques that can contribute to hydrogeologic investigations/surveys.
- Fractures and faults appear on aerial photos and satellite images as tonal variations in surface soils caused by the difference in soil moisture.

- The lines of springs or seeps are caused by the movement of groundwater along the fracture zones they can be related to the porosity and permeability of subsurface formations, and ultimately well yield.
- The RS technology, with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time
- It has emerged as a powerful tool for the assessment, monitoring and management of groundwater resources.
- In particular, the integrated use of RS, GIS and multicriteria decision analysis (MCDA) techniques has been found to be efficient and very useful for mapping and evaluating groundwater potential as well as for identifying sites suitable for artificial recharge

2.5 Seismic Methods

- Seismic techniques involve the measurement of seismic waves travelling through the subsurface.
- seismic techniques require special equipment and trained persons for operation and data interpretation,
- They have been applied to a relatively limited extent for groundwater investigations. Three most commonly used seismic methods are:

I. Seismic refraction,

II. Seismic reflection, and

III. Seismic surface wave analysis.

Subsurface Methods of Groundwater Exploration

- Detailed and comprehensive examination of groundwater and conditions under which it occurs can be made by subsurface investigations only.
- Subsurface investigations are conducted by a person or a group of persons on the earth's surface who operate the equipment/instruments extending underground through a borehole which provides direct access to subsurface formations and groundwater.
- Various subsurface methods of groundwater exploration can be classified into three major groups:

I. Test drilling,
II. Borehole sensing ('television logging'), and
III. Geophysical logging.

- **Test drilling** provides information regarding subsurface formations in a vertical line from the ground surface.

- **Borehole sensing** provides more detailed information about the borehole, geologic strata, and well casing and screen.

- **Geophysical logging** techniques provide information on physical properties of subsurface formations, groundwater quality, and well construction.

1 Test Drilling

- Drilling a small-diameter (usually 1" or 1.5" diameter) hole to ascertain geologic and groundwater conditions at a particular location/site is known as test drilling.
- Test drilling is the most reliable method to obtain information about subsurface formations at different depths, which is very useful in verifying the results of other investigation methods as well as to obtain assurance of underground conditions before well drilling.
- During test drilling, geologic samples are collected at regular depth intervals and the air-dried samples are subject to sieve analysis (also called 'grain-size or particle-size analysis' or sometimes 'mechanical analysis') for determining the proportion of sand, silt, clay and gravel in a given geologic sample.
- If such information is presented in a graphical or physical manner as a function of depth at a given site/location, it is known as a 'well log', 'borehole log' or 'geologic log' of that site/location provide reliable information about subsurface conditions (i.e., variation of subsurface materials and their thickness, availability and type of aquifers, type of other layers, etc.

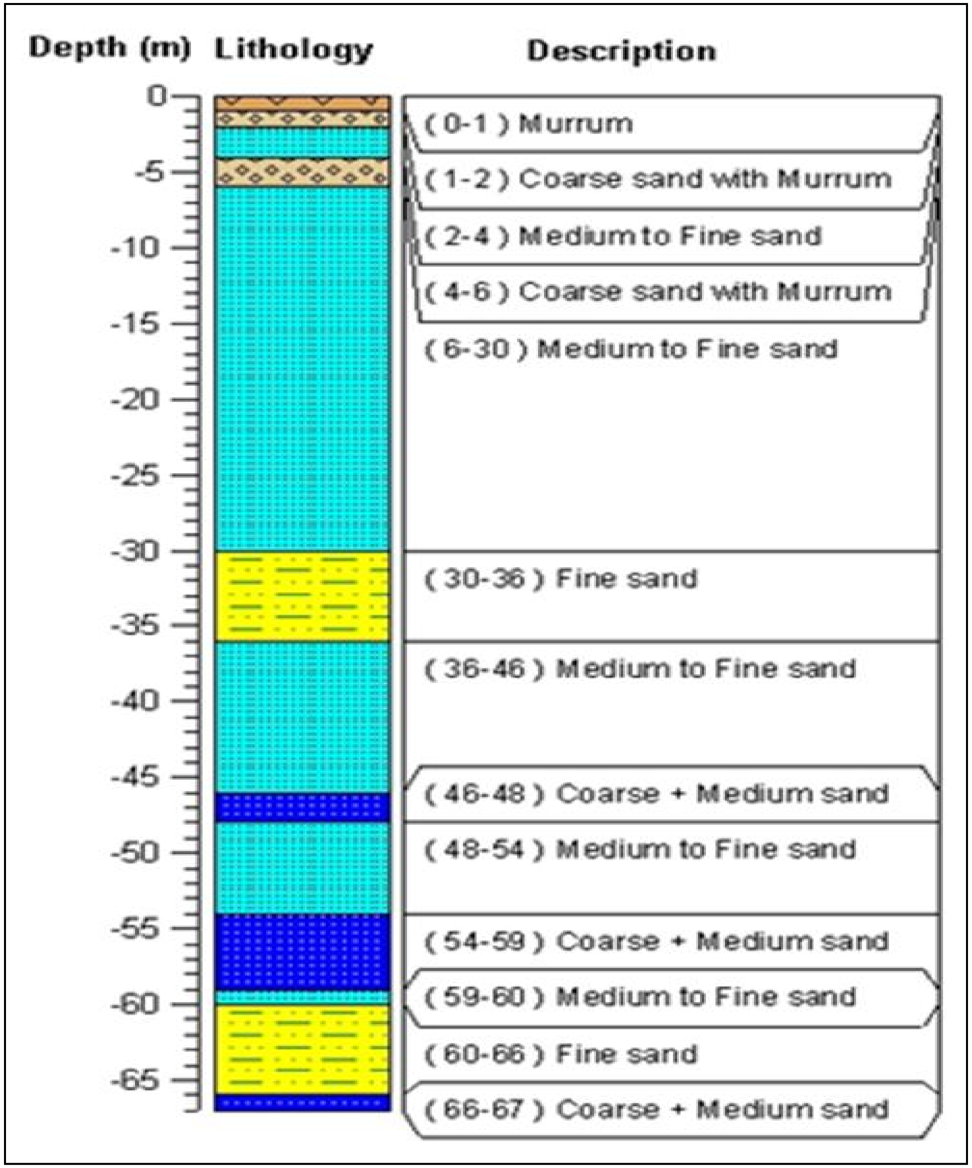


Fig. Well log of a site prepared from geologic samples collected during observation–well drilling in an unconsolidated formation.

- If the test drilling proves fruitful, it is re-drilled to a larger diameter to form a pumping well (also called '**production well**').

- The test holes created by test drilling also serve as observation wells (also called '**monitoring wells**') for measuring groundwater levels, taking groundwater samples, or for conducting pumping tests

2 Borehole Sensing

- A borehole sensing or television logging is a convenient technique with increasing use for investigating boreholes (uncased or cased).

- Specially designed wide-angle cameras, typically less than 7 cm in diameter are equipped with lights and when lowered into a borehole (uncased or cased).

- provide continuous visual inspection of the borehole which can be preserved in electronic storage devices.

- Borehole sensing has a variety of applications such as locating changes in geologic strata, pinpointing large pore spaces, inspecting the condition of well casing and screen, checking for debris in wells, locating zones of sand entrance, and searching for lost drilling tools.

3 Geophysical Logging

- This involves lowering sensing devices in a borehole (cased or uncased) and recording a physical parameter that may be interpreted in terms of :

I. subsurface formation characteristics;
II. groundwater quantity,
III. quality and movement; or
IV. physical structure of the borehole.

THANK YOU

GROUND WATER ENGINEERING
CV0612

Conjunctive Use of Ground Water

Prepared By:
Prof. Nirali Padhiyar

ADVANTAGES OF CONJUNCTIVE USE OF SURFACE AND GROUND WATER

(i) The Water Requirements of Crops is Met :

- Timely supply of irrigation water in adequate quantities is essential for a good crop yields.
- It is all the more necessary in case of high yielding verities.
- Surface water schemes do not have sufficient flexibility and so, the roster of the operating channels cannot be adjusted to provide timely irrigation in the command area for various crops with different base and critical periods.
- The needs cannot also be economically met from groundwater alone on account of pumping efforts required for lifting the water.
- Thus, conjunctive use can help meet the requirements both in respect of quantity and time.

(ii) Controls Water-Logging and Salinization:

- Continuous and excessive use of surface water in canal command areas without proper surface drainage and/or adequate groundwater development results in alarming rise of waters table,

- creating problem of water-logging and salinization, affecting crop growth adversely and rendering large areas unproductive.

- With increasing intensities of irrigation and tendency on the part of the cultivators to over supply irrigation from surface-water, the problem gets aggravated further.

(iii) Remedies Problem of Salinity Ingress:

- In case of coastal areas, the excessive pump-age of groundwater has been responsible for causing gradual movement of seawater into inland aquifers.

- This salt water intrusion makes fresh groundwater saline, rendering it unfit for many purposes. Such a condition can also occur in the inland areas due to lowering of water level as a result of excessive withdrawal of fresh water in the vicinity of a saline water zone.

- This situation can be controlled by increased application of surface waters by encouraging conjunctive use.

(iv) Control on Over-pumping of Groundwater Reservoirs is Made Possible:

- Continuous increased withdrawals from a groundwater reservoir in excess of replenishable recharge has resulted in regular lowering of waters table leading to mining of the groundwater.

- In such a situation a serious problem is created resulting in drying of shallow wells and increase in pluming head for deeper wells and tube wells.

- The remedy lies in providing more surface water irrigation with the help of storage reservoirs, inter-basin transfer, etc.

- In some cases recourse will also have to be taken for providing artificial recharge to groundwater.

(v) It Makes Use of Saline Water Possible:

- In certain areas the surface water is not able to meet full demand of irrigation water.
- At the same time, groundwater being saline, direct application is not possible.
- In such cases, conjunctive use can be made by construction of augmentation tube wells and mixing the saline water with canal water to the extent that the quality of mixed water remains within tolerable limits of corps.

(vi) Helps in Augmentation of Water Resources in Project Command:

- In certain areas, ground water is available but there is no direct use in that area.
- it can be transferred to other needy areas by construction of augmentation canals fed by battery of augmentation tube wells.
- This has already been done in Haryana and Punjab. In U.P. it is proposed in Gandak and Sarda Sahayak Commands.
- In respect of augmentation tube wells (ATW), Haryana was the first State to install 160 ATWs for conjunctive use in the year 1972, in Western Yamuna canal tract to feed the 75 km long augmentation canal to the extent of 14 cumec during the lean season.

(vii) Helps in Recovering Lost Seepage Water for Irrigation Use:

- Leakage from unlined canals may be recovered in certain areas by pumping in preference to control of seepage through costly canal lining; this water may be pumped back into the canal or used directly for irrigation.

CONJUNCTIVE USE OF SURFACE AND GROUNDWATER AS PART OF INTEGRATED RIVER BASIN MANAGEMENT

- The increasing acuteness of water scarcity problems, worldwide, requires the adoption of a double approach of water supply management and water demand management.

- Governments tend to consider river basins as water resources management units and as a spatial basis for the formulation of water management strategies integrating all cross-sectoral issues such as water resources conservation, environment, water resources allocation, water demand management, etc.

- The conjunctive use of surface and groundwater is one of the strategies of water supply management which has to be considered to optimize the water resources development, management and conservation within a basin, and artificial recharge of aquifers is certainly one of the tools to be used for that purpose.

- The use of the river basin as the spatial unit for analyzing the interactions and interrelations between the various components of the system, and for defining the water management policy, is well justified, and is increasingly becoming common practice.

- in China, river basin plans have legal status and development projects are required to be consistent with the provisions of the plans.

- in Indonesia, the Government recently adopted new water management policies in order to prepare spatial management plans and to link water and land use through river basin plans, to centre water management at the river basin level, and to centralize water management responsibilities through a more effective participation and collaboration of beneficiaries.

- in Italy, a 1989 law introduced the river basin as a management unit to regulate the programmers of the various sectoral and regional institutions;

- in the United Kingdom, Spain, France, and in most European countries, water resources management is now essentially centered on river basins.

WHY IS SURFACE WATER STORAGE ALWAYS PREFERRED TO GROUNDWATER DEVELOPMENT?

- When looking at these advantages and disadvantages, groundwater seems to be a better alternative that should be preferred, but this not the case; large and concentrated water demand such as that from large irrigation schemes is usually supplied from surface water storage, and there are various reasons for that choice:
- groundwater aquifers seldom offer large storage capacity able to absorb large volumes of flood in a short period of time, and are unable to return them as significant discharge per unit production system of well or borehole,
- **surface water storage**, because of the large investments involved, is often preferred because it offers a much higher political visibility and because high construction costs give an opportunity for private profit and corruption, opening the way for improper influence on decision making.

Assuming that the mixed solution is part of the national policy, several problems need to be carefully studied before selecting the different options and elaborating a programmed of conjunctive use of surface and groundwater:

- underground storage availability to be determined
- production capacity of the aquifer(s) in term of potential discharge
- natural recharge of the aquifer(s)
- induced natural recharge of the aquifer(s)
- potential for artificial recharge of the aquifer(s)
- comparative economic and environmental benefits derived from the various possible options.

The suitability of an aquifer for recharging

- surface material has to be highly permeable so as to allow water to percolate easily;

- The unsaturated zone should present a high vertical permeability, and vertical flow of water should not be restrained by less permeable clayey layers;

- Depth to water level should not be less than 5 to 10 m;

- Aquifer transmissivity should be high enough to allow water to move rapidly from the mound created under the recharge basin but should not be too high so that water cannot be recovered.

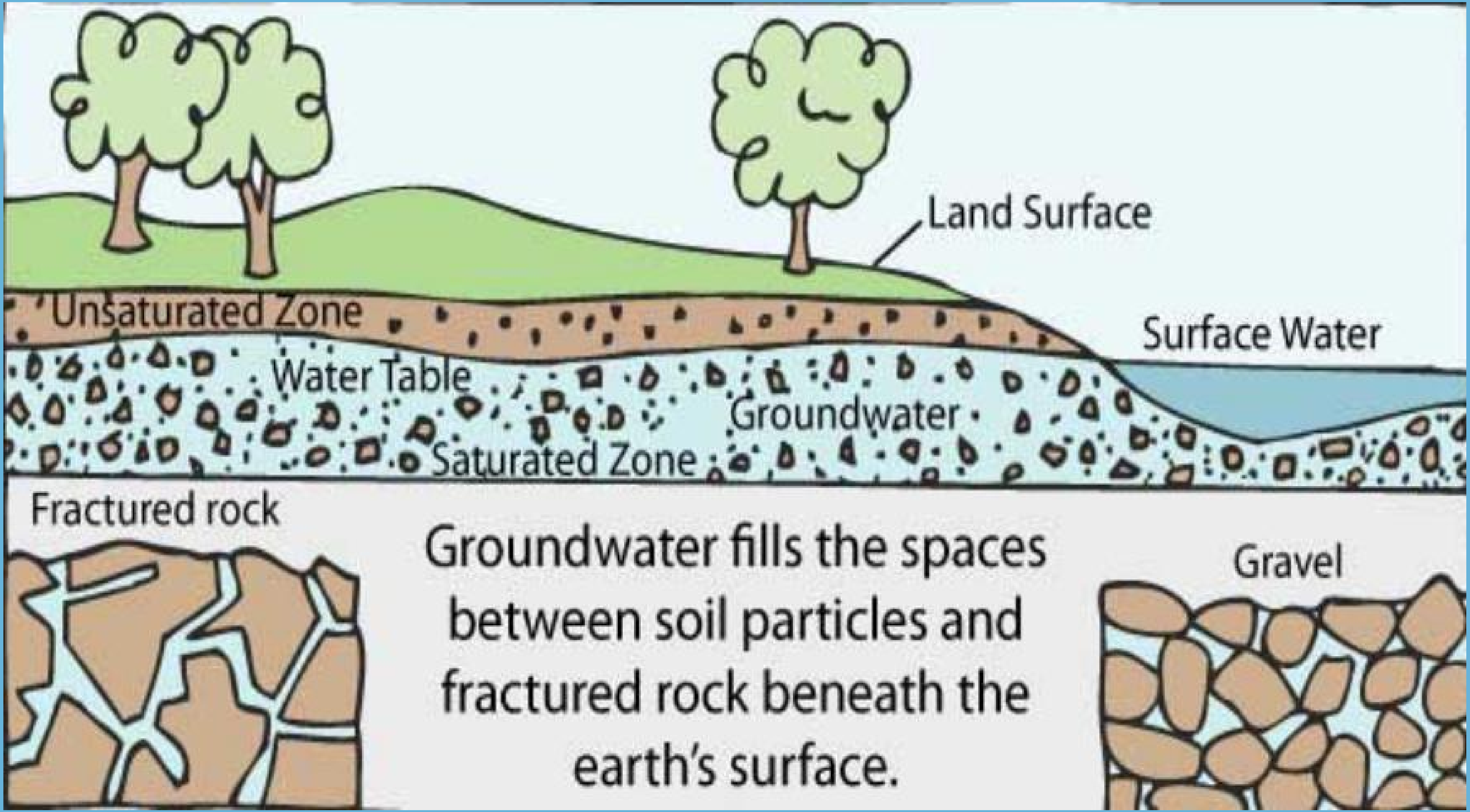
ARTIFICIAL RECHARGE OF AQUIFER

- **Surface spreading**
- **Diversion structures**
- **infiltration scheme**
- **Spate irrigation**
- **Check dams**
- **Underground dams**
- **Watershed management and water harvesting**
- **Recharge wells**

GROUND WATER QUALITY

INTRODUCTION

- Groundwater –
- Ground water is an essential and vital component of our life support system. The ground water resources are being utilized for drinking, irrigation and industrial purposes.


Land Surface
Unsaturated Zone
Surface Water
Water Table
Groundwater
Saturated Zone
Fractured rock
Groundwater fills the spaces between soil particles and fractured rock beneath the earth's surface.
Gravel

FACTORS AFFECTING GROUNDWATER QUALITY

- SEDIMENTATION
- RUNOFF
- EROSION
- DISSOLVED OXYGEN
- pH
- Temperature
- Decayed organic materials
- Pesticides

WATER QUALITY REQUIREMENTS

Designated Best Use	Class	Criteria
Drinking Water Source without conventional treatment but after disinfection	A	1.Total Coliforms Organism MPN/100ml shall be 50 or less 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 6mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 2mg/l or less
Outdoor bathing (Organised)	B	1.Total Coliforms Organism MPN/100ml shall be 500 or less 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 5mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 3mg/l or less
Drinking water source after conventional treatment and disinfection	C	1. Total Coliforms Organism MPN/100ml shall be 5000 or less 2. pH between 6 and 9 3. Dissolved Oxygen 4mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 3mg/l or less
Propagation of Wild life and Fisheries	D	1. pH between 6.5 and 8.5 2. Dissolved Oxygen 4mg/l or more 3. Free Ammonia (as N) 4. Biochemical Oxygen Demand 5 days 20 °C, 2mg/l or less
Irrigation, Industrial Cooling, Controlled Waste disposal	E	1. pH between 6.0 and 8.5 2. Electrical Conductivity at 25 °C micro mhos/cm, maximum 2250 3. Sodium absorption Ratio Max. 26 4. Boron Max. 2mg/l
	Below-E	Not meeting any of the A, B, C, D & E criteria

Characteristics	Designated best use				
	A	B	C	D	E
Dissolved Oxygen (DO)mg/l, min	6	5	4	4	-
Biochemical Oxygen demand (BOD)mg/l, max	2	3	3	-	-
Total coliform organisms MPN/100ml, max	50	500	5,000	-	-
pH value	6.5-8.5	6.5-8.5	6.0-9.0	6.5-8.5	6.0-8.5
Colour, Hazen units, max.	10	300	300	-	-
Odour	Un-objectionable			-	-
Taste	Tasteless	-	-	-	-
Total dissolved solids, mg/l, max.	500	-	1,500	-	2,100
Total hardness (as $CaCO_3$), mg/l, max.	200	-	-	-	-
Calcium hardness (as $CaCO_3$), mg/l, max.	200	-	-	-	-
Magnesium hardness (as $CaCO_3$), mg/l, max.	200	-	-	-	-

WATER QUALITY REQUIREMENTS

Importance of Water

- Water is an essential commodity to all life.
- Without water, there can be no life.
- Every living thing plants, animals, and people must have water to live.
- Water is used in almost all activities of life support systems.
- Water is a major abiotic factor in the environment

CHARACTERISTICS OF WATER

- Water is a good solvent.
- Water never occurs in its pure form.
- All waters contain some dissolved substances.
- The quality of water is determined by these substances.
- It has the ability to dissolve many inorganic and organic substances.

QUANTITY AND QUALITY

- On an average, each person in a developed country uses about 260 liters of water a day in the home.

- The Quality of water is equally important than quantity.

- Even if present in huge amounts, we can not use salt water in many life support activities.

WATER QUALITY PARAMETERS

1. PHYSICAL PARAMETERS
2. CHEMICAL PARAMETERS
3. BIOLOGICAL PARAMETERS

PHYSICAL PROPERTIES

- Temperature
- Colour
- Odour
- Turbidity

TEMPERATURE OF WATER

- Measured using Thermometers.
- It ranges from 0 to 100 degree Celsius .
- Unit of measurement is degree Celsius.
- The temperature of Surface water is influenced by the atmospheric conditions.
- The temperature of groundwater is controlled by the thermal characteristics of bedrocks and the depth.

COLOUR OF WATER

- The color of water is due to the suspended particles and organic matter.
- Ranges form light to dark brown.
- Brownish color in water comes due to the presence of iron.
- Greenish color in pond water is seen due to the presence of organic substances including algae

ODOUR

- Pure water is odour less.
- When water dissolves other substances, the odour is determined by them.
- Mostly decayed organic substances give fouling smell & Inorganic substances give earthy smell

TURBIDITY

- Muddiness in water .

- Comes due to suspended particles from clay, silt and organic matter.

- Controls the transparency of water.

- Transparency is measured using Secchi Disc   Water Turbidity is measured using Nephelometer.

CHEMICAL PROPERTIES

- pH
- Total Dissolved Solids(TDS)
- Major ions
- Minor or trace elements
- Hardness
- Salinity
- Alkalinity

pH OF WATER

- Refers to the effective concentration of hydrogen ions in water.
- It ranges from 0 to 14. Measured using pH meters.
- Water is said to be acidic (less than 7) or alkaline (above 7) depending on the relative concentration of hydrogen ions from the neutral value which is 7.

TOTAL DISSOLVED SOLIDS(TDS)

- Concentration of non-volatile substances present in colloidal or molecular state.
- Total of all ions present in water, expressed in ppm or mg/L.
- Increases due to dissolution of more mineral substances by water on its path.
- TDS determines the suitability of water for our use and consumption.

HARDNESS

- Hardness of water is defined as amount of calcium and magnesium ions present in water.

- Expressed as total concentration of Calcium and Magnesium in ppm.

- It can be
  1. Temporary hardness (removed by boiling)
  2. Permanent hardness (removed by chemical treatment)

SALINITY OF WATER

- Comes due to sodium and chloride.
- Sea water contains 35,000 ppm or mg/L of dissolved salts.

ALKALINITY OF WATER

- When the pH of the water is above 7, ie. Concentration of OH^- is more
- It creates a deep impact on the material it is been transported through.
- Alkalinity is to be reduced especially when it is used in the boilers

BIOLOGICAL PROPERTIES

- Dissolved Oxygen (DO)
- Biochemical Oxygen Demand(BOD)
- Chemical oxygen Demand(COD)
- Microorganisms-Bacterial counts

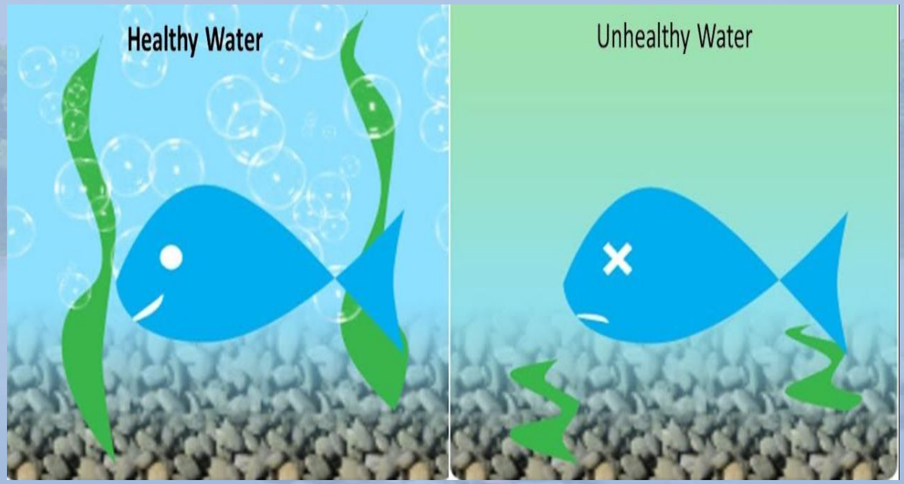
DISSOLVED OXYGEN(DO)

- Is related to the solubility of air in water at 0^{0}C
- Solubility of oxygen in water decreases with high temperatures.
- Important property for aquatic organisms.
- Surface water bodies should have enough DO.
- If DO depletes, it will be difficult to many aquatic organisms for their survival.

BIOCHEMICAL OXYGEN DEMAND(BOD)

- Is a measure of the biodegradable material.

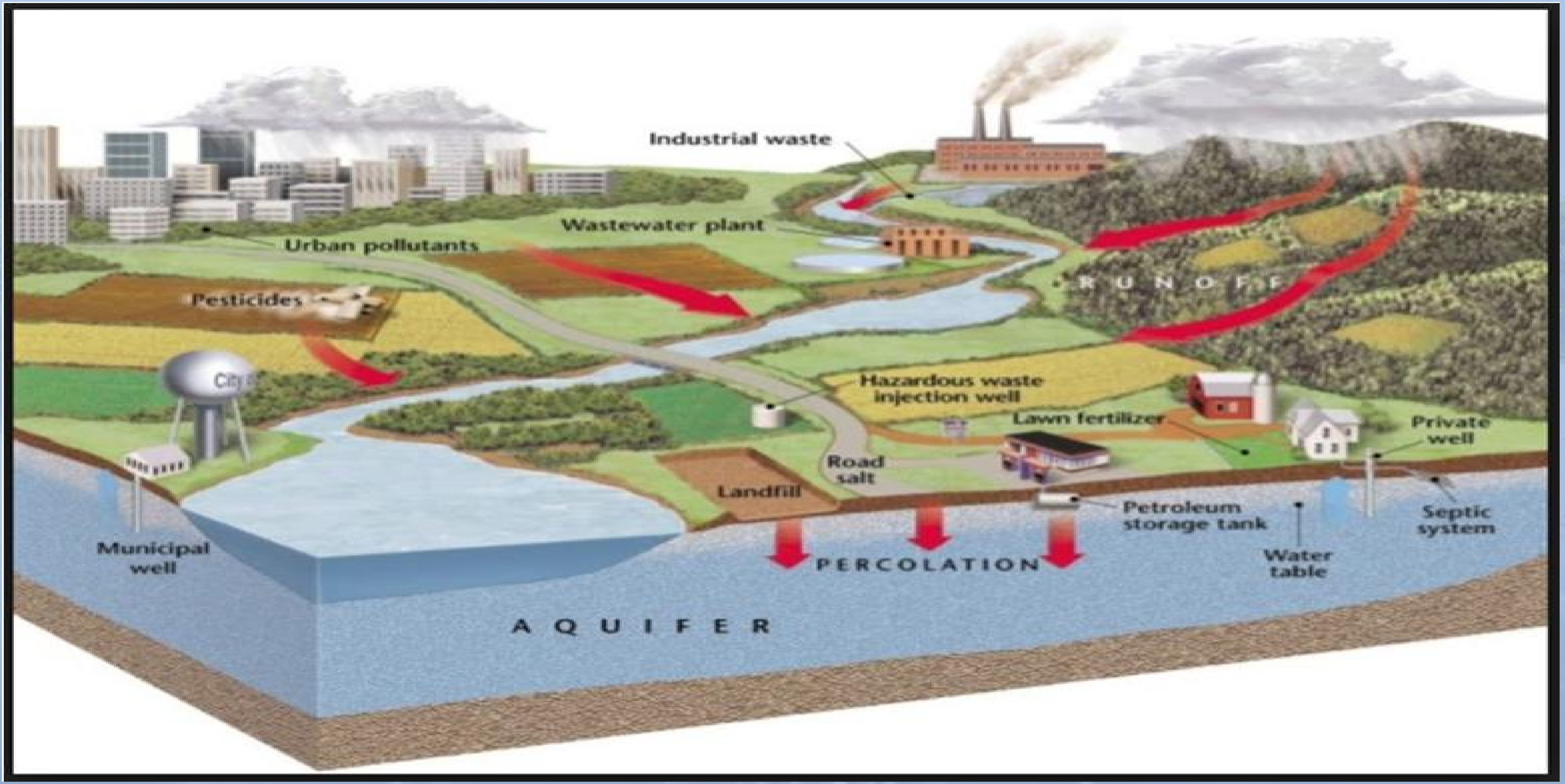
- It is determined by incubating a water sample and measuring the decrease in dissolved oxygen as bacteria decompose these materials.



CHEMICAL OXYGEN DEMAND(COD)

- Total amount of oxygen required to chemically oxidize the bio-degradable and non bio-degradable organic matter.

REASONS OF GROUND WATER QUALITY DEGRADATION



POLLUTION OF GROUND WATER

- Defined as the artificially induced degradation of natural ground water quality.

- Pollution can impair the use of water and can create hazards to public health through toxicity or the spread of disease.

- In contrast with surface water pollution, subsurface pollution is difficult to detect and control, and may persist for decades.

SOURCES AND CAUSES OF POLLUTION

- All sources and causes of pollution can be classified as to their geometry

a. Point source :- Originates from a single location.
b. Line source :- Predominantly linear arrangement.
c. Diffuse use :- Occupies an extensive area.

PRINCIPLES SOURCES AND CAUSES OF POLLUTION WITH REGARD TO THEIR OCCURENCE

a. Municipal sources and causes
b. Industrial sources and causes
c. Agriculture sources and causes
d. Miscellaneous sources and causes

Municipal sources and causes

a. Sewer leakage

- Sources:- Poor workmanship, defective sewer pipe, breakage by tree roots, ruptures from heavy loads, earthquakes, loss of foundation support etc.

- Results:- Introduce high concentrations of BOD, COD, nitrate, organic chemicals, bacteria and heavy metals into groundwater.

Municipal sources and causes

b. <u>Liquid wastes</u>

- Sources :- Domestic wastes, disposal wells industries, storm, runoff.

- Results :- Introduce bacteria, viruses, trace elements and heavy metals, inorganic and organic chemicals etc.

Municipal sources and causes

c. <u>Solids wastes</u>

- Sources:- Landfills

- Results:-

1. Leachate from landfills pollute ground water
2. Leachate include iron manganese, nitrate, trace elements etc.

INDUSTRIAL SOURCES AND CAUSES

a. Liquid wastes

Sources :- Industrial waste water discharges into pits, ponds, lagoons etc.

Results :- Introduction of hazardous and toxic industrial wastes into groundwater.

INDUSTRIAL SOURCES AND CAUSES

b. Tank and pipeline leakage

Sources :- Gasoline stations, fuels oil tanks, petroleum and petroleum products from industrial pipelines and tanks.

Results :- Immiscible liquids like oil and petroleum, liquid radioactive wastes etc. reaches the water table and pollutes the groundwater.

INDUSTRIAL SOURCES AND CAUSES

c. Mining activities

- Sources :-

1. Coal, phosphate and uranium mines
2. Stone, Sand and gravel quarries

- Results :- Low pH, increase in iron, aluminium and sulphate content in the soil.

AGRICULTURAL SOURCES AND CAUSES

a. Irrigation return flows

- Sources :- Irrigation return flow drains to surface channels or joints the underlying water.

- Results :-

1. Increases salinity of groundwater
2. Increases the amount of bicarbonates, sulphate, chlorides, nitrates etc. in the groundwater.

AGRICULTURAL SOURCES AND CAUSES

b. Animal wastes

Sources :- Wastes from slaughter houses

Results :-

1. The natural assimilative of the soil become overtaxed
2. Salts, organic loads and bacteria are transported into the soil
3. Nitrate-Nitrogen is the most important persistent pollutant that may reach the water table

AGRICULTURAL SOURCES AND CAUSES

c. <u>Fertilizer and soil Amendments</u>

Sources :-

1. Leachate of phosphate and potassium fertilizers
2. Leachate of soil amendments like lime, gypsum and Sulphur

Results :- Increases salinity of water

AGRICULTURAL SOURCES AND CAUSES

d. Pesticides, insecticides and herbicides

Sources :- Leachate and pesticides, insecticides and herbicides used in agricultural fields

Result :- Causes serious consequences in relation to the portability of water

Miscellaneous sources and causes

a. Urbanisation

Groundwater pollution can occur both in rural as well as urban area and is affected by differences in chemical composition, biological and chemical reactions, density and distance from discharge areas

Miscellaneous sources and causes

b. Stockpiles

Solid materials are frequently stockpiled near industrial plants, construction site etc

Precipitation falling on unsheltered stockpiles causes leaching of heavy metals, salts and other pollutants into the groundwater

Miscellaneous sources and causes

c. Roadway de-icing

Results from the application of de-icing salts to streets and highways in winter

Sodium chloride and calcium chloride are generally used

Salt reaches the groundwater in sodium after spreading on roadways and also from stockpiles

Miscellaneous sources and causes

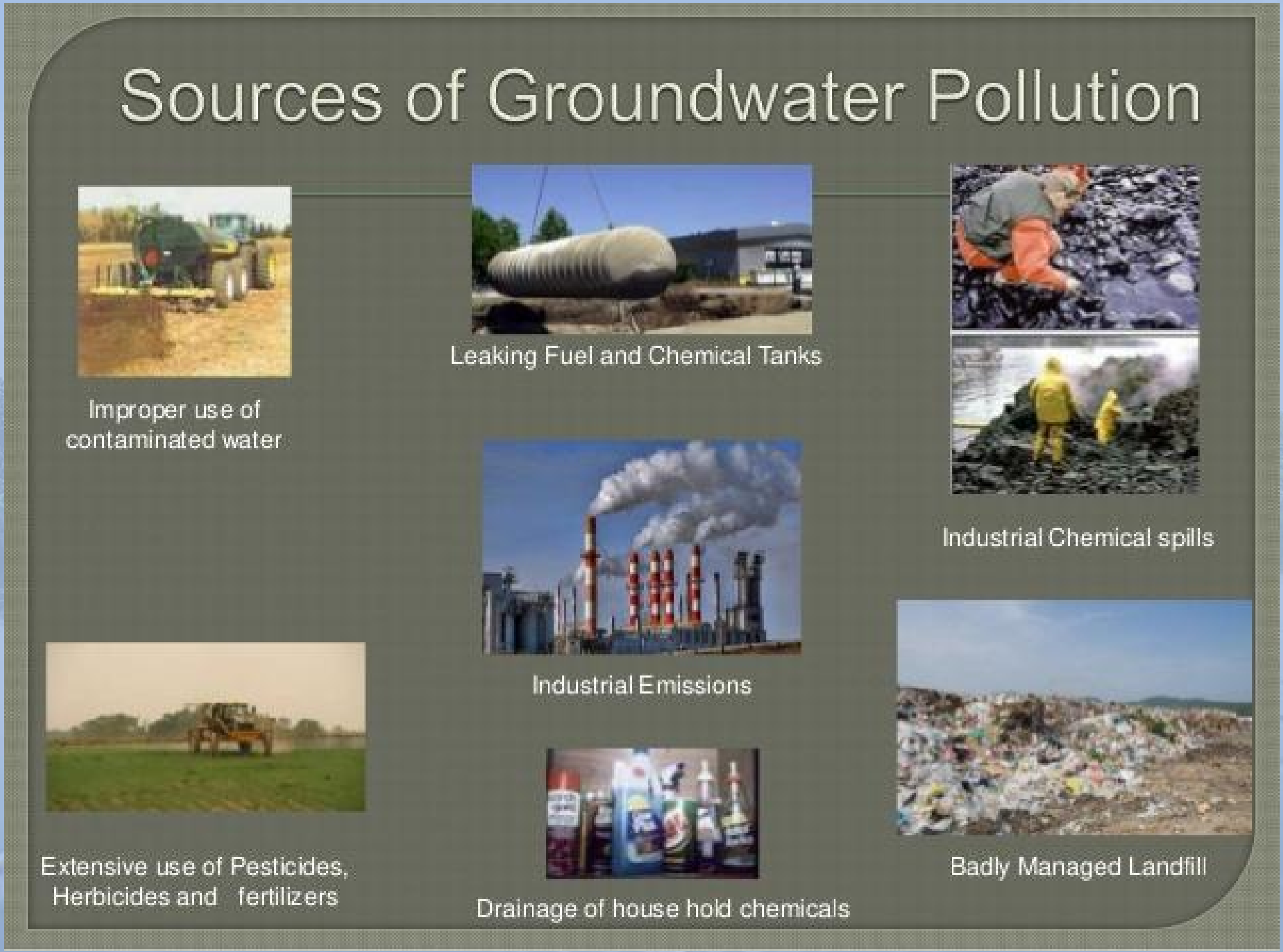
d. Saline water intrusion

Salt water may invade freshwater aquifers to create point or diffuse pollution sources

e. Surface water

Polluted surface water bodies that contribute groundwater recharge become sources of groundwater pollution

REMEDIAL MEASURES FOR IMPROVING GROUND WATER QUALITY


Sources of Groundwater Pollution
Improper use of contaminated water
Leaking Fuel and Chemical Tanks
Industrial Chemical spills
Industrial Emissions
Extensive use of Pesticides, Herbicides and fertilizers
Drainage of house hold chemicals
Badly Managed Landfill

PREVENTION OF GROUNDWATER CONTAMINATION

PARTICIPATION OF INDUSTRIES :

- Minimize use of toxic / hazardous raw materials
- Maintain integrity of the storage tanks, pipelines, surface impoundments
- Adopt good engineering practice for selecting proper materials for tanks and pipes
- Manage properly : waste materials, their transport and disposal
- Install monitoring wells

PREVENTION OF GROUNDWATER CONTAMINATION

<u>Participation of community</u>

- Minimize use of house hold chemicals containing hazardous substances
- Avoid draining chemicals, motor oil, insecticides in community areas
- Reduce pesticide application
- Immediately clean any spills and report any leakages to concemed department

GROUNDWATER REMIDIATION

Groundwater remediation techniques are mainly divided into two technologies : 1)Ex-Situ technology

2)In-Situ technology

- Ex-Situ technology: involves treatment of groundwater by dewatering the polluted aquifer (pumping out), then treating the water on surface by Physical, chemical and biological technology and finally reinjecting the treated water into aquifer.
- In-Situ technology : involves treatment of groundwater within the aquifer (in the sub-surface) by using thermal, chemical and biological treatment technology.

