GROUND WATER ENGINEERING

Unit 1

Lectures 1 to 6

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SYLLABUS

- **Unit I:**
  - ✓ ***Introduction: Role of groundwater in hydrological cycle, groundwater bearing formations, classification of aquifers, flow and storage characteristics of aquifers, Darcy's law, anisotropy and heterogeneity.***
- **Unit II:**
  - ✓ ***Governing Equations for Groundwater Flow: Dupuit- Forchheimer assumptions, general differential equations governing groundwater flows, analytical solutions.***
- **Unit III:**
  - ✓ ***Wells and Well Hydraulics: Types of wells, construction of wells, steady and unsteady state solutions for confined, unconfined and leaky aquifers, effect of boundaries, image well theory, interference of wells, well losses, pumping and recovery test analysis.***

SYLLABUS

- **Unit IV:**
  - ***Groundwater Conservation: Regional groundwater budget; resource assessment; estimation of recharge, Indian practice for artificial recharge,***
  - ***Groundwater Quality: Contamination of groundwater, sources, remedial and preventive measures, seawater intrusion in coastal aquifers.***
- **Unit V:**
  - ***Groundwater Flow Modeling: Role of groundwater flow models, Hele-Shaw and analog models, introduction to numerical modeling – boundary conditions, Planning of Groundwater Development: constraints, optimal groundwater development.***

TEXT BOOKS

1) *Groundwater Hydrology by Todd and Mays*
2) *Groundwater Hydrology by H M Raghunath*
3) *Introduction to Groundwater by Schwartz and Hubao Zhang*
4) *Hand book of Groundwater by Jcques Delluer*
5) *Groundwater Assessment, Development and Management by K R Karant*

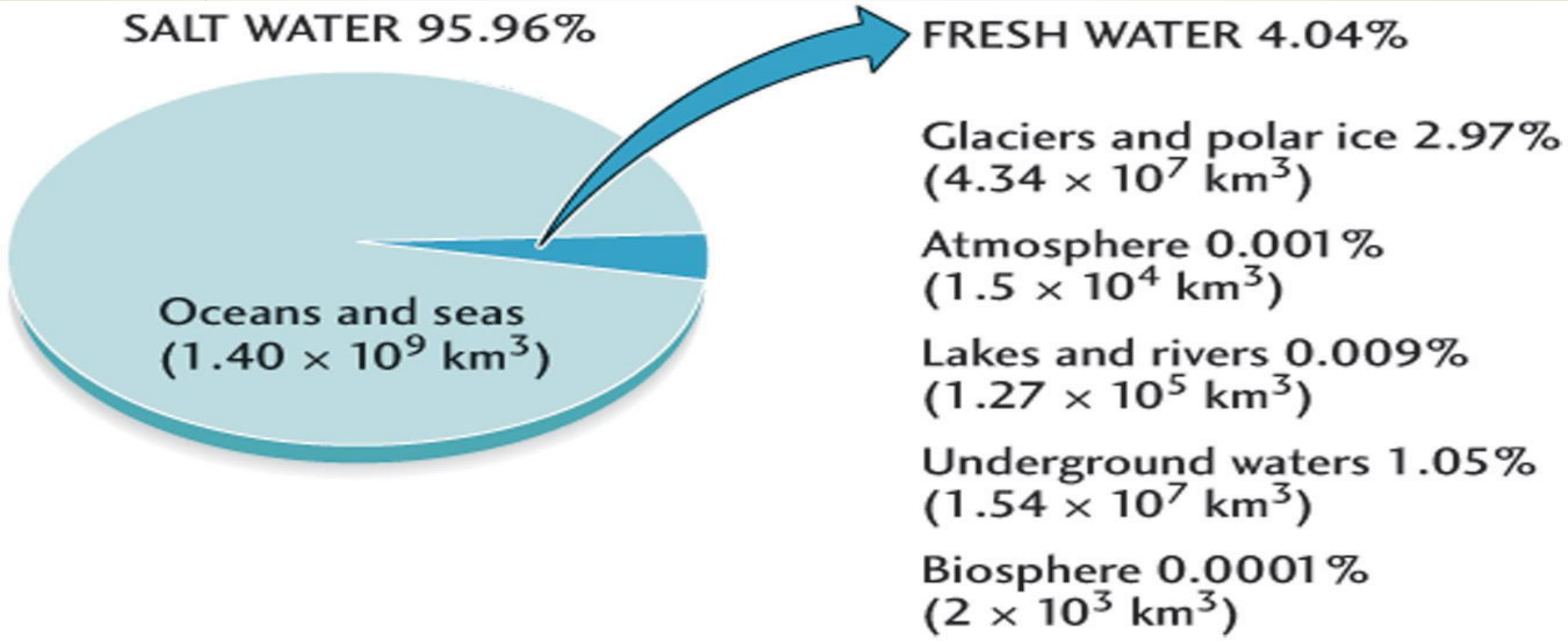
UNIT 1

- ***Introduction:***
  - ✓ *Role of groundwater in Hydrological Cycle,*
  - ✓ *Groundwater bearing formations,*
  - ✓ *Classification of aquifers,*
  - ✓ *Flow and storage characteristics of aquifers,*
  - ✓ *Darcy's law, anisotropy and heterogeneity.*

INTRODUCTION

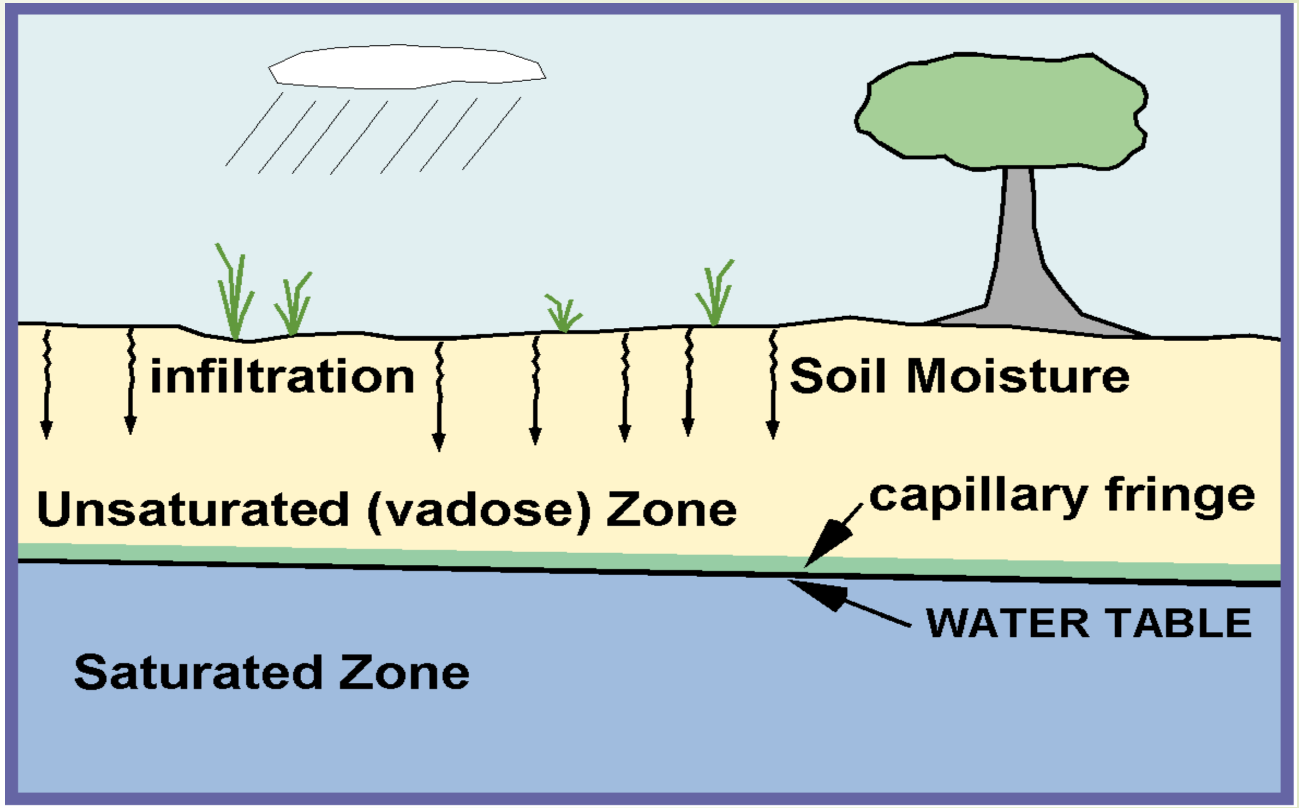
- *The total ground water potential is estimated to be one third the capacity of oceans.*
- *Source of Ground Water*
- *Practically the main source of all ground water is "Precipitation". A portion of the rain falling on the earth's surface infiltrates into ground, and travels down. When it is met with impervious layer, its movements are checked and ground water reservoir formed.*
- *Sometimes even "sea water enters the ground" along coasts where hydraulic gradients slope downward in an inland direction.*
- *Sometimes "artificial recharge" also occurs from excessive irrigation, canal seepage etc. water bearing formations of earth's crust act as conduits for transmission and storage reservoirs of water.*

Water Distribution on Earth



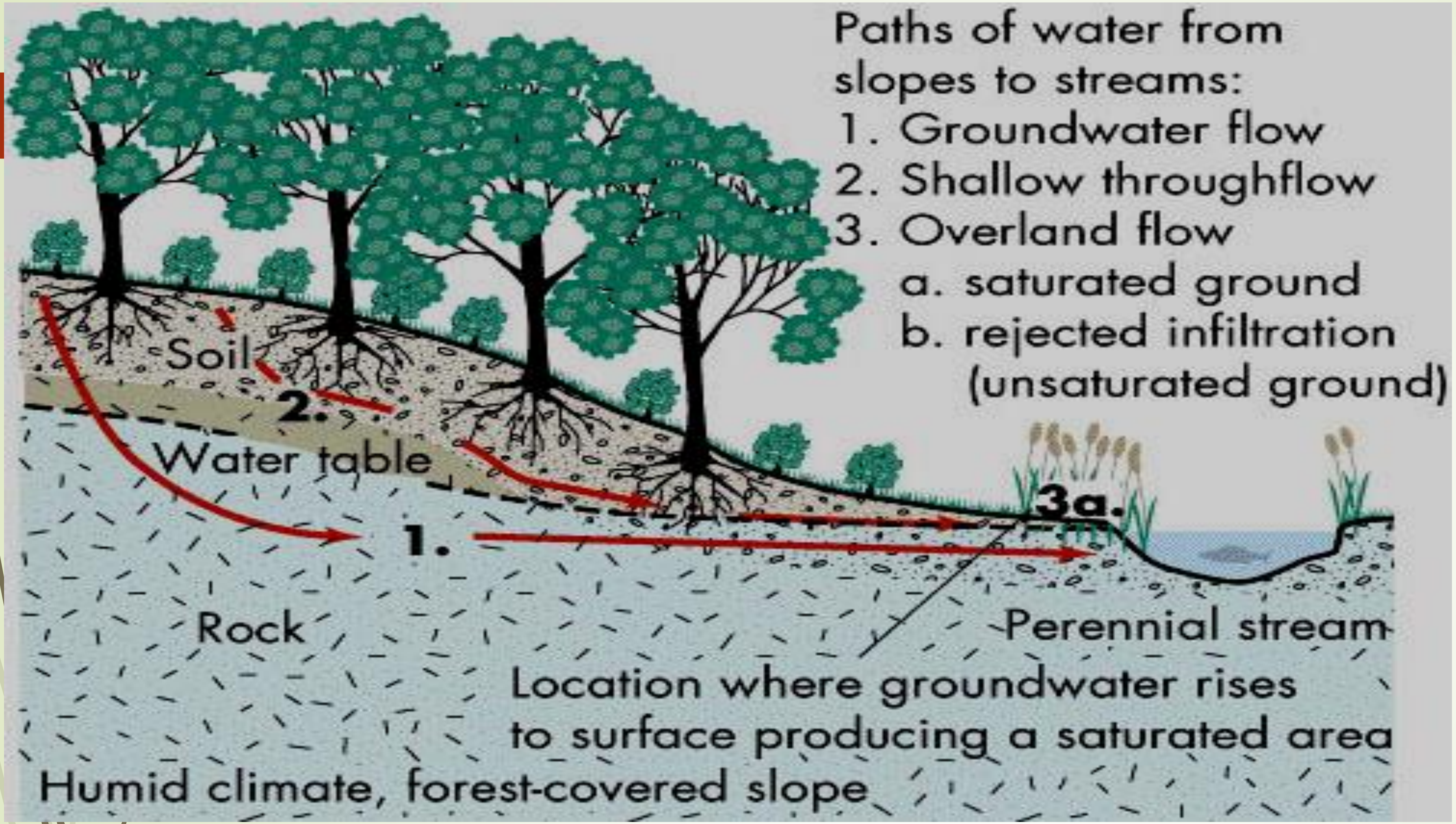
Essential components of groundwater

The rate of infiltration is a function of soil type, rock type, antecedent water, and time.



S. Hughes, 2003

The vadose zone includes all the material between the Earth's surface and the zone of saturation. The upper boundary of the zone of saturation is called the water table. The capillary fringe is a layer of variable thickness that directly overlies the water table. Water is drawn up into this layer by capillary action.