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GROUND WATER ENGINEERING CV0612

GROUND WATER POLLUTION

Prepared By:
Prof. Nirali Padhiyar

What is Groundwater Pollution?

- Groundwater pollution occurs as a result of release of pollutants into the ground to natural underground water reservoirs known as aquifers.

- Once the pollutants released find their way into groundwater, they cause contamination.

- It is a type of water pollution that is mainly caused by release of substances either intentionally or accidentally through anthropogenic activities or natural causes.

- The pollutants usually move within an aquifers depending on biological (bacteria or harmful microorganisms), physical (sediments or organic material), and chemical (nitrogen, bleach, salt, pesticides, toxins, drugs)properties.

- Processes such as diffusion, dispersion, adsorption, and the speed of moving water often facilitates the movement.

- But in general, the movement of the contaminants within an aquifer is usually slow and as such, their concentration tends to be high and in a form called a plume (polluted water within the Aquifer).

- As the plume spreads it might connect with springs and ground wells making them unsafe for human consumption.

Major Ground Water Issue

- Over–exploitation of resource
- Contamination–
- Limited availability and sustainability in hard rock areas
- Less recharge potential and resource availability in arid areas
- Water logging and salinity problems
- Impact of climate change on ground
- water regime

Causes of Groundwater Pollution

- 1. **Natural Sources**

- Naturally occurring substances found in the soils and rocks can be dissolved in water causing contamination.
- This substances are sulfates, iron, radionuclides, fluorides, manganese, chlorides and arsenic.
- Others such as the decaying materials in the soil may seep in underground water and move with it as particles.
- Reports by WHO indicate that the most common pollutants are fluoride (found in soil, water & food) and arsenic (it's a strong poison).
- Fluoride effect the bones, teeth, neurological development.
- Natural cause of pollution can be tested using the Groundwater Assessment Platform (GAP).
- GAP estimates contamination levels using environmental, geological and the topographical data.

- 2. **Septic Systems**
- Across the world, septic systems are the main cause of pollution of underground water.
- The pollutants are out flow from privies (toilet disposal), septic tanks (underground structure for domestic wastewater) and the cesspools (container for temporary storage of liquid waste & sewage).
- 25% of household in the USA, for instance, heavily depend on the septic systems to dispose of their waste.
- This huge number of users relying on the system makes it one of the main pollutants.
- Additionally, improperly designed and leaking septic systems release contaminants such as nitrates, oils, bacteria, chemicals, detergents and viruses into underground water.
- Commercial septic tanks pose even a much bigger threat because they release organic chemicals such as trichloroethane.
- Laws in most countries require the septic tank to be constructed far from the water sources to prevent contamination but at times this is not usually the case.

3. Hazardous waste Disposal

- Hazardous wastes such as photographic chemicals, motor oil, cooking oil, paint thinners, medicines, swimming pool chemicals, paints, and garden chemicals should not be disposed into septic tanks or directly into the environment as they cause serious contamination.
- These chemicals should be disposed of with the help of a licensed hazardous waste handler.

4. Petroleum Products

- Petroleum storage tanks are either located underground or above ground.
- Also, the transportation of petroleum products is mainly done underground using pipeline.
- Leakages from this substances can lead to contamination of water.
- In USA it is estimated that 16,000 chemical spills each year are from trucks, storage containers and train spillages especially when transferring oil.
- The chemicals spilled become diluted with water and seep into the ground and may cause groundwater contamination.

5. Solid Waste

- Palmer Developmental Group estimated that in developing countries approximately 0.3 to 0.6 kg/person/day of waste is released into the ground.
- On the hand, in developed countries 0.7 to 1.8 kg/person/day is released.
- The chemicals from this substances are leached into the ground water through precipitation and surface run off.
- The wastes can also be collected and taken to landfills.
- If the landfills lack a clay liner and leachate the chemicals from the wastes will leach and pose a threat to the groundwater.

6. Surface impoundments

- It is a natural topographic depression, manmade.
- Made with earthen material which hold liquid wastes.
- These are shallow lagoons used to store liquid wastes.
- The USA, for example, has over 180,000 surface impoundments which can pose a threat to ground water.
- Therefore, the impoundments are required to have clay liners or leachates to prevent the leaching.
- In some cases the leachates may be defective and leakages may occur leading to contamination of water.

7. Agricultural Chemicals

- Millions of tons of agricultural chemicals such as fertilizers and pesticides are used worldwide to increase crop production.
- Other institutions such as the golf courses also use these chemicals.
- Excessive use of these chemicals can lead to contamination of groundwater.
- Chemicals such as pesticides are known to remain in the ground for years and when diluted with the rain water they seep deeper into the groundwater.

8. Injection wells

- They have various uses ranging from collection or storm water to disposal of industrial and commercial effluents.
- When not properly regulated, hazardous chemicals can be disposed of from injection wells.
- For this reason, if not properly located, regulated, and designed; they can cause contamination of ground water.

9. Other causes

- Other causes of ground pollution are abandoned wells which can act as a pathway for contaminants to reach the aquifers.

- Also poorly constructed wells that may lack proper casing and covers may cause ground water contamination that is pollutants find their way into such wells.

- Another cause of pollution is mining activities where through precipitation the soluble minerals can be leached(remove chemicals from soil by liquid passing through it) from the sites to the ground water.

Effects of Groundwater Pollution

- **1. Health Issues**
- Contaminated ground water have detrimental effects on health.
- In areas where septic tanks installation is not set up correctly, the human waste may contaminate the water source.
- The waste may contain hepatitis causing bacteria that may lead to irreversible damage to the liver.
- Also, it may cause dysentery which leads to severe diarrhea, dehydration and in some cases death.
- Additional health problems include poisoning that may be as a result of use of excessive pesticides and fertilizers or natural chemicals.
- The chemicals leach into water sources and poison them.
- Drinking of water from such a source may lead to serious health effects.

2. Affects economic growth

- Contamination of ground water sources renders the area incapable of sustaining plant, human, and animal life.
- The population in the area reduces and the land value depreciates.
- Another effect is that it leads to less stability in industries relying on ground water to produce their goods.
- Therefore, the industries in affected areas will have to outsource for water from other regions which may turn out to be expensive.
- In addition, they may be forced to close down due to the poor quality of water.

3 Impacts on the environment

- Groundwater pollution can lead to devastating environmental changes.
- One such alteration is loss of certain nutrients that are essential for self-sustenance of the ecosystem.
- Also, when the pollutants mix with water bodies, alteration of the aquatic ecosystem may also occur.
- Aquatic animals such as fishes may die off quickly as a result of too much contaminants in the water bodies.
- Animals and plants using the contaminated water may also be affected.
- Toxic substances accumulate with time in the aquifers and once the prime spreads it may render the ground water unsuitable for human and animal consumption.
- The effects are serious especially in people who rely on groundwater during drought periods

Effects of Water Pollution

Effects on Agriculture - use of wastewater and polluted surface and groundwater which contaminate crops and transmit disease to consumers and farm workers; Depositions of deleterious chemicals in soil leading to loss of soil fertility.

Effects on Environment/ecosystems - pungent smell, decolourisation; increased temps; contamination; change the pH; decreased oxygen; detergents that create a mass of white foam in the river waters; Enrichment of groundwater with salts, nutrients from irrigated lands; eutrophication/algal blooms-what is the effect on recreational activities, water treatment plants/water providers; Loss of aesthetic value; Algae clogs our waterways.

Domestic effects - *toxic substances such as lead, mercury, cadmium, and chromium* or cyanide, which may affect the use of the receiving water for domestic use *or for aquatic life.*

Effects on industry - *boiler scales, Heavy metals cause unpleasant taste and odour to drinking water; Suspended particles cause unpleasant taste & discoloration to drinking water.*

Solutions of Groundwater Pollution

- **1. Legislation**
- There are federal laws in most countries that help in protecting the quality of ground water.
- Safe Drinking and Clean Water regulations should ensure protection of drinking water by establishing measures for them to meet the health standards.

2. THE USE OF WATER CLEANING SYSTEMS

- Point–of–use treatment systems should be installed in outlets that dispense water for human consumption.
- The techniques used include chemical disinfection, boiling, solar distillation, filtration, ozone water disinfection, activated charcoal absorption and ultraviolet disinfections.
- Arsenic Removal Filters (ARFs) are usually installed to remove arsenic compounds present.
- Maintenance of this filters is essential to ensure that the drinking water is always safe.
- Ground water Remediation is also another management technique.
- The biological treatment techniques employed are bioaugmentation,bioslurping, bioventing, phytoremediation and biosparging. Chemicals techniques such as ion exchange, ozone gas injection, membrane separation and chemical precipitation can also be used.

3. Proper management of the sources of pollution

- The landfills (large amount of waste material are dumped) should be designed with proper clay and leachates (liquid has extracted dissolved and suspended matter).
- The maintenance should be done regularly.
- The location of the landfill should also be far from groundwater areas.
- Further, any hazardous wastes should not be dumped in the landfill unless it is designed for that purpose.
- In constructing and managing underground storage tanks, it is important to comply with the set regulations and policies to avoid contamination or even law suits.
- A containment device that acts as a leak back up should be put in place and any unused underground tanks should be removed. Underground pipelines installation should be designed professionally.
- Inspections should be done regularly and causes of corrosion or leakages noted should be resolved immediately.

4. Recycling

- Most landfills in various countries have a recycling plant nearby.
- Therefore, used petroleum products should be taken to such places.
- Apart from oil, other recyclable materials such as plastic, bottle and paper wastes can also be taken to recycling plants.
- The state should provide designated recycling pick up areas in places that they are not established.
- Together with other environmental organizations, the state can mobilize people to participate in the recycling initiative.
- They can do this through holding awareness campaigns and educating communities of the importance of recycling.

Thank You

CHAPTER ONE

OCCURRENCE OF GROUNDWATER

1.1 Introduction

Groundwater is water that exists in the pore spaces and fractures in rocks and sediments beneath the Earth's surface. It originates as rainfall or snow, and then moves through the soil and rock into the groundwater system, where it eventually makes its way back to the surface streams, lakes, or oceans.

- Groundwater makes up about 1% of the water on the Earth (most water is in oceans)
- But, groundwater makes up to 35 times the amount of water in lakes and streams.
- Groundwater occurs everywhere beneath the Earth's surface, but is usually restricted to depth less than about 750 meters.
- The volume of groundwater is equivalent to a 55-meter thick layer spread out over the entire surface of the Earth.
- **Technical note**: Groundwater scientists typically restrict the use of the term "groundwater" to underground water that can flow freely into a well, tunnel, spring, etc. This definition excludes underground water in the unsaturated zone. The unsaturated zone is the area between the land surface and the top of the groundwater system. The unsaturated zone is made up of earth materials and open spaces that contain some moisture but, for the most part, this zone is not saturated with water. Groundwater is found beneath the unsaturated zone where all the open spaces between sedimentary materials or in fractured rocks are filled with water and the water has a pressure greater than atmospheric pressure.

To understand the ways in which groundwater occurs, it is needed to think about the ground and the water properties.

- Porosity, which is the property of a rock possessing pores or voids.
- Saturated and unsaturated zones.
- Permeability, which is the ease with which water can flow through the rock.
- Aquifer, which is a geologic formation sufficiently porous to store water and permeable enough to allow water to flow through them in economic quantities.
- Storage coefficient, which is the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of area normal to surface.

1.2 Origin of Groundwater

The origin of groundwater is primarily one of the following:

- Groundwater derived from rainfall and infiltration within the normal hydrological cycle. This kind of water is called **meteoric water.** The name implies recent contact with the atmosphere.

- Groundwater encountered at great depths in sedimentary rocks as a result of water having been trapped in marine sediments at the time of their deposition. This type of groundwater is referred to as **connate waters**. These waters are normally saline. It is accepted that connate water is derived mainly or entirely from entrapped sea water as original sea water has moved from its original place. Some trapped water may be brackish.

- **Fossil water** if fresh may be originated from the fact of climate change phenomenon, i.e., some areas used to have wet weather and the aquifers of that area were recharged and then the weather of that area becomes dry.

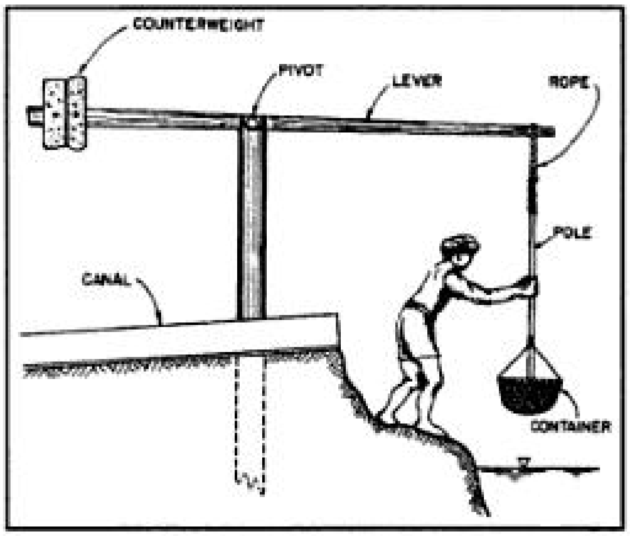


Figure 1.3. Water-lift method used by the Egyptians early as 2000 B.C. (McWhorter and Sunada, 1977).

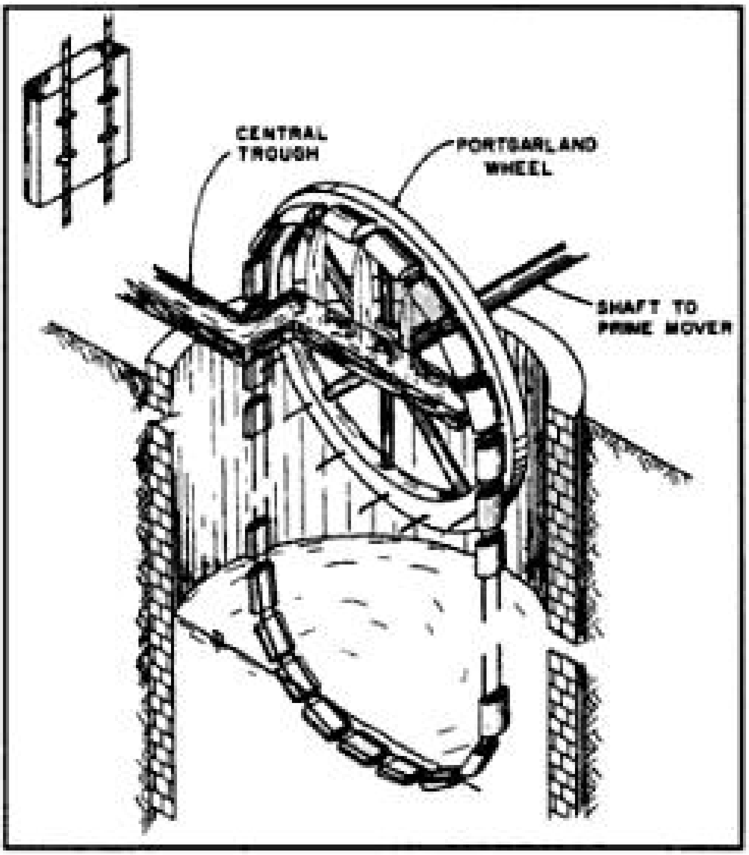


Figure 1.4. Persian wheel (McWhorter and Sunada, 1977).

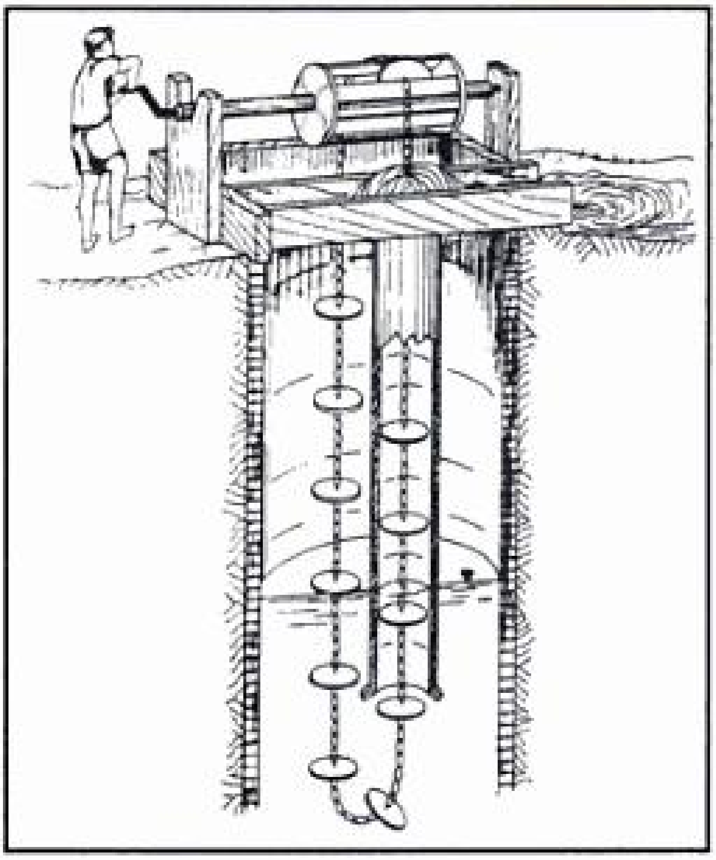


Figure 1.5. Chinese water ladder (McWhorter and Sunada, 1977).

1.3 Groundwater and the Hydrologic Cycle

- The hydrological cycle is the most fundamental principle of groundwater hydrology.
- The driving force of the circulation is derived from the radiant energy received from the sun.

Water **evaporates** and travels into the air and becomes part of a cloud. It falls down to earth as precipitation. Then it evaporates again. This happens repeatedly in a never-ending cycle. This **hydrologic cycle** never stops. Water keeps moving and changing from a solid to a liquid to a gas, repeatedly.

Precipitation creates **runoff** that travels over the ground surface and helps to fill lakes and rivers. It also **percolates** or moves downward through openings in the soil and rock to replenish **aquifers** under the ground. Some places receive more **precipitation** than others do with an overview balance. These areas are usually close to oceans or large bodies of water that allow more water to **evaporate** and form clouds. Other areas receive less. Often these areas are far from seawater or near mountains. As clouds move up and over mountains, the water vapor condenses to form precipitation and freezes. Snow falls on the peaks. **Figure 1.1** shows a schematic representation of the hydrological cycle.

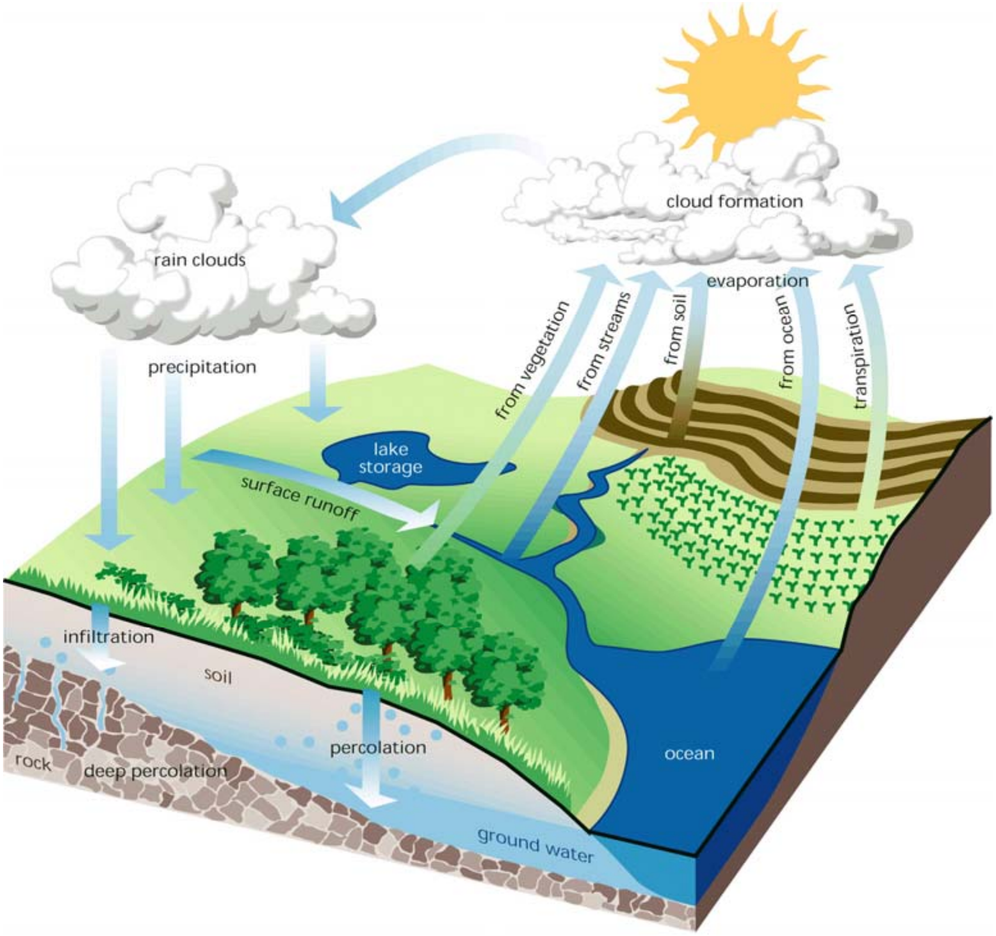


Figure 1.1 Schematic Representation of the Hydrological Cycle

In recent years there has been considerable attention paid to the concept of the **world water balance**, and the most recent estimates of these data emphasize the ubiquitous nature of groundwater in hydrosphere. With reference to **Table 1.1**, if we remove from consideration the 94% of the earth's water that rests in the oceans and seas at high levels of salinity, then groundwater accounts for about two-thirds of the freshwater resources of the world.

Table 1.1 Estimate of the Water Balance of the World

Parameter	Surface area $(Km^2)*10^6$	Volume $(Km^2)*10^6$	Volume (%)	Equivalent depth (m)*	Resident time
Oceans and seas	361	1370	94	2500	~ 4,000 years
Lakes and reservoirs	1.55	0.13	< 0.01	0.25	~ 10 years
Swamps	< 0.1	< 0.01	< 0.01	0.007	1-10 years
River channels	< 0.1	< 0.01	< 0.01	0.003	~ 2 weeks
Soil moisture	130	0.07	< 0.01	0.13	2 weeks – 1 year
Groundwater	130	60	4	120	~ 2 weeks – 10,000 years
Icecaps and glaciers	17.8	30	2	60	10-1000 years
Atmospheric water	504	0.01	< 0.01	0.025	~ 10 days
Biospheric water	< 0.1	< 0.01	< 0.01	0.001	~ 1 week

* Computed as though storage were uniformly distributed over the entire surface of the earth.

1.4 Vertical Distribution of Groundwater

1.4.1 Volumetric Properties

Flow in soils and rocks takes place through void spaces, such as pores and cracks. The hydraulic properties of soils and rocks therefore depend on the sizes and shapes of the void spaces. These vary over very short distances (e.g. micrometers or millimeters). The idea of defining volumetric or hydraulic properties which apply at a given point in the unsaturated zone therefore has sense only if the properties relate to a finite volume of the soil/rock centered at that point. This volume is usually called the **representative elementary volume** (REV) and the properties defined in this fashion are sometimes called **point-scale** properties.

The point-scale properties vary in space. Part of this variation is associated with variations in the degree of compaction, weathering, cracking, and holing (such as holes left by decayed plant roots). The term **macropore** is often used to describe a feature such as a crack which allows rapid subsurface flow. Macropores and their effects on flow (and chemical transport) lie at the heart of many of the difficult, unresolved, problems in Near-Surface Hydrology.

At many locations, the subsurface flow is dominated by flow through complex networks of macropores. There may even be a few large soil pipes or subsurface channels (for example, subsurface pipes in steep hill slopes and channels in karst areas) which completely dominate the local flow conditions.

At present, there are no reliable techniques for measuring and quantifying macropore networks, and the modelling of macropore flow is in its infancy. The theory given below therefore concentrates on matrix flow (i.e. flow through the pores in media which do not contain macropores).

The point-scale properties can also vary in a systematic manner. There is usually **vertical layering**, resulting from the long-term evolution of the soil/rock profile by deposition processes, weathering, land management, etc. There are also variations associated with gradual horizontal changes (for instance, as shown in geological maps for a hill slope, catchment or region).

The concept of defining large-scale properties (e.g. a single, average, property for an entire hill slope) is controversial, but is being considered by some research workers.

The **porosity** n at a point is defined as:

$$n = \frac{volume\ of\ voids}{total\ volume} \tag{1.1}$$

The **volumetric moisture content** θ is:

$$\theta = \frac{volume\ of\ water}{total\ volume} \tag{1.2}$$

and the **relative moisture content** R is

$$R = \frac{volume\ of\ water}{volume\ of\ voids} \tag{1.3}$$

where, total volume = volume of solids + volume of voids.

In the geotechnical literature, property values are often quoted in mass terms (the moisture content by mass, for example), making use of data for the **bulk dry density** ρ_d of the medium (i.e. the dry mass per unit volume of soil/rock).

Approximate properties such as **field capacity** and **wilting point** are used in the hydrological and agricultural literature. Field capacity is the volumetric moisture content left in the medium after it has drained under gravity from saturation for a period of two days (definitions vary), and the wilting point is the volumetric moisture content which is just low enough so that any plants growing in the medium will fail to transpire, so will wilt and die.

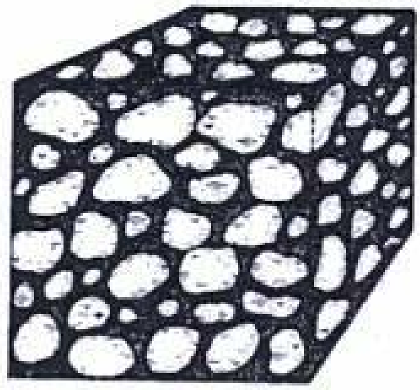


Figure 2.1. Pores in unconsolidated sedimentary rock (Heath, 1984).

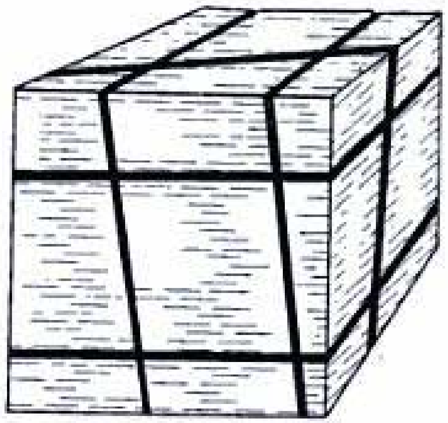


Figure 2.2. Fractures in intrusive igneous rocks (Heath, 1984).

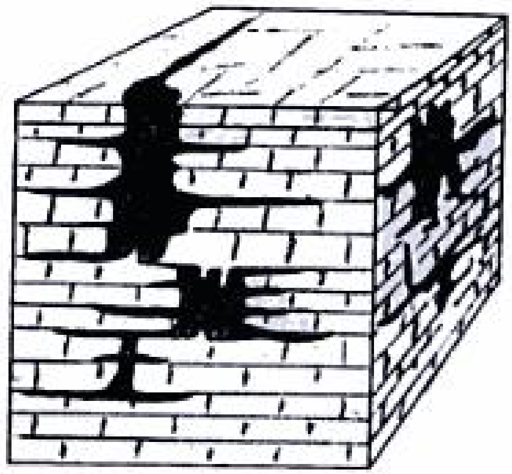


Figure 2.3. Caverns in limestone and dolomite (Heath, 1984).

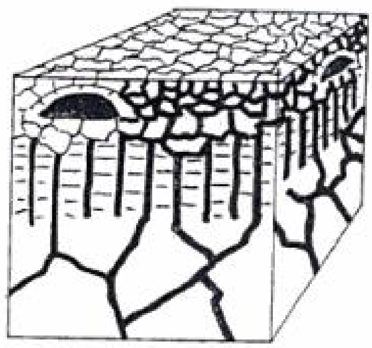


Figure 2.4. Lava tubes and cooling fractures in extrusive igneous rocks (Heath, 1984).

1.4.2 The Occurrence of Subsurface Water

The subsurface occurrence of groundwater may be divided into zones of aeration and saturation. The zone of aeration consists of interstices occupied partially by water and partially by air. In the zone of saturation all interstices are filled with water, under hydrostatic pressure. One most of the land masses of the earth, a single zone of aeration overlies a single zone of saturation and extends upward to the ground surface, as shown in **Figure 1.2**.

In the zone of aeration (unsaturated zone), *Vadose water* occurs. This general zone may be further subdivided into the soil water zone, the intermediate Vadose zone (sub-soil zone), and capillary zone (**Figure 1.2**).

The saturated zone extends from the upper surface of saturation down to underlying impermeable rock. In the absence of overlying impermeable strata, the *water table*, or *phreatic surface*, forms the upper surface of the zone of saturation. This is defined as the surface of atmospheric pressure and appears as the level at which water stands in a well penetrating the aquifer. Actually, saturation extends slightly above the water table due to capillary attraction; however, water is held here at less than atmospheric pressure. Water occurring in the zone of saturation is commonly referred to simply as *groundwater*, but the term *phreatic water* is also employed.

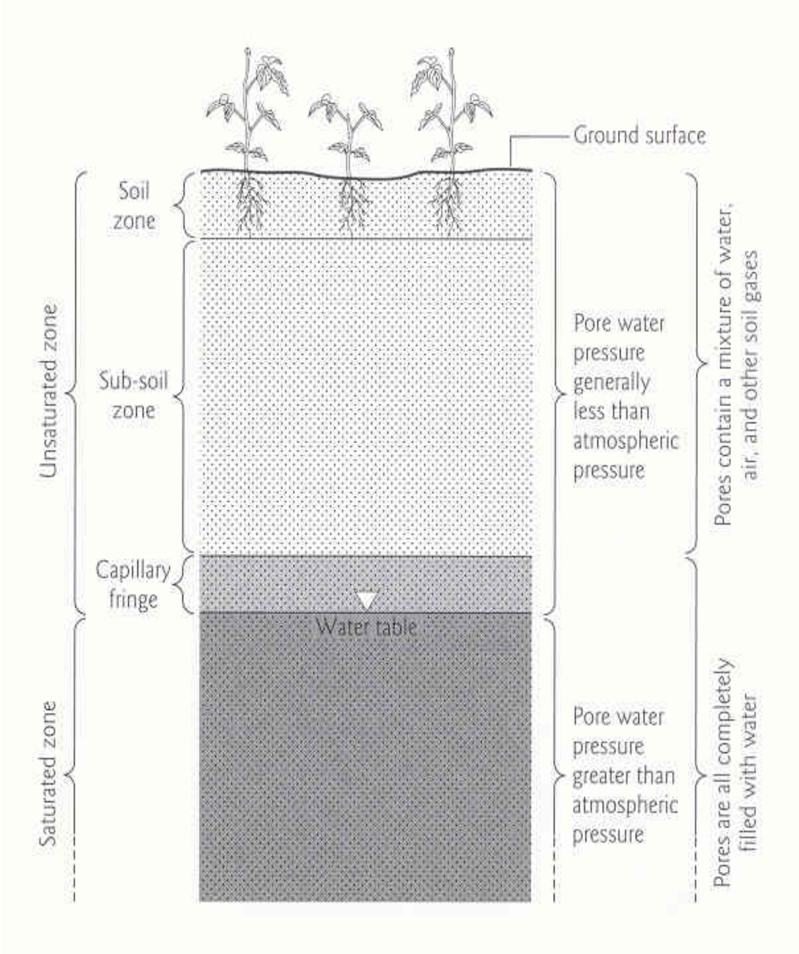


Figure 1.2 A schematic cross-section showing the typical distribution of subsurface waters in a simple "unconfined" aquifer setting, highlighting the three common subdivisions of the unsaturated zone and the saturated zone below the water table.

1.5 Types of Geological Formations and Aquifers

There are basically four types of geological formations (Aquifers, Aquitard, Aquiclude, and Aquifuge)

1.5.1 Aquifer

An aquifer is a ground-water reservoir composed of geologic units that are saturated with water and sufficiently permeable to yield water in a usable quantity to wells and springs. Sand and gravel deposits, sandstone, limestone, and fractured, crystalline rocks are examples of geological units that form aquifers. Aquifers provide two important functions: (1) they transmit ground water from areas of recharge to areas of discharge, and (2) they provide a storage medium for useable quantities of ground water. The amount of water a material can hold depends upon its porosity. The size and degree of interconnection of those openings (permeability) determine the materials' ability to transmit fluid.

Types of Aquifers

Most aquifers are of large areal extent and may be visualized as underground storage reservoirs. Water enters a reservoir from natural or artificial recharge; it flows out under the action of gravity or is extracted by wells. Ordinarily, the annual volume of water removed or replaced represents only a small fraction of the total storage capacity. Aquifers may be classed as unconfined or confined, depending on the presence or absence of a water table, while a leaky aquifer represents a combination of the two types.

Unconfined Aquifer. An unconfined aquifer is one in which a water table varies in undulating form and in slope, depending on areas of recharge and discharge, pumpage from wells, and permeability. Rises and falls in the water table correspond to changes in the volume of water in storage within an aquifer. **Figure 1.2** is an idealized section through an unconfined aquifer; the upper aquifer in **Figure 1.3** is also unconfined. Contour maps and profiles of the water table can be prepared from elevations of water in wells that tap the aquifer to determine the quantities of water available and their distribution and movement.

A special case of an unconfined aquifer involves ***perched water bodies***, as illustrated by **Figure 1.3.** This occurs wherever a groundwater body is separated from the main groundwater by a relatively impermeable stratum of small areal extent and by the zone of aeration above the main body of groundwater. Clay lenses in sedimentary deposits often have shallow perched water bodies overlying them. Wells tapping these sources yield only temporary or small quantities of water.

Confined Aquifers. Confined aquifers, also known as ***artesian or pressure aquifers***, occur where groundwater is confined under pressure greater than atmospheric by overlying relatively impermeable strata. In a well penetrating such an aquifer, the water level will rise above the bottom of the confining bed, as shown by the artesian and flowing wells of **Figure 1.3.** Water enters a confined aquifer in an area where the confining bed rises to the surface; where the confining bed ends underground, the aquifer becomes unconfined. A region supplying water to a confined area is known as a ***recharge area;*** water may also enter by leakage through a confining bed. Rises and falls of water in wells penetrating confined aquifers result primarily from changes in pressure rather than changes in storage volumes. Hence, confined aquifers display only small changes in storage and serve primarily as conduits for conveying water from recharge areas to locations of natural or artificial discharge.

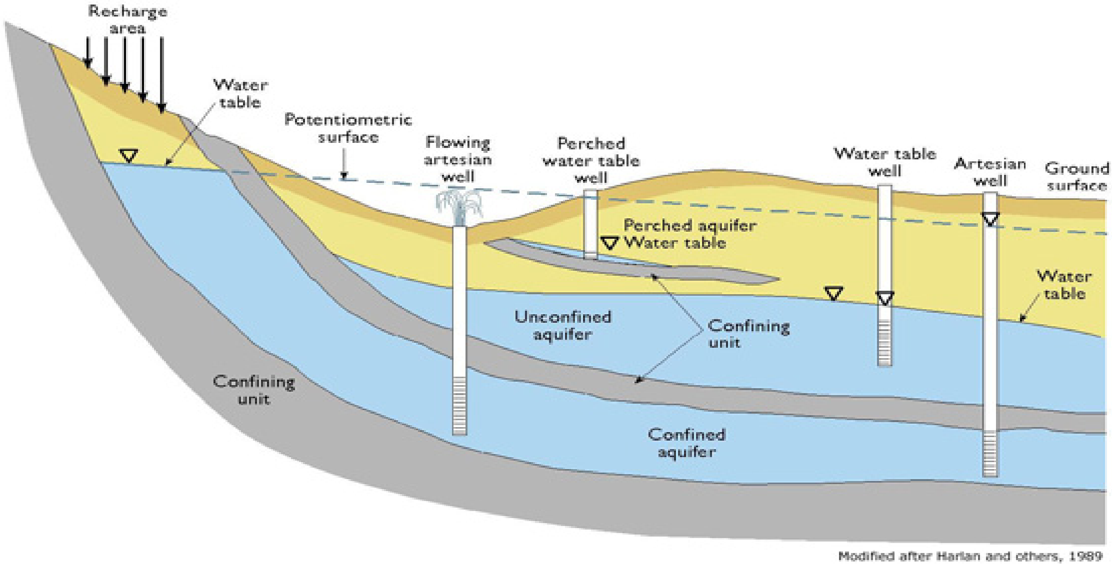


Figure 1.3 Schematic Cross-sections of Aquifer Types

Leaky Aquifer. Aquifers that are completely confined or unconfined occur less frequently than do *leaky,* or *semi-confined*, aquifers. These are a common feature in alluvial valleys, plains, or former lake basins where a permeable stratum is overlain or underlain by a semi-pervious aquitard or semi-confining layer. Pumping from a well in a leaky aquifer removes water in two ways: by horizontal flow within the aquifer and by vertical flow through the aquitard into the aquifer (see **Figure 1.4**).

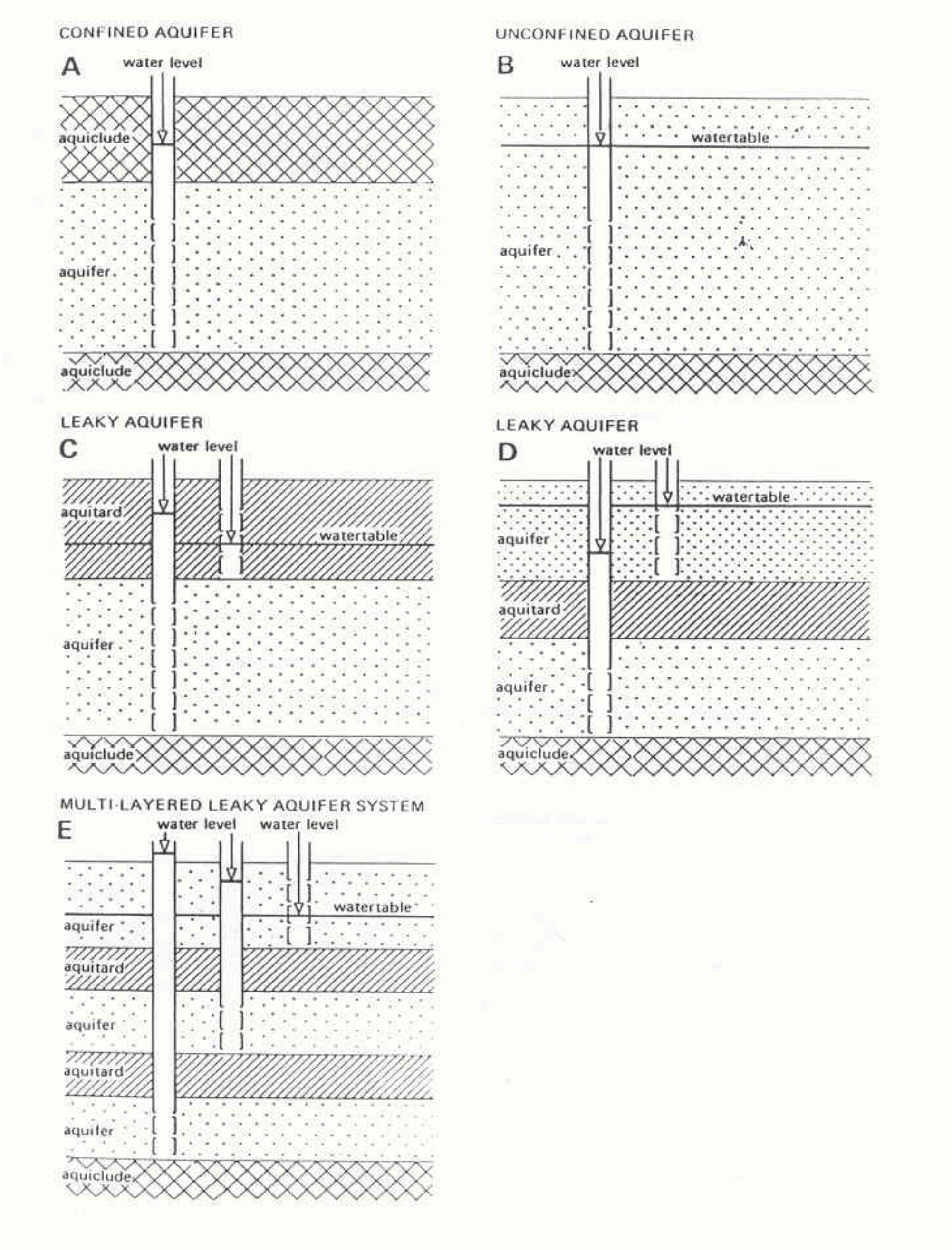


Figure 1.4 Different types of aquifers; A. Confined aquifer, B. Unconfined Aquifer, C. and D. Leaky aquifers, E. Multi-layered leaky aquifer system.

1.5.2 Aquitard

An aquitard is a partly permeable geologic formation. It transmits water at such a slow rate that the yield is insufficient. Pumping by wells is not possible. For example, sand lenses in a clay formation will form an aquitard.

1.5.3 Aquiclude

An aquiclude is composed of rock or sediment that acts as a barrier to groundwater flow. Aquicludes are made up of low porosity and low permeability rock/sediment such as shale or clay. Aquicludes have normally good storage capacity but low transmitting capacity.

1.5.4 Aquifuge

An aquifuge is a geologic formation which doesn't have interconnected pores. It is neither porous nor permeable. Thus, it can neither store water nor transmit it. Examples of aquifuge are rocks like basalt, granite, etc. without fissures.

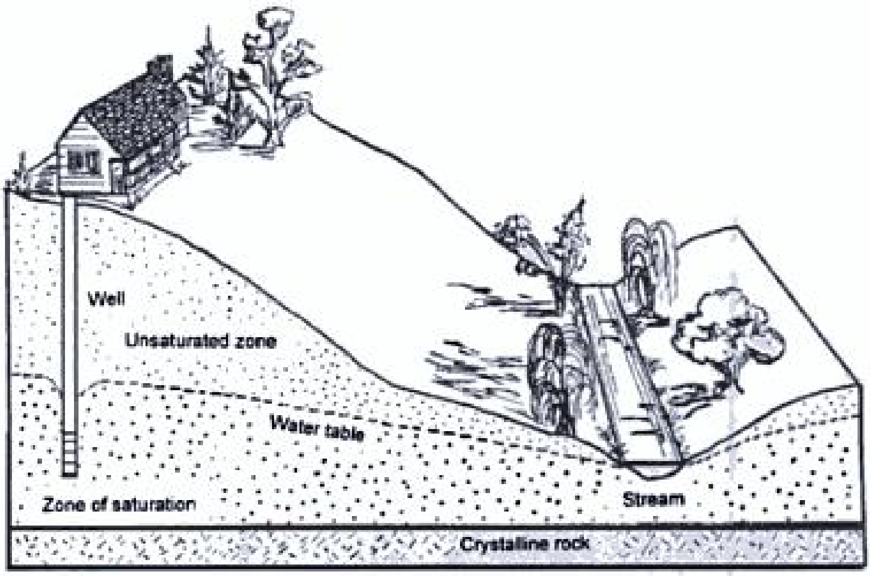


Figure 2.5. Unconfined aquifer. Simple riverine system comprised of sand.

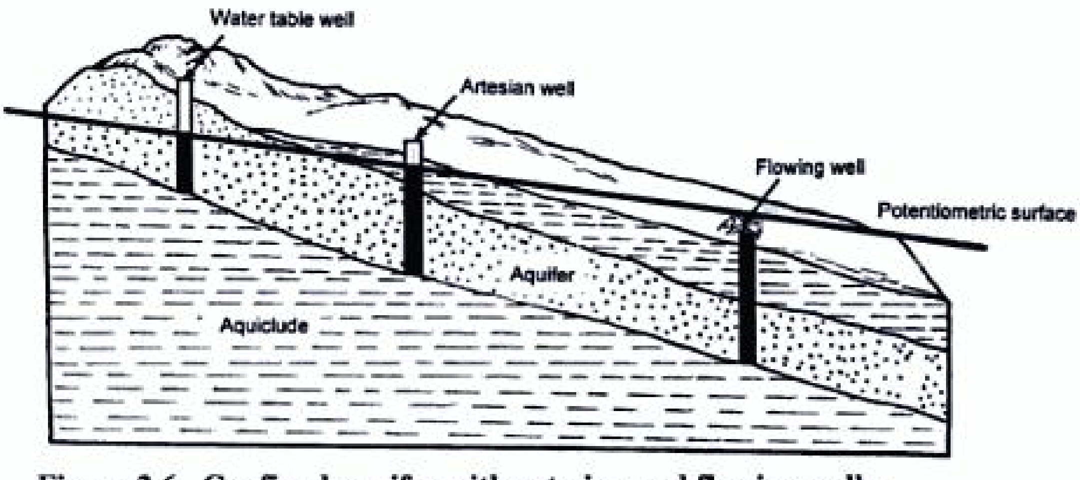


Figure 2.6. Confined aquifer with artesian and flowing wells.

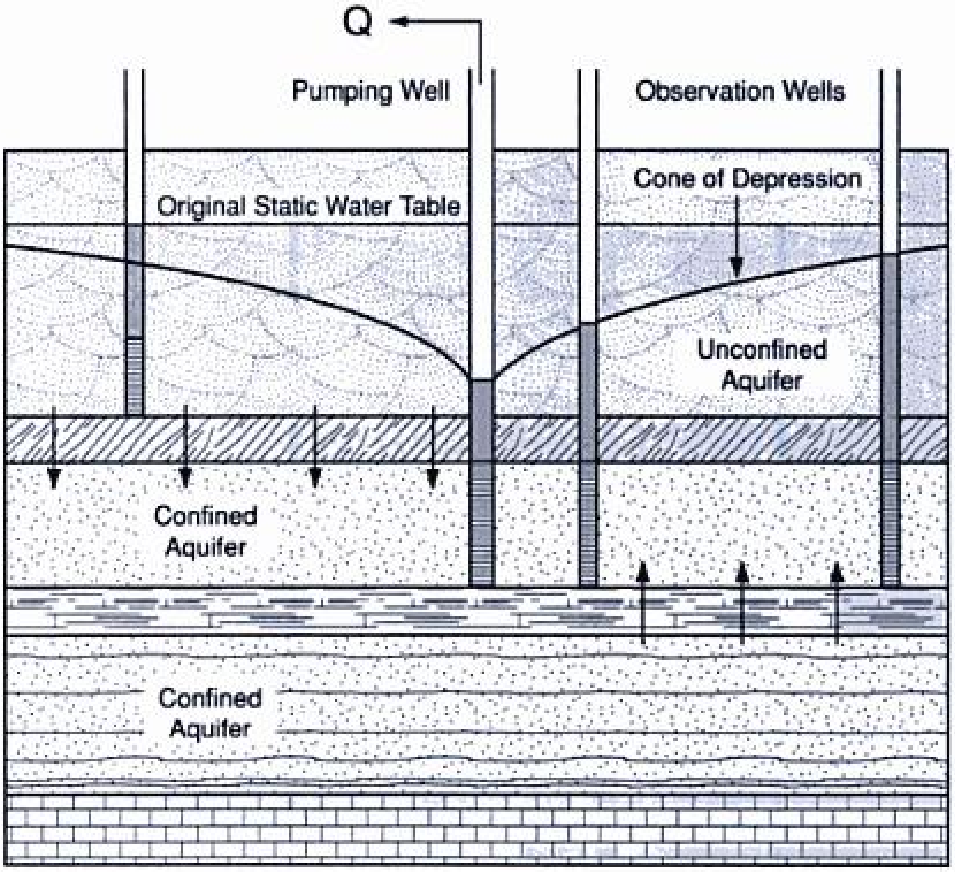


Figure 2.7. Development of a leaky confined aquifer during a pumping period.

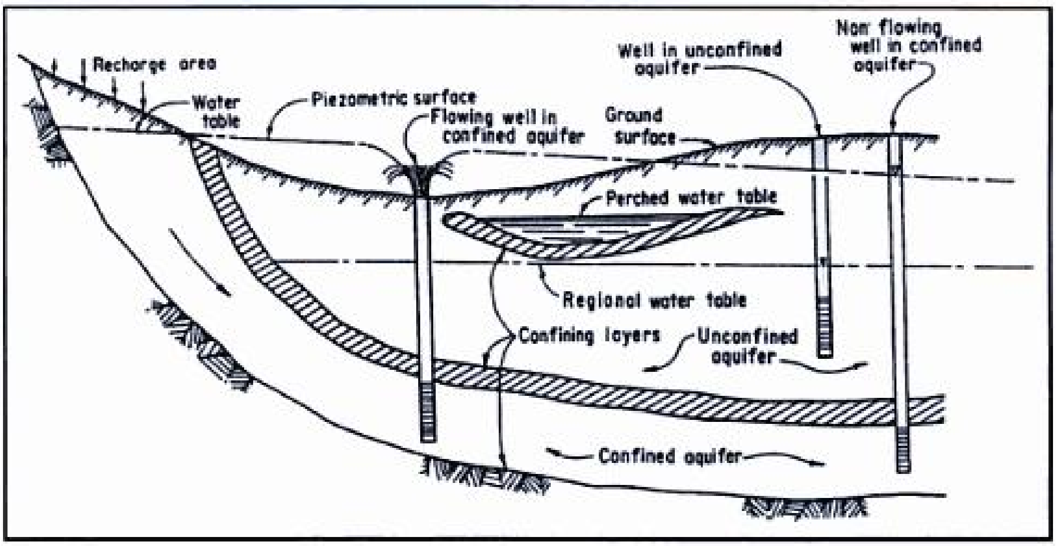


Figure 2.8. Confined, unconfined and perched aquifers (Source: USDI, 1981).

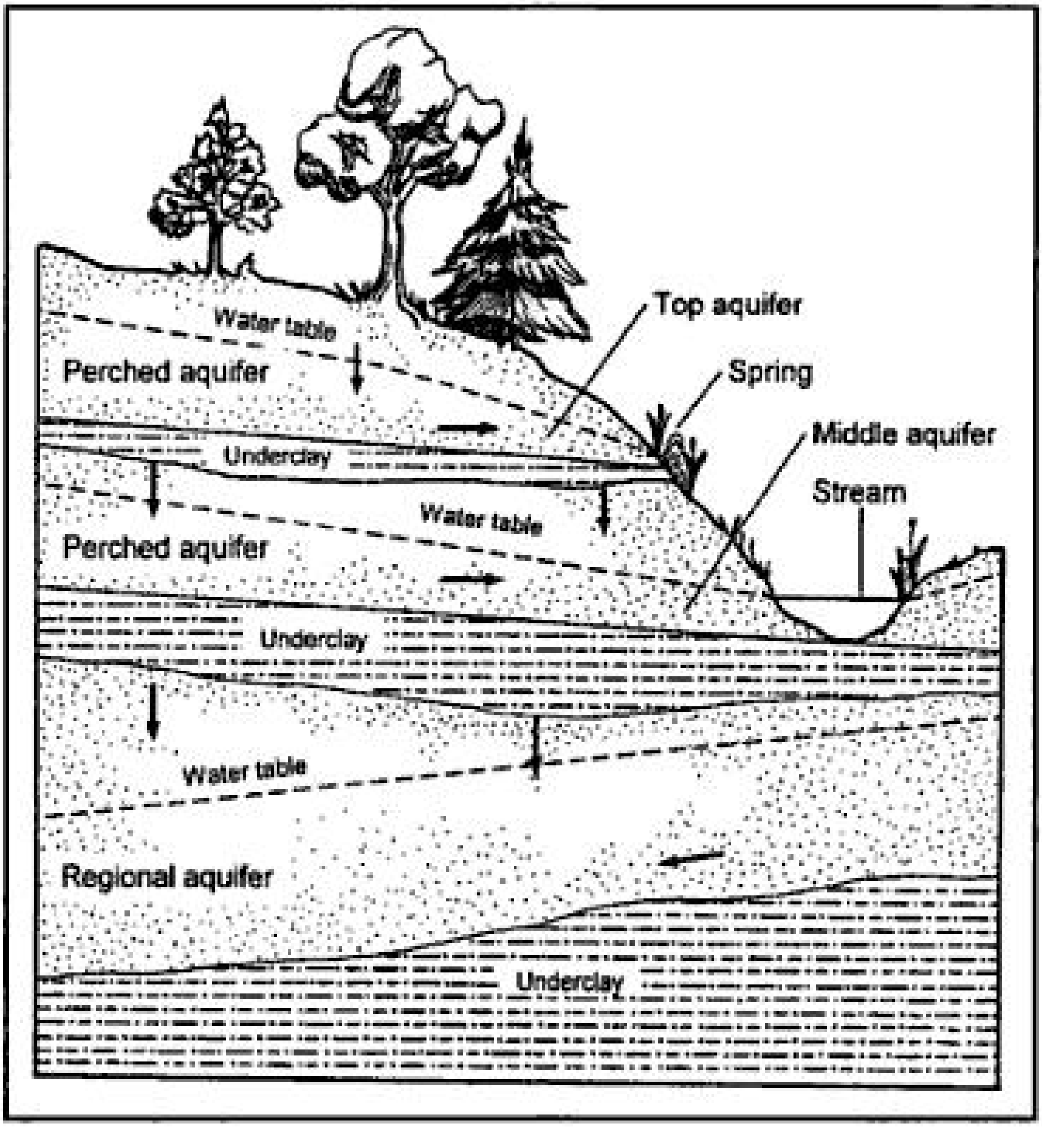


Figure 2.9. Perched aquifers above a regional aquifer system.

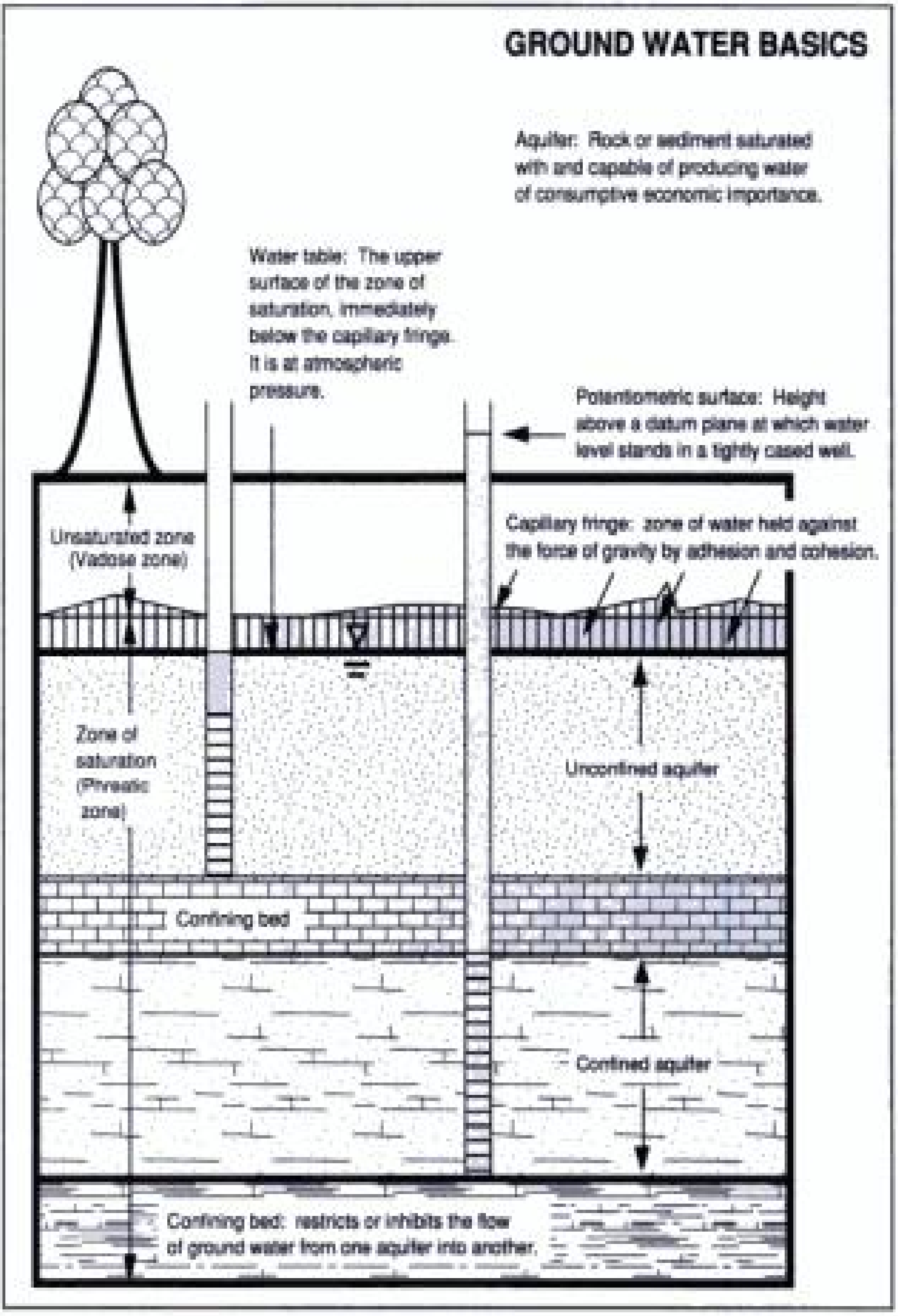


Figure 2.10. Ground-water basics (as defined by Heath, 1983).

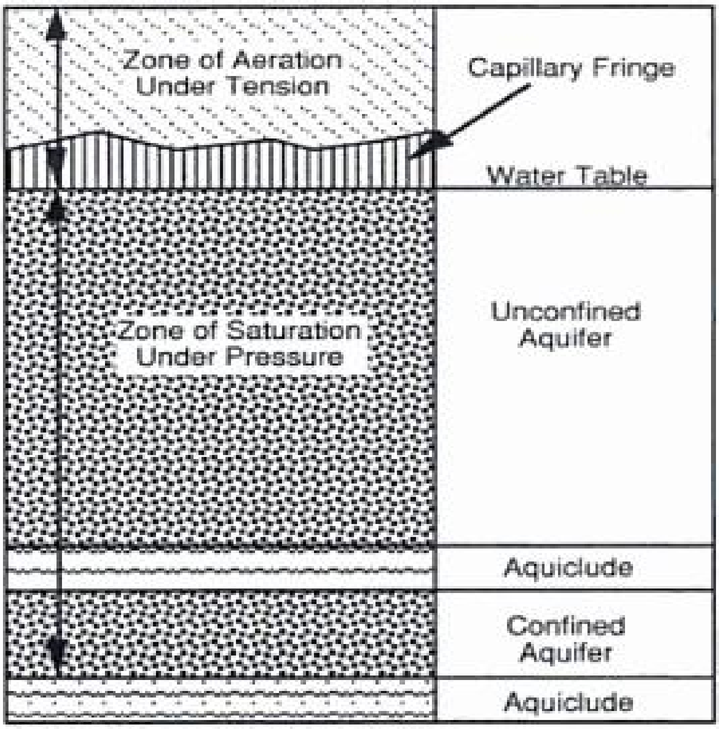
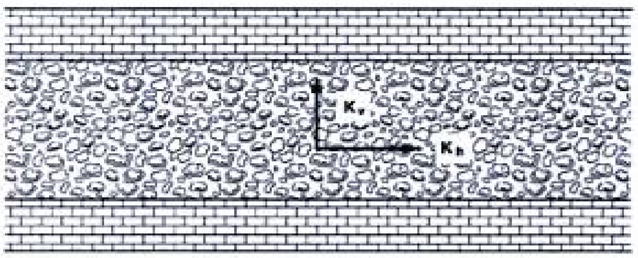
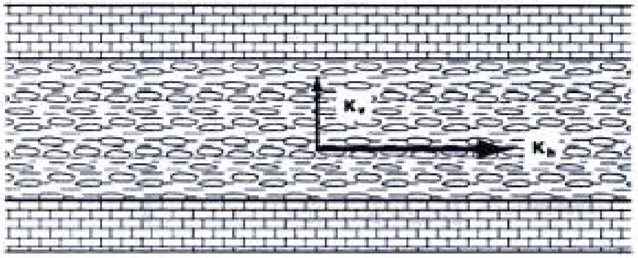


Figure 2.11. Ground-water zones according to Meinzer (1949).



Homogeneous, isotropic aquifer: rounded or sub-rounded sediment.



Homogeneous, anisotropic aquifer: sediment laid in the direction of their long axis.

Figure 2.12. Homogeneous aquifers.

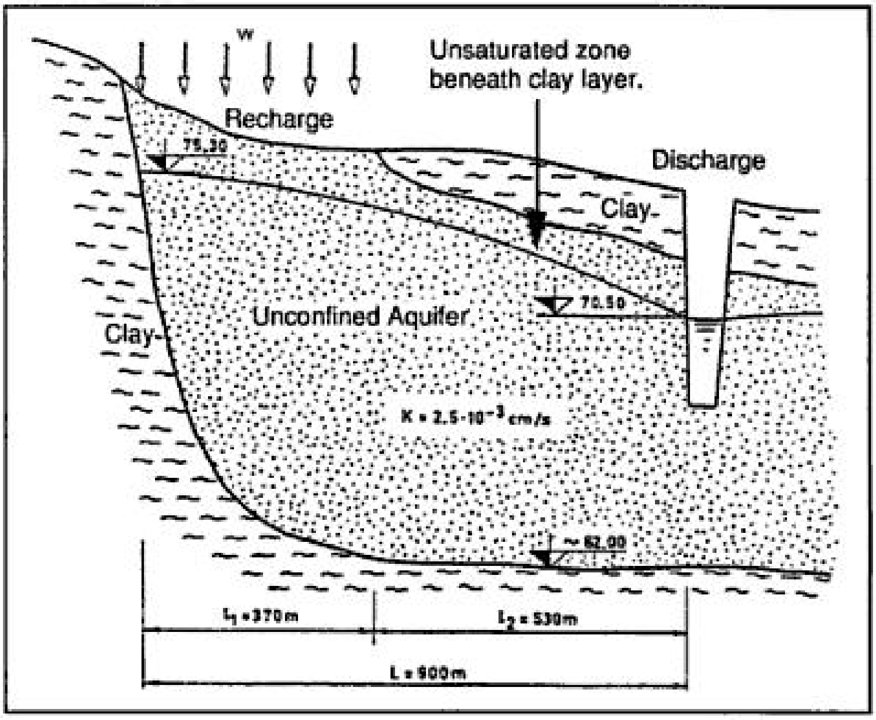


Figure 2.19. Unconfined aquifer with a thick clay layer above the local water table. Note the areas of recharge and discharge (modified from Vukovic and Soro, 1997).

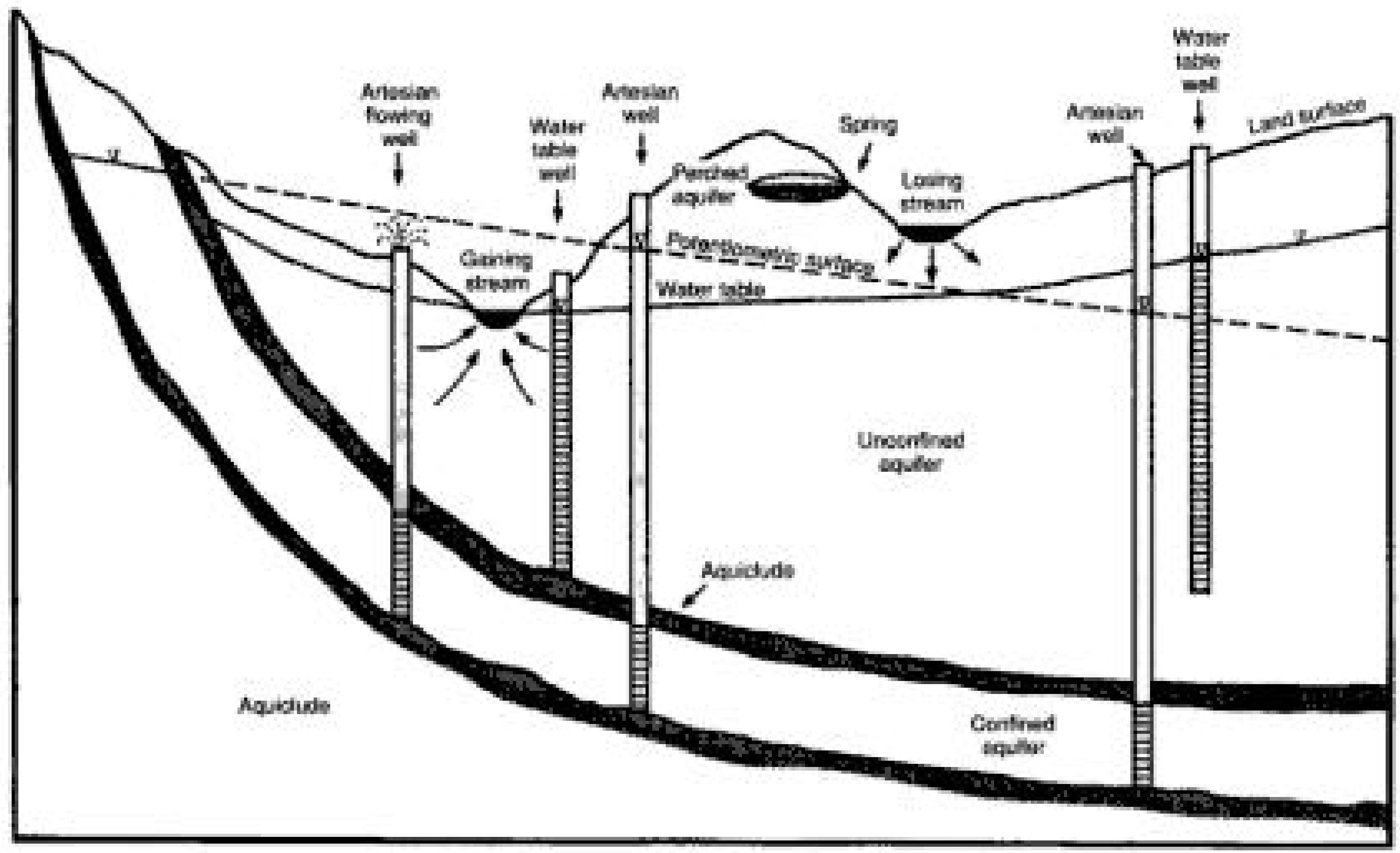


Figure 2.20. Relationship between the unconfined water table and the potentiometric surface (National Engineering Handbook 18, 1978, U.S. Soil Conservation Service).

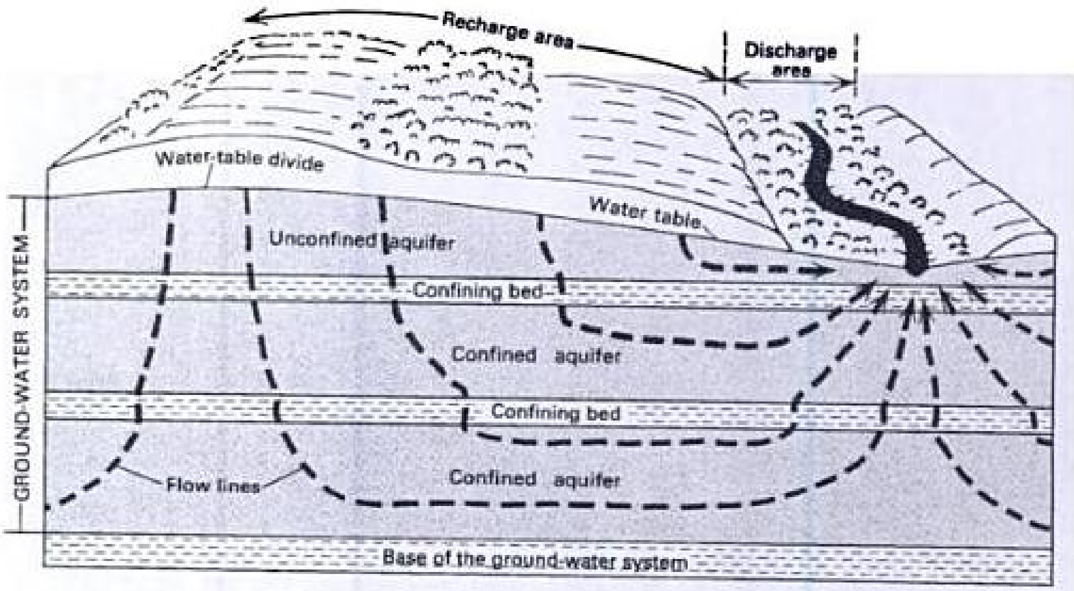


Figure 2.21. Multi-layered aquifer system (Heath, 1983).

1.6 Water Table and Piezometric Surface

1.6.1 Water table

Water table is the surface of water level in an unconfined aquifer at which the pressure is atmospheric. It is the level at which the water will stand in a well drilled in an unconfined aquifer. The water table fluctuates whenever there is a recharge or an outflow from the aquifer. In fact, the water table is constantly in motion adjusting its surface to achieve a balance between the recharge and the out flow. Generally, the water table follows the topographic features and is high below ridges and low below valleys. However, sometimes the topographic ridge and the water table ridge may not coincide and there may be flow from one aquifer to the other aquifer, called **watershed leakage.** Wherever the water table intersects the ground surface, a seepage surface or a spring is formed.

Perched water table when a small water body is separated from the main groundwater body by a relatively small impermeable stratum. Wells drilled below the perched water table up to the small impervious stratum yield very small quantity of water and soon go dry.

1.6.2 Piezometric surface

The water in a confined aquifer is under pressure. When a well is drilled in a confined aquifer, the water level in it will rise above the top of aquifer. The piezometric surface is an imaginary surface to which the water level would rise if a piezometer was inserted in the aquifer. Thus, it indicates the pressure of the water in the aquifer. Hence, a piezometric surface is the water table equivalent of the confined aquifer (see **Figure 1.5**).

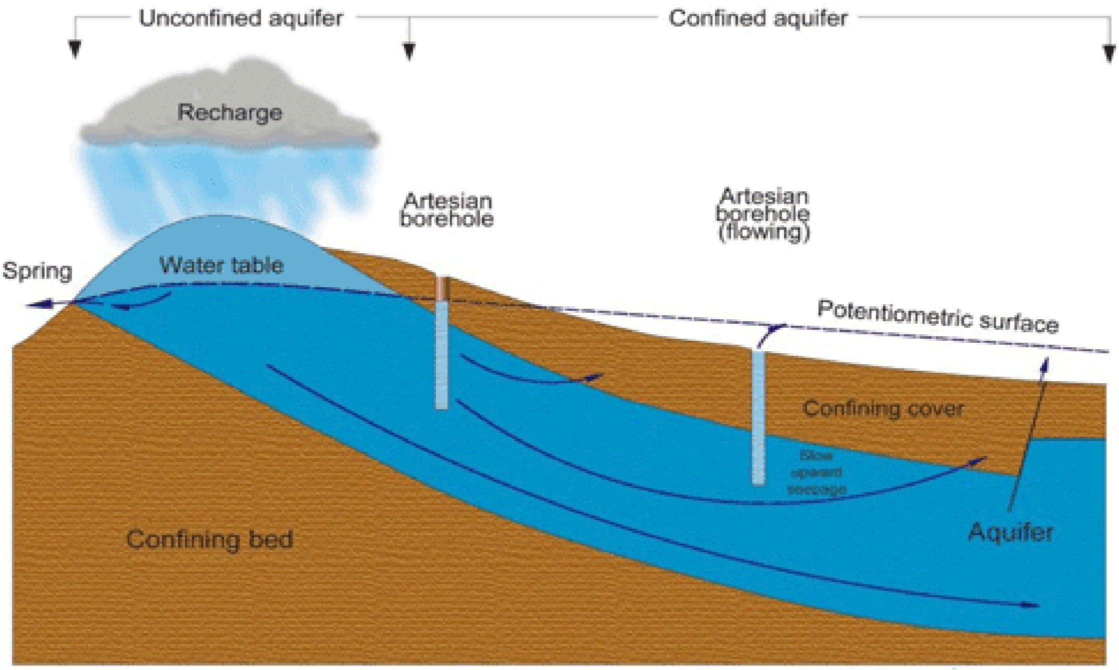


Figure 1.5 Water Table and Piezometric Surface

1.7 Aquifer Properties

The following properties of the aquifer are required for study of groundwater hydrology:

1. Porosity
2. Specific Yield
3. Specific Retention
4. Coefficient of permeability
5. Transmissibility
6. Specific Storage
7. Storage Coefficient

1.7.1 Porosity

Definition of Porosity

Porosity (n) is the percentage of rock or soil that is void of material. The larger the pore space or the greater their number, the higher the porosity and the larger the water-holding capacity. It is defined mathematically by the equation:

$$n = \frac{V_v}{V} \times 100\% \quad \textbf{(1.4)}$$

Where,

n is the porosity (percentage)

V_v is the volume of void space in a unit volume of earth materials (L^3, cm^3 or m^3)

V is the unit volume of earth material, including both voids and solids (L^3, cm^3 or m^3)

In sediments or sedimentary rocks the porosity depends on **grain size**, the **shape of the grains**, the **degree of sorting** and the **degree of cementation.** In rocks, the porosity depends upon the **extent, spacing** and **pattern of cracks** and **fractures.**

- The porosity of well-rounded sediments, which have been sorted so that they are all about the same size, is independent of particle size, depending upon the packing.
- Well-rounded coarse-grained sediments usually have higher porosity than fine-grained sediments, because the grains don't fit together well (see **Figure 1.6**)

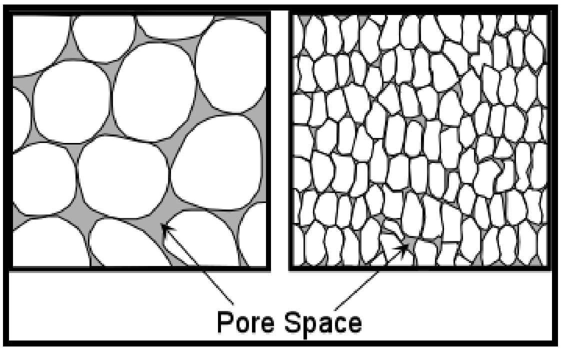


Figure 1.6 Porosity of Well-Rounded Coarse-Sediments vs. Fine Grained Sediments

- In igneous and metamorphic rocks porosity is usually low because the minerals tend to be intergrown, leaving little free space. Higher fractured igneous and metamorphic rocks, however, could have high secondary porosity.
- Since cements tend to fill in the pore space, highly cemented sedimentary rocks have lower porosity (see **Figure 1.7**).