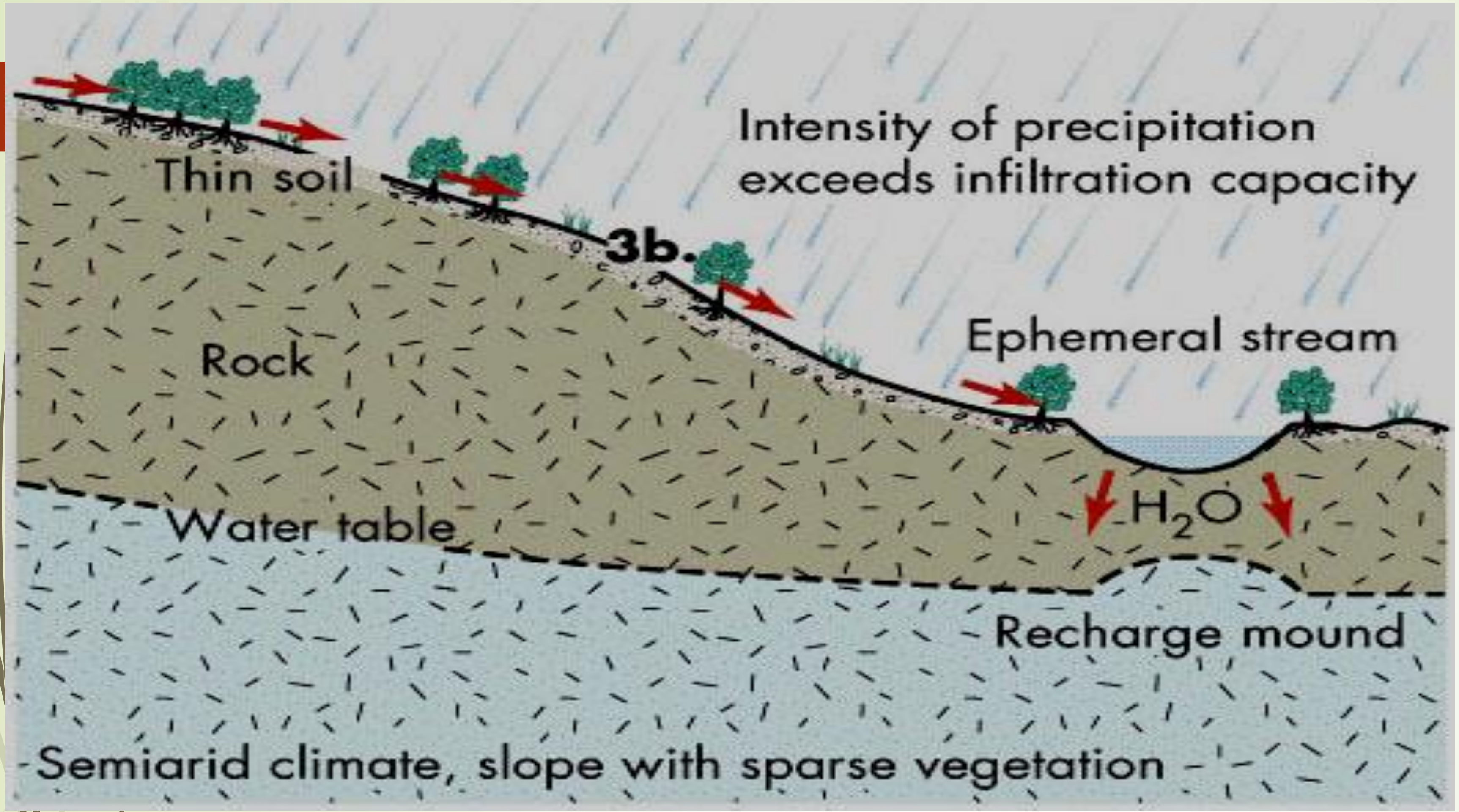
Perennial Stream (effluent)

- ***Humid climate***
- ***Flows all year -- fed by groundwater base flow (1)***
- ***Discharges groundwater***

S. Hughes, 2003

PECULIARITIES OF GROUNDWATER

- It is normally free from pollution but vulnerable to the pollution entering from the surface sources with infiltration.
- It can be made available on the surface at a small capital cost and in a short duration, but involves repetitive cost of energy for lifting it to the surface.
- It is very useful for domestic purposes, for small towns and isolated places since it requires minimum treatment.
- It is available up to a depth of 3 km.
- It is not an unlimited source and hence has to be managed against excessive exploitation and contamination.



Ephemeral Stream (influent)

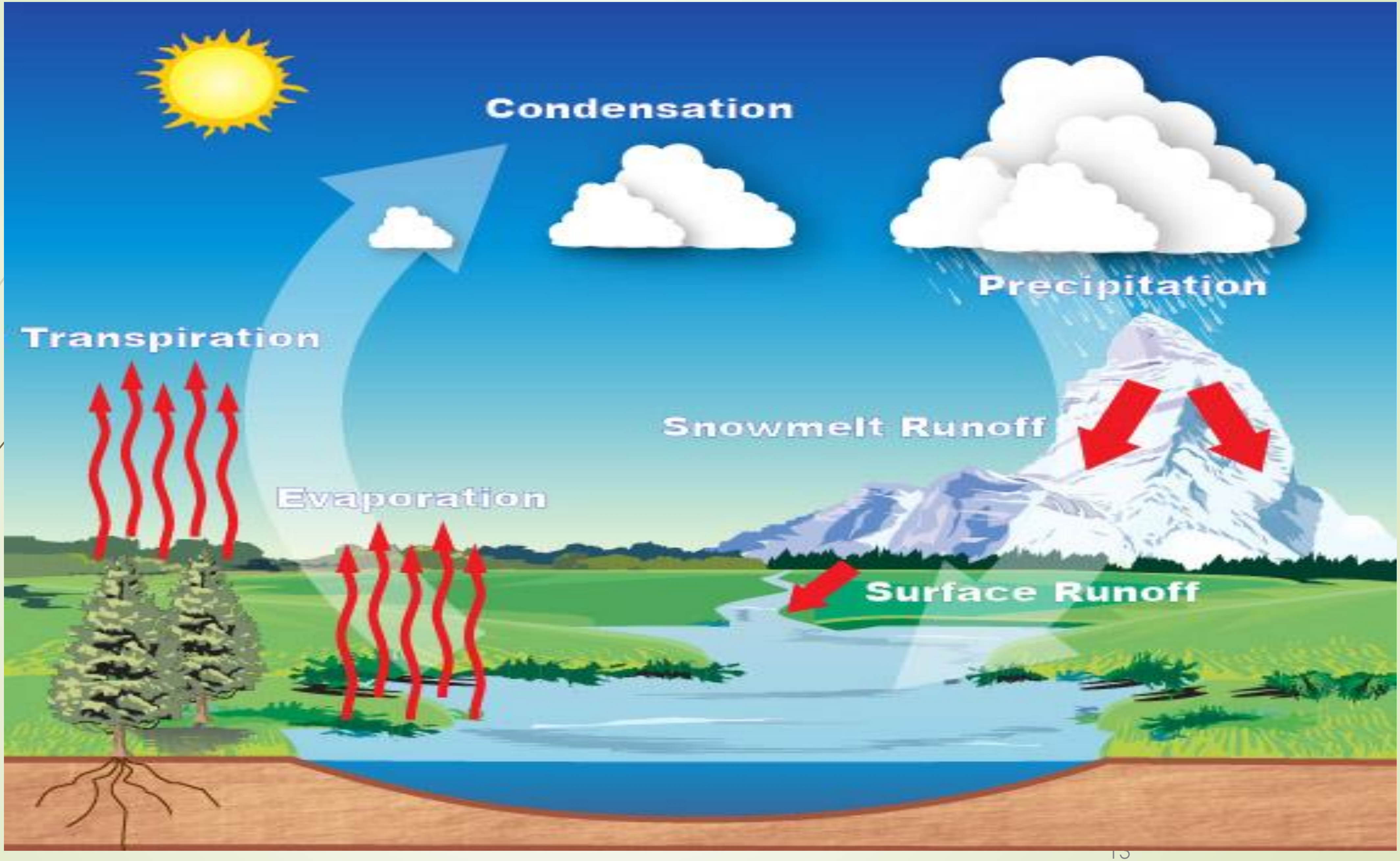
- ***Semiarid or arid climate***
- ***Flows only during wet periods (flashy runoff)***
- ***Recharges groundwater***

S. Hughes, 2003

HYDROLOGIC CYCLE

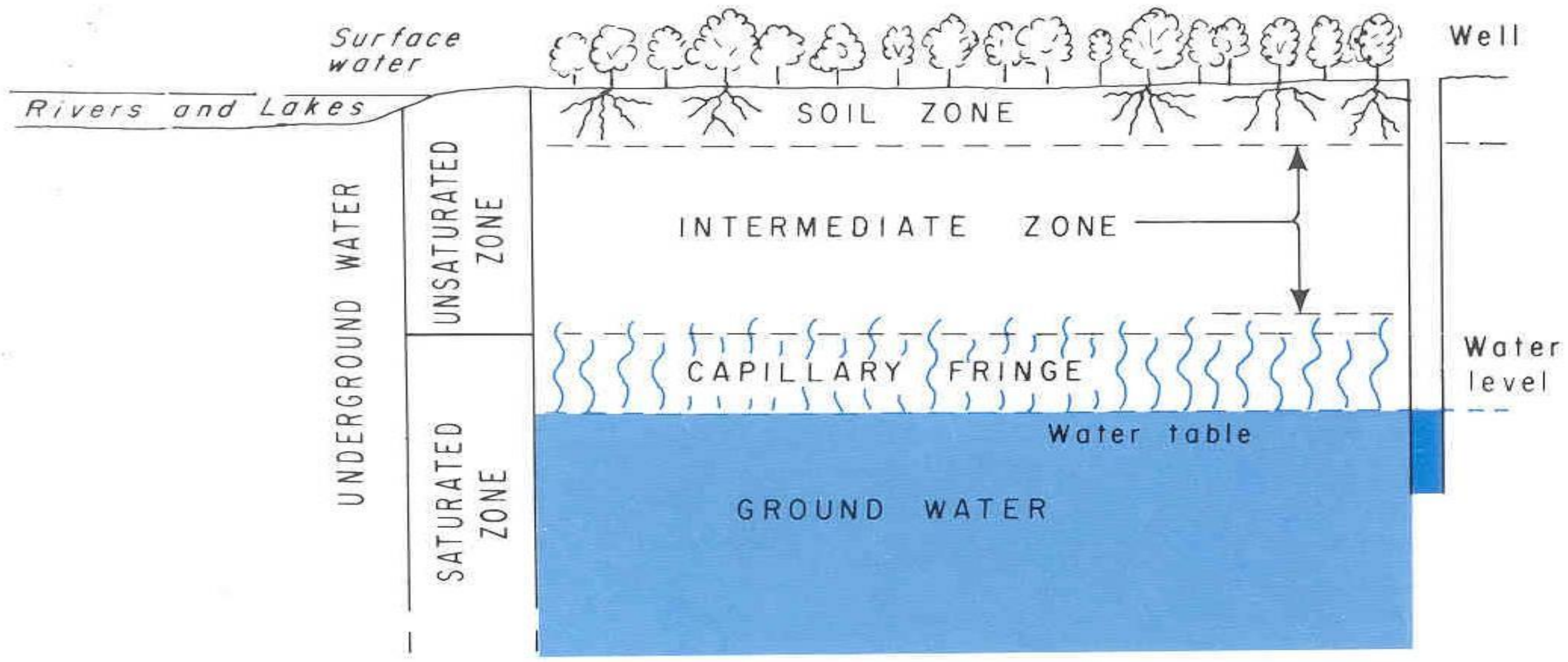
- **Cycle of Water**
  - **The basics that you already know:**
    - **Precipitation, percolation, runoff, evapotranspiration, groundwater, surface water**
  - **Sources of Drinking water**
    - **Groundwater and Surface Water0**
  - **Groundwater terms**
    - **Zone of aeration, zone of saturation, water table, aquifer, confined aquifer, & artesian well**

HYDROLOGIC CYCLE



PECULIARITIES OF GROUNDWATER

- ***It exhibits less fluctuations in alternate wet and dry periods as compared to the surface water.***
- ***It is free from weeds, plant organisms, turbidity and bacterial pollution.***
- ***It is uniform in quality, temperature, chemical composition and soluble mineral contents, compared to the surface water.***



UNDERGROUND WATER

VERTICAL DISTRIBUTION OF GROUNDWATER

The ground water can be divided into different zones as below:

Sub Surface Water

- **Aeration Zone**
  - **Soil Water Zone**
  - **Intermediate Zone**
  - **Capillary Zone**
- **Saturation Zone**

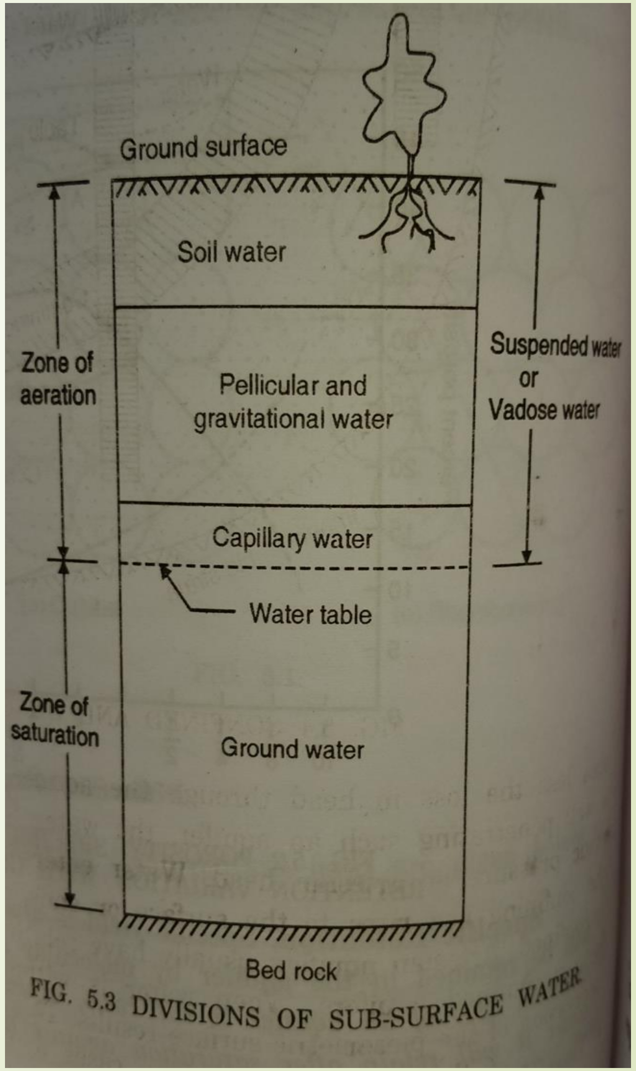


FIG. 5.3 DIVISIONS OF SUB-SURFACE WATER

- *The moisture diagram shown in Fig indicates the relative position of the soil water classes and equilibrium points.*
- *Saturation Zone: In this zone the interstices are partly filled with water and partly with air.*