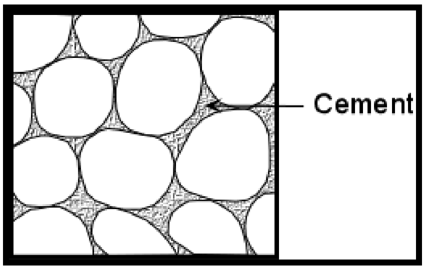


Figure 1.7 Highly Cemented Sedimentary Rock

- Poorly sorted sediments (sediments contains a mixture of grain sizes) usually have lower porosity because the fine-grained fragments tend to fill the open spaces (see **Figure 1.8**).
- The porosity of sediments is affected by the shape of the grains. Well-rounded grains may be almost perfect spheres, but many grains are very irregular. They can be shaped like rods, disks, or books. Sphere-shaped grains will pack more tightly and have less porosity than particles of other shapes. The fabric or orientation of the particles, if they are not spheres, also influences porosity (**Figure 1.8**).
- Porosity can range from zero to more than 60%. Recently deposited sediments have higher porosity. Dense crystalline rock or highly compacted soft rocks such as shale have lower porosity.

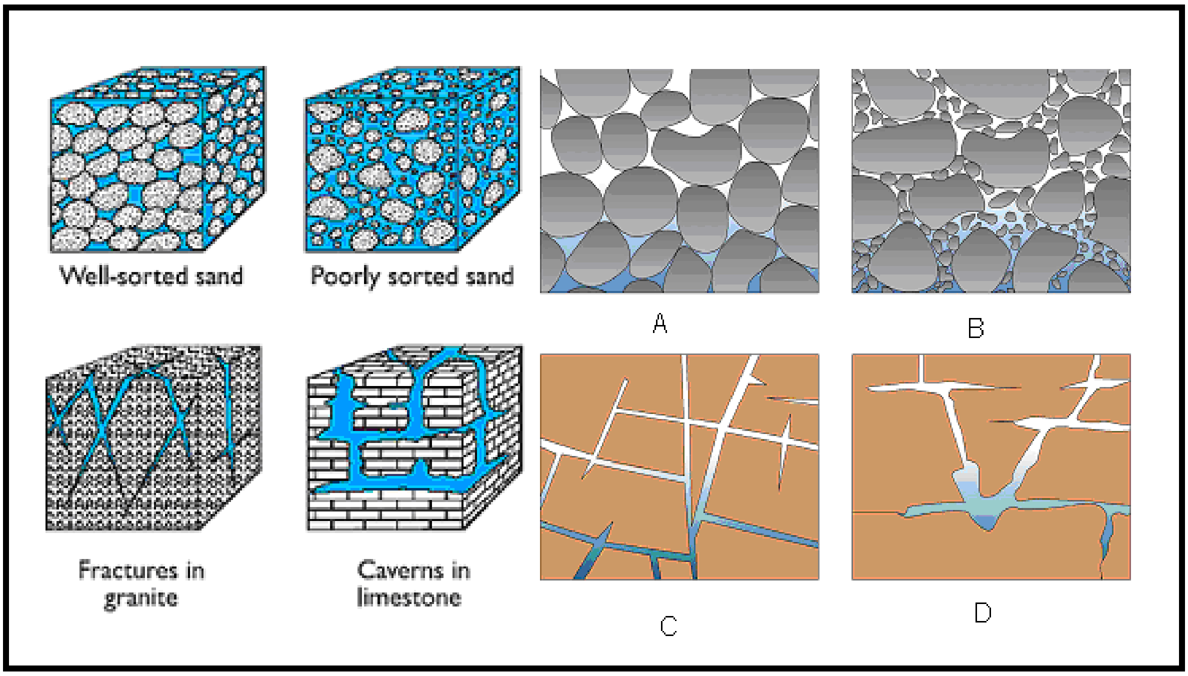


Figure 1.8 Relation Between Texture and Porosity **A.** Well –Sorted Sand Having High Porosity; **B.** Poorly- Sorted Sand Having Low Porosity; **C.** Fractured Crystalline Rocks (Granite); **D.** Soluble Rock-Forming Material (Limestone).

- In porous rock, there may be small pores known as dead end pores which have only one entrance, and so water molecules can diffuse in and out of them, but there can be no hydraulic gradient across them to cause bulk flow of groundwater. In extreme cases, there may be pores containing water that are completely closed so that the water in them is trapped. This may occur during digenetic transformations of the rock. Since we are frequently interested in the movement of groundwater, it is useful to define a porosity that refers only to the movable water in the rock.

This is called **the kinematic or effective porosity n_e [dimensionless**]

$$n_e = \frac{volume\ of\ rock\ occupied\ by\ movable\ water}{total\ volume\ of\ rock} \quad \textbf{(1.5)}$$

- It is worth distinguishing between **Intergranular** or **matrix** or **primary porosity** as the latter is the porosity provided by small spaces between adjacent grains of the rock, and **secondary porosity** of **fractured rocks** is the porosity provided by discrete rock mass discontinuities (faults, joints and fractures).

➢ **Table 1.2** lists representative porosity ranges from various geologic materials.

Table 1.2 Range of Values of Porosity (after Freeze & Cherry, 1979)

Formation	n (%)
Unconsolidated deposits	
Gravel	25 - 40
Sand	25 - 50
Silt	35 - 50
Clay	40 - 70
Rocks	
Fractured basalt	5 - 50
Karst limestone	5 - 50
Sandstone	5 - 30
Limestone, dolomite	0 - 20
Shale	0 – 10
Fractured crystalline rock	0 - 10
Dense crystalline rock	0 – 5

Classification of Sediments

Sediments are classified on the basis of the size (diameter) of the individual grains. There are many classification systems in use. The engineering classification of sediments is somewhat different that the geological classification. The American Society of Testing Materials defines sediments on the basis of the grain-size distribution shown in **Table 1.3.**

Table 1.3 Engineering grain-size classification (after Fetter, 1994)

Formation	Size Range (mm)	Example
Boulder	> 305	Basketball
Cobbles	76 – 305	Grapefruit
Coarse gravel	19 – 76	Lemon
Fine gravel	4.75 – 19	Pea
Coarse sand	2 – 4.75	Water softener salt
Medium sand	0.42 – 2	Table salt
Fine sand	0.075 – 0.42	Powdered sugar
Fines	< 0.075	Talcum powder

The grain-size distribution of a sediment may be conveniently plotted on semi-log paper. The cumulative percent finer by weight is plotted on the arithmetic scale and the grain size is plotted on the logarithmic scale. The grain size of the sand fraction is determined by shaking the sand through a series of sieves with decreasing mesh openings. The 200 mesh screen, with an opening of 0.075 mm, separates the sand fraction from the fines (see **Figure 1.9**).

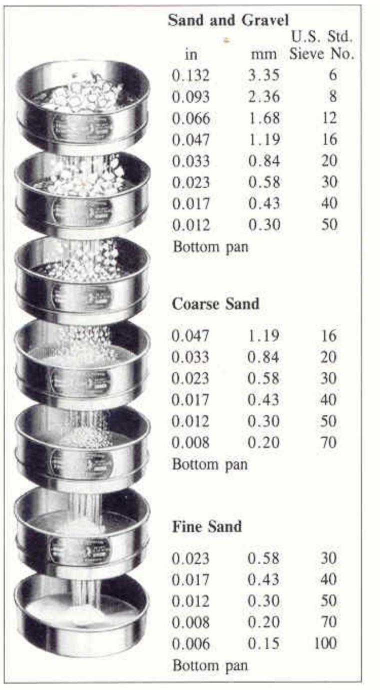


Figure 1.9 Recommended sieve groups suitable for sieving various classes of unconsolidated sediments.

The gradation of the fines is determined by a hydrometer test, which is based on the rate that the sediment settles in water. **Figure 1.10** is a grain size distribution curve for a silty fine to coarse sand. This sample is somewhat poorly sorted as there is a wide range of grain sizes present. **Figure 1.11** is the grain-size distribution curve for well-sorted fine sand. Less than 5% of the sample consisted of fines that pass the 200 mesh sieve.

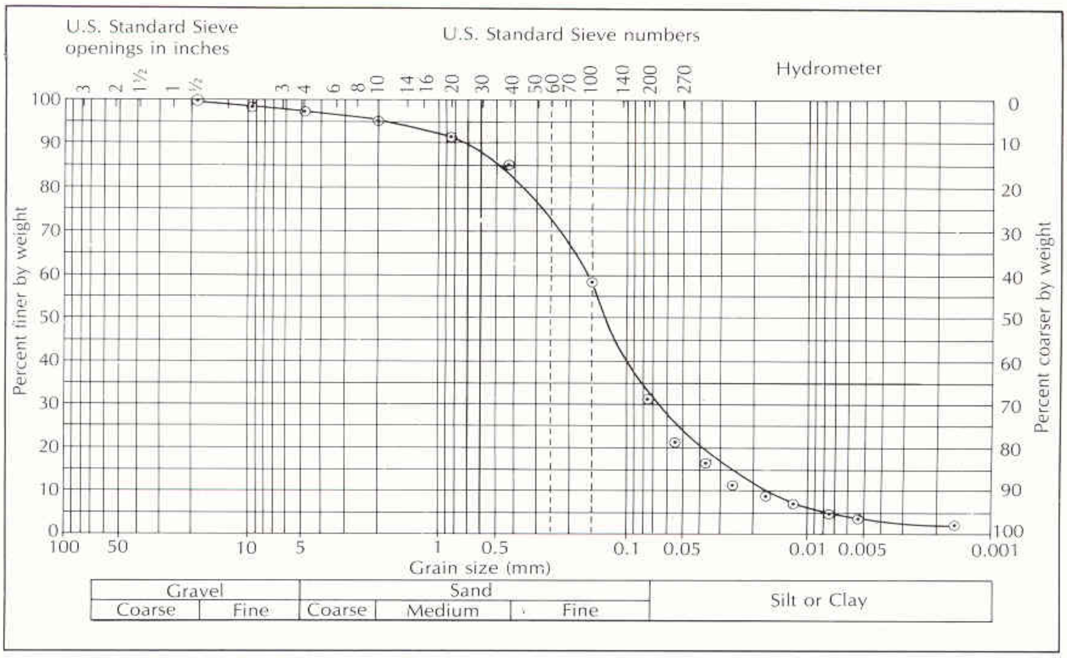


Figure 1.10 Grain-size distribution curve of a silty fine to medium sand

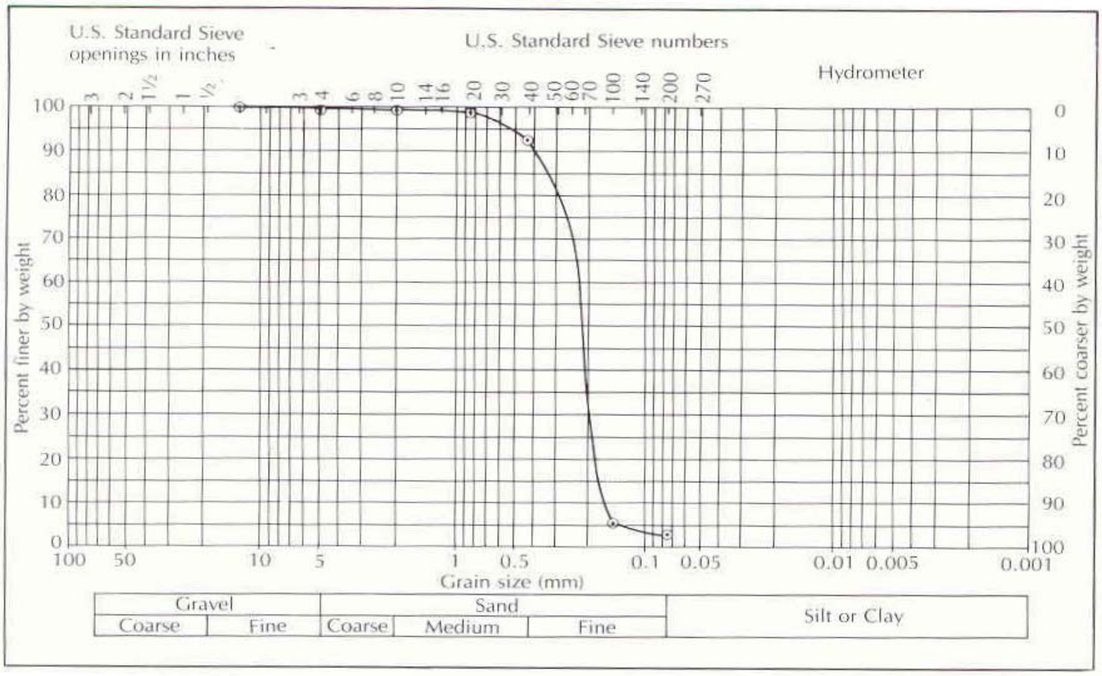


Figure 1.11 Grain-size distribution curve of a fine sand

The **uniformity coefficient** of a sediment is a measure of how well or poorly sorted it is. The uniformity coefficient, U_c, is the ratio of the grain size that is 60% finer by weight, D_{60}, to the grain size that is 10% finer by weight, D_{10}.

$$U_c = \frac{D_{60}}{D_{10}} \qquad \textbf{(1.6)}$$

where,

D_{60} grain size in which 60 percent of sample is passed
D_{10} grain size in which 10 percent of sample is passed (effective diameter)

A sample with an U_c less than 4 is well sorted; if the U_c is more than 6 it is poorly sorted. The poorly sorted silty sand in **Figure 1.10** has a U_c of 8.3, whereas the well-sorted sand of **Figure 1.11** has a U_c of 1.4.

1.7.2 Specific Yield (S_y)

Specific yield (S_y) is the ratio of the volume of water that drains from a saturated rock owing to the attraction of gravity (or by pumping from wells) to the total volume of the saturated aquifer. It is defined mathematically by the equation:

$$S_y = \frac{V_w}{V} \times 100\% \qquad \textbf{(1.7)}$$

where,

V_w is the volume of water in a unit volume of earth materials (L^3, cm^3 or m^3)
V is the unit volume of earth material, including both voids and solids (L^3, cm^3 or m^3

All the water stored in a water bearing stratum cannot be drained out by gravity or by pumping, because a portion of the water is rigidly held in the voids of the aquifer by molecular and surface tension forces (see **Table 1.4**).

Table 1.4 Specific Yield in Percent (after Freeze & Cherry, 1979)

Formation	S_y (range)	S_y (average)
Clay	0 - 5	2
Sandy clay	3 - 12	7
Silt	3 - 19	18
Fine sand	10 - 28	21
Medium sand	15 - 32	26
Coarse sand	20 - 35	27
Gravelly sand	20 - 35	25
Fine gravel	21 - 35	25
Medium gravel	13 - 26	23
Coarse gravel	12 - 26	22
Limestone		14

1.7.3 Specific Retention (S_r)

Specific retention (S_r) is the ratio of the volume of water that cannot be drained out to the total volume of the saturated aquifer. Since the specific yield represents the volume of water that a rock will yield by gravity drainage, hence the specific retention is the remainder. The sum of the two equals porosity.

$$n = S_r + S_y \qquad \textbf{(1.8)}$$

- The specific yield and specific retention depend upon the shape and size of particle, distribution of pores (voids), and compaction of the formation.
- The specific retention increases with decreasing grain size.
- It should be noted that it is not necessary that soil with high porosity will have high specific yield because that soil may have low permeability and the water may not easily drain out. For example, clay has a high porosity but low specific yield and its permeability is low.
- **Figure 1.12** illustrates the concept of specific yield.

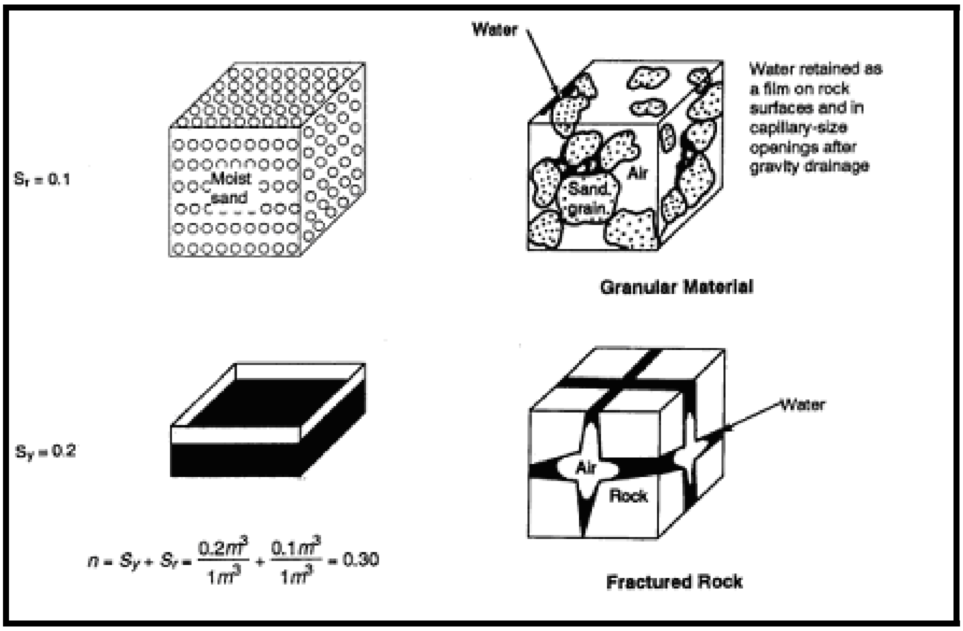


Figure 1.12 Specific Retention

1.7.4 Coefficient of Permeability (Hydraulic conductivity) (K)

Permeability is the ease with which water can flow in a soil mass or a rock. The **coefficient of permeability (K)** is equal to the discharge (m^3/s) per unit area (m^2) of soil mass under unit hydraulic gradient. Because the discharge per unit area equals to the velocity, the coefficient of permeability has the dimension of the velocity [L/T]. It is usually expressed as cm/s, m/s, m/day, etc. The coefficient of permeability is also called **hydraulic conductivity** (see **Figure 1.13**).

Hydraulic Conductivity can be determined and expressed as follows:

Formulas

1 [Hazen method]. The coefficient of permeability (K) depends on the properties of both porous medium and fluid. It can be expressed as,

$$K = \frac{[Cd_m^2]\rho g}{\mu} \tag{1.9}$$

where,

- C is the shape factor which depends upon the shape, particle size and packing of the porous media
- d_m is the mean particle size (d_{50}) (L, m)
- ρ is the mass density (M/L^3, kg/m^3)
- g is the acceleration due to gravity (L/T^2, m/s^2)
- μ is the viscosity (M/T.L, kg/s.m)

- ➢ Another coefficient of permeability, called **intrinsic permeability (k)**, is sometimes used. The intrinsic permeability depends upon the porous medium and is independent of the properties of the fluid. It is usually expressed as,

$$k = Cd_m^2 \tag{1.10}$$

- ➢ The intrinsic permeability k has the dimensions of [L^2] and is usually expressed in cm^2 or **Darcy,** where 1 Darcy = 0.987 * 10^{-8} cm^2.

- ➢ The intrinsic permeability is rarely used in groundwater hydrology, but this term is very popular in the petroleum, natural gas industries, and in density-dependent flow problems such as saline water intrusion.

- ➢ The intrinsic permeability is also called the absolute permeability.

- ➢ The rate of groundwater flow is controlled by the two properties of the rock, porosity and permeability.

- ➢ Low porosity usually results in low permeability, but high porosity does not necessarily imply high permeability. It is possible to have a highly porous rock with little or no interconnections between pores. A good example of a rock with high porosity and low permeability is a vesicular volcanic rock, where the bubbles that once contained gas give the rock a high porosity, but since these holes are not connected to one another, the rock has low permeability.

- ➢ Typical values of hydraulic conductivity for unconsolidated and hard rocks are given in **Table 1.5** which are taken from Marsily [1986].

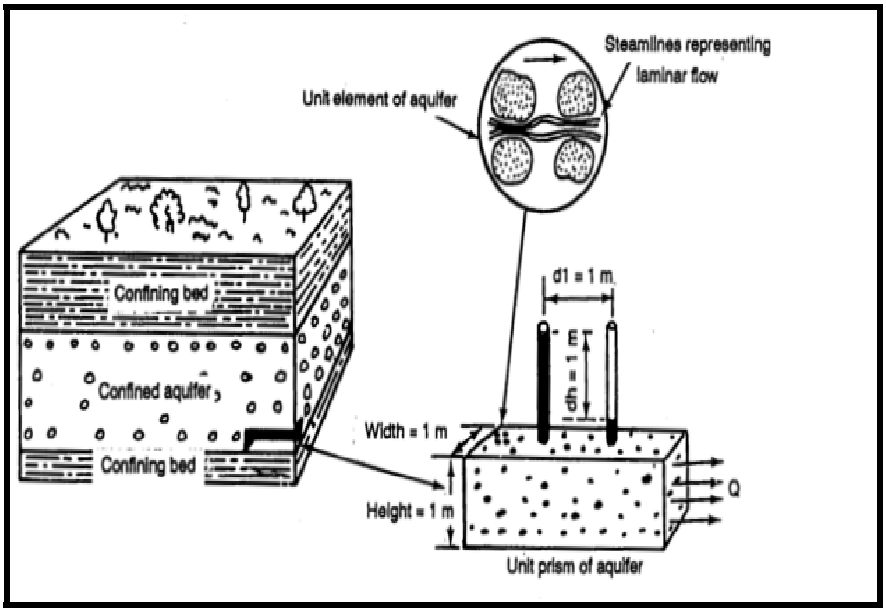


Figure 1.13 Hydraulic Conductivity

Tables 1.5 Hydraulic Conductivity for Unconsolidated and Hard Rocks

Medium	K (m/day)
Unconsolidated deposits	
Clay	$10^{-8} - 10^{-2}$
Fine sand	1 - 5
Medium sand	5 - 20
Coarse sand	$20 - 10^{2}$
Gravel	$10^{2} - 10^{3}$
Sand and gravel mixes	$5 - 10^{2}$
Clay, sand, gravel mixes (e.g. till)	$10^{-3} - 10^{-1}$
Hard Rocks	
Chalk (very variable according to fissures if not soft)	30.0
Sandstone	3.1
Limestone	0.94
Dolomite	0.001
Granite, weathered	1.4
Schist	0.2

2 [Kozeny-Carmen]

$$K = \frac{\rho g}{\mu} \cdot \left(\frac{n^3}{(1-n)^2} \right) \cdot \left(\frac{d_m^2}{180} \right) \qquad \textbf{(1.11)}$$

where, n is porosity,
d_m is representative of grain size (L, m).

3 [Shepherd] – Empirically derived

$$K = c\, d^{1.65\,to\,1.85} \qquad \textbf{(1.12)}$$

where c and d exponent values vary with material description

1.7.5 Transmissivity (T)

Transmissivity (T) is the discharge rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Thus,

$$T = Kb \quad [confined\ aquifer]$$
$$T = Kh \quad [unconfined\ aquifer] \qquad \textbf{(1.13)}$$

where, b is the saturated thickness of the aquifer. b is equal to the depth of a confined aquifer. It is equal to the **average** thickness of the saturated zone of an unconfined aquifer.

- Transmissibility is usually expressed as m^2/s, or m^3/day/m or l/day/m.
- Transmissibility of most formations lies between $1*10^4$ -$1*10^6$ l/d/m, with an average value of $1*10^5$ l/d/m.
- **Figure 1.19** illustrates the concepts of hydraulic conductivity and transmissivity.

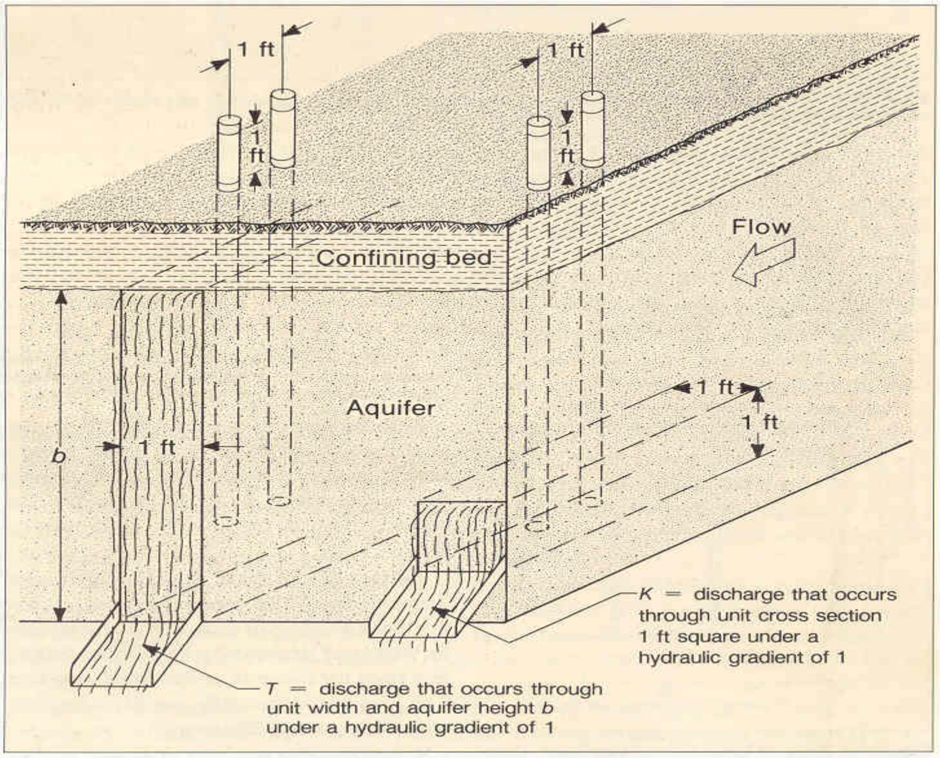


Figure 1.19 Illustration of the Coefficients of hydraulic conductivity and transmissivity. Hydraulic conductivity multiplied by the aquifer thickness equals coefficient of transmissivity.

Table 1.8 Classification of Transmissivity

Magnitude (m^2/day)	Class	Designation	Specific Capacity (m^2/day)	Groundwater supply potential	Expected Q (m^3/day) if s=5m
> 1000	I	Very high	> 864	Regional Importance	> 4320
100-1000	II	High	86.4 – 864	Lesser regional importance	432 – 4320
10-100	III	Intermediate	8.64 – 86.4	Local water	43.2 – 432

				supply	
1-10	IV	Low	0.864 – 8.64	Private consumption	4.32 – 43.2
0.1-1	V	Very low	0.0864 – 0.864	Limited consumption	0.423 – 4.32
<0.1	VI	Imperceptible	< 0.0864	Very difficult to utilize for local water supply	< 0.432

1.7.6 Specific Storage (S_s)

Specific Storage (S_s) is the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in head. This is also called the *elastic storage coefficient.* The concept can be applied to both aquifers and confining units.

The specific storage is given by the expression (Jacob 1940, 1950; cooper 1966):

$$S_s = \rho_w g(\alpha + n\beta) \tag{1.14}$$

where ρ_w is the density of the water (M/L^3; Kg/m^3)
g is the acceleration of gravity (L/T^2; m/s^2)
α is the compressibility of the aquifer skeleton ($1/(M/LT^2)$; m^2/N)
n is the porosity
β is the compressibility of water ($1/(M/LT^2)$; m^2/N)

The specific storage is usually expressed as cm^{-1} or m^{-1}. For most aquifers, the specific storage is about $3*10^{-7}$ m^{-1} (see **Table 1.9**).

Table 1.9 Values of Specific Storage Assuming Porosity Equal to 15 % (after Younger, 1993)

Typical Lithologies	Specific Storage (m^{-1})
Clay	9.81×10^{-3}
Silt, fine sand	9.82×10^{-4}
Medium sand, fine	9.87×10^{-5}
Coarse sand, medium gravel, highly fissured	1.05×10^{-5}
Coarse gravel, moderately fissured rock	1.63×10^{-6}
Unfissured rock	7.46×10^{-7}

SOURCE: (Younger, 1993)

In a confined aquifer, the head may decline-yet the potentiometric surface remains above the unit. Although water is released from storage, the aquifer remains saturated. Specific storage (*S_s*) of a confined aquifer is the storage coefficient per unit-saturated thickness of the aquifer. Thus,

$$S_s = \frac{S}{b} \quad \textbf{(1.15)}$$

where, **b** is the thickness of aquifer.

1.7.7 Storage Coefficient (S)

Storage coefficient (S) is the volume of water released from storage, or taken into storage, per unit of aquifer storage area per unit change in head.

- The storage coefficient is also called **Storativity**.
- The storage coefficient is a **dimensionless** as it is the ratio of the volume of water released from original unit volume.
- The water-yielding capacity of an aquifer can be expressed in terms of its storage coefficient.
- In unconfined aquifers, Storativity is the same as the specific yield of the aquifer.
- In confined aquifer, Storativity is the result of compression of the aquifer and expansion of the confined water when the head (pressure) is reduced during pumping.

For a vertical column of unit area extending through a confined aquifer, as in **Figure 1.20a**, the storage coefficient equals the volume of water released from the aquifer when the piezometric surface declines a unit distance. In most **confined aquifers**, values fall in the range **$0.00005 < S < 0.005$**, indicating that large pressure changes over extensive areas are required to produce substantial water yields. Storage coefficients can best be determined from pumping tests of wells or from groundwater fluctuation in response to atmospheric pressure or ocean tide variation.

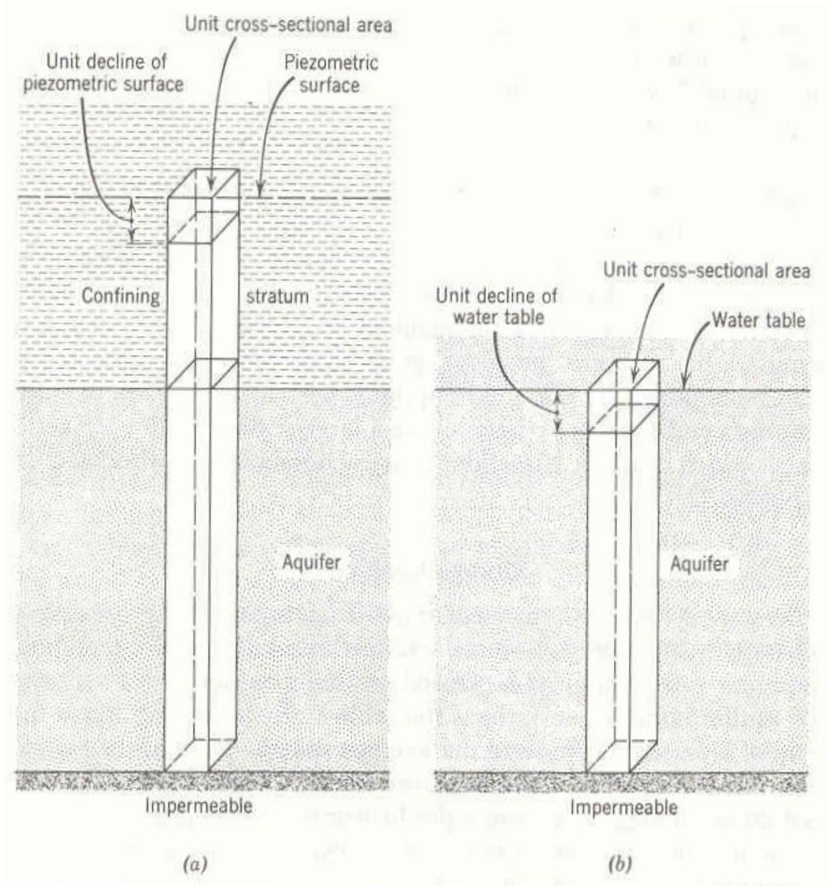


Figure 1.20 Illustrative sketches for defining storage coefficient of (a) confined and (b) unconfined aquifers

Storage coefficient normally varies directly with aquifer thickness

$$S = S_s \,.\, b \quad but \quad S_s = \rho g[\alpha + n\beta]$$
$$\Rightarrow \quad S = \rho g b[\alpha + n\beta] \qquad \textbf{(1.16)}$$

where *b* is the saturated aquifer thickness in meters to be applied for estimating purposes.

The storage coefficient for **unconfined aquifer** corresponds to its **specific yield**, as shown in **Figure 1.20b.**

In an unconfined unit, the level of saturation rises or falls with changes in the amount of water in storage. As the water level falls, water drains from the pore spaces. This storage or release is due to the specific yield (S_y) of the unit. Water is also stored or expelled depending on the specific storage of the unit. For an unconfined unit, the storativity is found by the formula

$$S = S_y + hS_s \qquad \textbf{(1.17)}$$

where h is the thickness of the saturated zone.

The value of S_y is several orders of magnitude greater than hS_s for an unconfined aquifer, and the storativity is usually taken to be equal to the specific yield. For a fine-grained unit, the specific yield may be very small, approaching the same order of magnitude as hS_s . Storativity of unconfined aquifers ranges from **0.02 to 0.30**.

The volume of the water drained from an aquifer as the head is lowered may be found from the formula

$$V_w = S.A.\Delta h \qquad \textbf{(1.18)}$$

where V_w is the volume of the water drained (L^3; m^3)
S is the storativity (dimensionless)
A is the surface area overlying the drained aquifer (L^2; m^2)
Δh is the average decline in head (L; m)

The **transmissivity** and **storage coefficients** are especially important because they define the hydraulic characteristics of a water-bearing formation. The coefficient of transmissivity indicates how much water will move through the formation, and the coefficient of storage indicates how much can be removed by pumping or draining. If these two coefficients can be determined for a particular aquifer, predictions of great significance can usually be made. Some of these are:

1 Drawdown in the aquifer at various distances from a pumped well.
2 Drawdown in a well at any time after pumping starts.
3 How multiple wells in a small area will affect one another?
4 Efficiency of the intake portion of the well.
5 Drawdown in the aquifer at various pumping rates.

1.8 Springs

A spring is a concentrated discharge of groundwater appearing at the ground surface as a current of flowing water. To be distinguished from springs are *seepage areas*, which indicate a slower movement pond and evaporate or flow, depending on the magnitude of the seepage, the climate, and the topography.

Springs occur in many forms and have been classified as to cause, rock structure, discharge, temperature, and variability. Springs can be divided into (1) those resulting from mongravitational forces, and (2) those resulting from gravitational forces. Under the former category are included volcanic springs, associated with volcanic rocks, and fissure springs, resulting from fractures extending to great depths in the earth's crust.

Gravity springs result from water flowing under hydrostatic pressure; the following general types are recognized, (see **Figure 1.21**)

1. **Depression Springs** – formed where the ground surface intersects the water table.

2. **Contact Springs** – created by permeable water-bearing formation overlying a less permeable formation that intersects the ground surface.

3. **Artesian Springs** – resulting from releases of water under pressure from confined aquifers either at an outcrop of the aquifer or through an opening in the confining bed.

4. **Impervious Rock Springs** – occurring in tubular channels or fractures of impervious rock.

5. **Tubular or fracture Springs** – issuing from rounded channels, such as lava tubes or solution channels, or fractures in impermeable rock connecting with groundwater.

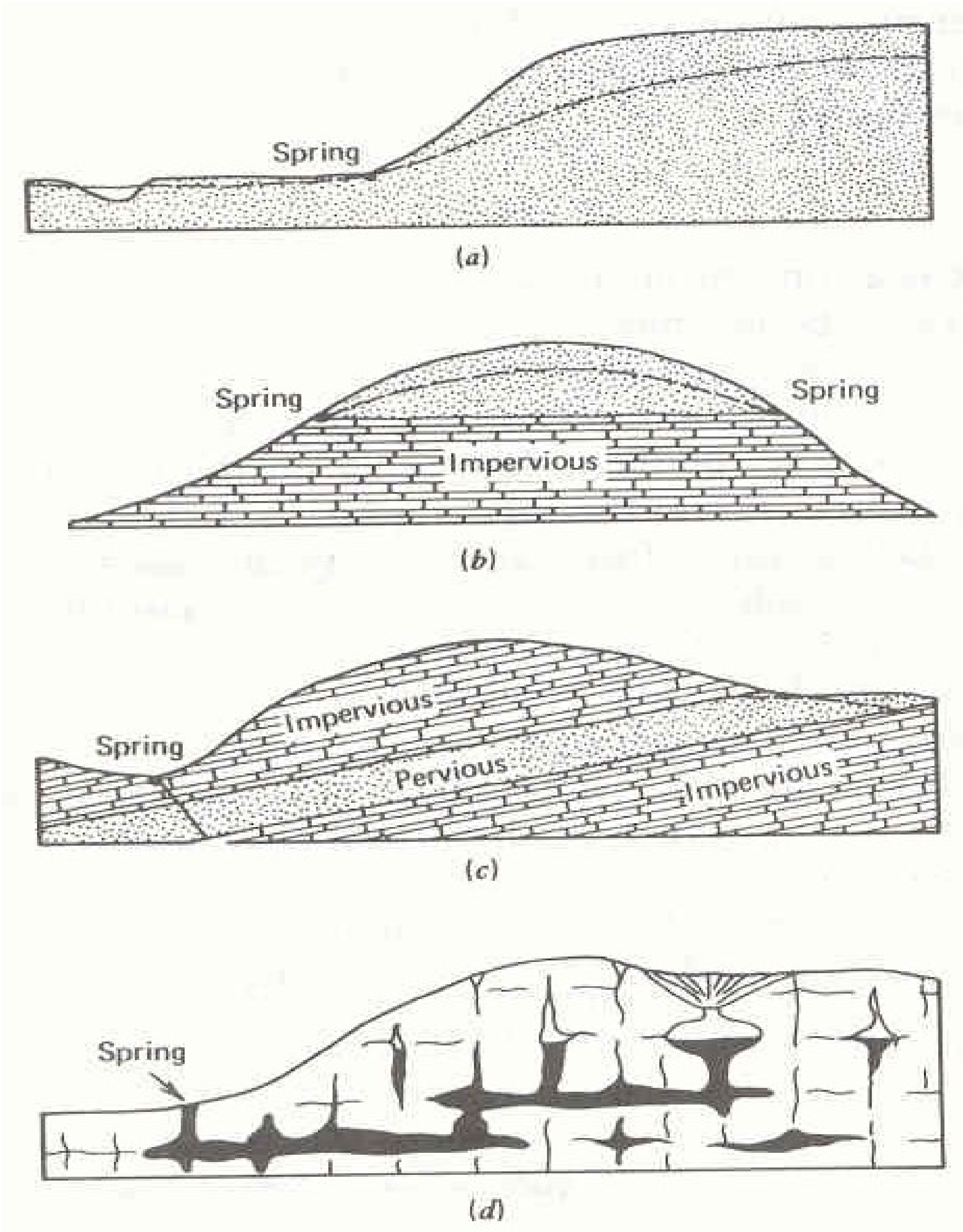


Figure 1.21 Diagrams illustrating types of gravity springs. (a) Depression spring. (b) Contact springs. (c) Fracture artesian spring. (d) Solution tubular spring (after Bryan, 1919).

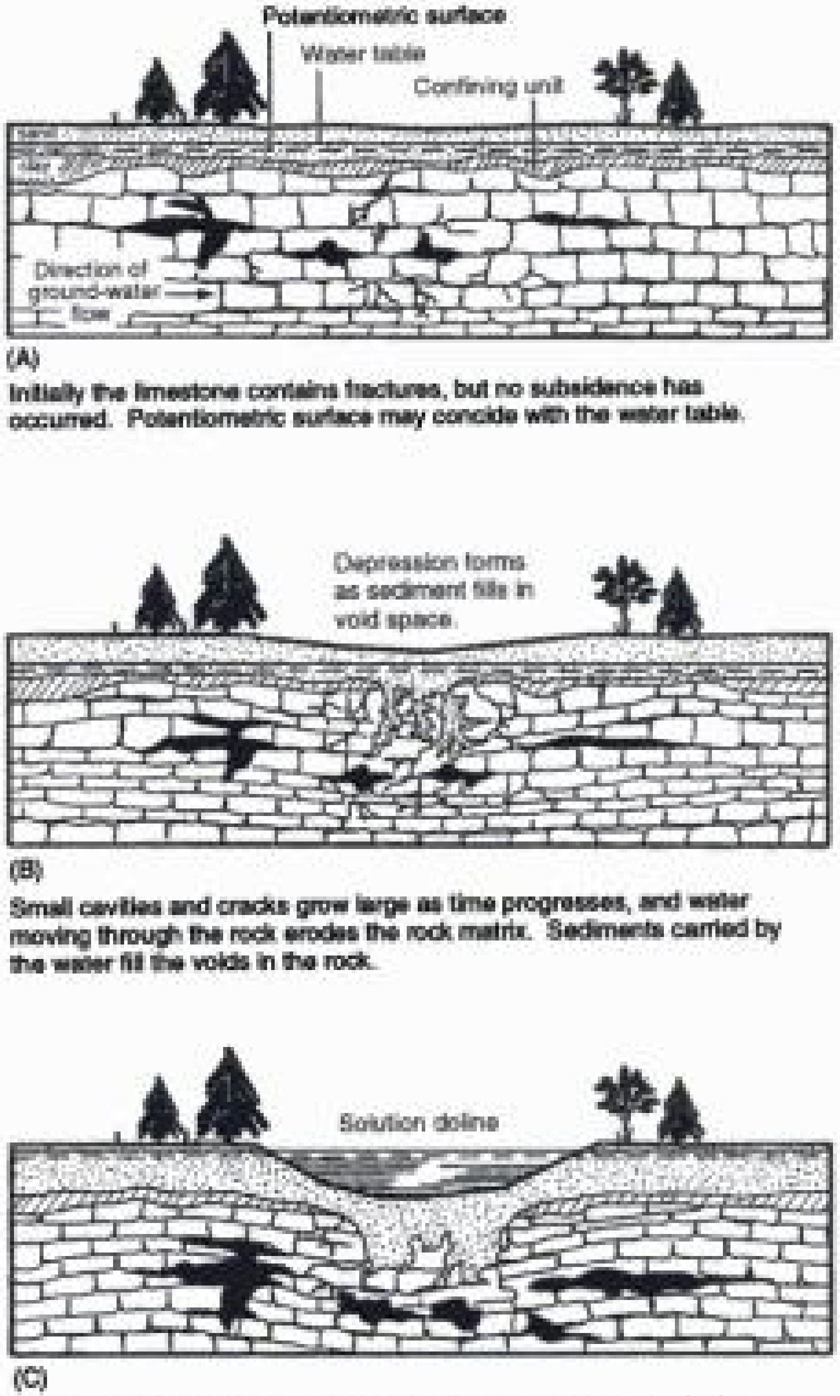
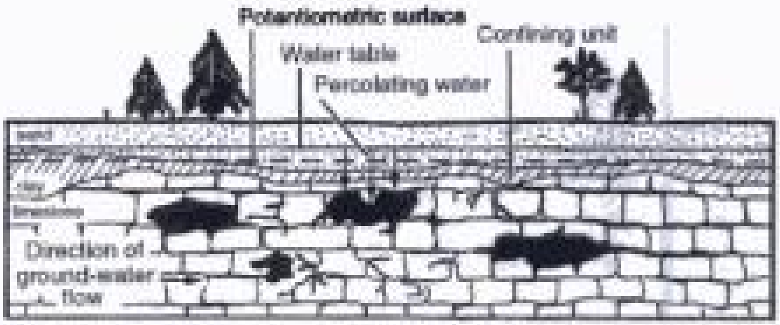
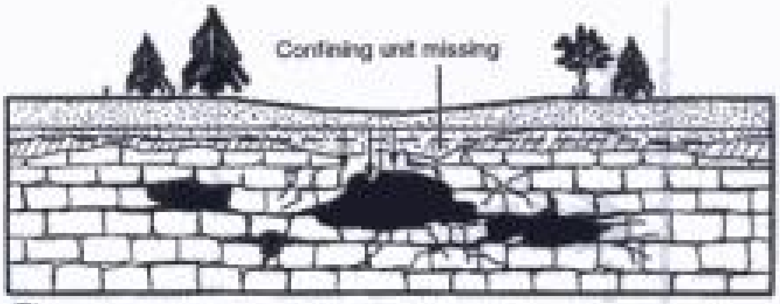


Figure 2.23. **Slow development of a solution doline (sinkhole) (source: USGS Circular 1137).**



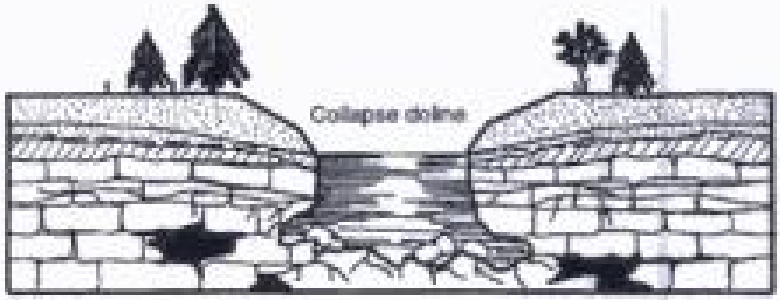
(A)

No evidence of land subsidence, small to medium sized cavities in the rock matrix. Water from subsurface percolates through the rock, and the erosion process begins.



(B)

Cavities in the limestone continue to grow larger. Note missing confining layer that allows more water to flow through to the rock matrix. Roof of the cavern is thinner, weaker.



(C)

As ground-water levels drop during the dry season, the weight of the overburden exceeds the strength of the cavern roof, and the overburden collapses into the cavern, forming a sinkhole.

Figure 2.24. Rapid development of a collapse doline (sinkhole) (source: USGS Circular 1137).

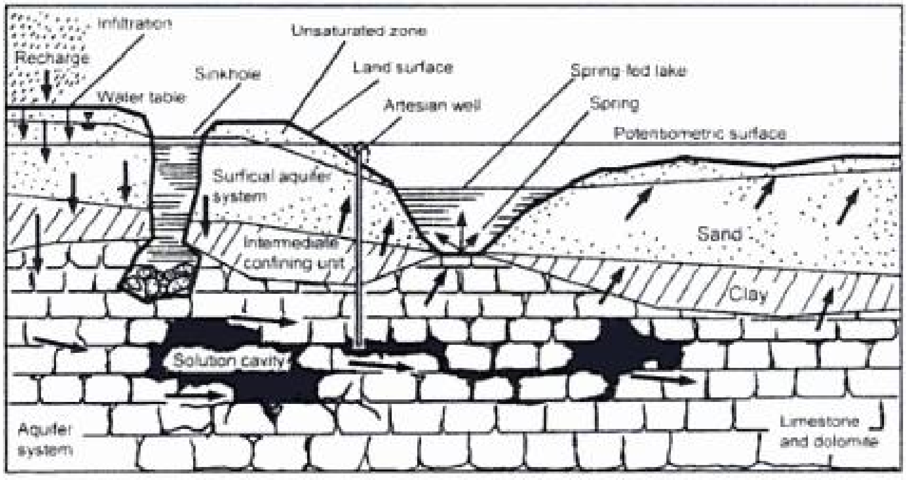
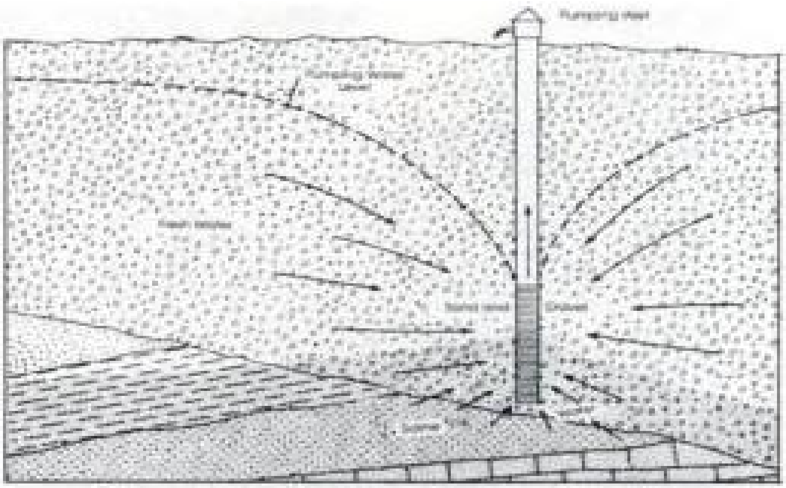
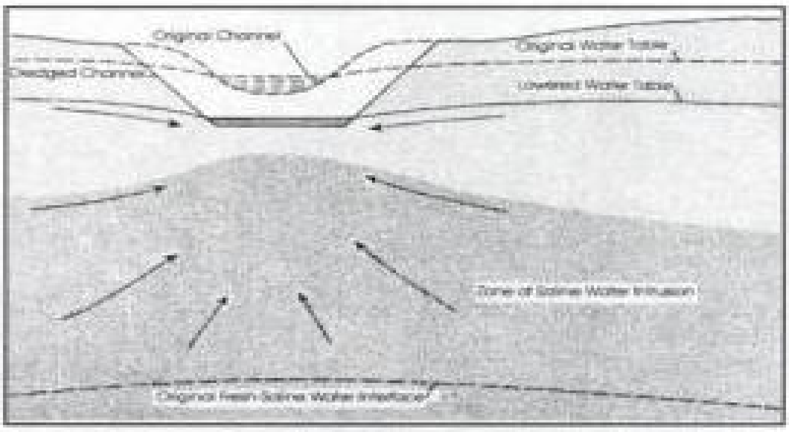


Figure 2.25. Karst ground-water flow system (source: USGS Circular 1137).



Saltwater rising into an aquifer due to pumping.



Migration of saline water caused by lowering of water levels in a gaining stream.

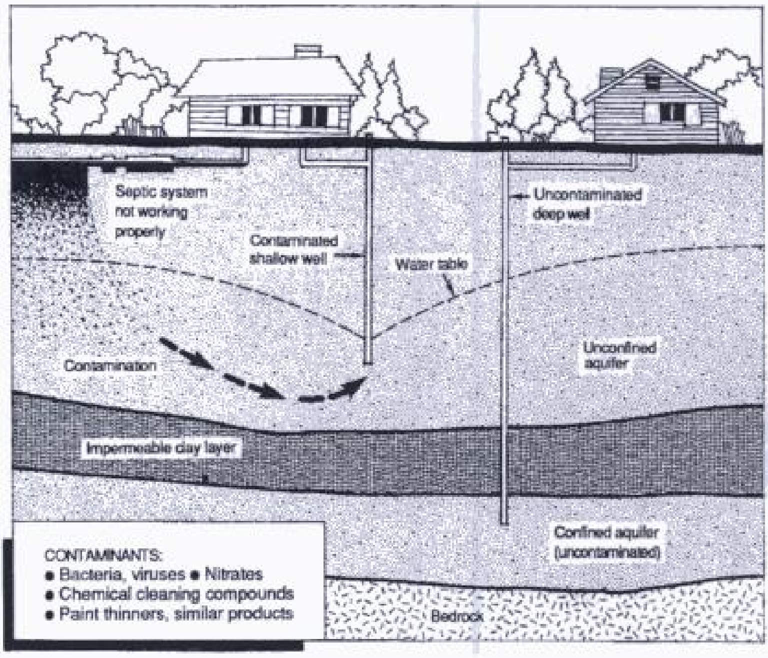
Figure 2.27. Freshwater aquifers contaminated by saline water from underlying rocks (Deutsch, 1963).

SEPTIC SYSTEMS

CONTAMINATION EVIDENCE:
- Wastewater shows above ground
- Detection of excessive bacteria, chemicals in well water tests

CAUSES:
- Poor installation and/or maintenance
- Disposal of household chemicals, such as paint thinners, into the system
- Overloading the system with a garbage disposal unit
- Use of septic tank cleaning additives
- Too many closely-spaced septic systems in a limited area

PREVENTION:
- Proper installation
- Inspection and cleaning every 2-4 years, annually if garbage disposal unit is used
- Do not dispose of household chemicals into the system
- Ban hazardous cleaning additives for septic systems
- Develop local septic system codes
- Public sewers when feasible
- Public information/education



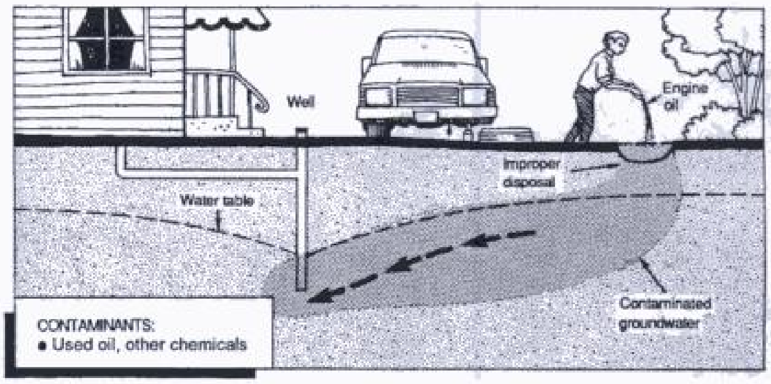
SMALL DISPOSAL PITS

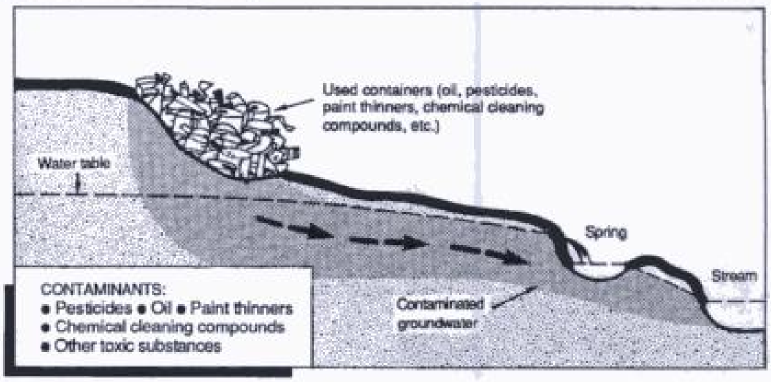
Used for dumping or burning wastes by businesses and households

CONTAMINATION EVIDENCE:
- Petroleum odor in well water
- Other chemical odors
- Detection of chemicals in well water tests

CAUSES:
- Improper disposal of chemicals, oil, pesticides, other wastes and used containers
- Lack of disposal facilities for small amounts of hazardous wastes

PREVENTION:
- Public information/education
- Disposal facilities for small hazardous wastes generators
- Enforcement against improper waste disposal



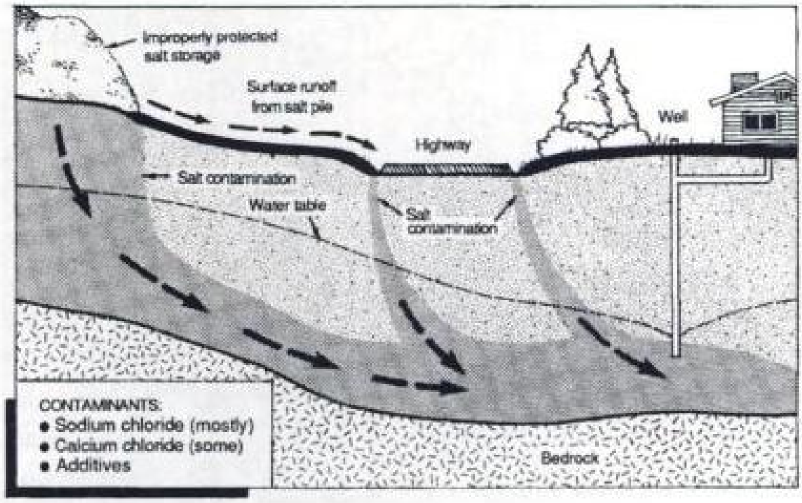


DEICING SALTS

CONTAMINATION EVIDENCE:
- **Salty taste in well water**
- **High chloride level in well water tests**

CAUSES:
- **Runoff from salt storage piles and highways**

PREVENTION:
- **Proper protection of salt storage piles**
- **Minimize use**
- **Use alternative deicing materials**



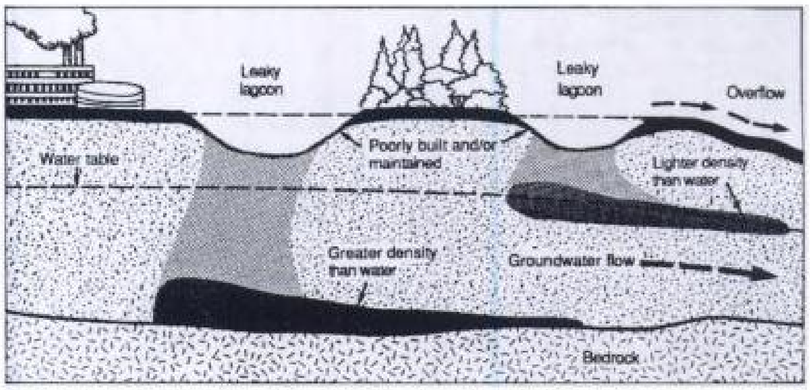
STORAGE LAGOONS

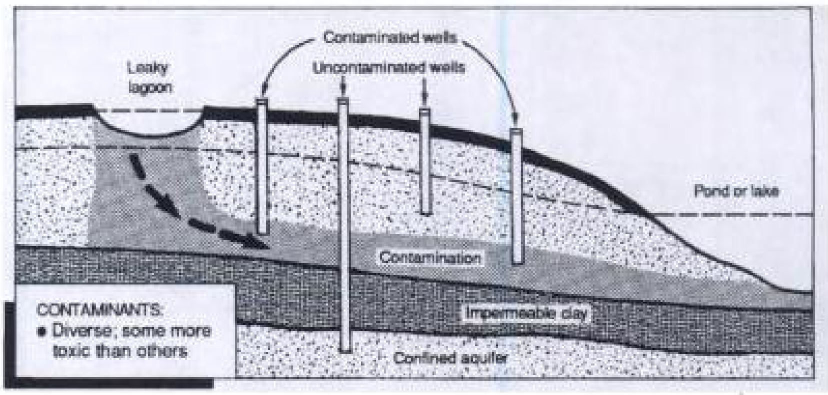
Used by industries, farms, municipalities, mining operations, oil/gas producers

CONTAMINATION EVIDENCE:
- Spills
- Changes in color, taste, odor of well water
- Unhealthy or dead vegetation near lagoon
- Greener and more vigorous plant growth near lagoon
- Detection of excessive bacteria, chemicals in well water tests

CAUSES:
- Poor installation and maintenance
- Overflows
- Seepage
- Liner failure
- Structural collapse
- Location in sensitive groundwater area

PREVENTION:
- Proper installation and maintenance
- Locate away from sensitive groundwater areas



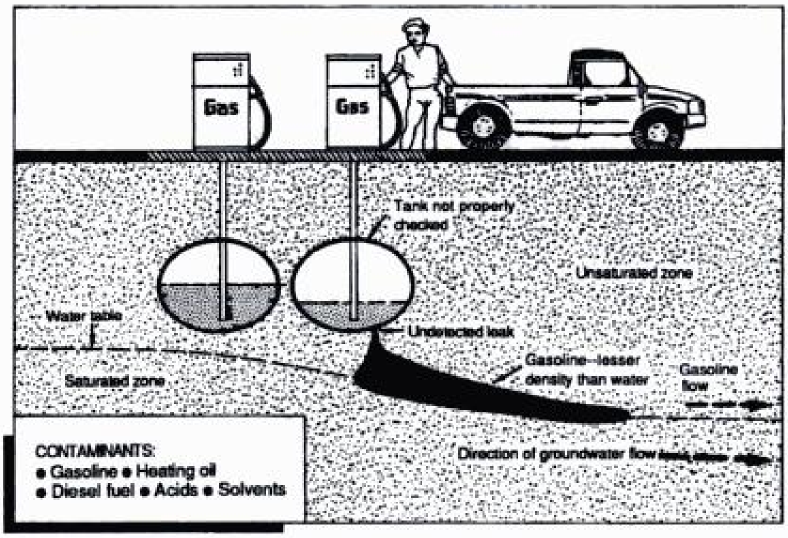


UNDERGROUND STORAGE TANKS

CONTAMINATION EVIDENCE:
- Petroleum odor in wells or basements
- Tank inventory losses
- Spills
- Detection of leaks

CAUSES:
- Corroded tanks
- Poor installation and/or maintenance
- No testing for tank leaks
- Poor inventory control
- No leak backup containment
- Deterioration of abandoned tanks

PREVENTION:
- Proper installation, maintenance, leak testing and inventory control
- Permit compliance
- Leak backup containment
- Removal of abandoned tanks or filling with inert material

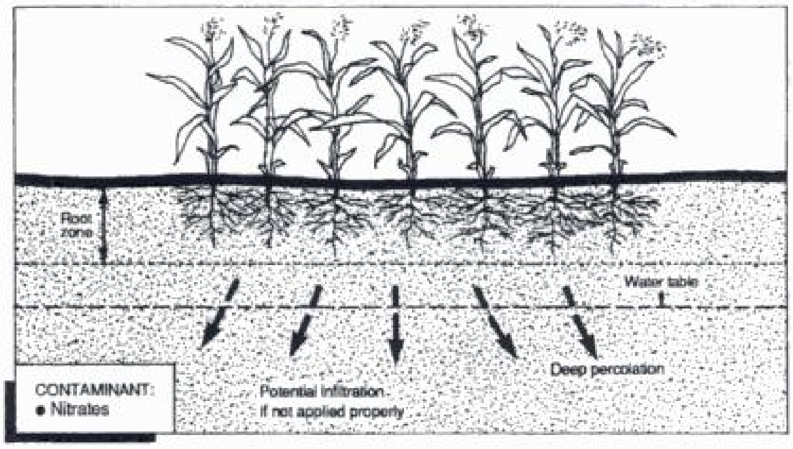


FERTILIZERS

CONTAMINATION EVIDENCE:
- High nitrate level in well water tests

CAUSES:
- Overfertilization
- Ill-timed application

PREVENTION:
- Careful adjustment of fertilizer application to plant needs and timing for maximum growth benefit
- Storage of animal manure to facilitate land spreading at appropriate times

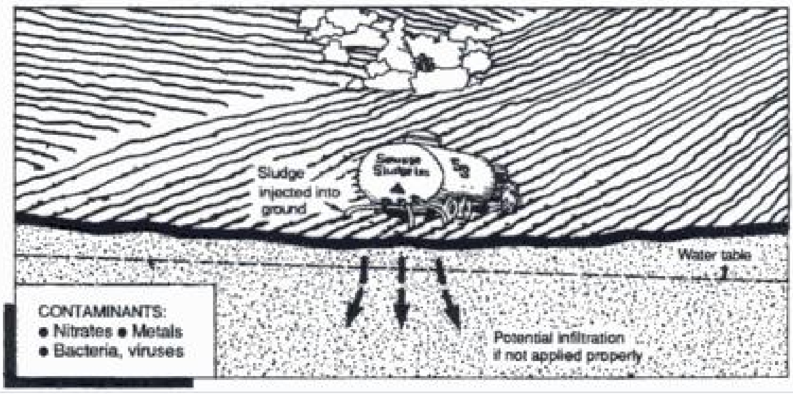


LAND APPLICATION
Sludges and Wastewater

CONTAMINATION EVIDENCE:
- High bacteria, nitrate levels in well water tests

CAUSES:
- Improper application methods
- Inappropriate soils for application

PREVENTION:
- Compliance with permit requirements

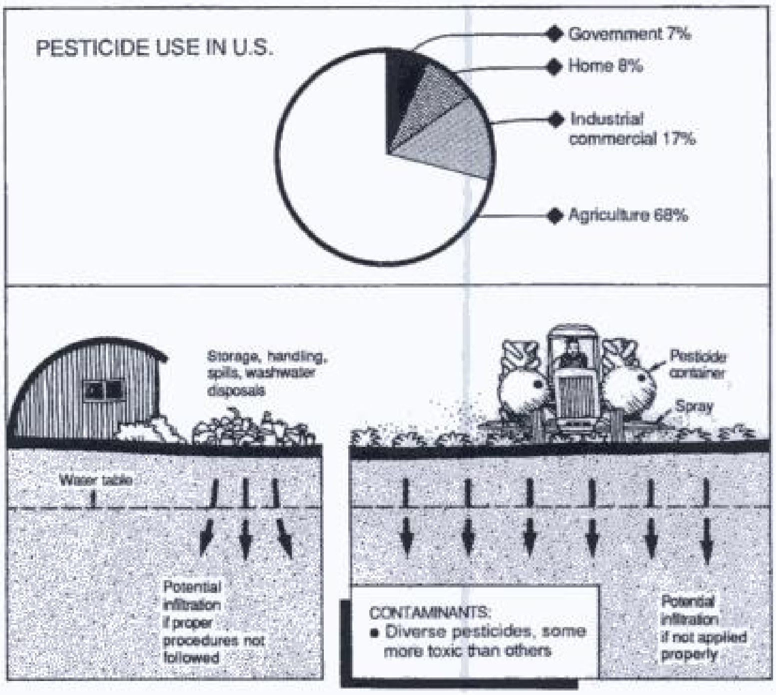


PESTICIDES

CONTAMINATION EVIDENCE:
- Detection of pesticides in well water tests
- Ill effects on animals drinking water from nearby wells, springs or surface water
- Ill effects on plants watered with nearby well water
- Ill effects on aquatic life

CAUSES:
- Excessive or ill-timed application
- Improper storage
- Leaching through the soil
- Improper disposal of excess pesticides and rinsewater

PREVENTION:
- Follow use instructions
- Compliance with pesticide certification requirements
- Reduce pesticide use in recharge areas for water wells
- Encourage alternative pest control methods
- Public information/education

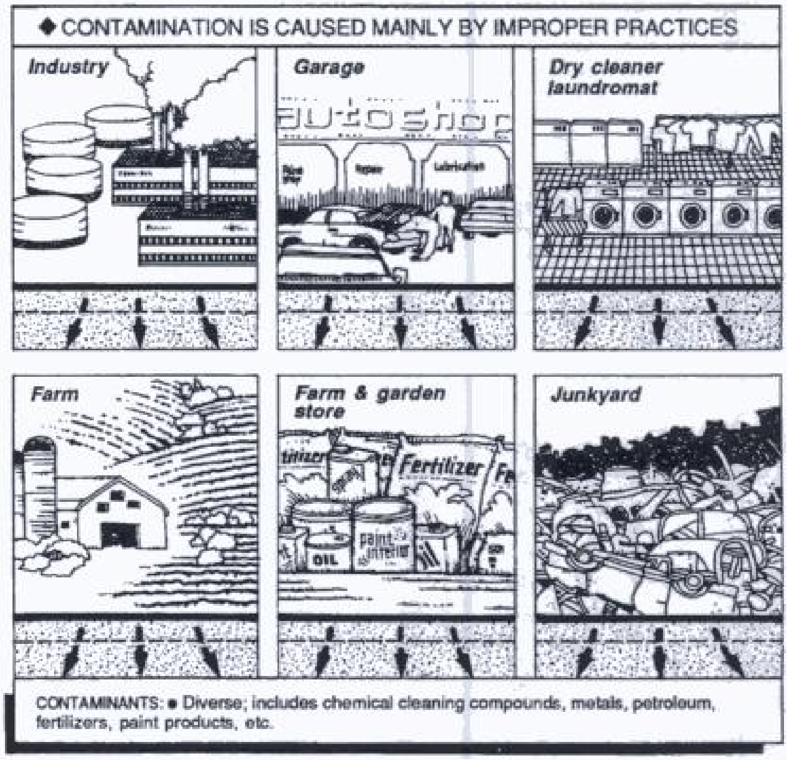


HAZARDOUS MATERIALS

CONTAMINATION EVIDENCE:
- Spills
- Detection of chemical solvents, metals, nitrates, other chemicals in well water tests

CAUSES:
- Improper storage, handling, use, and disposal
- Spills
- Leaks

PREVENTION:
- Proper storage, handling, use and disposal
- Spill prevention and containment measures
- Compliance with laws and regulations
- Zoning to locate heavy users of hazardous materials away from sensitive groundwater areas
- Public information/education



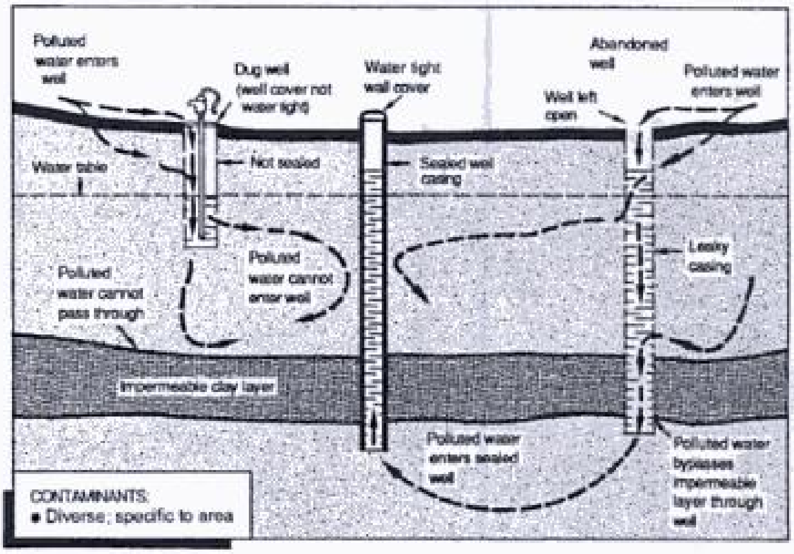
WELLS

Wells are potential pathways for contaminants to enter groundwater

CONTAMINATION EVIDENCE:
- Detection of high bacteria levels in well water tests
- Well water turbidity
- Detection of other contaminants in well water

CAUSES:
- No well casing or leaky casing
- Well cover not watertight
- Open abandoned wells
- Groundwater movement from contaminated to uncontaminated wells

PREVENTION:
- Watertight well cover
- Tight well casing
- Tight plumbing connections
- Identify and seal open abandoned wells

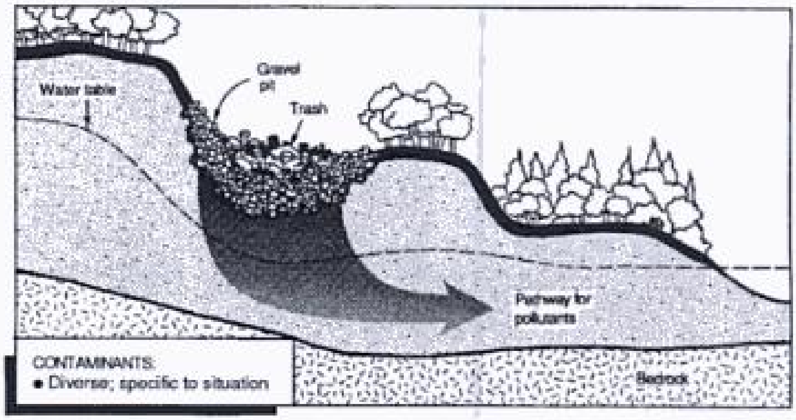


INACTIVE MINING SITES

CONTAMINATION EVIDENCE:
- (Potential) Dumping of wastes in inactive mining pits

CAUSES:
- Rapid infiltration of contaminants due to loss of topsoil filtering capacity

PREVENTION:
- Close unused mining pits by restoring topsoil cover
- Vigilance against waste dumping in inactive mining pits

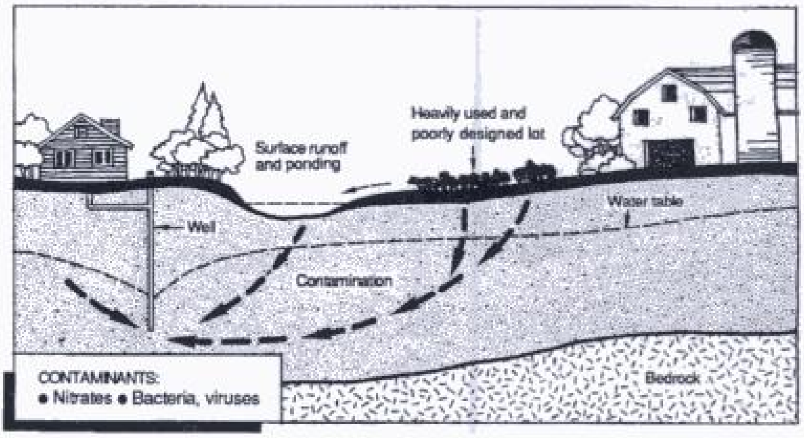


ANIMAL LOTS

CONTAMINATION EVIDENCE:
- High bacteria, nitrate levels in well water

CAUSES:
- High animal density
- Shallow depth to water table
- Poor lot drainage
- Failure to regularly clean lot

PREVENTION:
- Proper siting and design
- Control animal density
- Regular cleaning of lot

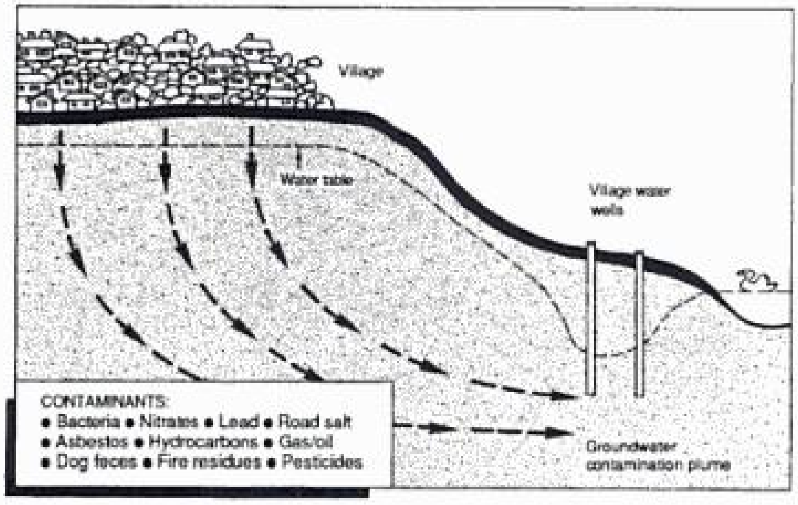


URBAN RUNOFF

CONTAMINATION EVIDENCE:
- Detection of chemicals, metals, nitrates, petroleum, etc. in well water