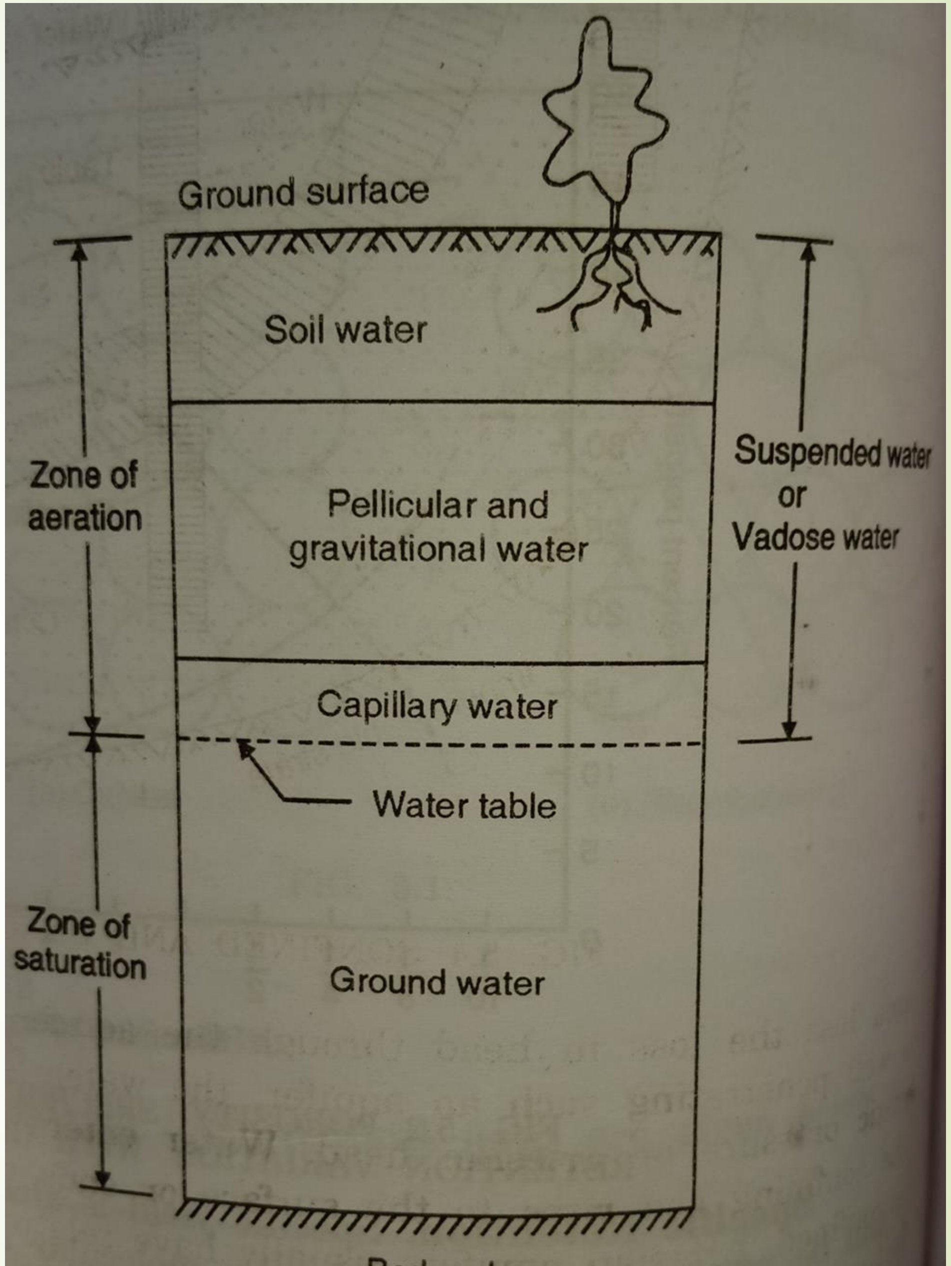
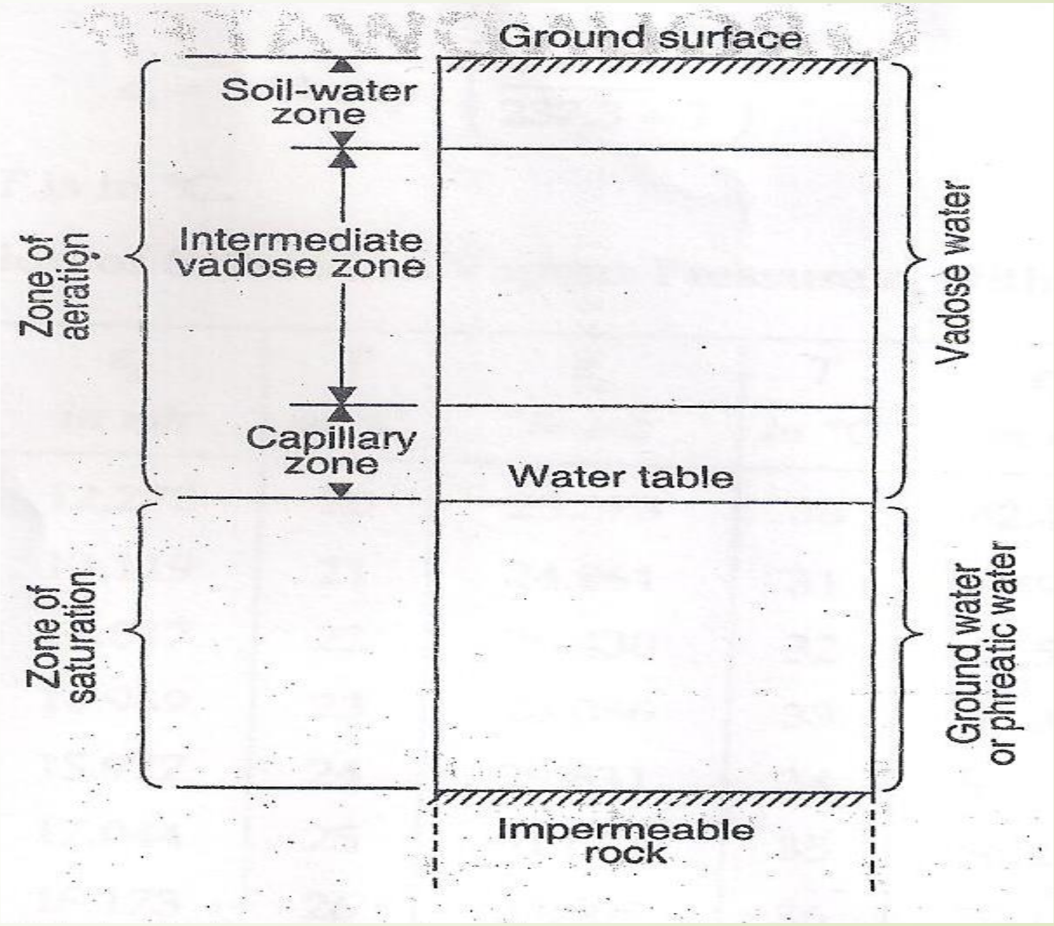


FIG. 5.3 DIVISIONS OF SUB-SURFACE WATER

DIVISION OF SUB-SURFACE WATER

- **Soil Water Zone**
- ***This zone extends "<u>from the ground surface down through the major root-zone of vegetations</u>". Its thickness varies with the type of soil and vegetation***

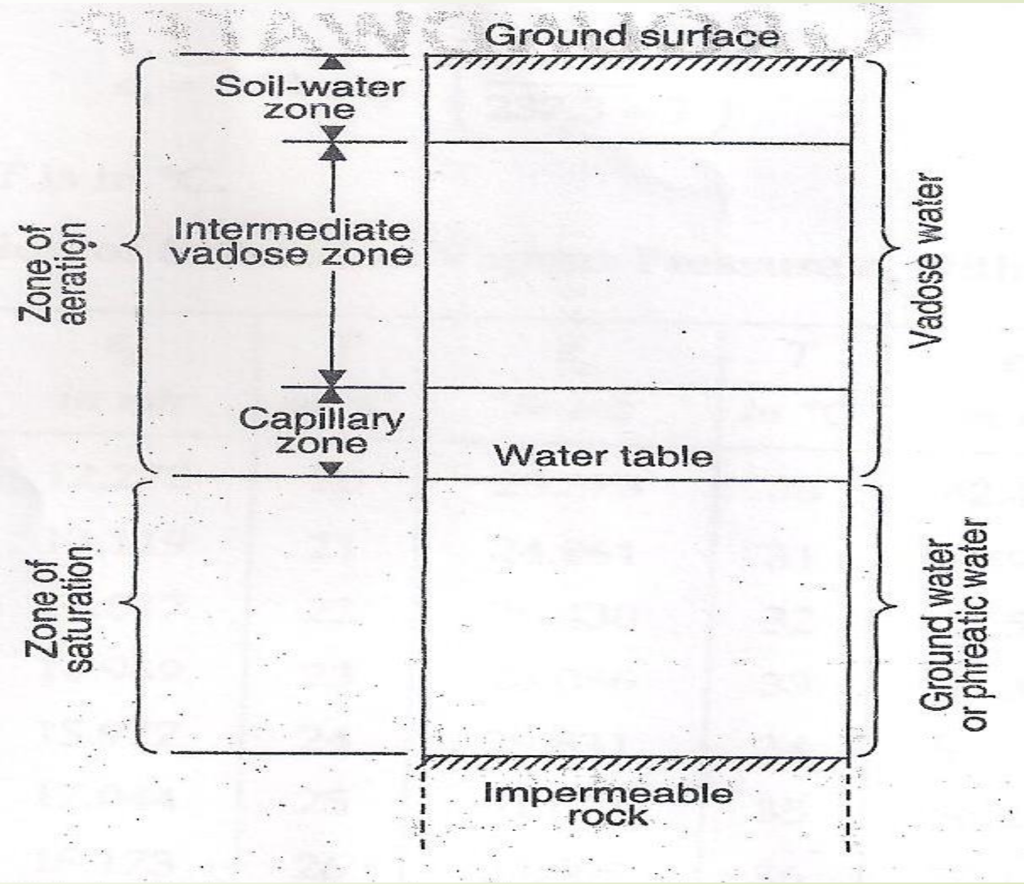


DIVISION OF SUB-SURFACE WATER

- *Intermediate Zone*

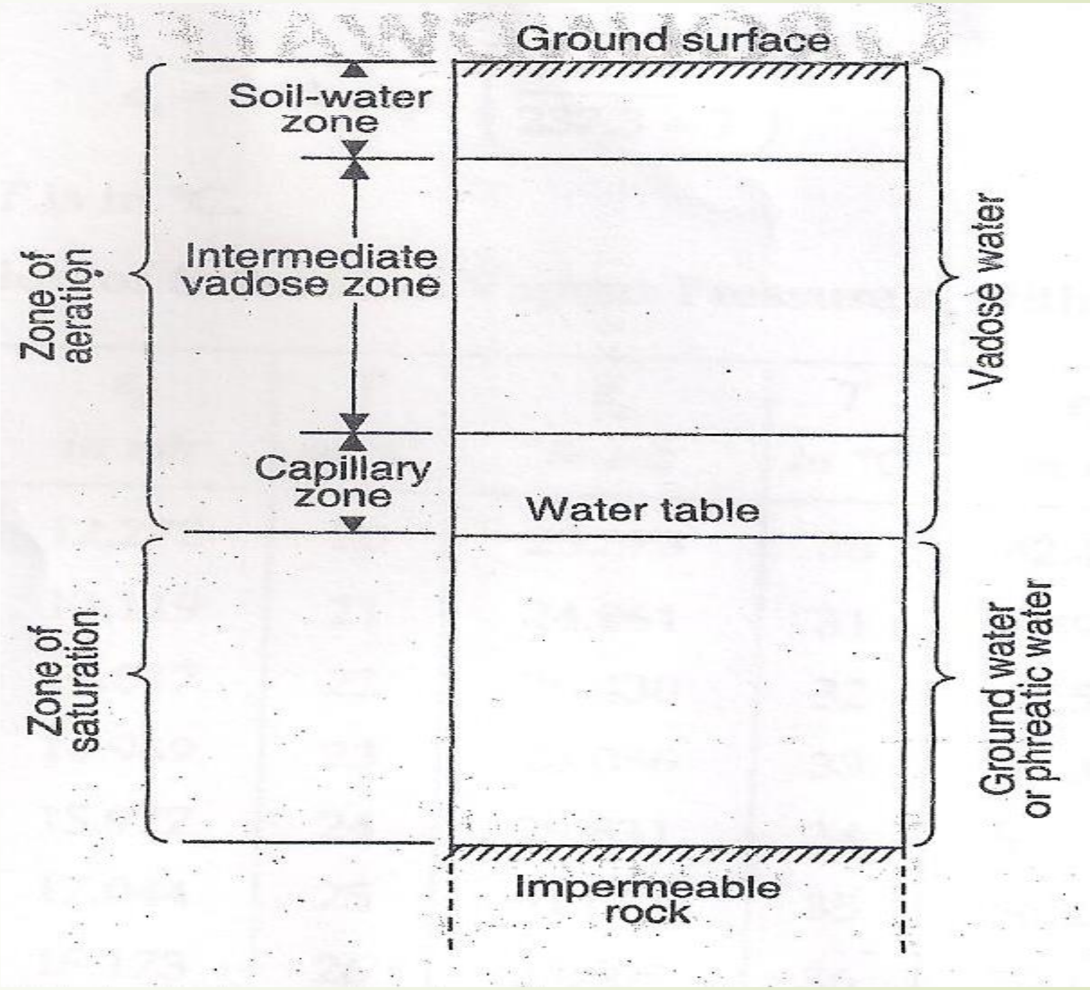
- ***This zone extends "from the lower edge of the soil water zone to the upper limit of the capillary zone".***

- ***This zone varies in thickness from zero, when the grounding zone merge with a high water table approaching to the ground, to several hundred meter under deep water table condition. This zone contains pellicular as well as gravitational water.***



DIVISION OF SUB-SURFACE WATER

- ***Capillary Zone***
- ***It extends "from the water table upto the limit of capillary rise of water".***



GROUNDWATER MOVEMENT

- ***PERMEABILITY** is the capability of a rock to allow the passage of fluids. Permeability is dependent on the size of pore spaces and to what degree the pore spaces are connected. Grain shape, grain packing, and cementation affect permeability.*
- ***SPECIFIC YIELD (S_y)** is the ratio of the volume of water drained from a rock (due to gravity) to the total rock volume. Grain size has a definite effect on specific yield. Smaller grains have larger surface area/volume ratio, which means more surface tension. Fine-grained sediment will have a lower Sy than coarse-grained sediment.*
- ***SPECIFIC RETENTION (S_r)** is the ratio of the volume of water a rock can retain (in spite of gravity) to the total volume of rock.*
- ***Specific yield plus specific retention equals porosity (often designated with the Greek letter phi):***

$$Sr + Sy = \Phi$$

Porosity and Specific Yield

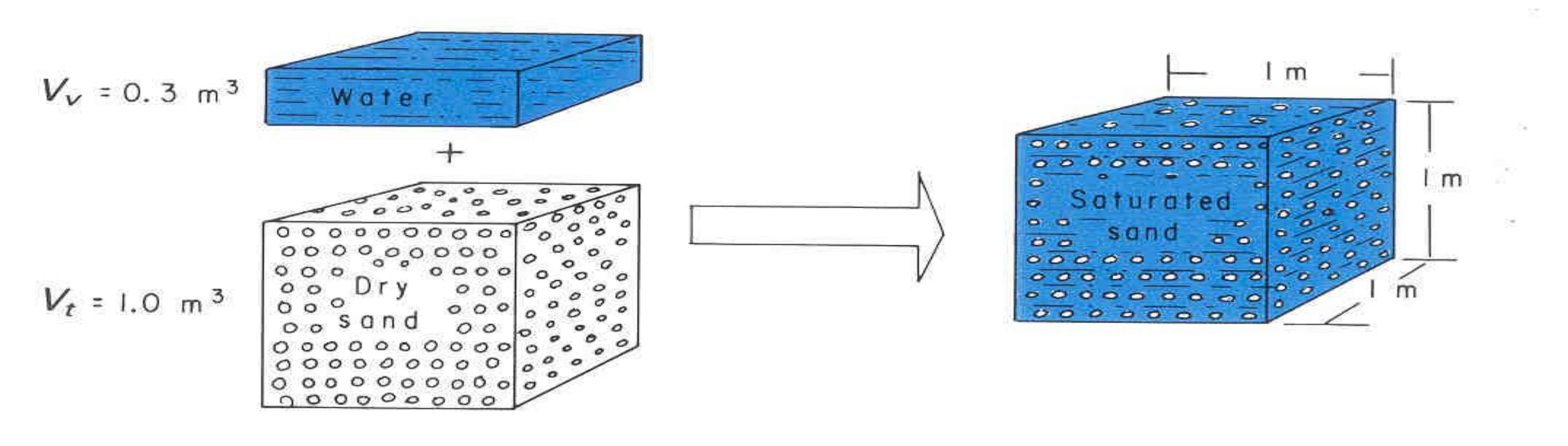
Porosity (Expressed as %)

- Ratio of openings (voids) to the total volume of a soil
- $n = (V_{t-Vs)/Vt = Vv/Vt}$
- Vt= total volume of the soil or rock
- Vs= Volume of solids in the sample
- Vv= Volume of openings (voids)

Table 6.2. Classification of Soils

S. No.	Material	Particles sizes in mm
1.	Gravel	Larger than 2.0 mm
2.	Very coarse sand	between 1.0 to 2.0 mm
3.	Coarse sand	between 0.5 to 1.0 mm
4.	Medium sand	between 0.25 to 0.5 mm
5.	Fine sand	between 0.125 to 0.25 mm
6.	Very find sand	between 0.07 to 0.125 mm
7.	Silt and clay	Finer than 0.07 mm

Porosity (Example)



- **Porosity n = ($V_{t-Vs)/Vt = Vv\ \ / Vt = 0.3 / 1.0 = 30\ \%}$**

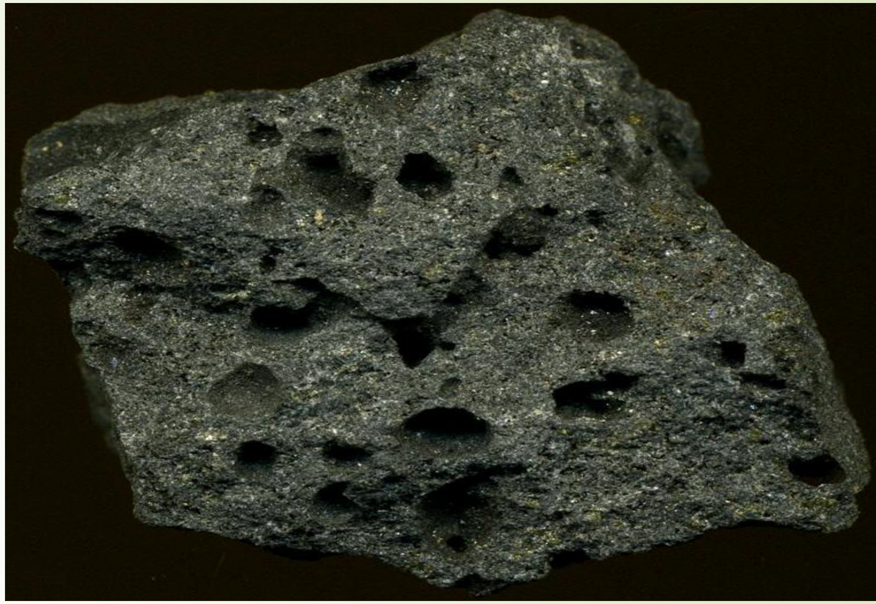
SELECTED VALUES OF POROSITY

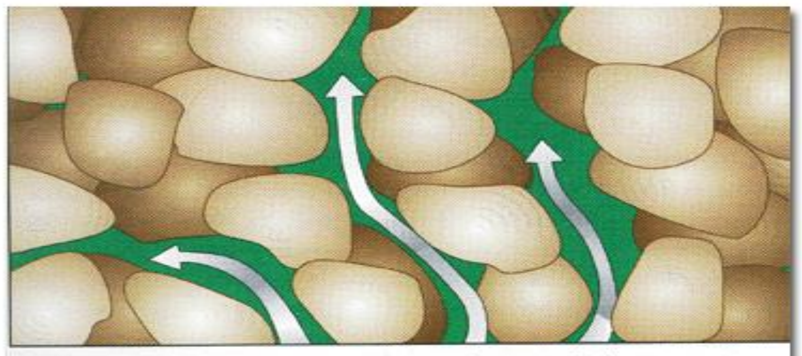
[Values in percent by volume]

Material	Primary openings	Secondary openings
Equal-size spheres (marbles):		
Loosest packing	48	--
Tightest packing	26	--
Soil	55	--
Clay	50	--
Sand	25	--
Gravel	20	--
Limestone	10	10
Sandstone (semiconsolidated)	10	1
Granite	--	.1
Basalt (young)	10	1

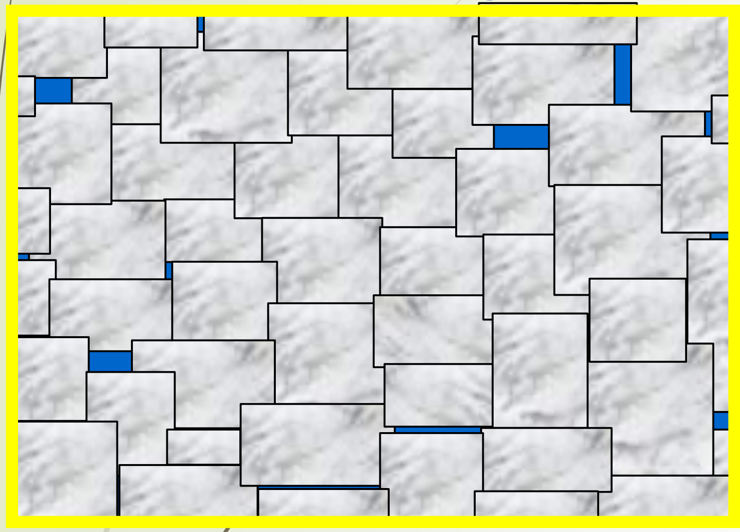
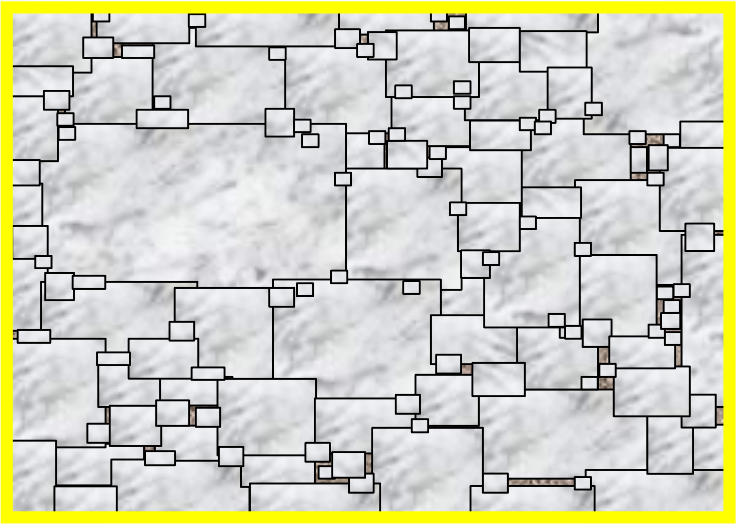
POROSITY AND PERMEABILITY

- ***Porosity - the percentage of rock that consists of voids or openings***
  - ✓ ***Volume of empty space in a rock***
  - ✓ ***A rock's ability to hold water***
  - ✓ ***Loose sand has ~30-50% porosity***
  - ✓ ***Compacted sandstone may have only 10-20% porosity***
- ***Permeability - the capacity of a rock to transmit fluid through pores and fractures***
  - ✓ ***Interconnectedness of pore spaces***





Connected pores give a rock permeability.

WELL SORTED Coarse (sand-gravel)	POORLY SORTED Coarse - Fine	WELL SORTED Fine (silt-clay)
		

Permeability and Hydraulic Conductivity

High ⟷ Low

Sorting of material affects groundwater movement. Poorly sorted (well graded) material is less porous than well-sorted material.

GROUNDWATER MOVEMENT

- *POROSITY = F or n (units - fraction or %)*
  - ✓ *= fraction of void space (empty space) in soil or rock.*
  - ✓ *Represents the path water molecules can follow in the subsurface*

    Primary porosity – intergranular
  - ✓ *Secondary porosity - fractures, faults, cavities, etc.*
  - ✓ *Porosity = volume of pore space relative to the total volume (rock and/or sediment + pore space).*
- *Primary porosity (% pore space) is the initial void space present (intergranular) when the rock formed.*
- *Secondary porosity (% added by openings) develops later. It is the result of fracturing, faulting, or dissolution.*
- *Grain shape and cementation also affect porosity.*

S. Hughes, 2003

GROUNDWATER MOVEMENT

- ***Movement of groundwater depends on rock and sediment properties and the groundwater's flow potential. Porosity, permeability, specific yield and specific retention are important components of hydraulic conductivity.***
- ***HYDRAULIC CONDUCTIVITY = K (or P)***
  - ✓ ***units = length/time (m/day)***
  - ✓ ***Ability of a particular material to allow water to pass through it***
- ***The definition of hydraulic conductivity (denoted "K" or "P" in hydrology formulas) is the rate at which water moves through material. Internal friction and the various paths water takes are factors affecting hydraulic conductivity. Hydraulic conductivity is generally expressed in meters per day.***

S. Hughes, 2003

POROSITY & VOID RATIO

- *The amount of water that can be stored in an aquifer is equal to the volume of space between the soil grains*
- ***It is defined as <u>the ratio of the voids ‘V_p’ space in the rock or soil to the total volume V_t, of the mass</u> and is expressed as percentage. It is a measure of contained interstices. Usually it is denoted by n.***
- ***$n = [V_p / V_t]$, where, V_p= Volume of Voids in a sample and V_t = Total Volume of the sample***
- ***$e = [V_p / V_s]$, where, V_p= Volume of Voids in a sample and V_s= Total Volume of the solids.***

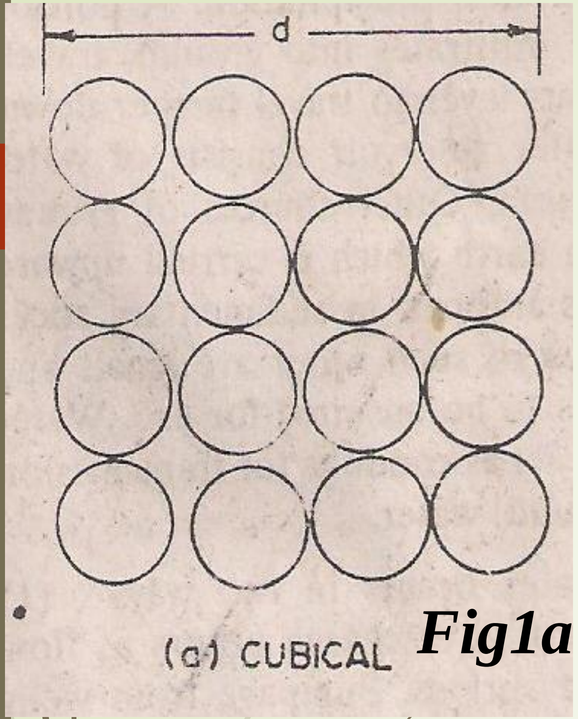


Fig1a

POROSITY

➢ $$n = \frac{1}{[1+(1/e)]}$$

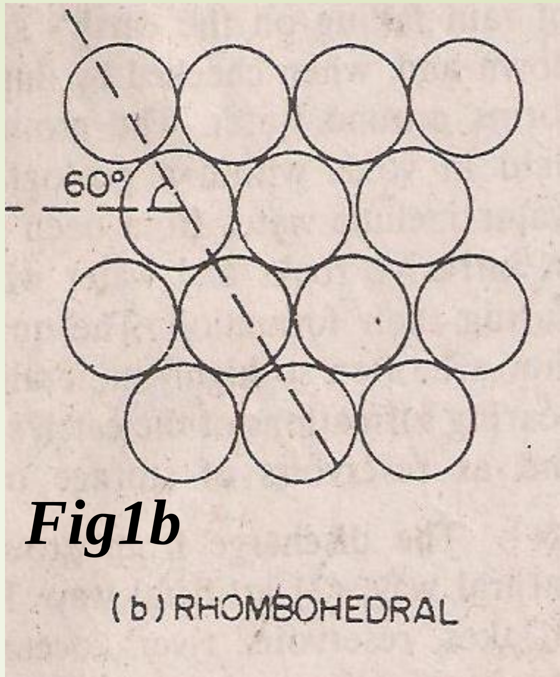


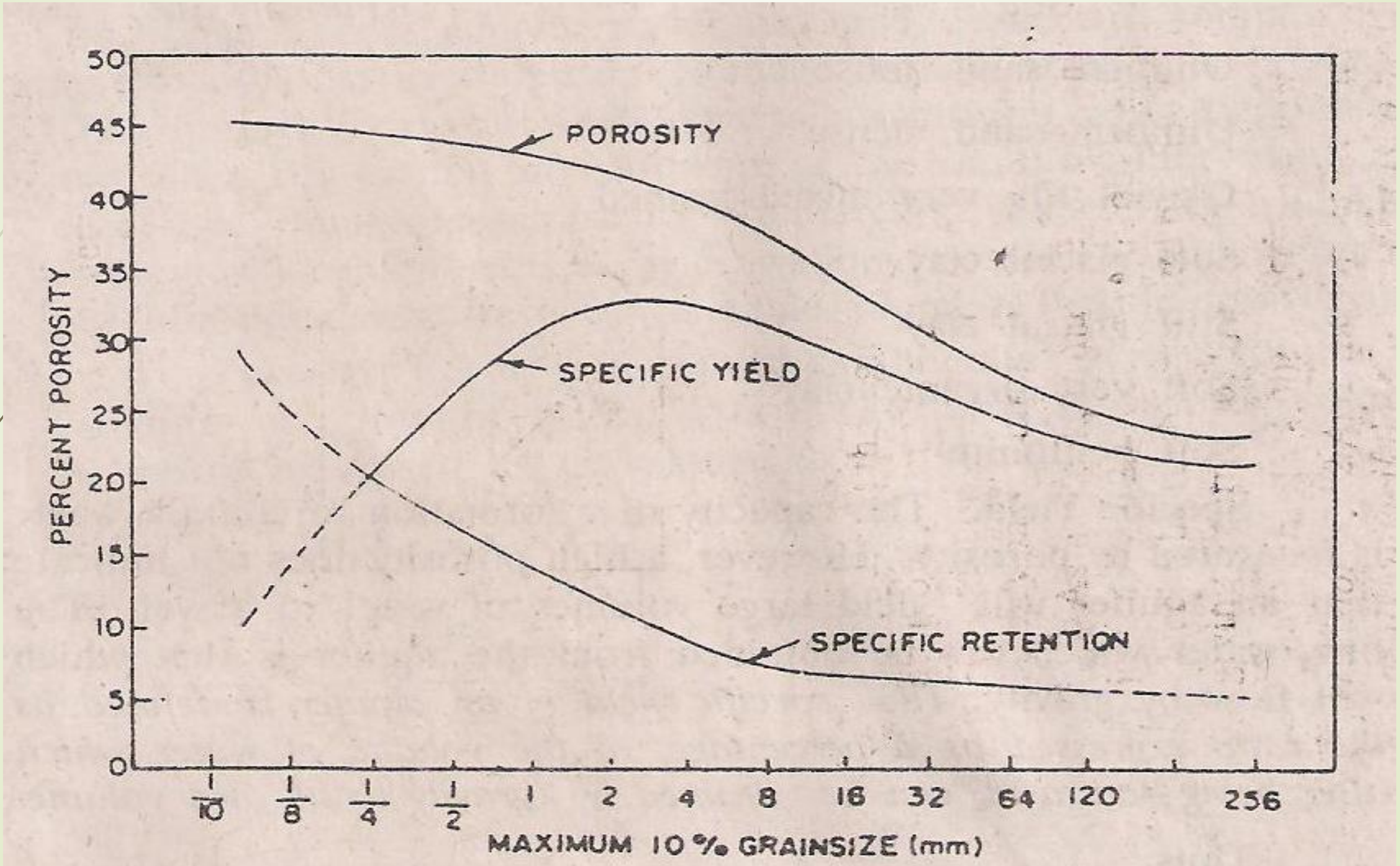
Fig1b

- ***Porosity of a rock or soil is determined largely by the packing arrangement of its grains and the uniformity of the grain-size distribution.***
- ***The greatest ideal porosity that could be attained in a material with uniform spherical grains is 47.65%; this is known as cubic packing (Fig1a) because the centers of eight such grains form the vertices of a cube.***
- ***The least porosity that can be attained with the same grains is found in Rhombohedral packing with a value of 25.95% (Fig1b). The centers of the eight adjacent spheres form the vertices of a rhombus.***