CAUSES:
- Spills
- Random waste disposal
- Abandoned commercial/industrial sites
- Motor vehicle emissions
- Fires

PREVENTION:
- Public information/education
- Street sweeping
- Anti-dumping codes
- Vegetated collection and infiltration basins for street runoff
- Clean up abandoned commercial/industrial sites
- Proper cleanup of fire sites

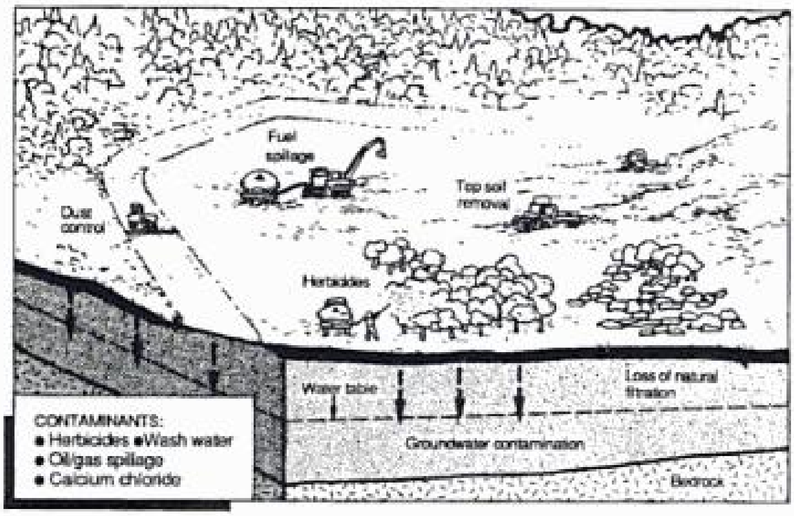


CONSTRUCTION EXCAVATION

CONTAMINATION EVIDENCE:
- Spills
- Changes in color, taste, odor, turbidity of water in nearby wells

CAUSES:
- Fuel, chemical spills
- Road dust control runoff
- Excessive and/or improper use of chemicals

PREVENTION:
- Spill containment and cleanup procedures
- Follow recommended practices for safe use of fuels and other hazardous substances

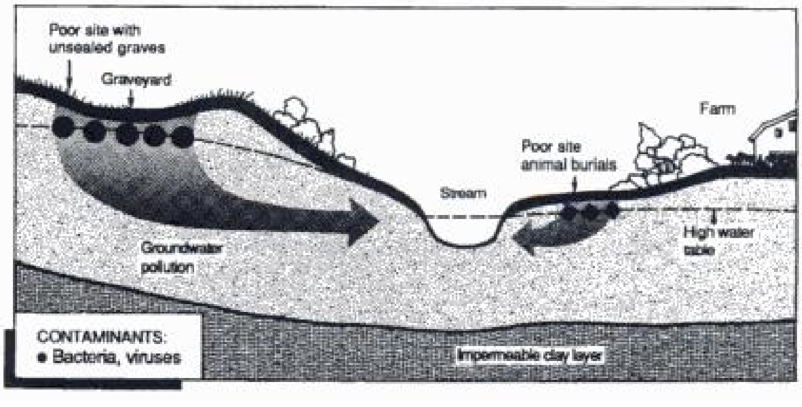


CEMETERIES and ANIMAL BURIALS

CONTAMINATION EVIDENCE:
- Detection of high bacteria levels in nearby well water tests

CAUSES:
- High water table

PREVENTION:
- Avoid high water tables for burial sites
- Use watertight caskets in cemeteries with high water tables

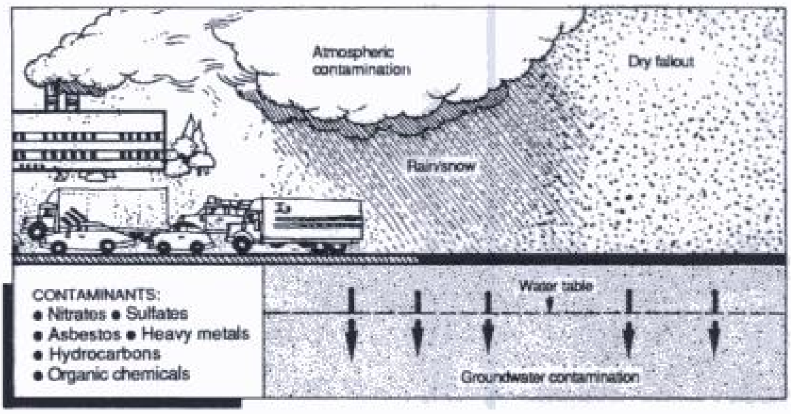


ATMOSPHERIC POLLUTANTS

CONTAMINATION EVIDENCE:
- Detection of elevated levels of sulfates, nitrates, heavy metals, asbestos, hydrocarbons, other chemical compounds in well water tests

CAUSES:
- Emissions from motor vehicles, power plants, industries

PREVENTION:
- Federal and state emission controls

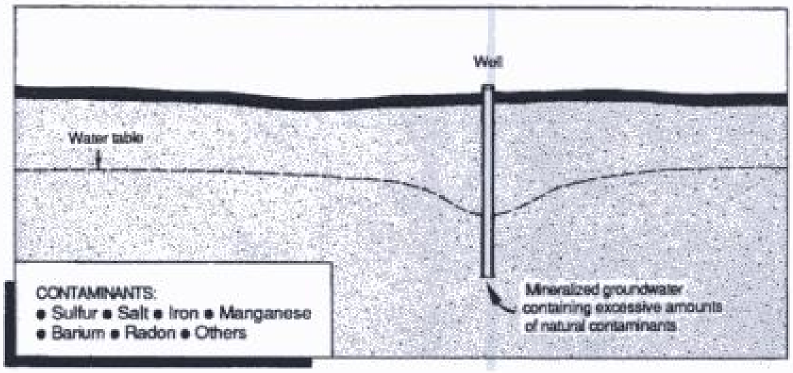


NATURAL SUBSTANCES

CONTAMINATION EVIDENCE:
- Bad taste or odor in well water
- Stains on water fixtures
- Detection in well water tests

CAUSES:
- Natural origin

PREVENTION:
- Avoid areas where natural groundwater problems exist, if feasible
- Use water treatment devices
- Change to public water supply, if feasible



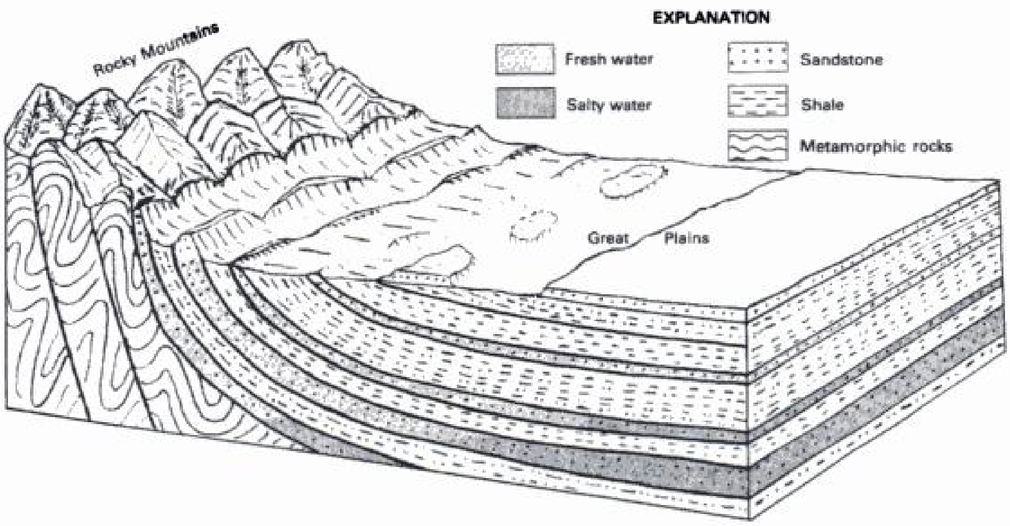


Figure 3.1. Confined aquifer where sedimentary rocks are uplifted (Heath, 1984).

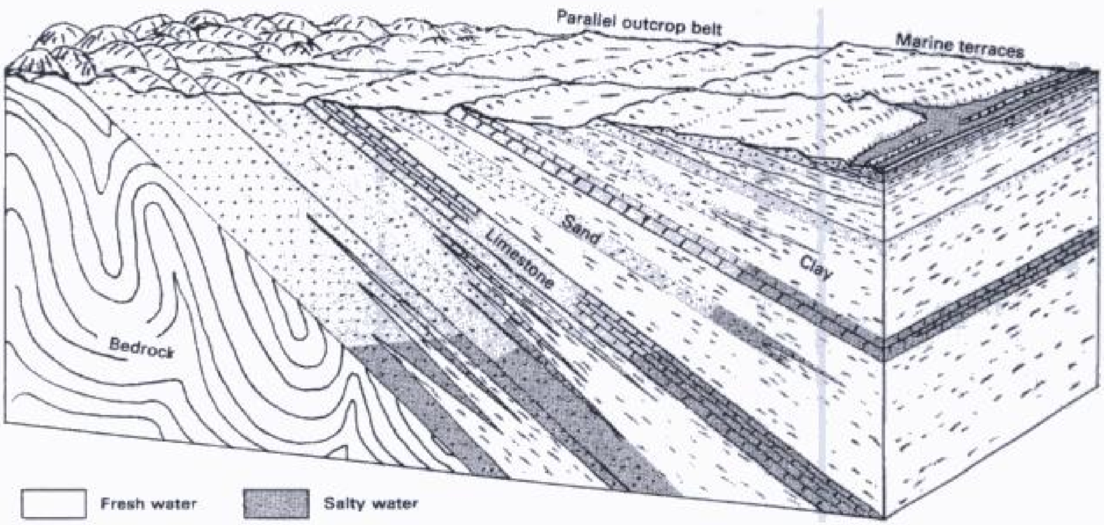


Figure 3.2. Confined aquifer development on a regional dip (Heath, 1984).

Figure 3.3. Alluvial fan development.

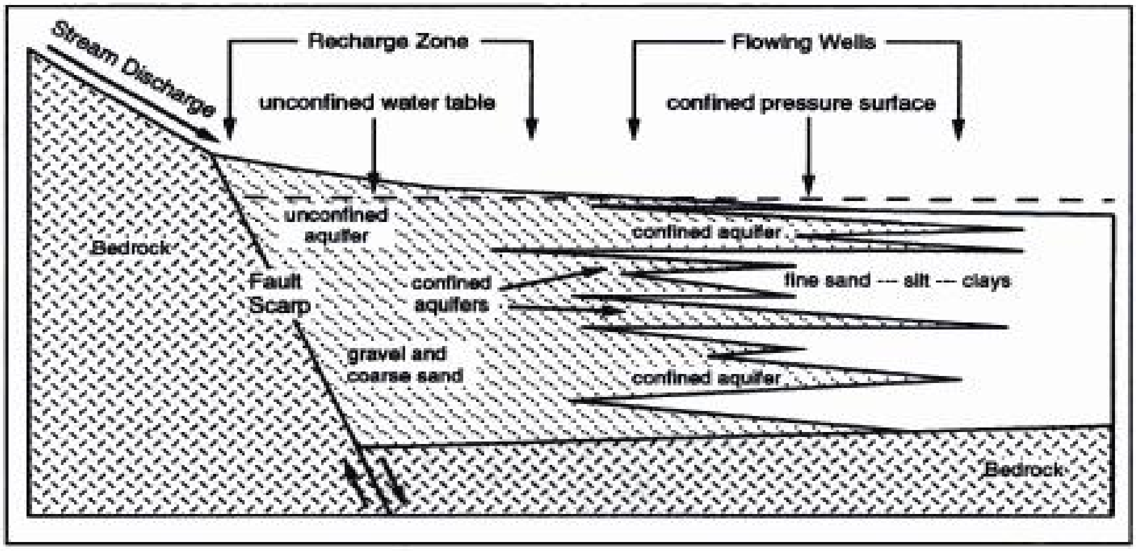
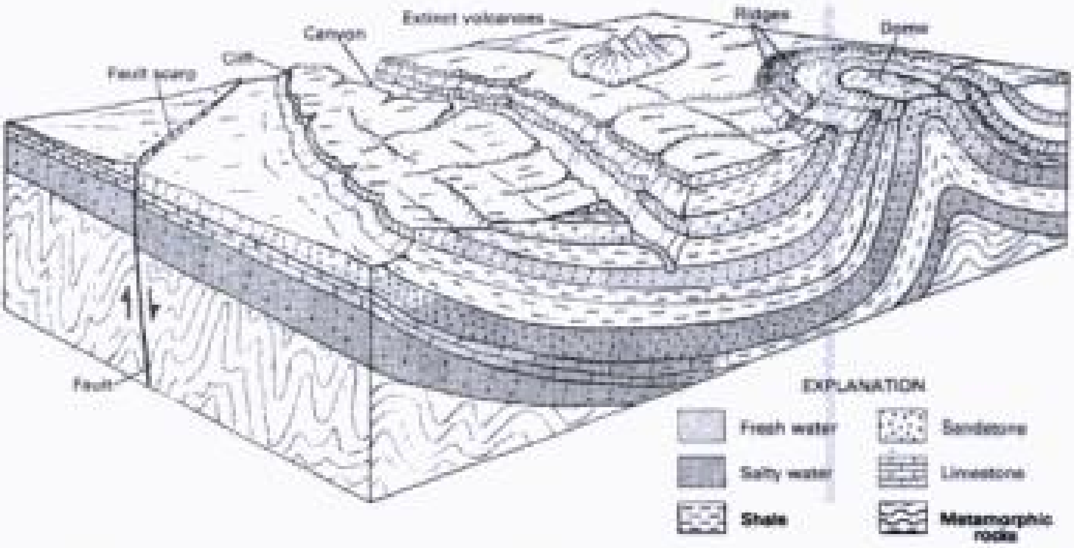
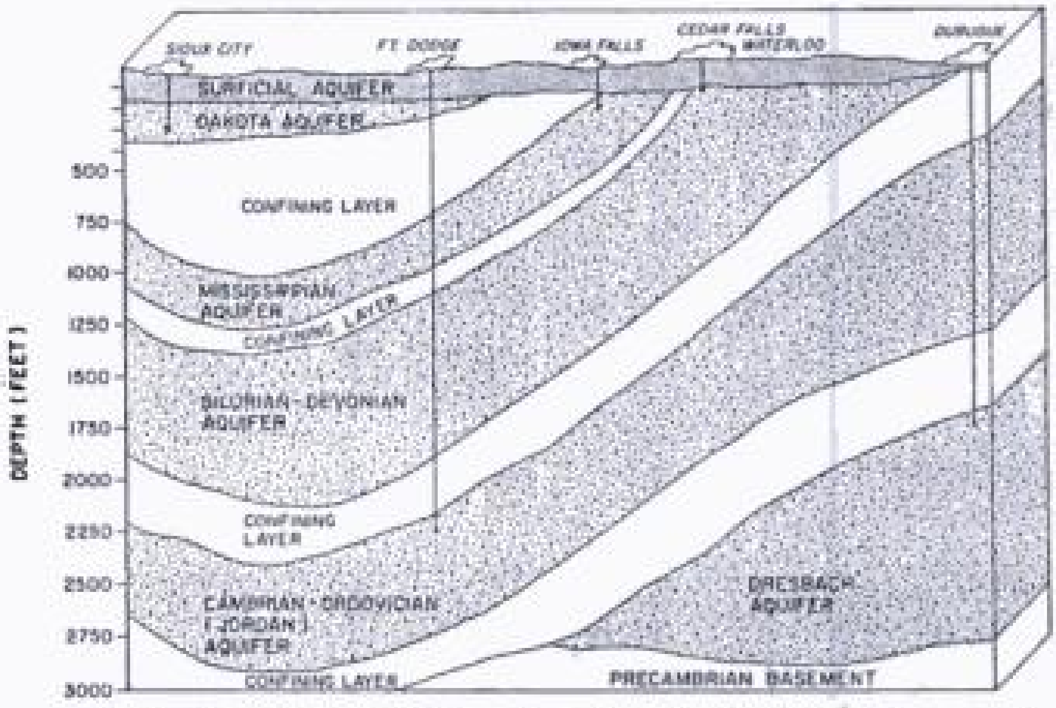


Figure 3.4. Development of confined aquifers in an alluvial valley at the foot of a mountain.



Typical geologic features of the Colorado Plateau and Wyoming Basin (Heath, 1984).



Synclinal aquifers beneath Iowa (Iowa Department of Natural Resources).

Figure 3.5. Development of confined aquifers in folded rock.

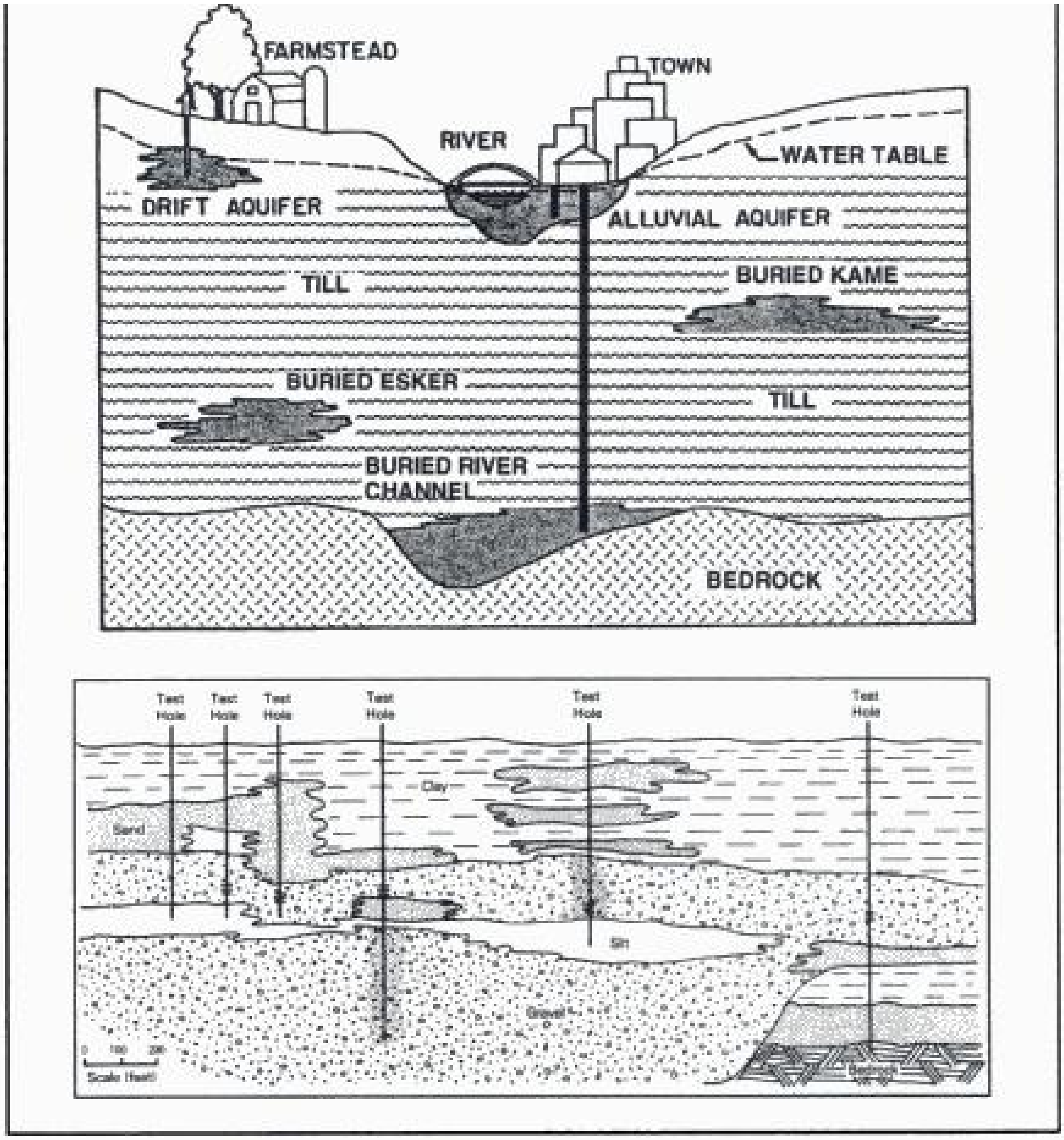


Figure 3.6. Confined aquifers in glacial terrain.

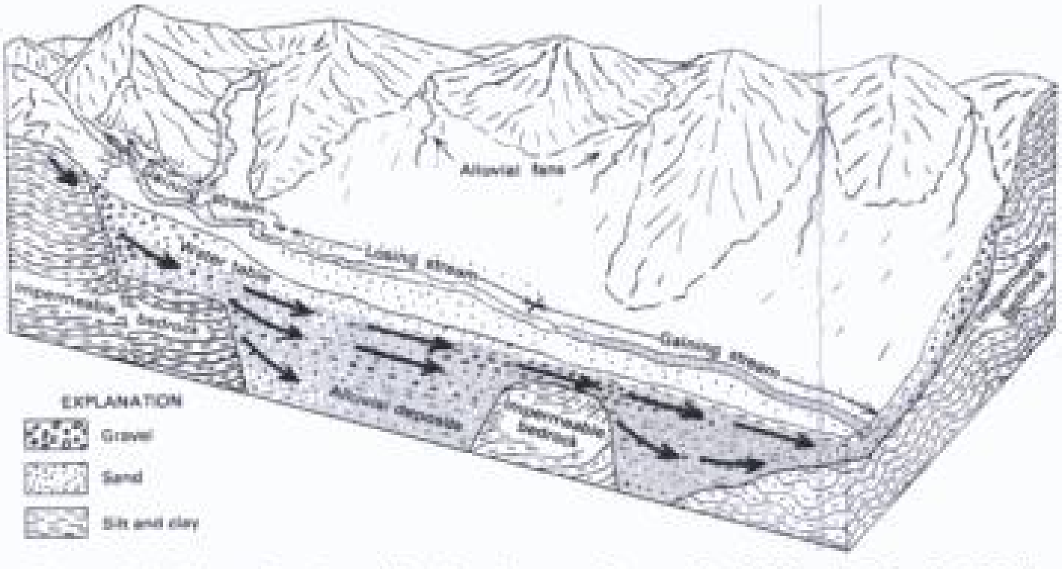


Figure 3.9. Unconfined aquifer development in an alluvial basin (Heath, 1984).

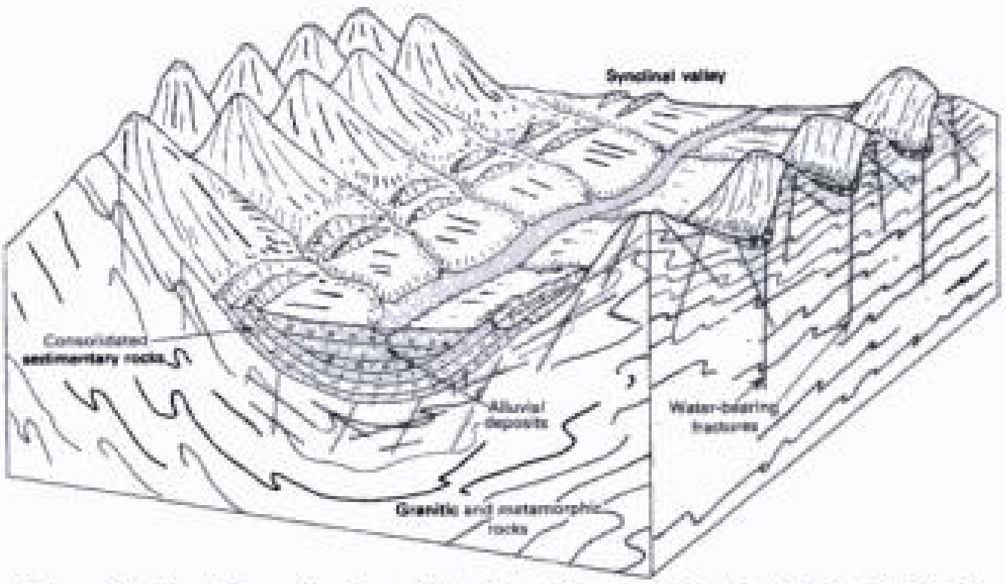
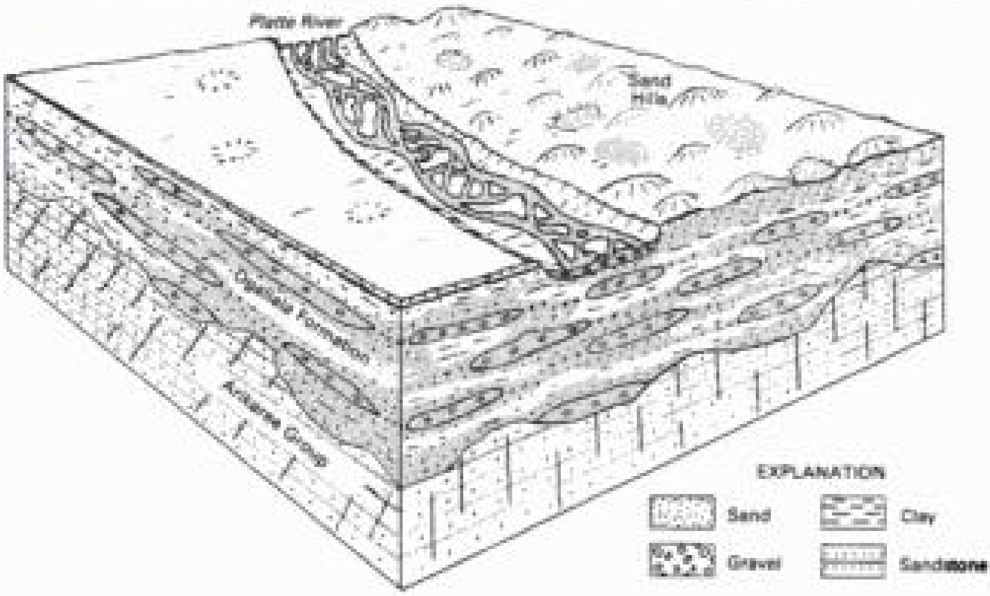


Figure 3.10. Unconfined aquifer above fractured bedrock (Heath, 1984).



Unconfined aquifer development of the High Plains region (Top).
Unconfined aquifers along the flow direction of the Mississippi River (Bottom).

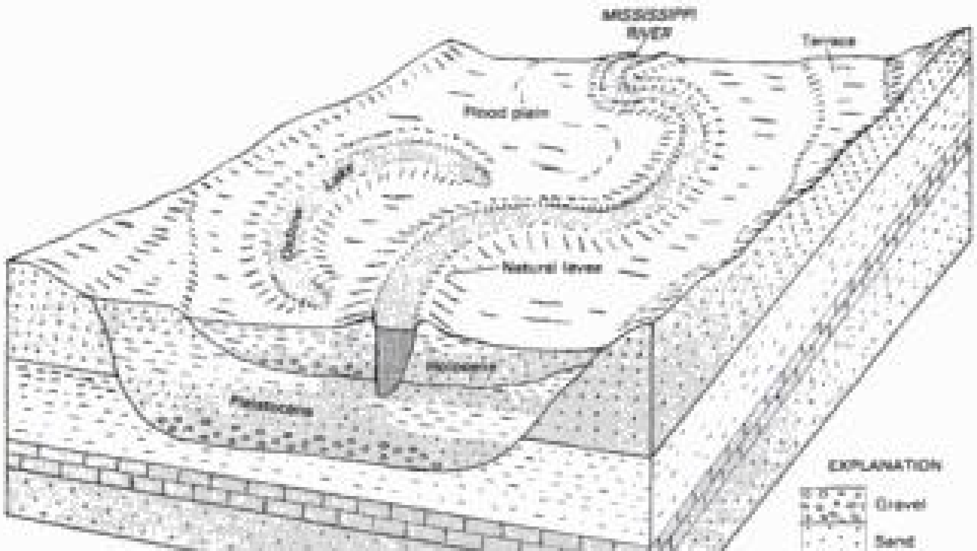


Figure 3.11. Unconfined aquifers in unglaciated river valleys (Heath, 1984).

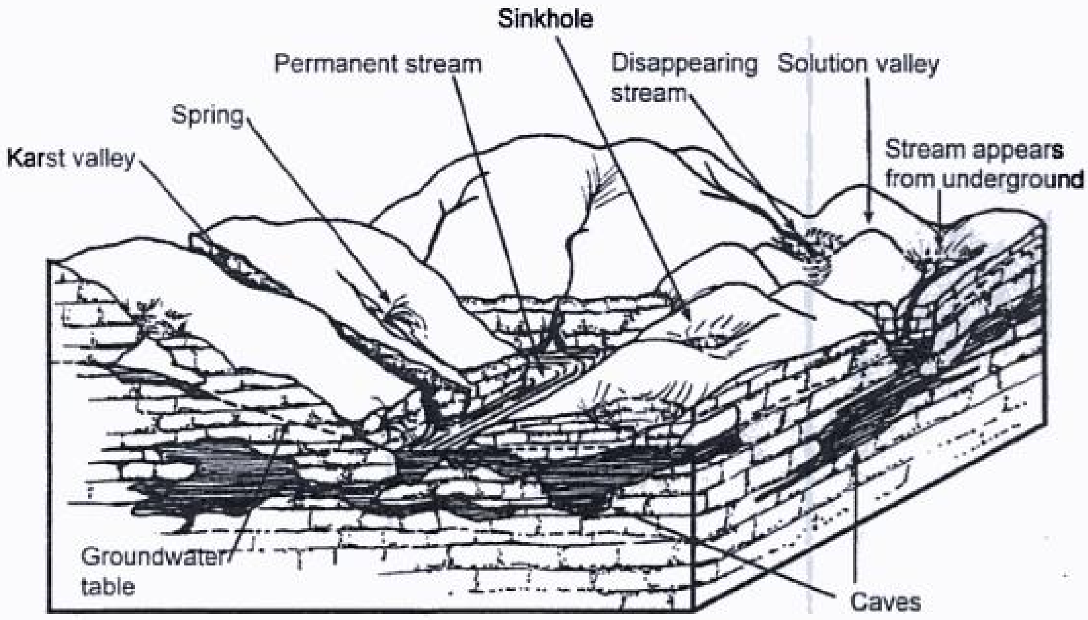


Figure 3.13. Karst system.

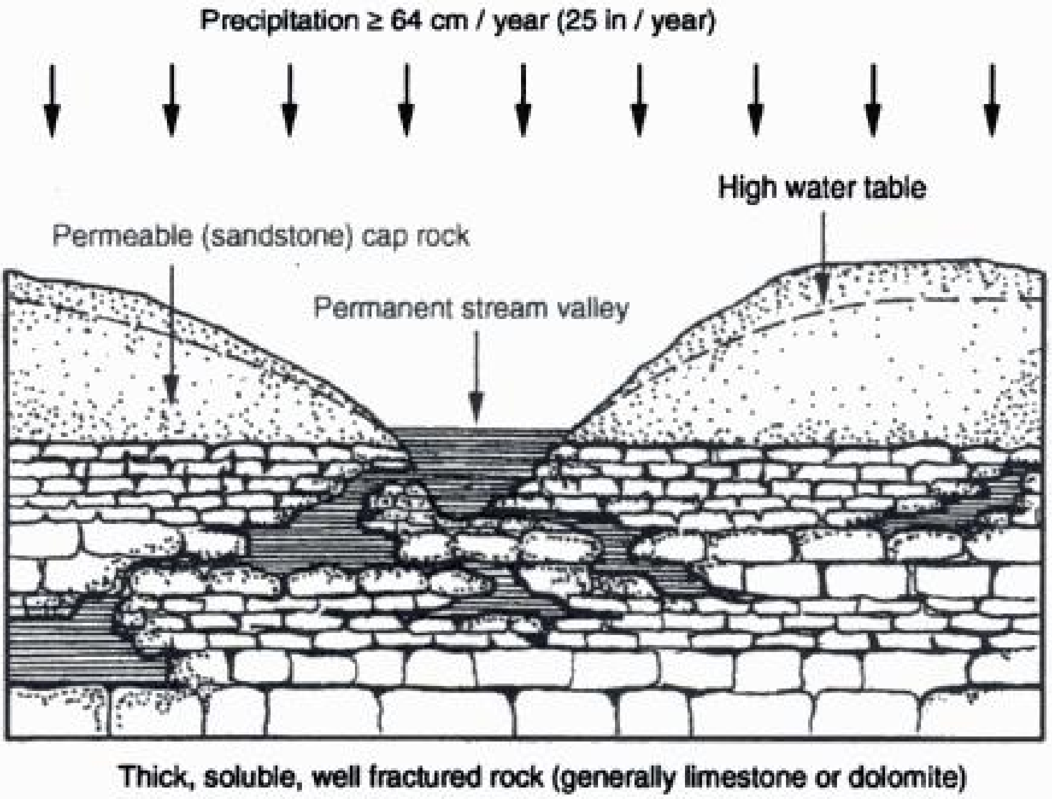


Figure 3.14. Criteria for optimum karst environment.

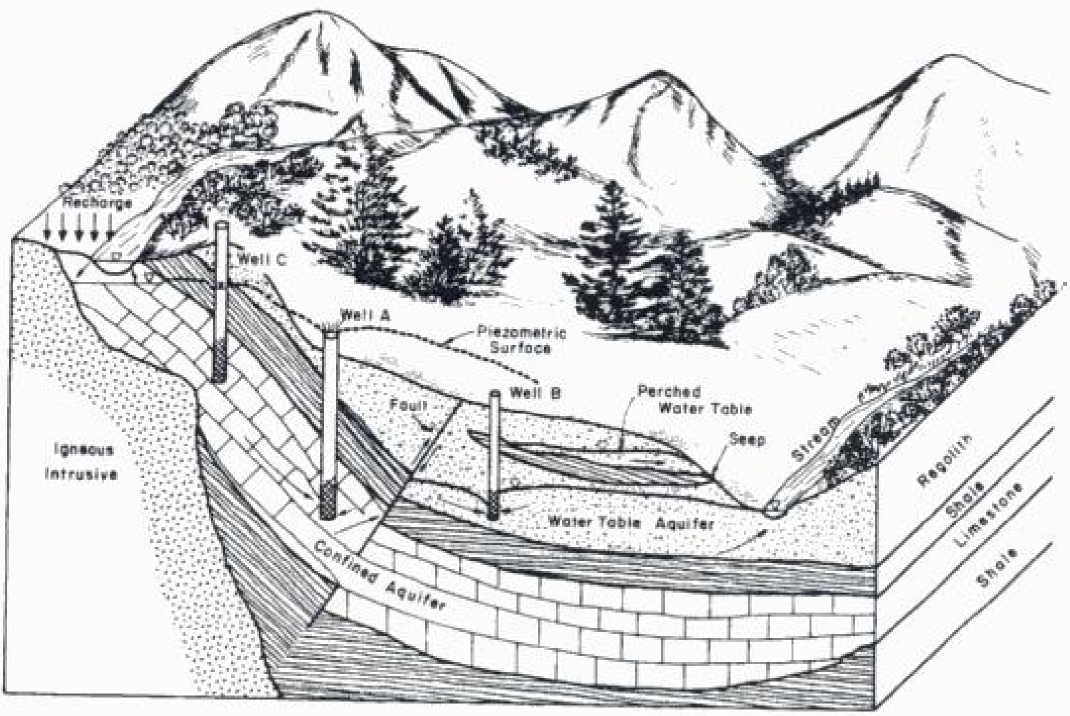


Figure 3.15. Confined aquifer in limestone (McWhorter and Sunada, 1977).

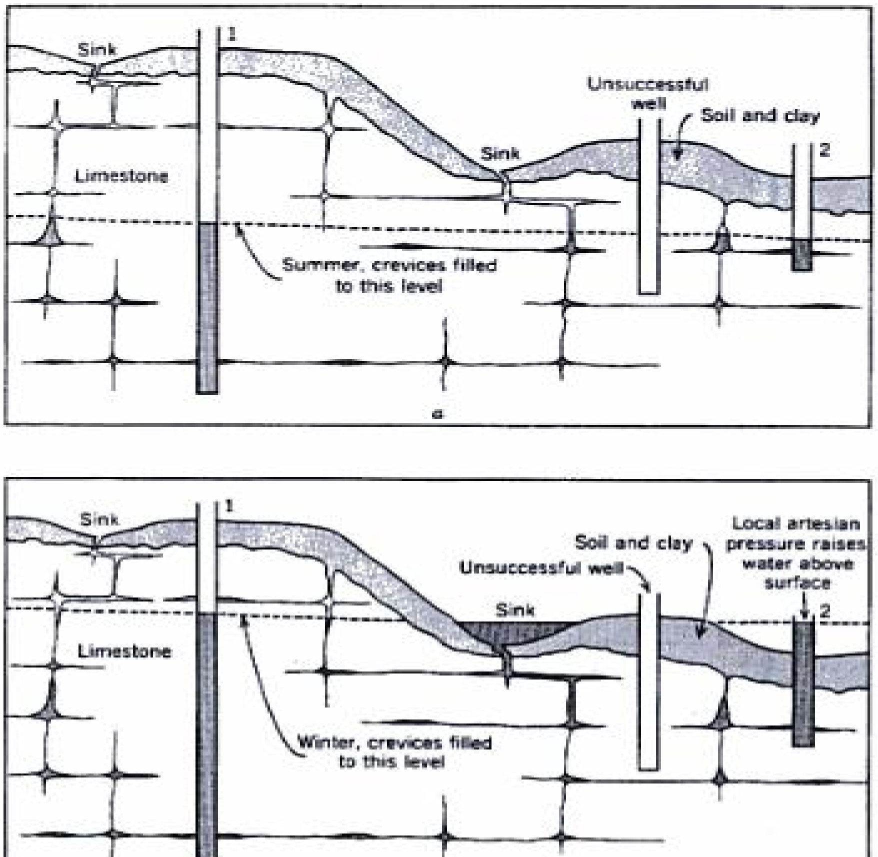


Figure 3.16. Wells constructed in karst fractures (Walker, 1956).