POROSITY

Type of Material	Porosity %
Lime stone	1 – 10
Shale	1 – 10
Sand stone	10 – 20
Gravel and sand	20 – 35
Gravel	30 – 40
Fine to medium mixed sand	30 – 35
Uniform sand	30 – 40
Medium to coarse sand mixed	35 – 40
Silt	40 – 50
Clay	45 – 50
Soils	50 - 60

POROSITY VS GRAIN SIZE



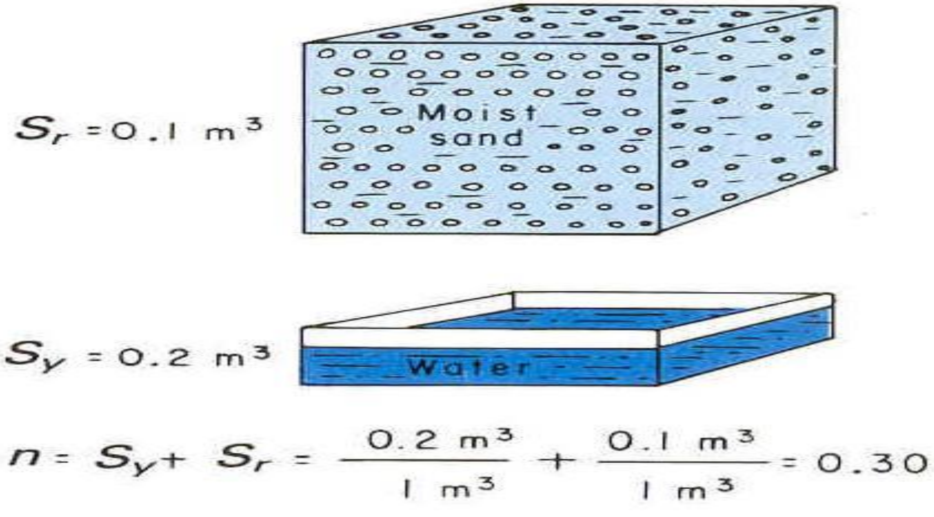
CAPACITY & YIELD

- **Capacity**
  - ***"The amount of water which can be held by an formation is known as its capacity and it is measured by porosity".***
  - ***However high porosity does not indicate that larger amount of water will be collected in a well from the aquifer.***
  - ***Only that amount of water will be obtained from the aquifer which can flow under gravity.***
- **Yield**
  - ***The amount of groundwater extracted by gravity drainage from a saturated water bearing strata is known as "Yield".***

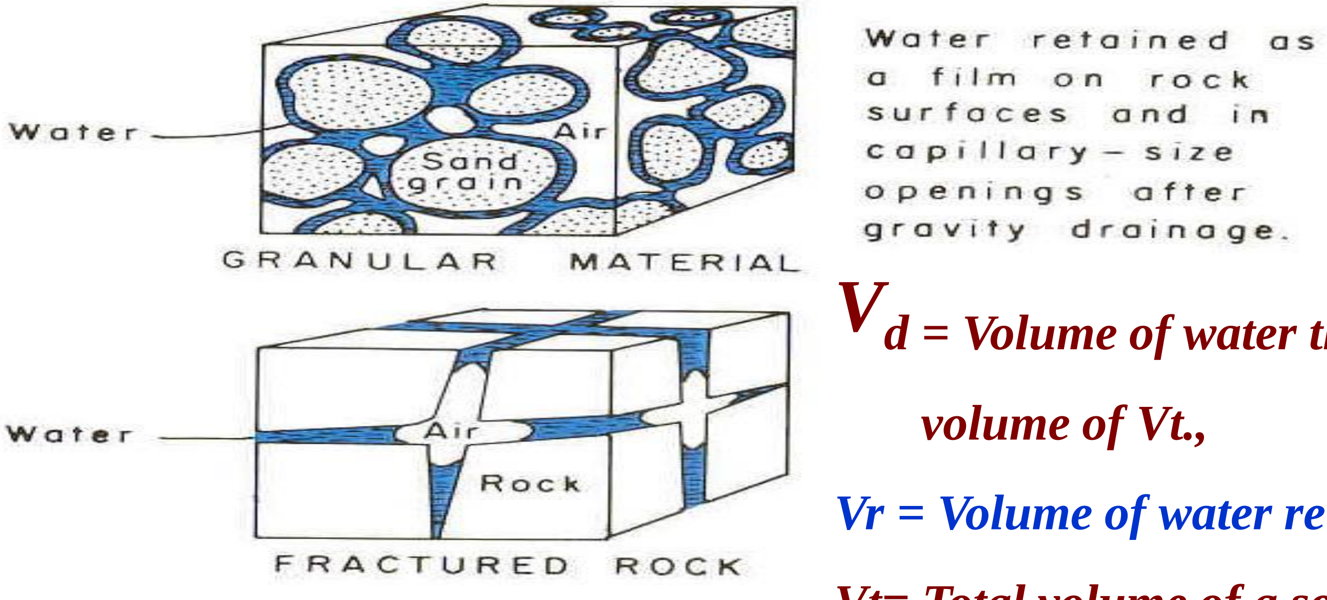
Specific Yield and Retention

- **Porosity:** ***Maximum amount of water that a rock can contain when saturated.***
- ***SPECIFIC YIELD : Portion of the GW draining under influence of gravity***
- ***SPECIFIC RETENTION: Portion of the GW retained as a film on rock surfaces and in very small openings***

SPECIFIC YIELD AND RETENTION



(1)



(2)

$n = S_{y+Sr}$; $Sy=Vd / Vt$; $Sr=Vr / Vt$

n = porosity

S_{y}*= specific yield*

Sr= specific retention

V_d *= Volume of water that drains from a total volume of Vt.,*

Vr = Volume of water retained in a total volume of Vt

Vt= Total volume of a soil or rock sample

SPECIFIC YIELD

- *All Water present in an aquifer is not available for extraction*
- *Indication of water yielding capacity of an unconfined aquifer.*
- *Ratio expressed as a % of the total volume of water which after being saturated can be drained by gravity to its own volume.*
- *It is a fraction of the porosity of an aquifer.*
- *Value of specific yield depends on Grain size, Shape, Distribution of pores and compaction of the strata.*
- $S_y = [V_w / V_t]$ *where,* V_w *= Volume of water that will drain freely from a soil in a sample and* V_t *= Total Volume of water in the soil.*
- *For uniform sand the value of specific yield may be upto 30%, but for most of the alluvial deposits it varies from 10 to 20%.*

SPECIFIC RETENTION

- *Specific yield is always less than porosity since some water will be retained in the aquifer by molecular and surface tension forces.*
- *"The specific retention (S_r) of an aquifer is the ratio, expressed as a percentage, of the volume of water it will retain after saturation against the force of gravity to its own volume"*
- *$S_r = [V_r / V_t]r \times 100$ where, V_w = Volume of water retained in soil and V_t = Total Volume of water in the soil.*
- *Porosity = Sy + Sy*

GROUNDWATER FLOW

- ***Groundwater moves through different soils at different rates based on the experimentally determined coefficient of permeability, K***
  - ✓ ***K as high as 10 m/s to 10^{-14} m/s***
  - ✓ ***Models are available for the subsurface that are simple and complex***
  - ✓ ***Very hard to predict because of the heterogeneity of most aquifers***

SELECTED VALUES OF POROSITY, SPECIFIC YIELD, AND SPECIFIC RETENTION

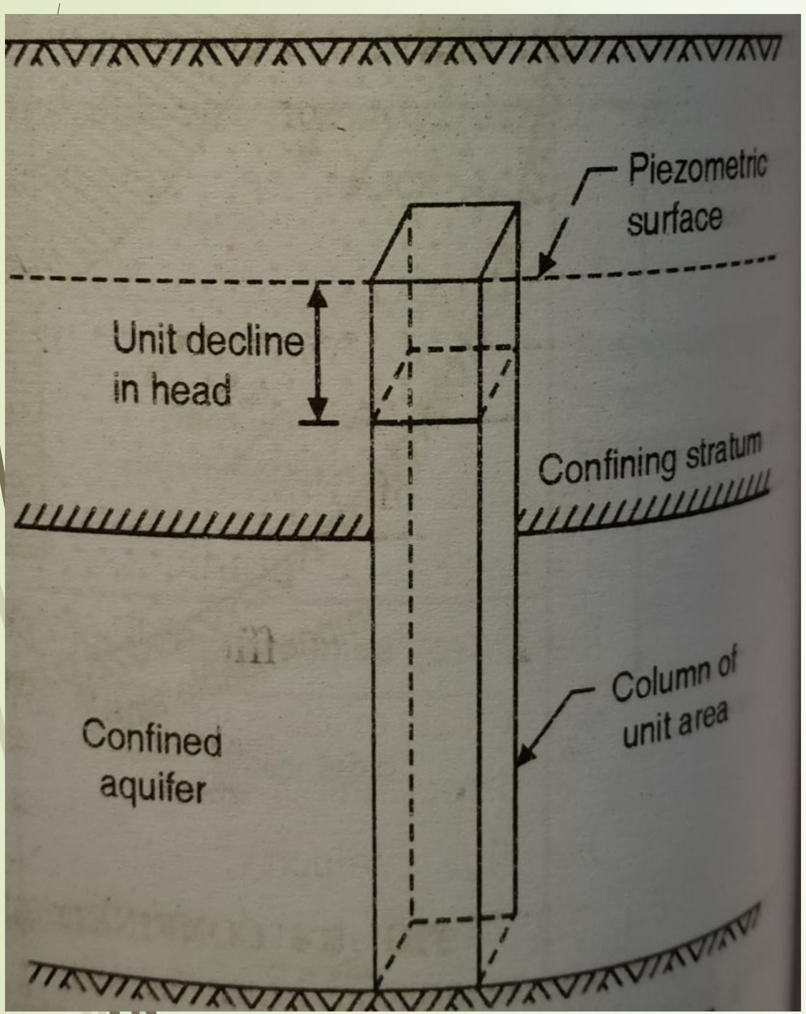
[Values in percent by volume]

Material	Porosity	Specific yield	Specific retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semiconsolidated)	11	6	5
Granite	.1	.09	.01
Basalt (young)	11	8	3

Table 6.3. Permeability Coefficients

S. No.	Type of soil	Coefficient of permeability in cm/s
1.	Clean gravel	1.0 and above
2.	Coarse sand (clean)	1.0 to 1.01
3.	Medium sand	0.01 to 0.005
4.	Fine sand	0.005 to 0.001
5.	Sand mixed with silt	2×10^{-3} to 1.0×10^{-4}
6.	Silt	5×10^{-4} to 1.0×10^{-5}
7.	Clay	1.0×10^{-6} and less

STORAGE COEFFICIENT (S)



- *Water yielding capacity*
- *Volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer.*
- *S = Volume of water, in m^3, released from the aquifer under unit decline of piezometric head*
- *For Confined aquifers S ranges from 0.00005 to 0.005*
- *For unconfined aquifers when the water table is lowered by 1 m, the water from 1 m height of the vertical column of unit area drains freely under gravity - Specific yield*

COEFFICIENT OF PERMEABILITY(K) TRANSMISSIVITY (T)

- ***k: Defined as the velocity of flow which will occur through the total cross-sectional are of the aquifer under a unit hydraulic gradient.***
- ***k varies 0.000001to a value >1.0***
- ***T defined as the rate of flow of water in $m^{3/day}$ (or gpd) through the vertical strip of aquifer of unit width (1 m) and extending the full saturation height of the aquifer under unit hydraulic***

$$T = k * b$$

COEFFICIENT OF TRANSMISSIBILITY

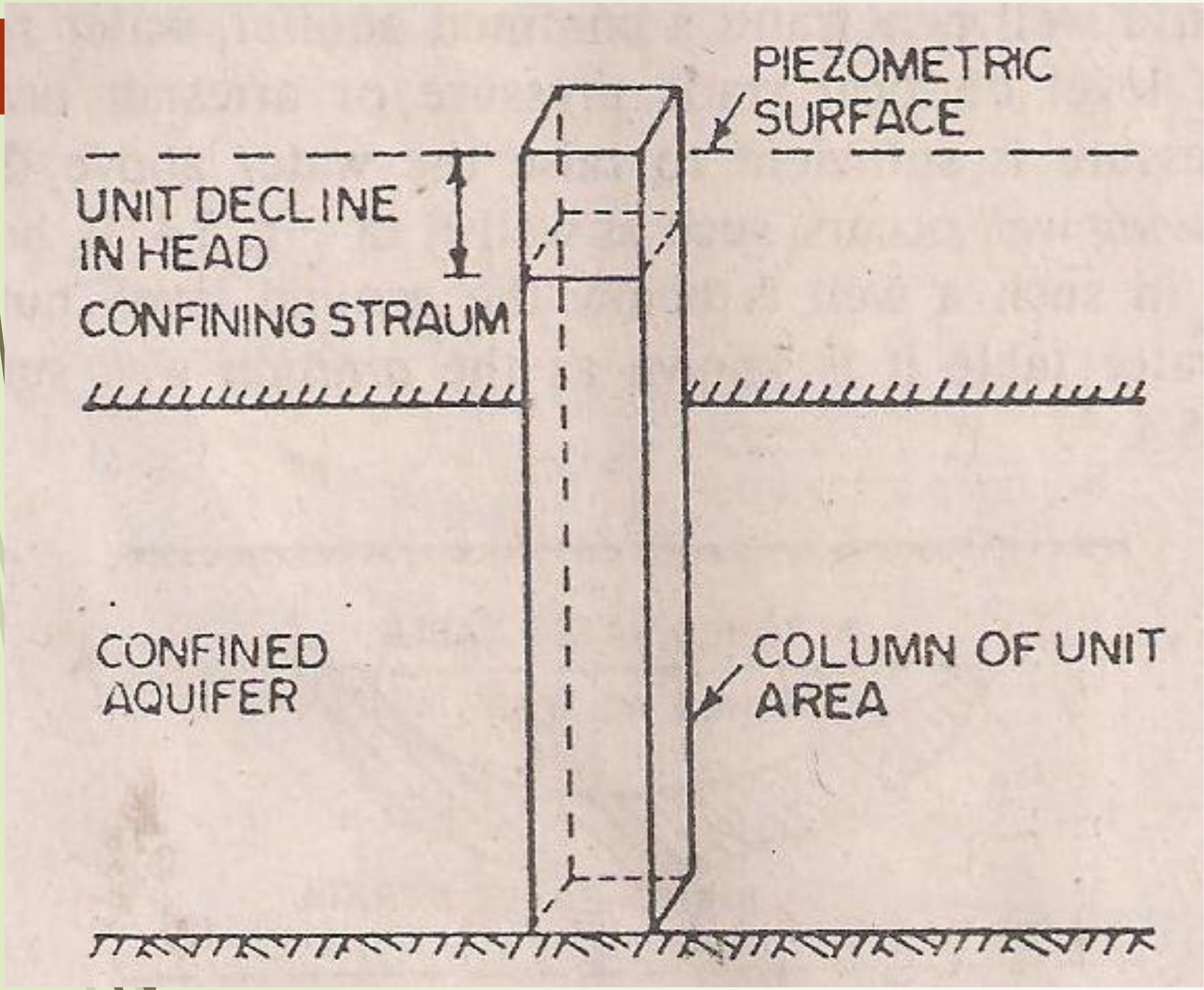
"It is defined as the rate of flow of water (cm/sec) through the aquifer per unit cross-sectional area under per unit hydraulic gradient". It indicates the velocity of seepage through soil (cm/sec) and is denoted by 'K'.