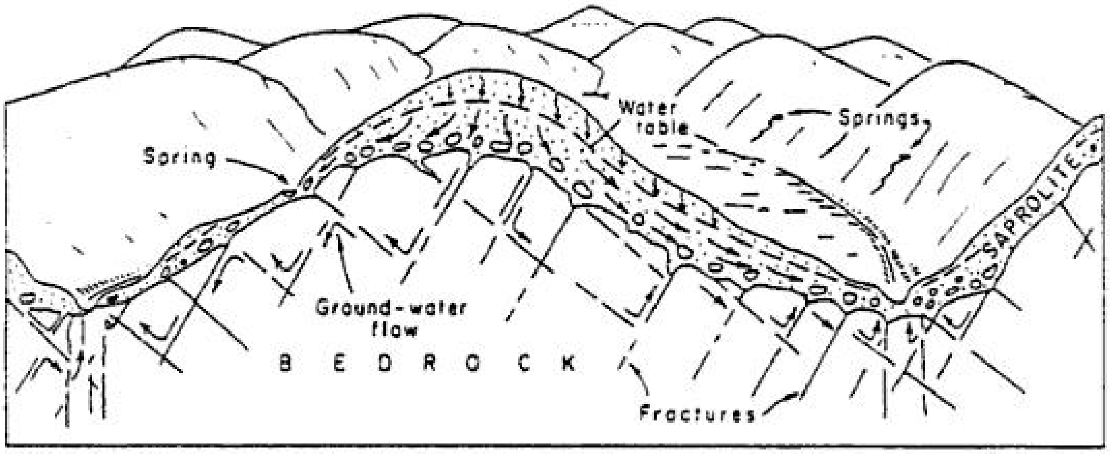
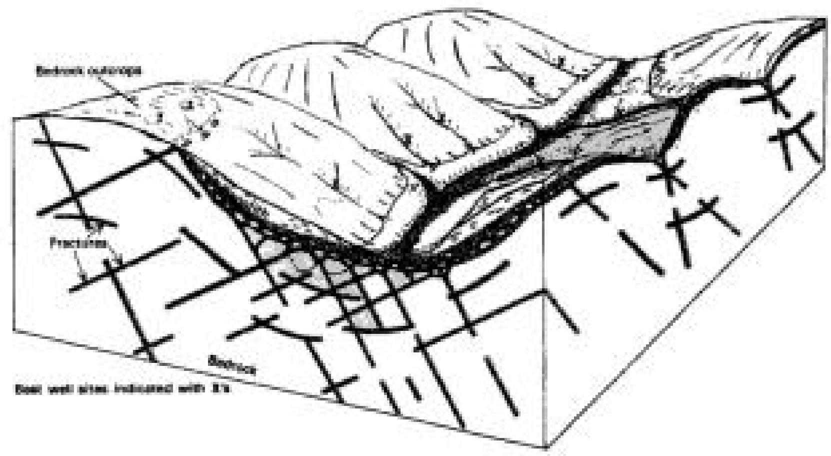
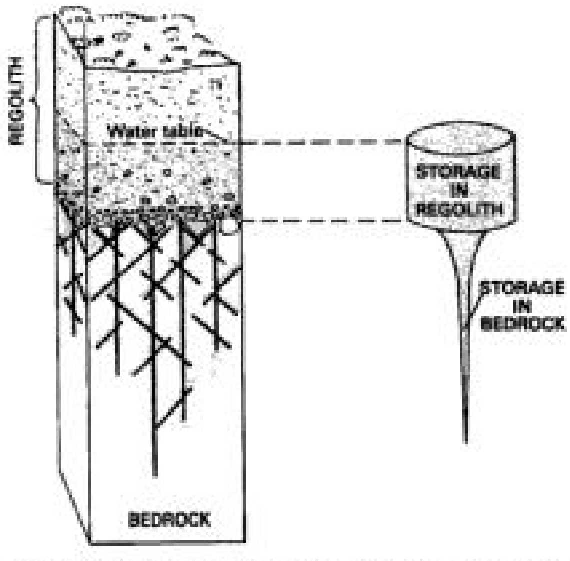


Figure 3.17. Fractures in bedrock acting as "pipelines" (Heath, 1980).

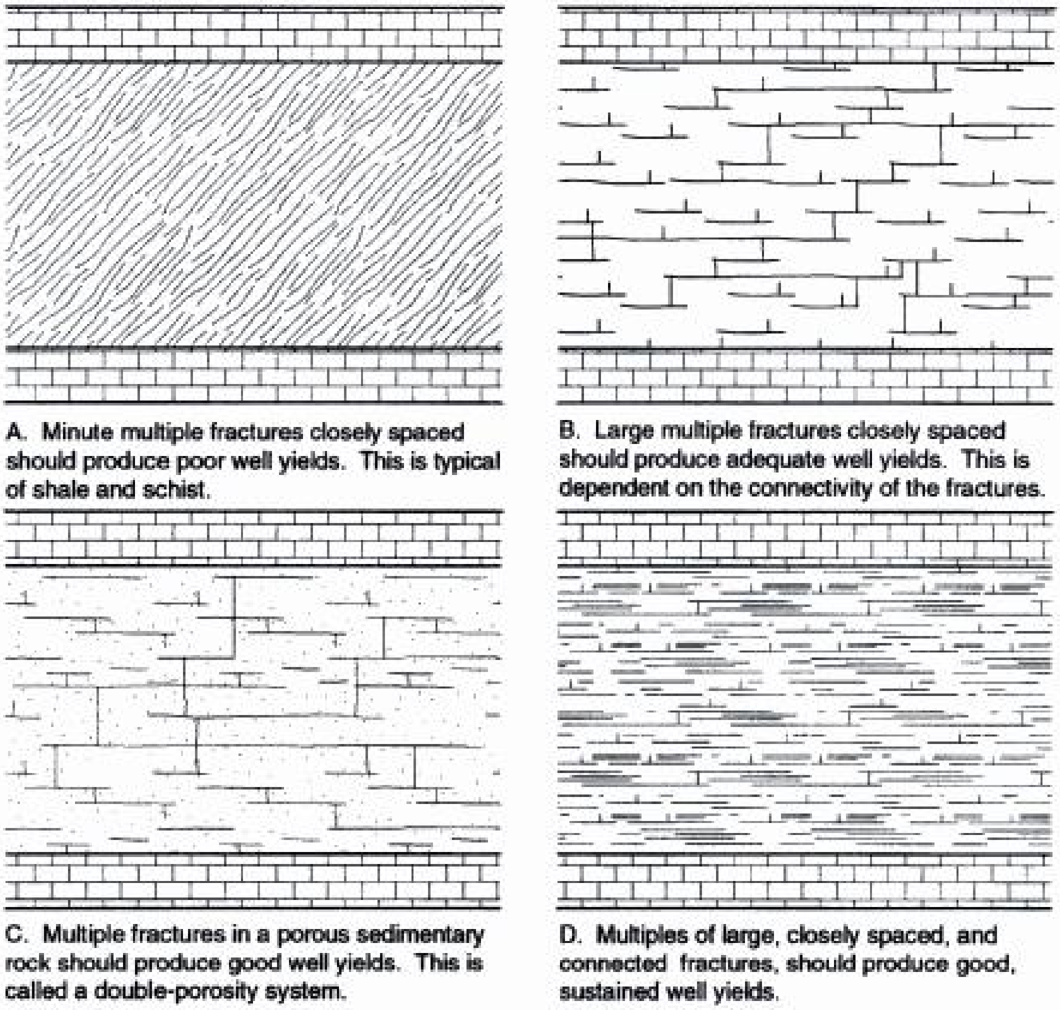


Thin regolith overlying fractured bedrock of the Piedmont Blue Ridge region.



Difference in storage capacity of regolith and bedrock.

Figure 3.18. Fractured rock aquifer and storage capacity (Heath, 1984).



A. Minute multiple fractures closely spaced should produce poor well yields. This is typical of shale and schist.

B. Large multiple fractures closely spaced should produce adequate well yields. This is dependent on the connectivity of the fractures.

C. Multiple fractures in a porous sedimentary rock should produce good well yields. This is called a double-porosity system.

D. Multiples of large, closely spaced, and connected fractures, should produce good, sustained well yields.

Figure 3.19. Fractures in rock relative to ground-water supply.

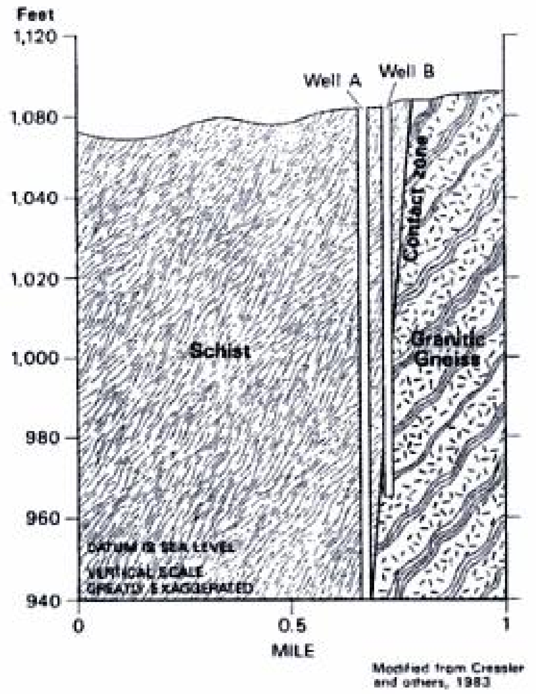


Figure 3.20. Two wells completed within a crystalline environment. Well-A, completed in schist, yielded only about 5.5 m^3/day, while well-B, which is screened within the granitic gneiss and the contact zone, produced about 550 m^3/day (USGS Hydrologic Investigations Atlas 730-G).

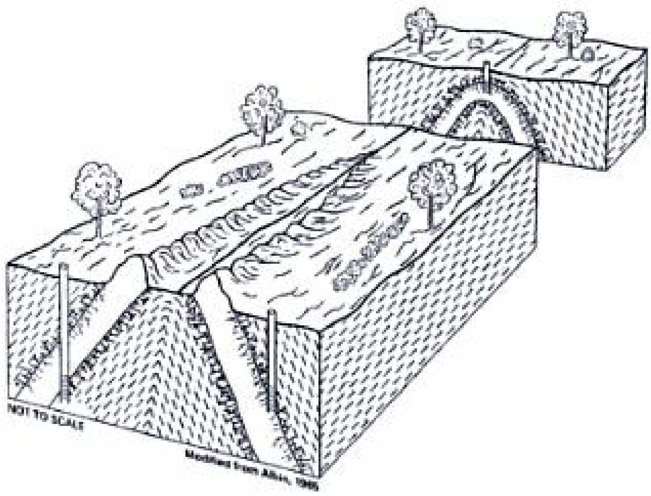


Figure 3.21. Contact zones between fractured sandstone (anticline) and shale (matrix) are favorable places to complete water wells (USGS Hydrologic Investigations Atlas 730-F).

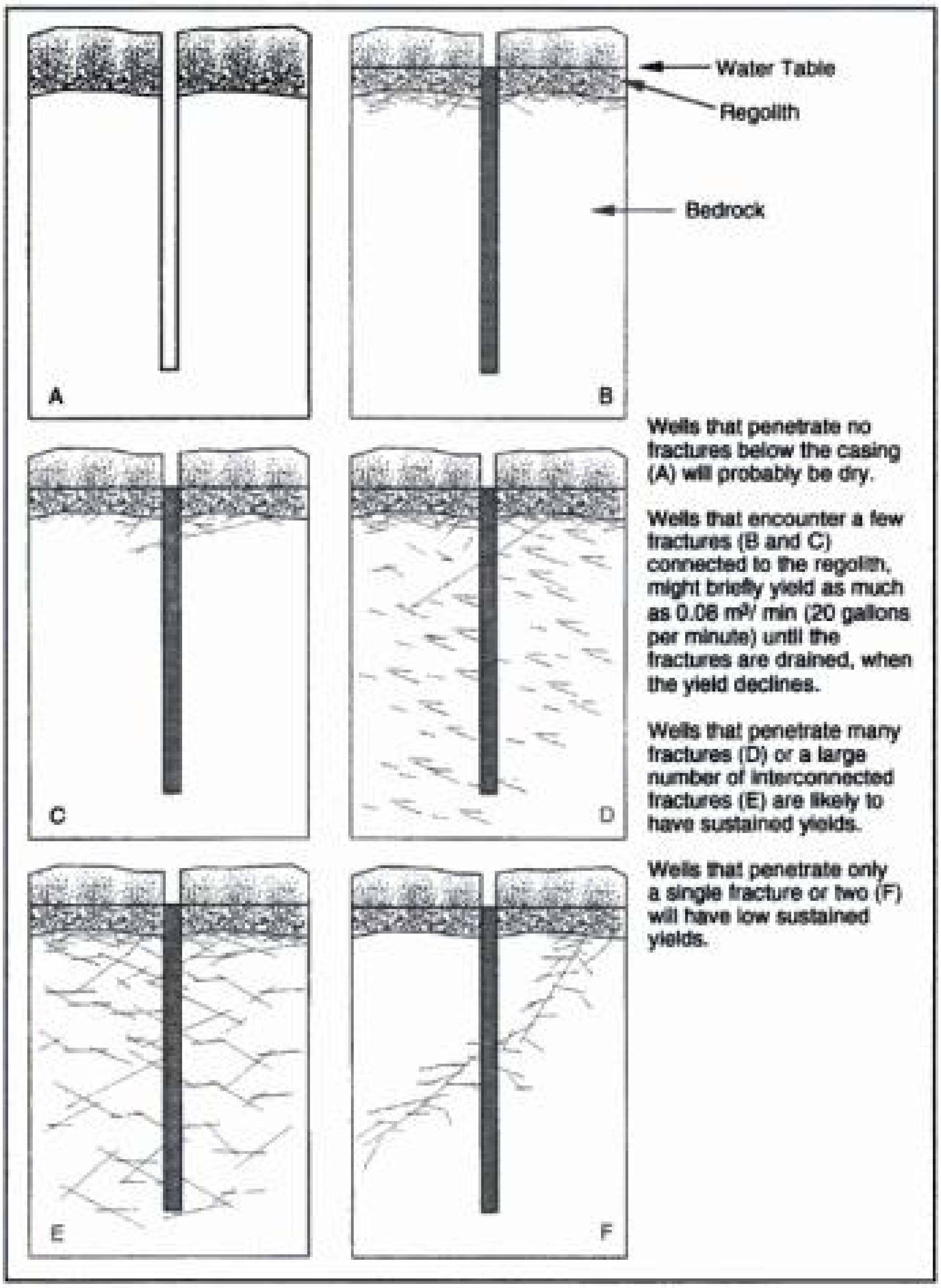


Figure 3.22. Wells constructed in crystalline rocks will have greater yields if they penetrate many fractures or fractures that are interconnected and encounter the surface (After LeGrand, 1967).

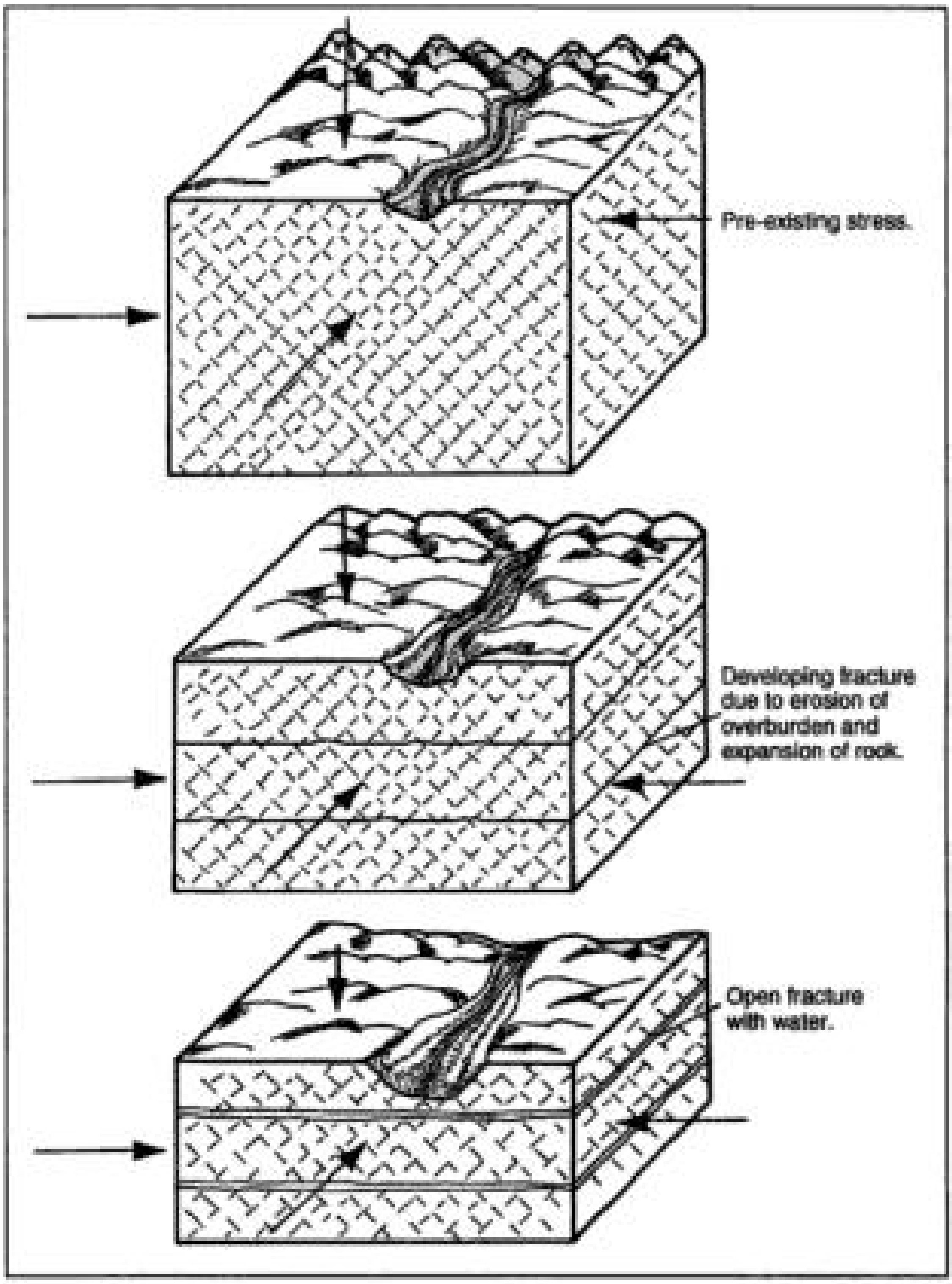


Figure 3.23. Development of horizontal fractures.

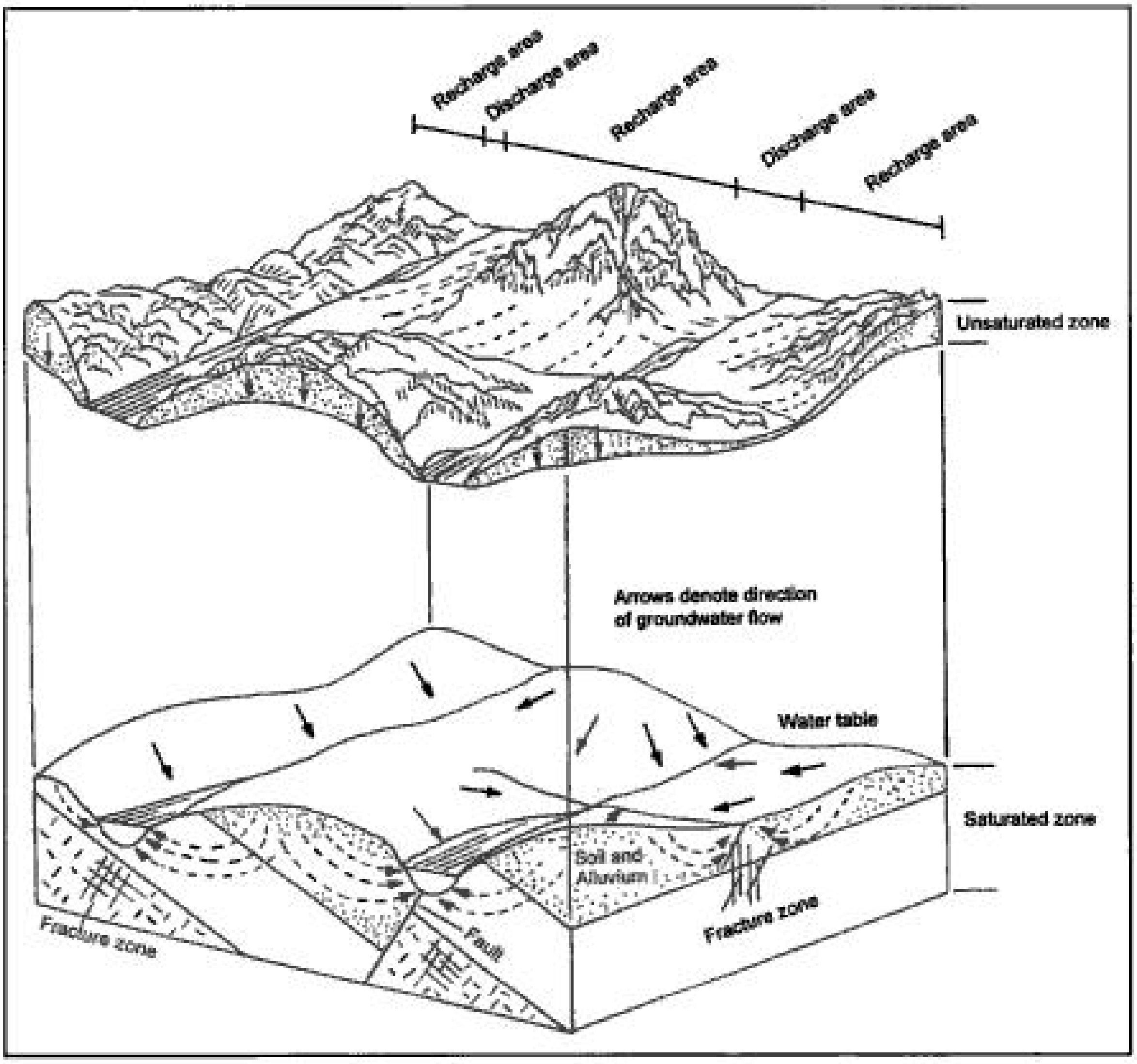


Figure 3.24. Interaction between a fault zone, fractures and permeable soil.

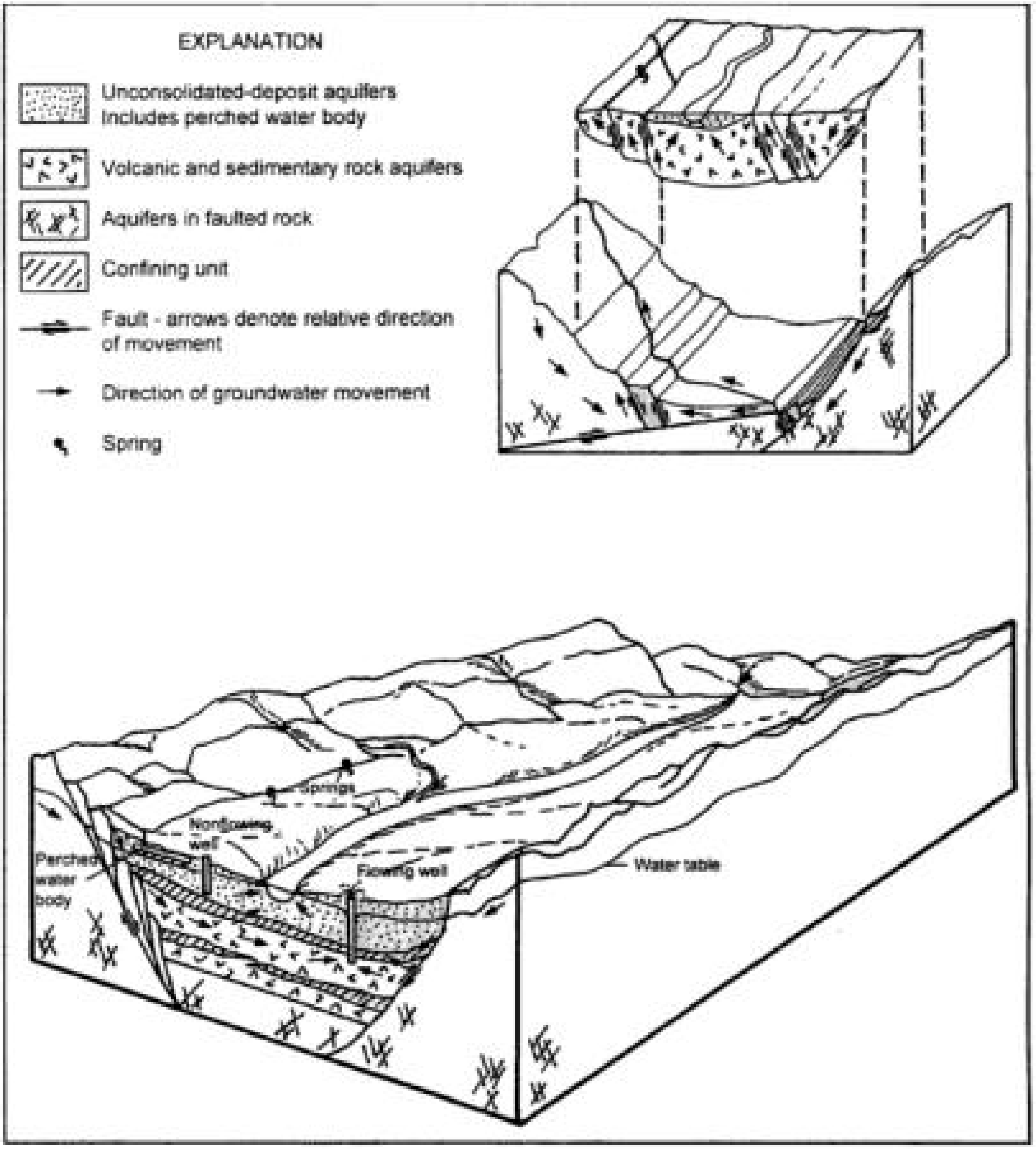


Figure 3.25. Fault zones acting as conduits in horst and graben structures. Unconfined aquifer system (top); complex system with confined aquifer (bottom).

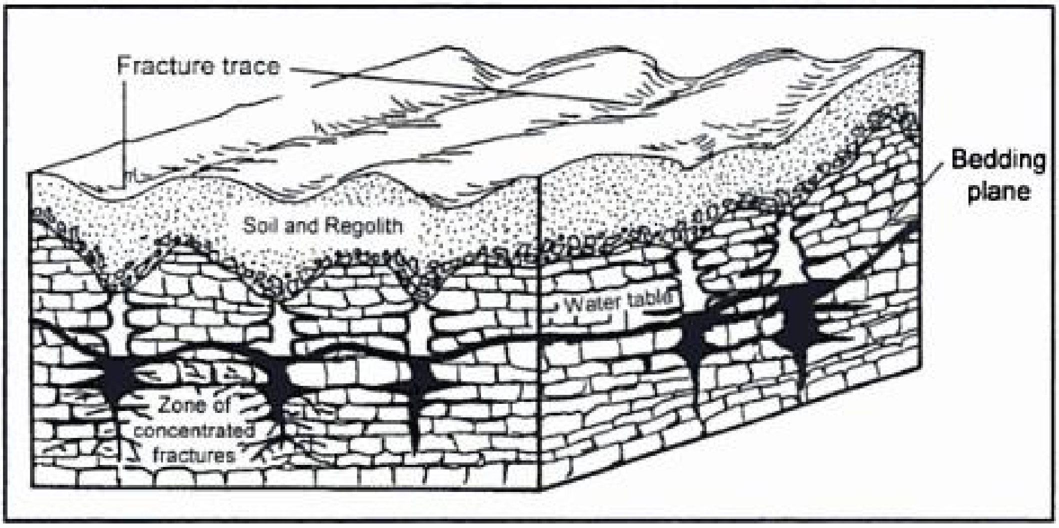


Figure 3.26. Fracture trace analysis is often used to identify zones of high permeabilty, which are identified by locating linear zones of subsidence at the surface.

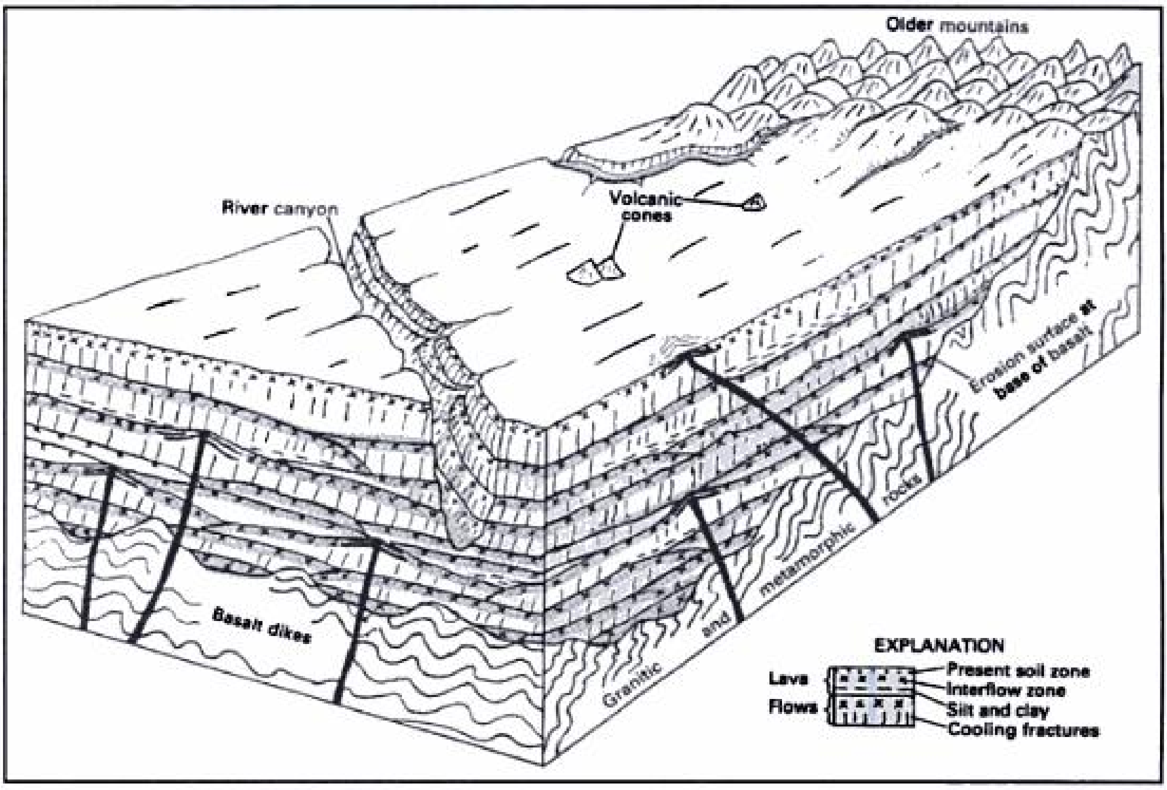


Figure 3.27. Topographic and geologic features of the Columbia Lava Plateau region (Heath, 1984). The interflow zones are represented in gray.

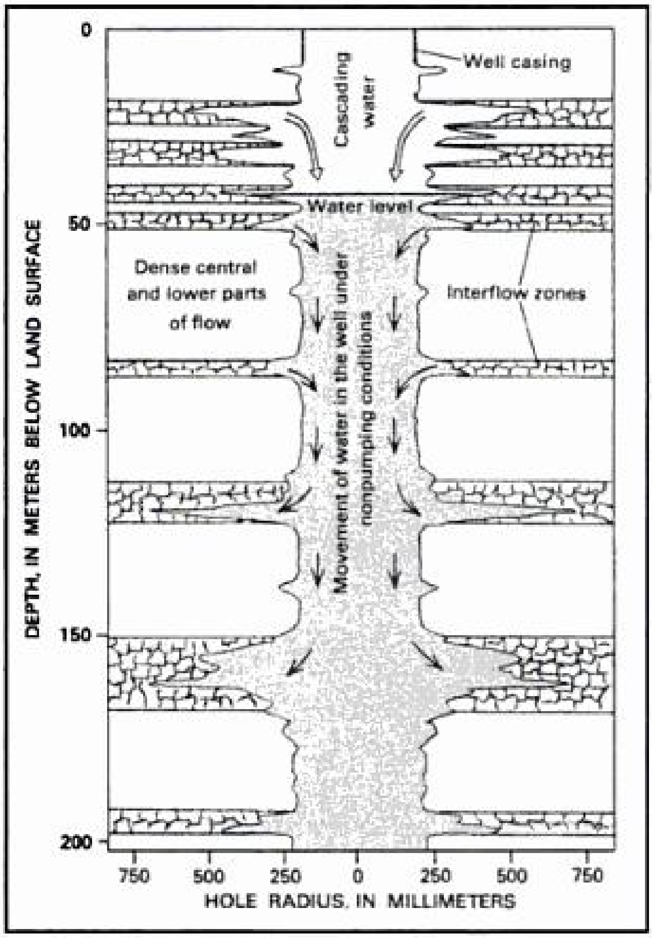


Figure 3.28. Well constructed within interflow zones in the Columbia River Group (Heath, 1984; modified from Luzier and Burt, 1974).

GROUND-WATER STORAGE

4.1 THE IDEAL AQUIFER

The aquifer system has two basic functions: it stores and transmits water; therefore, it is a reservoir and a conduit system. Water is stored between pore spaces of sediment, or in faults, fractures or solution cavities of rock. Ground water is transmitted from areas of recharge to areas of discharge when these void spaces are connected. Quantification of aquifers is concerned with these storage and transmissive properties. The **ideal aquifer** is often assumed for ease of mathematical calculations. Of course, the ideal aquifer does not exist, but this assumption generally results in good approximations, especially over a large area when average values are of concern. The ideal aquifer is rectangular and infinite, and comprised of homogeneous and isotropic sedimentary material.

4.2 HOMOGENEITY AND ISOTROPY

To review, geologic material that is **homogeneous** is of the same size and shape; therefore, it has the same hydraulic properties at all locations. If these properties are independent of direction the formation is said to be **isotropic**. Well rounded quartz beach sand is an example of homogeneous and isotropic sediment. Most geologic formations are **heterogeneous** and **anisotropic**, that is, the hydraulic properties change spatially and are more extreme in a given direction. Glacial till and alluvium are examples of such material.

The hydraulic property of general concern when considering the above conditions is **hydraulic conductivity (K)**. In simple terms, hydraulic conductivity is the rate at which a unit cube of geologic material will transmit a liquid under a hydraulic gradient. This important aquifer property will be discussed later in greater detail, for now, understand this, the hydraulic conductivity of a porous medium made of perfect spheres with the same diameter is equal in all directions. Anisotropy occurs as the shape of the material in the porous medium deviates from the geometry of a sphere, and increases as the material becomes progressively "flatter" or "oblong". Most sediment are laid on their flat sides or in the direction of their long axis; therefore, **horizontal hydraulic conductivity (K_h)** is generally greater when compared to **vertical hydraulic conductivity (K_v)** (Fig. 4.1).

Most mathematical equations that describe storage and flow of ground water assume homogeneous and isotropic conditions. As previously indicated, good quantitative values can be obtained when using these assumptions, because heterogeneities often cancel each other on a large scale where average values can be considered.

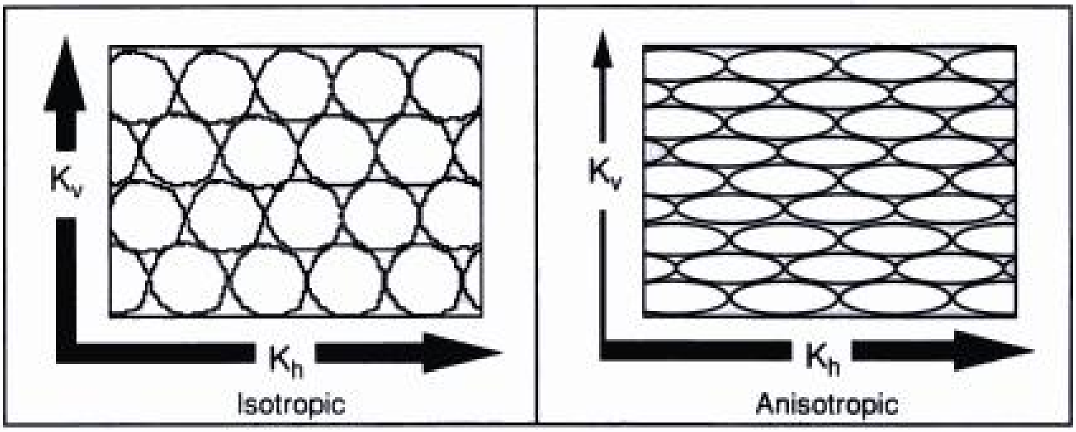


Figure 4.1. Isotropy and anisotropy resulting from grain shape and orientation.

Conditions that create anisotropy include (Fig. 4.2):

- facies changes • variations in sorting • sedimentary structures • fabric or grain orientations
- graded bedding • joints and fractures • layering of units with different K values • clay lenses
- thinning and thickening of adjacent units • inclusions • variations in cementation • faults

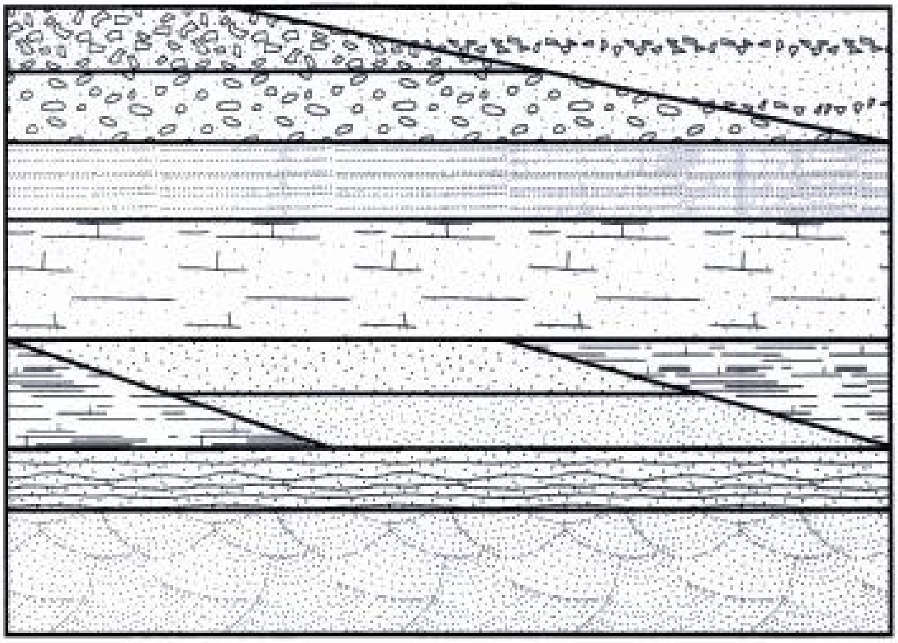


Figure 4.2. Horizontal and vertical spatial changes in sedimentary material produce variability in hydraulic conductivity, resulting in isotropic conditions.

4.3 POROSITY

Ground water is stored and moves through the pore spaces of rock or sediment. The volume of void space in geologic material is called **porosity** (Fig. 4.3).

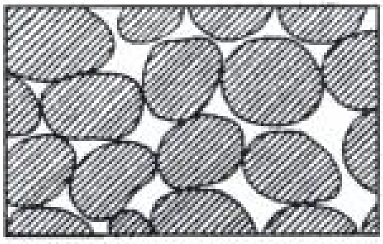


Figure 4.3 (Meinzer, 1942).

Porosity defines how much water a rock or sediment can hold when saturated. It can be expressed quantitatively as the ratio of the volume of voids to the total volume of material:

$$n = \frac{\text{volume of voids}}{\text{total volume of material}} = \frac{V_T - V_s}{V_T}(100) = \frac{V_v}{V_T}(100) = \text{percentage} \qquad (4.1)$$

where, for consistent units,

n = porosity = unitless

V_T = total volume of material = L^3

V_s = total volume of solids = L^3

V_v = total volume of voids = L^3

Primary porosity is the original void space created when the rock or soil was formed. In soil and sedimentary rock, the primary voids are the spaces between the mineral grains or pebbles. Sediment shape (sphericity and roundness), orientation, sorting and packing, generally determine primary porosity. Angularity of sediment may increase or decrease porosity, depending if the particles bridge openings or are packed together like pieces of a mosaic (Lohman, 1972). Well sorted sediment has greater porosity compared to poorly sorted sediment, because in poorly sorted sediment the smaller grains take up space between the larger grains, which reduces total porosity (Fig.4.4).

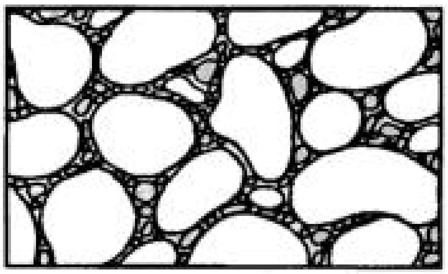


Figure 4.4.

Fine-grained materials tend to be well sorted and generally have large porosities. Clay often contains a porosity of 50%, silt 40%, sand 30% and gravel 25%; therefore, it can be generalized, that porosity by volume in clastic material increases as the actual grain size decreases. **Be careful of such generalities.** Porosity of clastic material of nearly uniform particle size is nonsensitive to actual particle size (McWhorter and Sunada, 1977). It can be shown, that for perfect spheres, porosity is independent of the size of the spheres. A volume of uniformly packed bowling balls has the same porosity as a volume of baseballs or marbles or beebees. In general, primary porosity increases with sphericity and roundness, but the highest degree of primary porosity often occurs in unconsolidated, subangular, well sorted sediment. Primary porosity in igneous and metamorphic rocks is usually negligible. If it exist, as in the extrusive rock pumice, the pore spaces are not connected; therefore, ground water cannot flow.

Secondary porosity is much more important in regard to igneous and metamorphic rocks. Secondary porosity develops after the material has formed. The cementing agent in a sedimentary rock reduces primary porosity, because it occupies part of the voids (Fig. 4.5). Fractures, joints and faults can develop in all rocks after formation, which can increase porosity (Fig. 4.6).

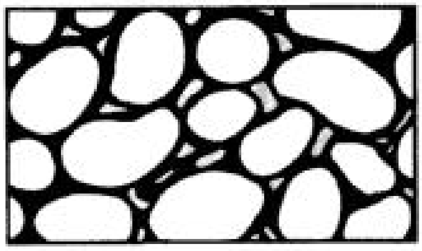


Figure 4.5.

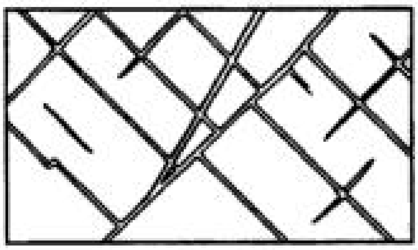


Figure 4.6.

Solution cavities that occur along joints and bedding planes in limestone, dolomite and other carbonate rocks greatly increase porosity (Fig. 4.7). The solution and transport of easily dissolvable mineral salts, such as halite, anhydrite and gypsum, from within sedimentary beds, can also increase porosity.

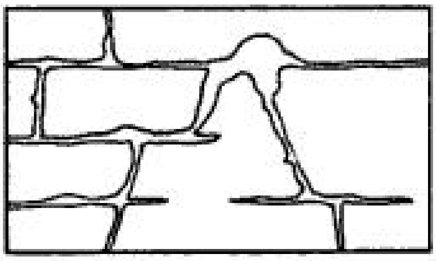


Figure 4.7.

Repacking of earth material due to stresses applied by overburden, earthquakes, landslides and subsidence can reduce primary porosity. When considering spheres, the least compact arrangement produces the greatest porosity -- about 47.6% -- this is called **cubic packing** (Fig. 4.8). The most compact arrangement, **rhombohedral packing**, produces the least porosity --- about 26% (Slichter, 1899). Therefore, the shape of the grains can increase or decrease porosity depending on how they are packed. Angular and irregular shaped, unconsolidated particles, tend to have larger porosities, although the difference is not always substantial (McWhorter and Sunada, 1977).

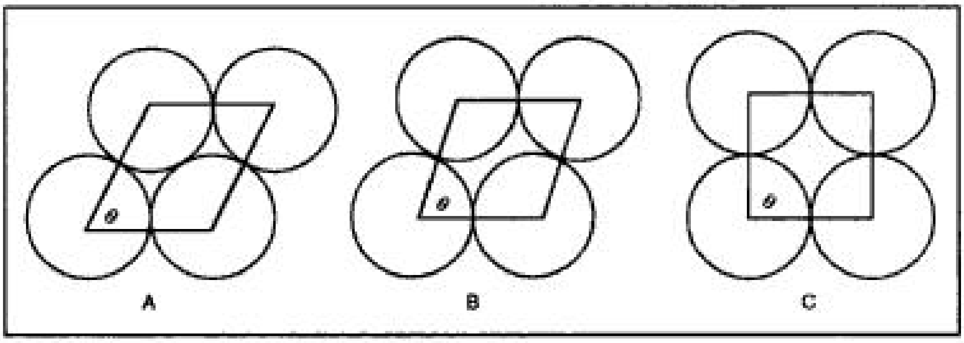


Figure 4.8. Porosity values resulting from different "packing" arrangements. "A" is the most compact arrangement, which has the lowest porosity. "B" has a higher porosity, because its compact arrangement is less than "A". "C" has the least compact arrangement and the highest porosity (after Slichter, 1899).

Porosity can range from 0 in crystalline rocks up to 60% for recent sedimentary deposits and dried, powdery clay. Values generally range between 20 to 50% for most clastic material (Table 4.1). On a relative scale clay has the highest porosity by volume (45-60%), even though clay impedes and often confines ground-water movement. Clays are comprised of extremely tiny plate-like particles with relatively large surface areas, which cause high-molecular attraction between the clay and water. Even though clays by volume have a high percent of voids, these pore spaces are microscopic, which prevents the easy flow of water through clays. In addition, water is often hydrated or absorbed by clay particles, filling the tiny pores, and becoming part of

Table 4.1. Representative values of porosity and specific yield.

SEDIMENTARY MATERIAL	POROSITY PERCENT	SPECIFIC YIELD PERCENT
GRAVEL, COARSE	23.8 - 36.5 - R	13.2 - 25.2
GRAVEL, MEDIUM	23.7 - 44.1 - R	16.9 - 43.5
GRAVEL, FINE	25.1 - 38.5 - R	12.6 - 39.9
SAND, COARSE	30.9 - 46.4 - U	18.4 - 42.9
SAND, MEDIUM	28.5 - 48.9 - U	16.2 - 46.2
SAND, FINE	26.0 - 53.3 - U	1.0 - 45.9
SILT	33.9 - 61.1- U	1.1 - 38.6
CLAY	34.2 - 56.9 - U	1.1 - 17.6
SANDSTONE, FINE-GRAINED	13.7 - 49.3 - U	2.1 - 39.6
SANDSTONE, MEDIUM-GRAINED	29.7 - 43.6 - U	11.9 - 41.1
LIMESTONE	6.60 - 55.7 - U	0.2 - 35.8
DOLOMITE	19.1 - 32.7- U	---
DUNE SAND	39.9 - 50.7 - U	32.3 - 46.7
LOESS	44.0 - 57.2 - U	14.1 - 22.0
PEAT	92 - U	44
SILTSTONE	21.2 - 41.0 - U	0.9 - 32.7
CLAYSTONE	41.2 - 45.2 - U	--
TILL, HIGH CLAY CONTENT	--	--
TILL, HIGH SILT CONTENT	29.5 - 40.6 - U	0.5 - 13.0
TILL, HIGH SAND CONTENT	22.1 - 36.7 - U	1.9 - 31.2
TILL, HIGH GRAVEL CONTENT	22.1 - 30.3 - R	5.1 - 34.2
WASHED DRIFT WITH CLAY	38.4 - 59.3 - U	33.2 - 48.1
WASHED DRIFT WITH SILT	36.2 - 47.6 - U	29.0 - 48.2
WASHED DRIFT WITH SAND	34.6 - 41.5 - U	---

R = repacked sample; U = undisturbed.
Source: USGS Water Supply Papers 1662-D and 1839-D.

the structure of clay, in essence, impeding the movement of new water through the clay. This is especially true of expanding or swelling clays such as montmorillonite.

4.4 EFFECTIVE POROSITY

The discussion in Section 4.3 assumes that the pore spaces between sediment or rock are interconnected, which would allow ground water to flow from one location to another. This is referred to as **effective porosity** (n_e). Volcanic rocks like pumice and scoria have an abundance of voids that formed when hot gasses escaped; but the spaces are generally not connected; therefore, when considering ground-water flow, such rocks are useless.

Effective porosity applies to all types of rocks. In order for igneous and metamorphic rocks to have effective porosity the joints, faults or fractures must link together to form a natural conduit system. The fundamental importance of effective porosity, for any earth material, is to act as a natural pipeline through which ground water can move. For most practical field applications $n_e = n$, although some investigators contend that effective porosity is equal to specific yield.

4.5 SPECIFIC YIELD

The volume of water that will drain from soil or rock under the influence of gravity is called **specific yield** (S_y). It can be expressed by the following ratio (Meinzer, 1923):

$$S_y = \frac{V_g}{V_T} \tag{4.2}$$

where, for consistent units,

S_y = specific yield as a decimal fraction = unitless
V_g = volume of water drained by gravity = L^3
V_T = total volume = L^3.

Specific yield represents the amount of water that can be available for supply and consumption. It is maximum in sediment ranging from medium to coarse-grained sand (Cohen, 1965). Values of specific yield depend upon grain size, shape, sorting, compaction and time of drainage. Angular and well rounded particles tend to have higher specific yields when compared to subangular particles, especially when subangular particles are compacted in a dense arrangement. After drainage is complete, a thin film of water will remain on the surface of sediment due to surface tension. This is referred to as **specific retention** (S_r) by hydrogeologists and civil engineers, and as **field capacity** by soil scientists. Material dominated by finer grain sizes will have more surface area on which the thin film of water can cling to; therefore, specific retention increases with decreasing grain size. In general, poorly sorted sediment has a higher specific retention, when compared to well sorted samples, due to the increase in surface area. Specific retention can be expressed by the following ratio (Meinzer, 1923):

$$S_r = \frac{V_r}{V_T} \tag{4.3}$$

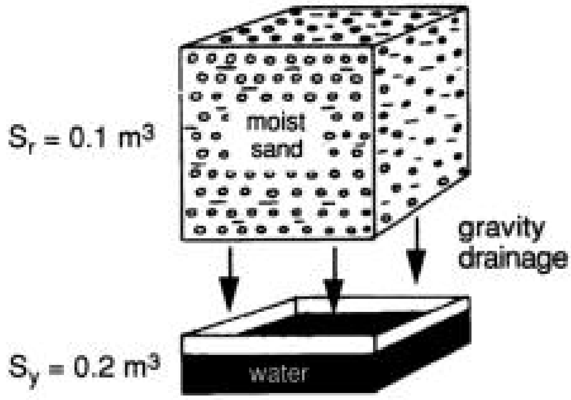
where, for consistent units,

S_r = specific retention as a decimal fraction = unitless
V_r = volume of water retained against gravity = L^3
V_T = total volume = L^3.

Porosity can be expressed as the sum of specific yield and specific retention:

$$n = \frac{V_g}{V_T} + \frac{V_r}{V_T} = S_y + S_r \tag{4.4}$$

The relationship between porosity, specific yield and specific retention is depicted in Figure 4.9.



$$n = S_y + S_r = \frac{0.2\ m^3}{1.0\ m^3} + \frac{0.1\ m^3}{1.0\ m^3} = 0.3$$

Figure 4.9. Relationship between n, S_y, and S_r, (modified from Heath, 1983).

4.6 MEASURING POROSITY AND SPECIFIC YIELD

Volume methods can be used to measure porosity and specific yield. A sample is dried to a constant weight and then saturated. Porosity is equal to the difference between the saturated volume and the original volume. If this sample is allowed to drain to completion, so that evaporation is not a factor, then specific yield is the drained volume of water. Specific retention is the difference between porosity and specific yield.

Example 4.1

A container is filled with 42.7 cm^3 of loose sand. This volume of sand is poured into a graduated cylinder partially filled with water. It is recorded that 28.4 cm^3 of water are displaced. The displaced volume is the volume of solids. Use equation (4.1) to determine porosity:

$$n = \frac{V_T - V_s}{V_T}(100) = \frac{42.7\ cm^3 - 28.4\ cm^3}{42.7\ cm^3} = 0.33 \qquad 4.1$$

Example 4.2

One cubic meter of uniform sand with a porosity of 0.30 is mixed with two cubic meters of uniform gravel that has a porosity of 0.25. What is the resulting porosity?

1) Pore space of gravel = 2(0.25) = 0.50 m^3
   Particles of gravel = 2(0.75) = 1.5 m^3

2) Particles of sand = 1(0.70) = 0.70 m^3
   Remaining volume of sand after the voids in the gravel are filled with sand:

   $1.00\ m^3 - 0.50\ m^3 = 0.50\ m^3$

3) $$n = \frac{V_T - V_s}{V_T}(100) = \qquad 4.1$$

$$\frac{(2.0\ m^3\ \text{gravel} + 0.50\ m^3\ \text{sand}) - (1.5\ m^3\ \text{gravel} + 0.70\ m^3\ \text{sand})}{(2.0\ m^3\ \text{gravel} + 0.50\ m^3\ \text{sand})} = 0.12$$

Example 4.3

The water table at the upper surface of an unconfined sand aquifer declines 7.6 meters ($\Delta h = 7.6$ m). The areal extent of the aquifer is about 10 km^2. The porosity of the sand is 40 percent. Specific retention is 12 percent. Rearrange equation (4.4) to calculate specific yield.

$$S_y = n - S_r = 0.40 - 0.12 = 0.28 \qquad (4.4.1)$$

What is the change in storage in m^3?

$$V_w = (S_y)(\Delta h)(A) = (0.28)(0.0076\ km)(10\ km^2) = 0.02128\ km^3$$
$$= 2.1 \times 10^7\ m^3$$

4.7 THE STORAGE COEFFICIENT

The **storage coefficient** (S) is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer when the head is lowered a unit distance (Heath, 1983):

$$S = \frac{\text{volume of water}}{(\text{unit area})(\text{unit change in head})} = \frac{(L^3)}{(L^2)(L)} = \frac{L^3}{L^3} = \text{unitless} \tag{4.5}$$

Head is the height of a column of water above a datum plane. In practical application, head is the elevation of water in a well. The storage coefficient for most unconsolidated and many loosely consolidated aquifers can be expressed as:

$$S = S_y + bS_s \tag{4.6}$$

where, for consistent units,

S_s = **specific storage** (Jacob, 1940,1950 and Cooper, 1966)

and

$$S_s = \rho_w g(\phi + n\beta) = n\gamma\beta + \phi\gamma = 1/L \tag{4.7}$$

β = compressibility of water = LT^2 / M: m^2 / N
ϕ = compressibility of aquifer skeleton = LT^2 / M: m^2 / N
g = acceleration due to gravity = L / T^2: m / s^2
ρ_w = density of water = M / L^3: kg / m^3
n = porosity = unitless
γ = specific weight of water = M / L^2T^2: N / m^3
b = aquifer thickness = L: m.

Specific storage (S_s) is the volume of water a unit volume of saturated aquifer stores or releases from storage per unit decline in hydraulic head. It is considered to be a constant with units of 1/L generally expressed as 1/m or 1/ft. The volume of water derived from specific storage in an unconfined aquifer is often negligible; therefore, when considering storage in a water table aquifer, the third term in equation (4.6) is neglected. Units cancel by the following relationship:

$$S_y = \frac{\text{volume of water}}{(\text{unit area})(\text{unit change in head})} = \frac{(L^3)}{(L^2)(L)} = \frac{\text{volume of water drained}}{\text{total volume of water}} = \frac{L^3}{L^3} = \text{unitless.}$$

Ground water drains under the force of gravity in an unconfined aquifer, and when drainage occurs the water table declines. The storage coefficient for a water table or unconfined aquifer generally ranges between 0.1 to 0.3.

4.8 STORAGE IN ELASTIC CONFINED AQUIFERS

The storage coefficient for an elastic confined aquifer, **storativity** is the product of specific storage (S_s) and the aquifer thickness (b): $S = S_s b$. It is not as intuitive as specific yield. Water released from storage in an elastic confined aquifer results from compressionof the aquifer and expansion of water. The overburden on top of a confined aquifer is supported by both sediment comprising the aquifer and hydraulic pressure exerted by the water in the aquifer. As the head declines in a confined aquifer water is released, but the aquifer remains filled with water. Hydraulic pressure is reduced as ground water is forced from the pores. Increased support of the overburden is transferred to the aquifer skeleton, the aquifer compacts, and the water forced from the pores represents that part of the storage coefficient due to compression. The aquifer remains filled with water because the pore spaces have been reduced (Fig. 4.10).

Hooke's Law states that strain is proportional to stress within the elastic limit; therefore, compressibility of the aquifer can be expressed by equation (4.8)(Table 4.2):

$$\phi = \frac{\Delta b / b}{\Delta P} \tag{4.8}$$

where, for consistent units,

ϕ = compressibility of the elastic confined aquifer = LT^2 / M: m^2 / N
b = original aquifer thickness = L: m
Δb = change in aquifer thickness = L: m
ΔP = change in hydraulic pressure = M / LT^2: N / m^2.

Table 4.2. Compressibility range of some earth material.

Material	Compressibility Range
Clay	10^{-6} to 10^{-8} m^2 / N
Sand	10^{-7} to 10^{-9} m^2 / N
Gravel	10^{-8} to 10^{-10} m^2 / N
Jointed Rock	10^{-8} to 10^{-10} m^2 / N
Competent Rock	10^{-9} to 10^{-11} m^2 / N
Water	4.4×10^{-10} to 4.6×10^{-10} m^2 / N

The amount of compaction or land subsidence for an elastic confined aquifer can be determined using equation (4.9):

$$\Delta b = \Delta P\left(\frac{S}{\gamma} - nb\beta\right) \tag{4.9}$$

where, for consistent units,

Δb = change in aquifer thickness = L: m
ΔP = change in hydraulic pressure = M / LT^2: N / m^2.
S = storage coefficient = $S_s b$ = unitless
γ = specific weight = M / L^2T^2: N / m^3
n = porosity = unitless
b = original aquifer thickness = L: m
β = compressibility of water = LT^2 / M: m^2 / N.

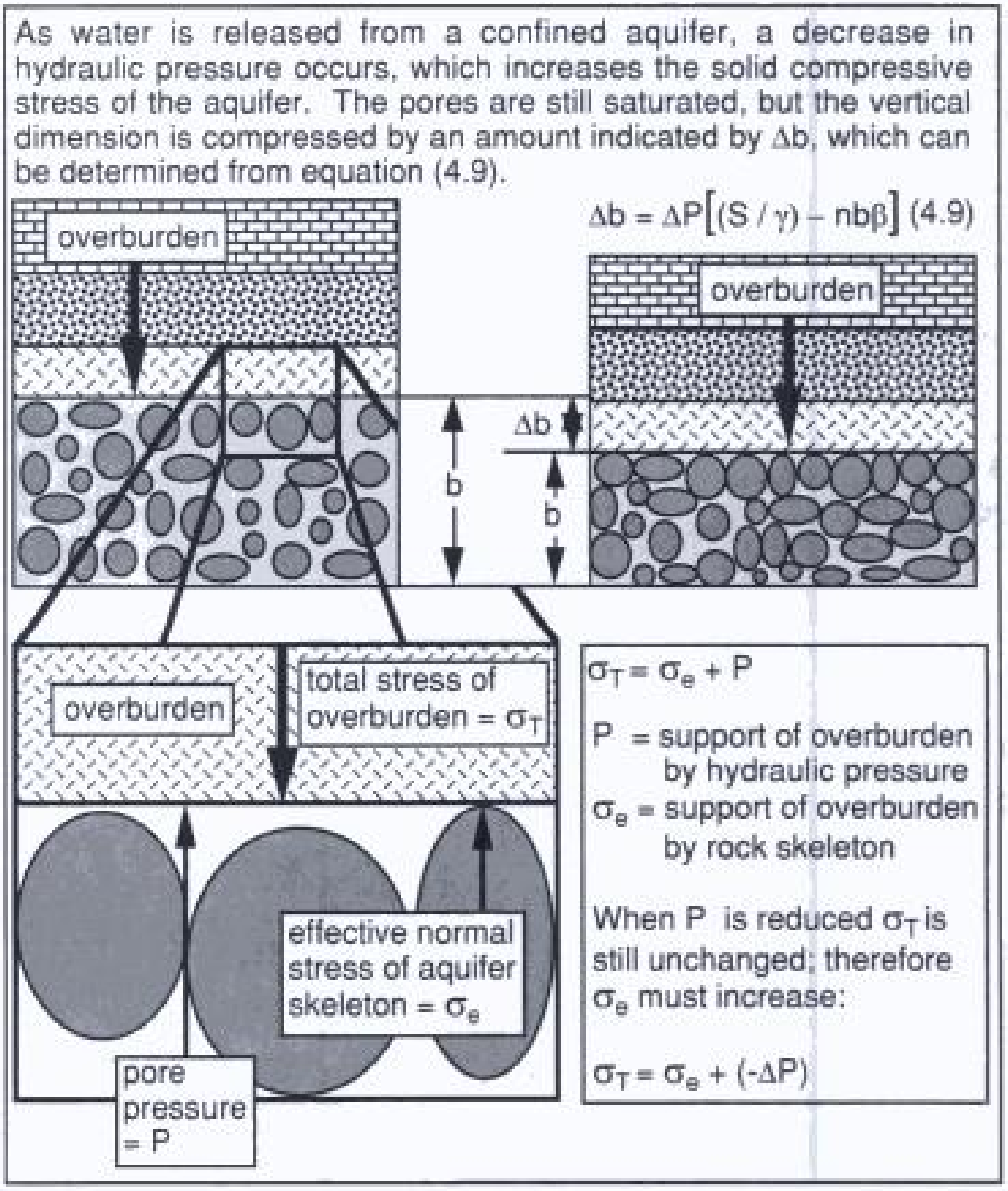


Figure 4.10. Water released from compressive storage in an elastic confined aquifer.

That part of the storage coefficient that results from the expansion of water (S_w) is small and is given by the following equation (Walton, 1962):

$$S_w = 4.6\times10^{-6}(nb)\text{, where n = porosity and b = aquifer thickness in meters.} \quad (4.10)$$

The English equivalent of equation (4.10) is

$$S_w = 1.4\times10^{-6}(nb)\text{, where b = feet.} \quad (4.11)$$

For consistent units

$$S_w = bn\gamma\beta \quad (4.12)$$

where

γ = ρg = specific weight of water = $M / L^2 / T^2$: N / m^3 (Table 1.4)
β = compressibility of water = LT^2 / M: m^2 / N (Table 1.4).

That part of the storage coefficient due to compression can be expressed as

$$S_c = b\phi\gamma \quad (4.13)$$

where, for consistent units,

ϕ = compressibility of the aquifer skeleton = LT^2 / M: m^2 / N

If the storage coefficient is known, equations (4.14) and (4.15) can be used to calculate that part of the storage coefficient that results from compression of the aquifer (S_c):

$$S_c = S - (4.6\times10^{-6}(nb)) = S - S_w \quad \text{(SI)} \quad (4.14)$$

$$S_c = S - (1.4\times10^{-6}(nb)) = S - S_w \quad \text{(English)} \quad (4.15)$$

Storativity can be expressed as:

$$S = b[\rho_w g(\phi + n\beta)] = b(n\gamma\beta + \phi\gamma) = bS_s \quad (4.16)$$

where

b = saturated aquifer thickness in a consistent unit.

An alternative expression for equation (4.16) is (Lohman, 1972):

$$S = n\gamma b\left(\beta + \frac{\phi}{n}\right). \quad (4.17)$$

Lohman (1972) used the relationship described by equation (4.11) to predict storativity using only the confined aquifer thickness (b = ft):

$$S = b(1.0 \times 10^{-6}). \qquad (4.18)$$

The metric equivalent for equation (4.18) is

$$S = b(3.281 \times 10^{-6}) \qquad (4.19)$$

where

b = aquifer thickness in meters.

For a confined aquifer, the second term in equation (4.6) is neglected. Units cancel by the following relationship:

$$S = bS_s = (\text{ft})\left(\frac{1}{\text{ft}}\right) \qquad (4.20)$$

or by definition

$$S = \frac{\text{volume of water}}{(\text{unit area})(\text{unit change in head})} = \frac{(L^3)}{(L^2)(L)} = \frac{L^3}{L^3} = \text{unitless} \qquad 4.5$$

The storage coefficient for a confined aquifer generally ranges between 0.00001 and 0.001. The storage coefficient for a leaky confined aquifer often ranges between 0.001 and 0.1.

4.9 UTILIZING THE STORAGE COEFFICIENT

A simple equation can be used to estimate the amount of water released from storage:

$$V_w = (S)(\Delta h)(A) \qquad (4.21)$$

where, for consistent units,

S = storage coefficient = unitless
V_w = volume of water released from storage = L^3
Δh = change or decline in the potentiometric surface or water table = L
A = area of aquifer = L^2.

Example 4.4

Calculate the change in storage (V_w) for a confined aquifer over 5.0 km². Assume a typical confined storage value of 0.0002. The Δh = 1.7 m. Determine V_w in both m³ and gallons.

$$V_w = (0.0002)(1.7\ \text{m})(5.0 \times 10^6\ \text{m}^2) = 1700\ \text{m}^3 \qquad 4.21$$

$$1700\ \text{m}^3 = 4.50 \times 10^5\ \text{gallons}$$

Clearly, large volumes of water can be released from confined aquifers even though the storage coefficient is small.

Example 4.5

Equation (4.10) can be used to calculate that part of the storage coefficient that results only from the expansion of water (S_w).

$$S_w = 4.6 \times 10^{-6}(\text{nb}) \qquad 4.10$$

For example: if n = 0.1 and b = 91 m, then S_w = 0.000042. Equation (4.10) offers a check in regard to the storage coefficient. When $S_w \geq S$ then the determined storage coefficient is incorrect.

Example 4.6

The storage coefficient can also be used in equation (4.9) to predict land subsidence for an elastic confined aquifer (Lohman, 1972):

$$\Delta b = \Delta P\left(\frac{S}{\gamma} - nb\beta\right) \qquad 4.9$$

For example, when

ΔP = 6,895,000 N / m²
S = 0.00035
γ = 9800 N / m³ (from Table 4)
n = 0.1
b = 91.44 m, and
β = 4.6×10^{-10} m² / N (from Table 1.4)

$$\Delta b = 6895000\ \text{N / m}^2\left(\frac{0.00035}{9800\ \text{N / m}^2} - (0.1)(91.44\ \text{m})(4.6 \times 10^{-10}\text{m}^2/\ \text{N})\right) = 0.22\ \text{m}.$$

Example 4.7

The storage coefficient can be calculated using equation (4.17)

$$S = n\gamma b\left(\beta + \frac{\phi}{n}\right); \qquad 4.17$$

For example (data from Ferris et al., 1962),

γ = $9800\ N/m^3$ (from Table 4)

n = 0.3

b = 15.24 m

β = $4.6\times10^{-10}\ m^2/N$ (from Table 1.4)

ϕ = $2.93\times10^{-10}\ m^2/N$.

$$S = (0.3)(9800\ N/m^2)(15.24\ m)\left((4.6\times10^{-10} m^2/N) + \frac{2.93\times10^{-10} m^2/N}{0.3}\right) = 0.000064.$$

Example 4.8

The storage coefficient can also be used to calculate, ϕ, the compressibility of the aquifer skeleton, by rearranging equation (4.17):

$$S = n\gamma b\left(\beta + \frac{\phi}{n}\right); \qquad 4.17$$

$$\phi = \left(\frac{S}{n\gamma b} - \beta\right)n \qquad (4.22)$$

For example, using equation (4.22) (data from Ferris et al., 1962),

S = 0.00006437

γ = $9800\ N/m^3$ (from Table 4)

n = 0.3

b = 15.24 m

β = $4.6\times10^{-10}\ m^2/N$ (from Table 1.4)

$$\phi = \left(\frac{0.00006437}{(0.3)(9800\ N/m^2)(15.24\ m)} - 4.6\times10^{-10} m^2/N\right)0.3 = 2.93\ x\ 10^{-10} m^2/N.$$

Hooke's Law can also be used to solve for ϕ,

$$\phi = \frac{\Delta b / b}{\Delta P}. \qquad 4.8$$

Example 4.9

The original thickness of an elastic confined aquifer is 38.10 m. The aquifer compacts 0.152 m after the head is lowered 19.81 m. Calculate the vertical compressibility of the aquifer using equation (4.8). Once this has been completed, calculated S_s and S.

$\Delta P = \Delta h$ in equation (4.8), therefore, Δh must be converted to hydraulic pressure, which can be expressed as

$$\Delta P = \Delta h(\rho g) = \Delta h(\gamma)$$

then

$$\Delta P = \Delta h(\gamma) = (19.81 \text{ m})(9800 \text{ N/m}^3) = 194{,}138 \text{ N / m}^2.$$

Using equation (4.8) with the given data results in

$$\phi = \frac{\Delta b / b}{\Delta P} = \frac{(0.152 \text{ m}) / (38.10 \text{ m})}{194{,}138 \text{ N / m}^2} = 2.0 \times 10^{-8} \text{m}^2 / \text{N}. \qquad 4.8$$

Now use the resulting and given data to calculate specific storage (S_s) and the storage coefficient (S). Porosity = n = 0.1; $\gamma = \rho g$.

From Table 1.4: $\beta = 4.6 \times 10^{-10} \text{ m}^2/\text{N}$

$$S_s = \rho_w g(\phi + n\beta) = 1 / L \qquad 4.7$$

$$S_s = \left(\frac{9800 \text{ N}}{\text{m}^3}\right)\left(2.0\times10^{-8}\frac{\text{m}^2}{\text{N}} + (0.1)\left(4.6\times10^{-10}\frac{\text{m}^2}{\text{N}}\right)\right) = 0.000196\frac{1}{\text{m}}$$

or

$$S_s = n\gamma\beta + \phi\gamma = 1 / L$$

$$S_s = \left[(0.1)\left(9800 \ \frac{\text{N}}{\text{m}^3}\right)\left(4.6\times10^{-10}\frac{\text{m}^2}{\text{N}}\right)\right] + \left[\left(2.0\times10^{-8}\frac{\text{m}^2}{\text{N}}\right)\left(9800 \ \frac{\text{N}}{\text{m}^3}\right)\right] = 0.000196\frac{1}{\text{m}}$$

Example 4.10 Water Balance

A groundwater basin in a coastal area has an area of 510 km^2. The land area is 500 km^2 and the area of the river is 10 km^2. There is no stream flow or groundwater flow into the basin. A water budget for the basin has the following long-term average annual values.

Precipitation	Evapotranspiration	Overland flow	Baseflow	Runoff	Sub-sea outflow
875 mm/yr	575 mm/yr	75 mm/yr	150 mm/yr	225 mm/yr	75 mm/yr

Notes:

- In order to prepare a water budget, identify all parameters in and out for each component assuming steady conditions.
- River flow or runoff is a combination of land flow and Baseflow.

1 Prepare an annual water budget for the basin as a whole.
2 Prepare an annual water budget for the river.
3 Prepare an annual water budget for the groundwater reservoir.
4 What is the annual river flow from the basin in m^3/sec?
5 What is the average rate of groundwater recharge in million m^3 per day per km^2 of surface area?

Answer 4.10

1 Water Budget for **the Whole Basin**

<table>
<tr><th></th><th>In</th><th>Out</th></tr>
<tr><td rowspan="3"></td><td rowspan="3">Precipitation = 875 mm</td><td>Evaporation = 575 mm</td></tr>
<tr><td>Runoff = 225</td></tr>
<tr><td>Sub-sea flow = 75 mm</td></tr>
<tr><td>Sum</td><td>875</td><td>875</td></tr>
</table>

2 Water Budget for **the River**

<table>
<tr><th></th><th>In</th><th>Out</th></tr>
<tr><td rowspan="2"></td><td>Over land flow = 75 mm</td><td rowspan="2">Runoff = 225</td></tr>
<tr><td>Base flow = 150 mm</td></tr>
<tr><td>Sum</td><td>225</td><td>225</td></tr>
</table>

3 Water Budget for the **Groundwater Reservoir**

	In	Out
	Prec. - Overland flow - Evap. = 875 - 75 - 575 (mm)	Baseflow = 150 mm
		Sub-sea flow = 75 mm
Sum	**225**	**225**

4 **Runoff** = 225 mm/yr

= $(0.225 \text{ m} \times 510 \times 10^6 \text{ m}^2) / (365 \times 24 \times 60 \times 60)$
= **3.64 m^3/sec.**

5 **Recharge** = 225 mm/yr

= 0.225 m/yr = 0.225 m/ 365 = 6.164×10^{-4} m/day.

= 6.164×10^{-4} m^3/m^2 per day = 6.164×10^{-4} $m^3/(m^2 \times 10^{-6} km^2/m^2 \times day)$

= $6.164 \times 10^{-4} \times 10^6$ m^3 per day per km^2

= **1.164×10^{-4} million m^3 per day per km^2.**