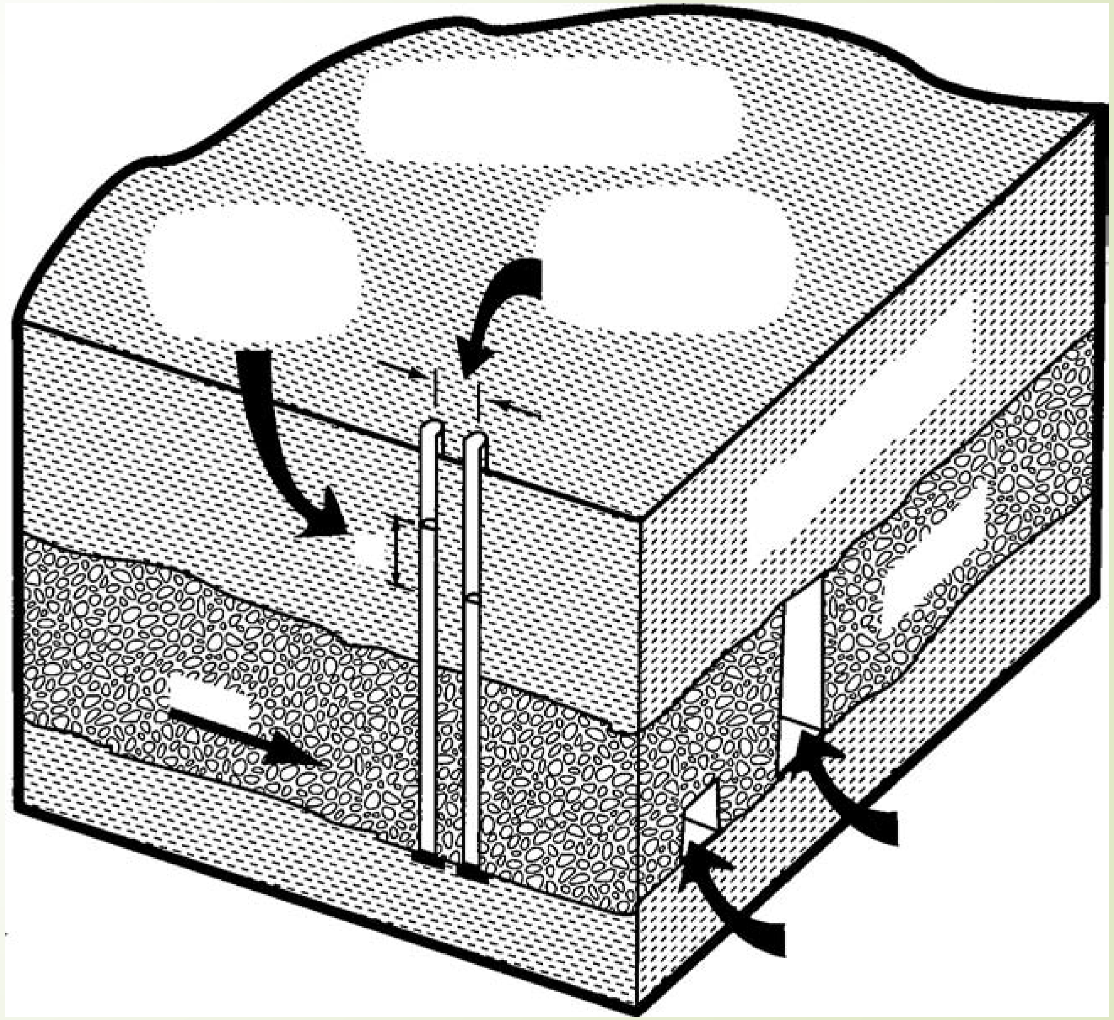
Sr. No.	Type of Soil	Coefficient of permeability in cm/sec
1	Clay	0.000001 and smaller
2	Silt	0.0005 to 0.00001
3	Silty sand	0.002 to 0.0001
4	Fine sand	0.05 to 0.001
5	Sand mixture	0.01 to 0.005
6	Clean sand (coarse)	1.0 to 0.01
7	Clean grovel	1.0 or more

WATER TABLE

- *"<u>It is defined as the rate of flow (m^3/day) through soil strip of aquifer of unit width extending the full saturation height under unit hydraulic gradient</u>". If the aquifer thickness is 'b', 'K' is the coefficient of permeability, then;*
- *$T = bK$*
- *"<u>It is defined as the volume of water that an aquifer releases from or takes into storage per unit area of aquifer per unit change in normal to the surface</u>".*
- *This coefficient is a dimensionless quantity involving a volume of water per volume of aquifer. In most confined aquifer, values fall in the range $0.00005 < S_c < 0.005$ and in unconfined aquifer $0.01 < S_c < 0.3$.*

STORAGE COEFFICIENT (S)



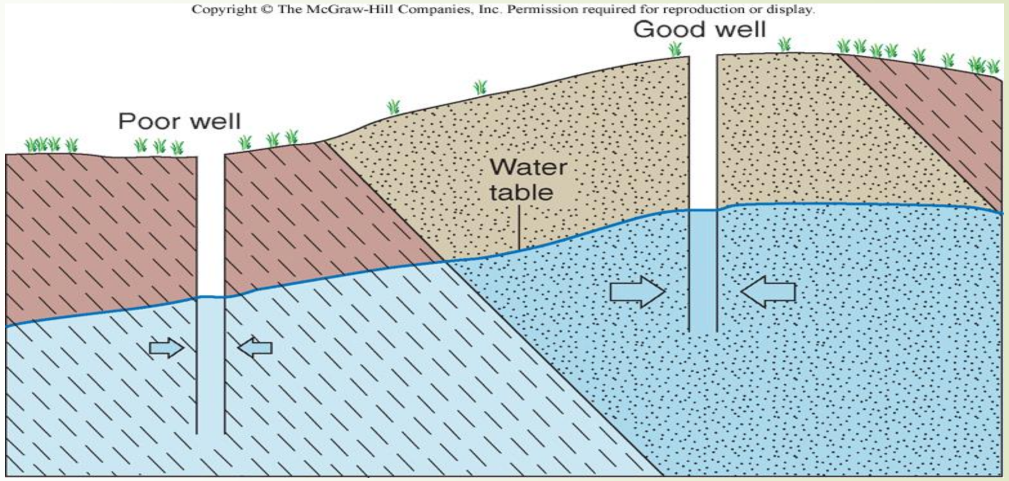


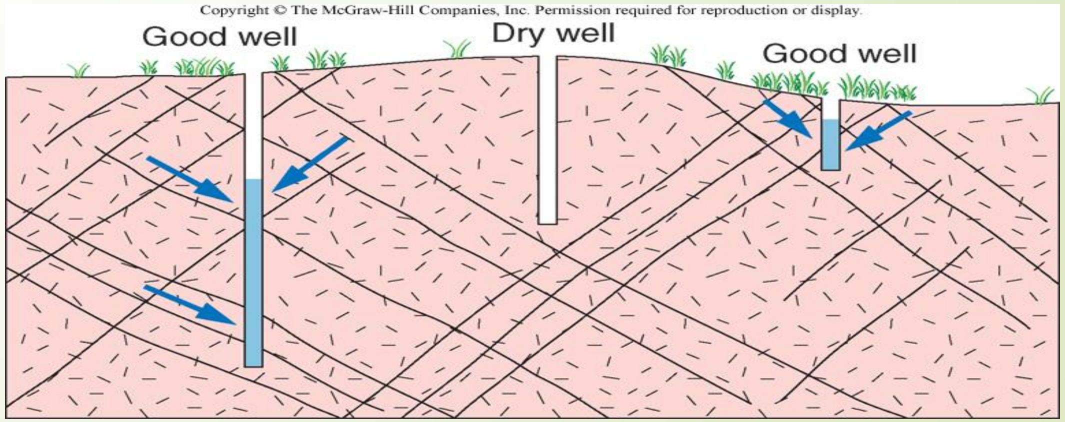
GROUND WATER

- **Aquifer**
  - ***Aquifer - Groundwater Reservoir and Water-bearing Formation.***
  - ***A rock unit that will yield water in a usable quantity to a well or spring.(saturated geological formation, containing and transmitting significant quantities of water under normal field quantities); rock: unconsolidated sediments***
  - ***"Geologic formation containing sufficient saturated permeable material that yields significant quantities of water is defined as aquifers".***
  - ***This implies an ability to store and to transmit water.***
  - ***The sand and gravel aquifers produce large quantities of water, most of which is replenished by seepage from streams into alluvial formations.***
  - ***All developed aquifers probably consist of unconsolidated rocks, chiefly gravel and sand.***

AQUIFERS AND AQUITARDS

- ***Aquifer - body of saturated rock or sediment through which water can move easily***
  - ***Sandstone***
  - ***Conglomerate***
  - ***Well-jointed limestone***
  - ***Highly fractured rock***





GROUND WATER

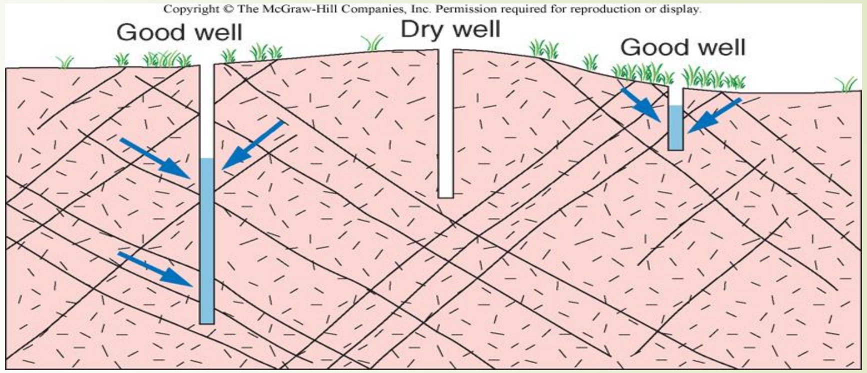
- ***Aquifers are generally extensive and may be overlain or underlain by a Confining Bed which may be defined as a relatively impermeable material stratigraphically adjacent to one or more aquifers.***
- ***Various types of confining Beds:***
  - ✓ ***Aquiclude - Formation containing water → Do not transmit significant quantities***
  - ✓ ***Saturated but relatively impermeable material that does not yield appreciable quantities of water to wells; Clay is an example***

GROUND WATER

- ✓ ***Formations with low permeability…includes both aquiclude and aquifuge***
- ✓ ***Aquifuge - Formation → doesnot contain nor transmit***
- ✓ ***Relatively impermeable formation neither contining nor transmitting water ; Solid Granite belongs to this category.***

AQUIFERS AND AQUITARDS

- *Aquitard - Saturated but poorly permeable stratum that impedes groundwater movement and does not yield water freely to wells, that may transmit appreciable water to or from adjacent aquifers and, where sufficiently thick, may constitute an important groundwater storage zone;*

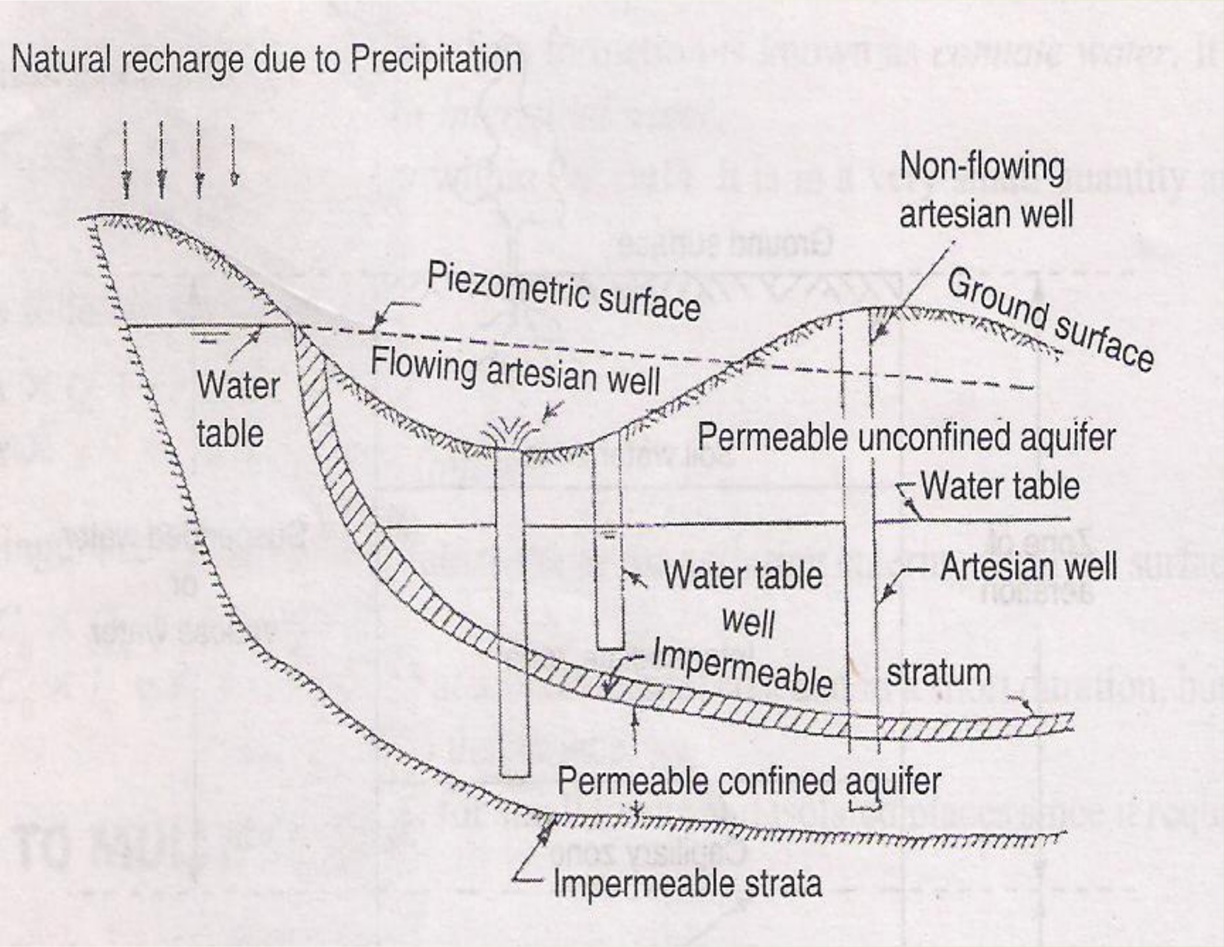


- *Sandy Clay is an example rock/sediment that retards ground water flow due to low porosity and/or permeability*
  - *Shale, clay, unfractured crystalline rocks*

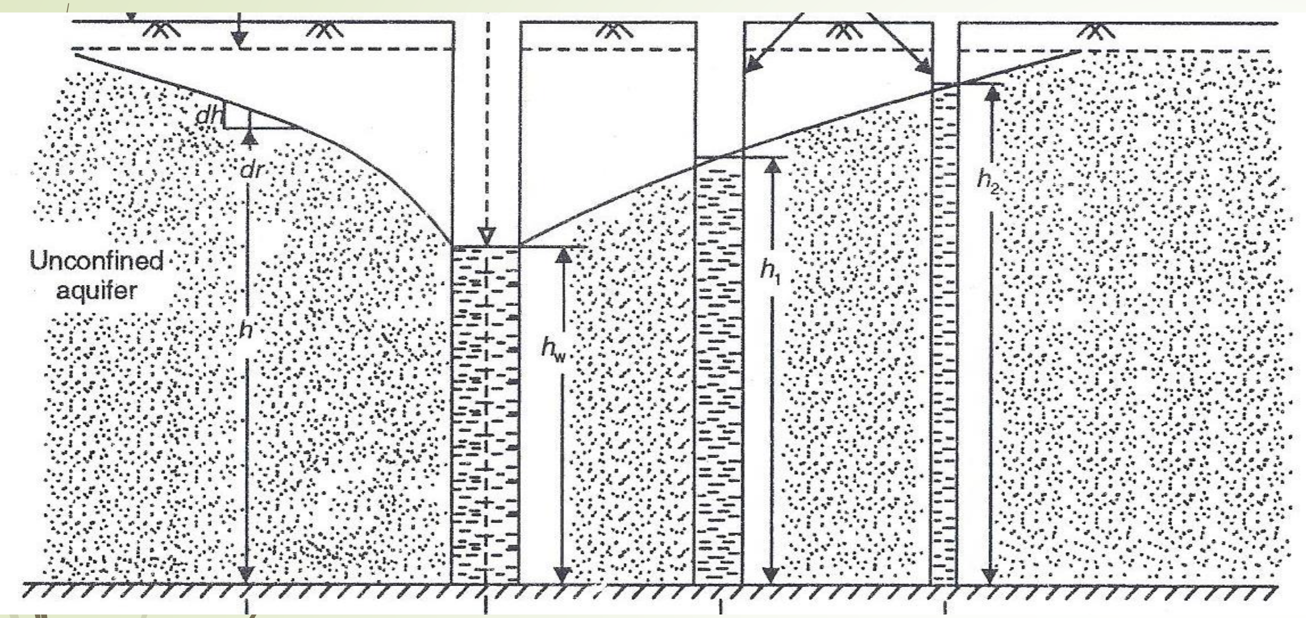
OCCURRENCE OF GROUND WATER

❖ *Types of Aquifers:*

- ✓ *Confined,*
- ✓ *Unconfined and*
- ✓ *Perched - Special case of unconfined aquifer and occurs where ever ground water body is separated from the main ground water" by a relatively impermeable stratum of small area extent and by the zone of aeration above the main body of ground water.*



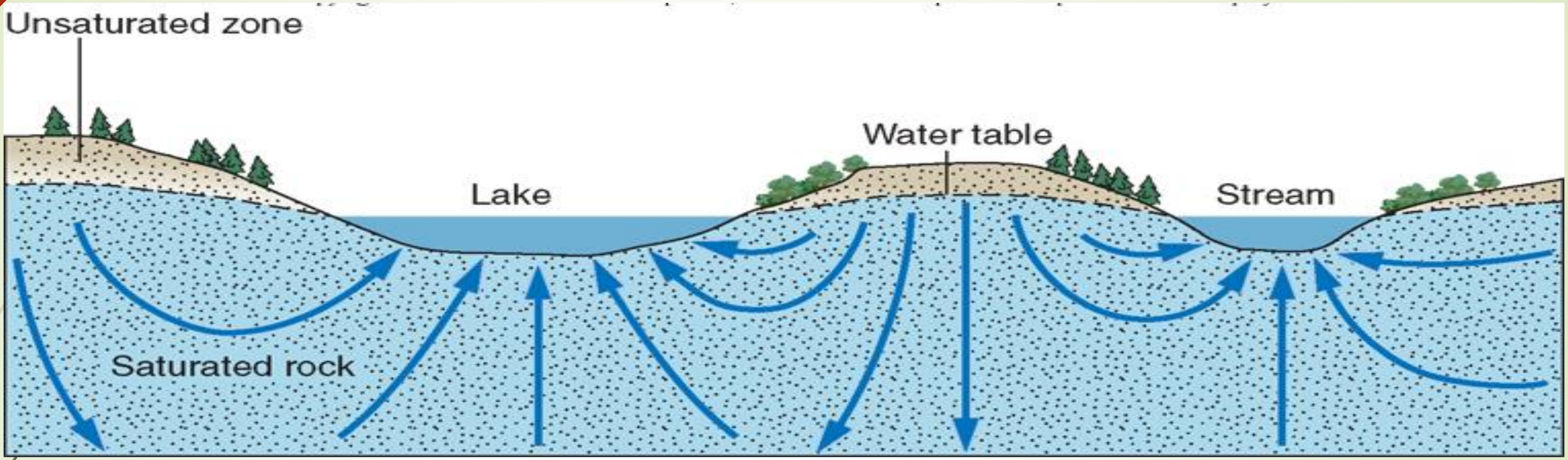
UNCONFINED AQUIFER



- **“An aquifer where the water table is the upper surface limit and extends below till the impermeable rock strata is called the unconfined aquifer” (Figure below). It is also known as free aquifer, phreatic aquifer, water table aquifer and non-artesian aquifer.**

- **The water level in a well is an unconfined aquifer will be upto the water table.**

UNCONFINED AQUIFER

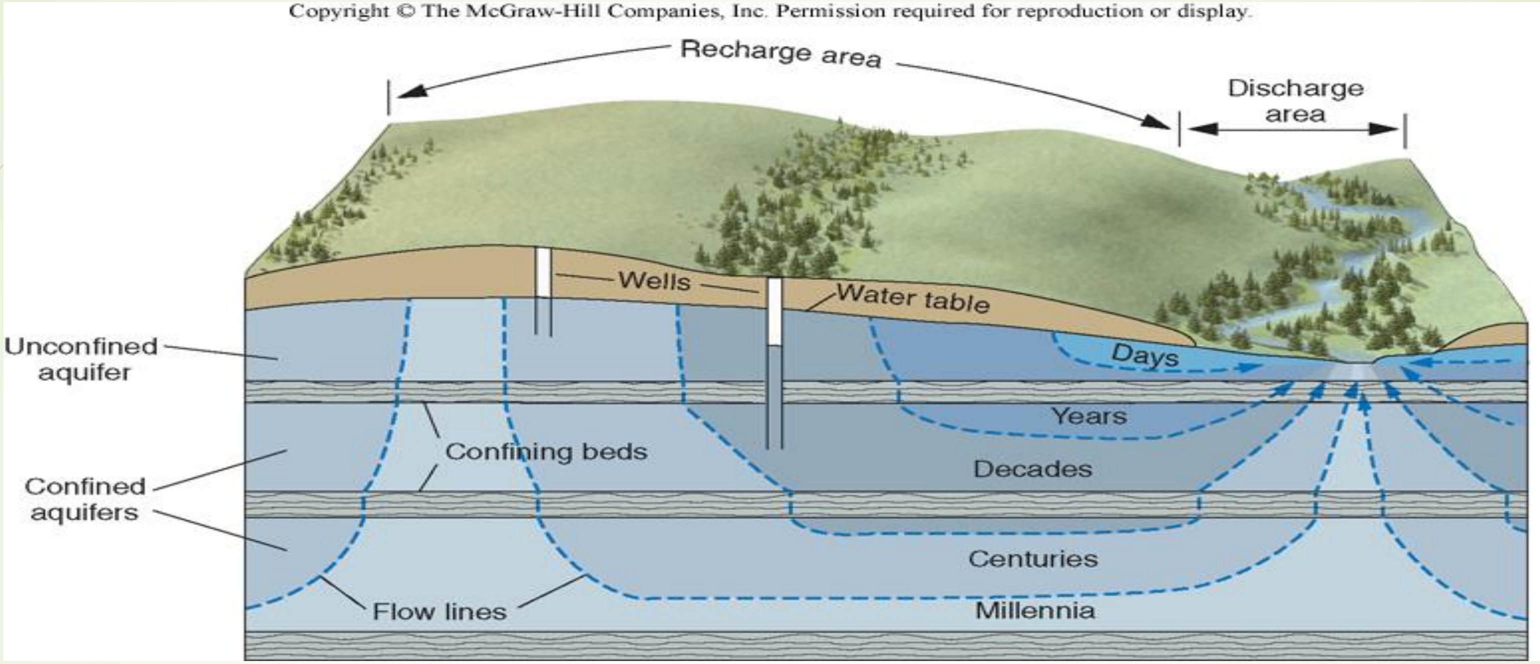


- *Has a water table, and is only partly filled with water*
- *Rapidly recharged by precipitation infiltrating down to the saturated zone*

UNCONFINED AQUIFERS

- *GW occurring in aquifers: water fills partly an aquifer: upper surface free to rise and decline: UNCONFINED or water-table aquifer: unsaturated or vadose zone*
- *Near surface material not saturated*
- *Water table: at zero gage pressure: separates saturated and unsaturated zones: free surface rise of water in a well*

CONFINED AQUIFERS



- *Completely filled with water under pressure (hydrostatic head)*
- *Separated from surface by impermeable confining layer / aquitard*
- *Very slowly recharged*

CONFINED AQUIFERS

- ***Artesian condition***
- ***Permeable material overlain by relatively impermeable material***
- ***Piezometric or potentiometric surface***
- ***Water level in the piezometer is a measure of water pressure in the aquifer***

CONFINED AQUIFER

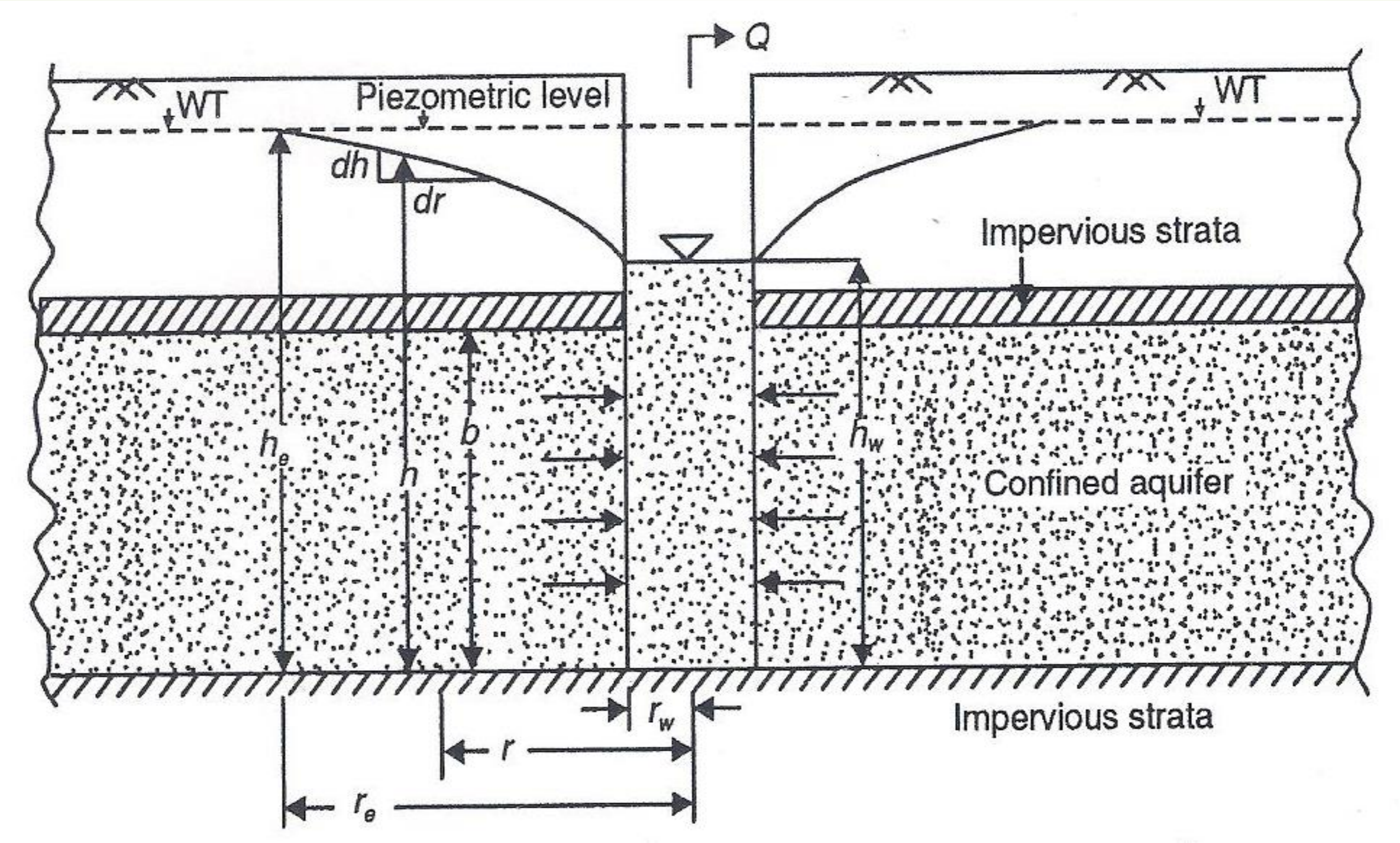
- ***"When an aquifer is sandwiched between two impermeable layers, it is known as a confined aquifer". It will not have a free water table, and the aquifer will be under pressure as shown in the figure.***

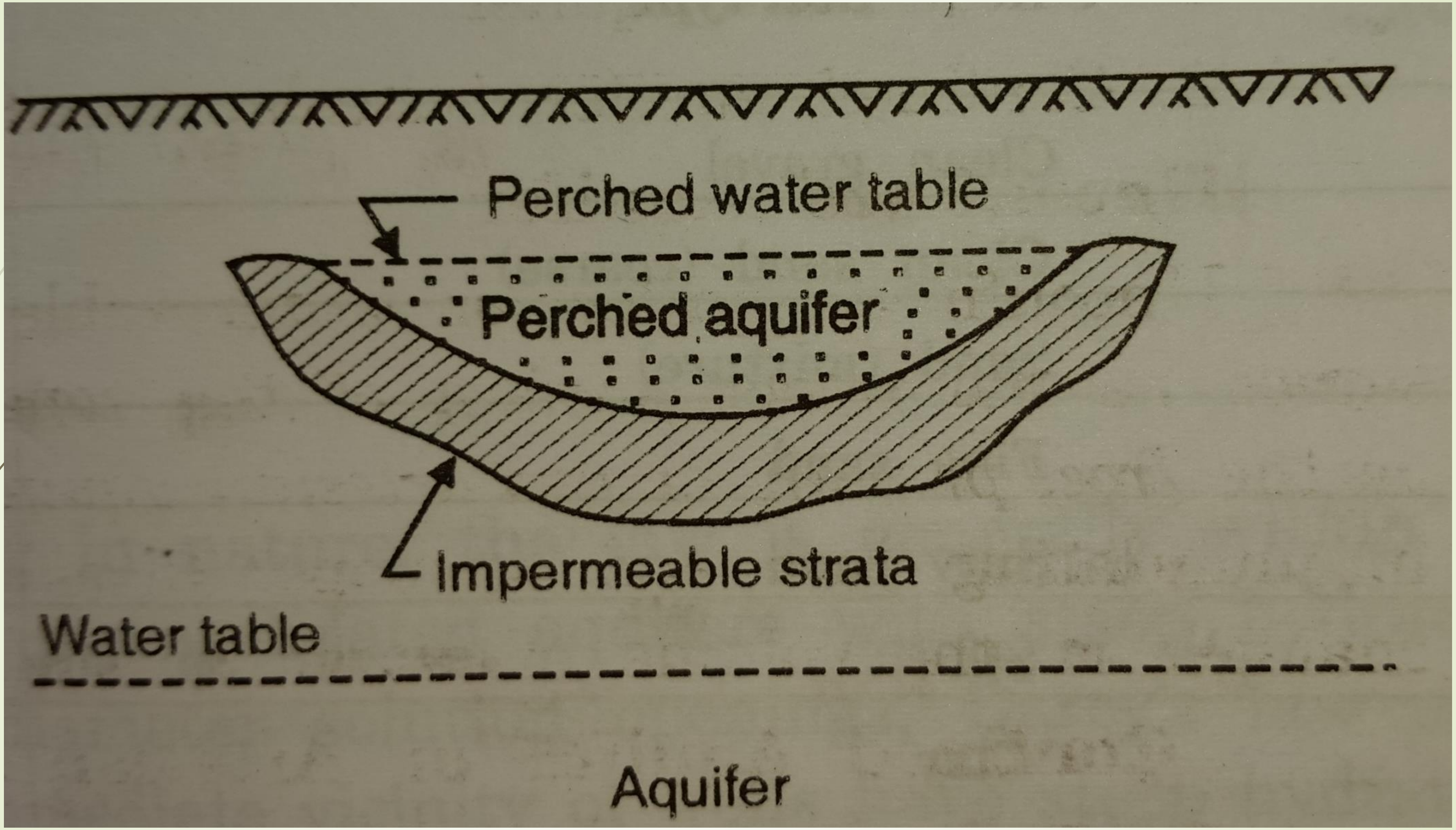
- ***If there is a well in this layer, the water in the well will rise up to the piezometric head. If the piezometric head is above the ground, then the water from the well in this layer will flow over the ground. Then the well is called as "free-flowing well or flowing well".***

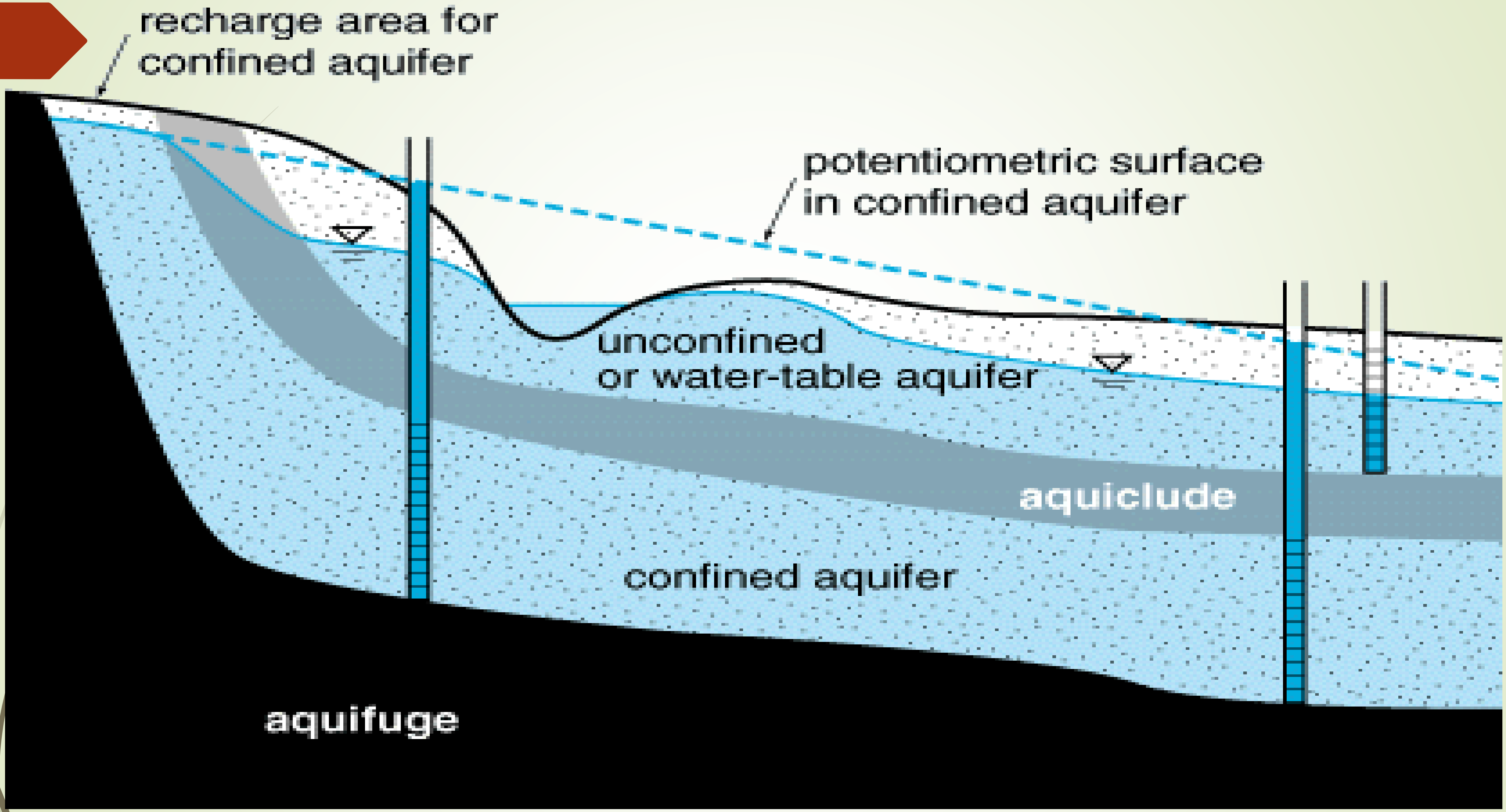
- ***If the water level in a well in this layer is above the upper-confining layer level, but below the ground level, then such a well is called as "Artesian Well".***

- ***Groundwater may move to the ground surface at a very small rate through faults, permeable material in joints, discontinuities, and so on. "It is then called a spring".***

CONFINED AQUIFER

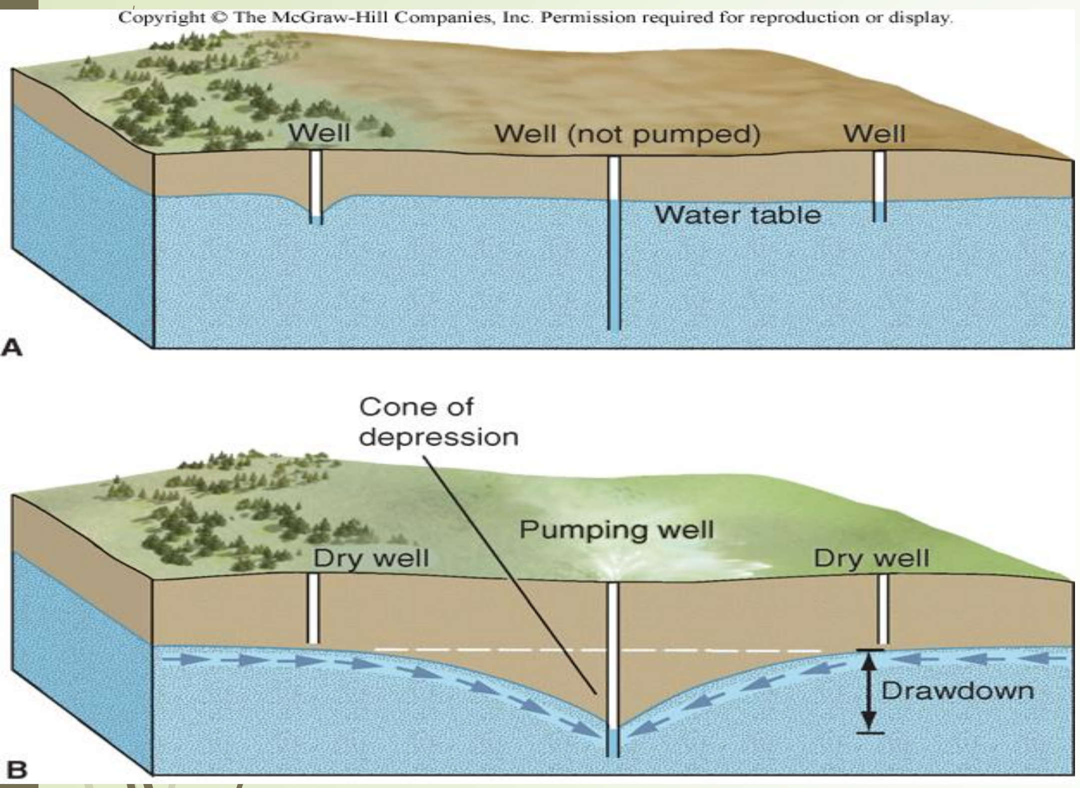



Perched water table
Perched aquifer
Impermeable strata
Water table
Aquifer

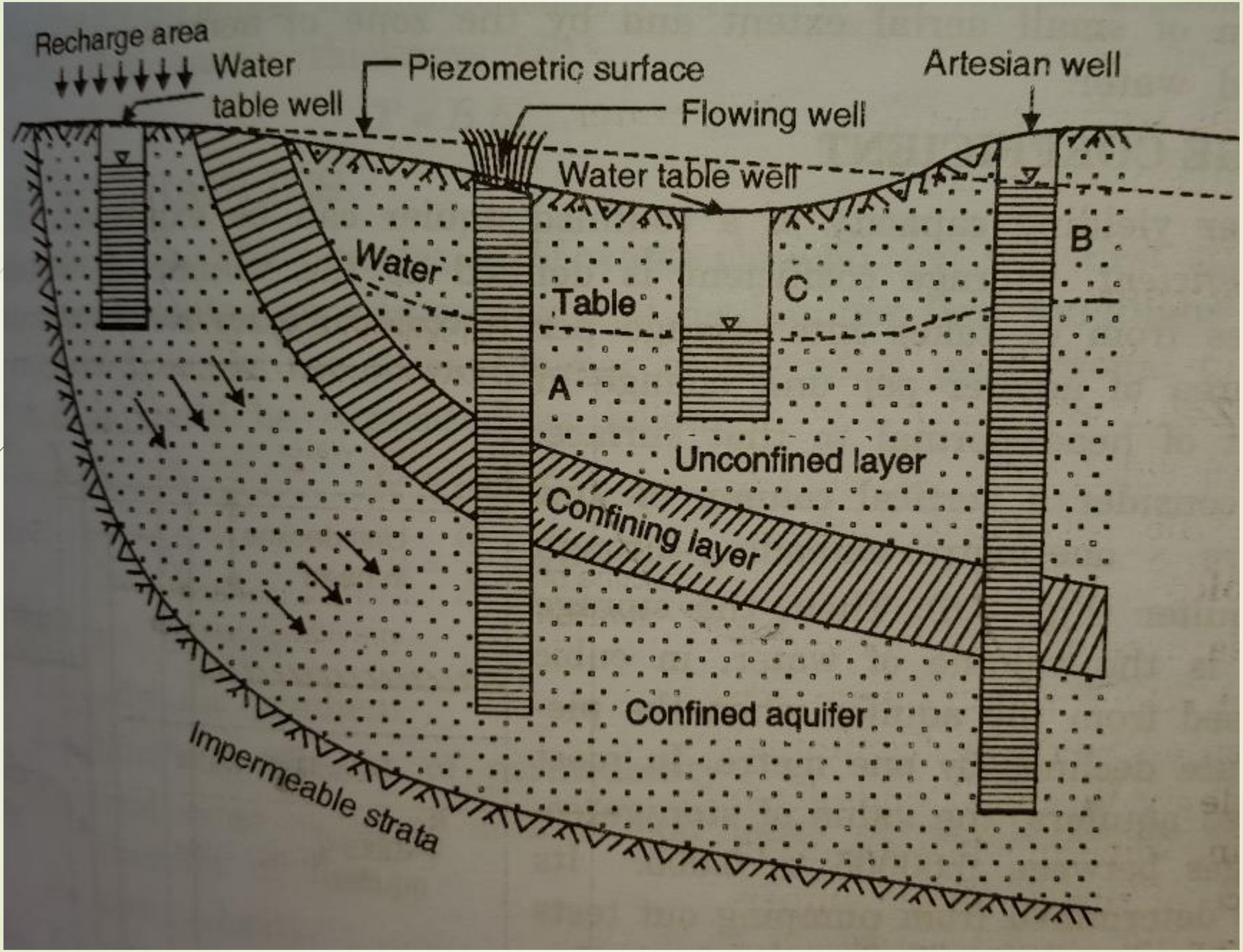


HYDROGEOLOGICAL UNITS

Wells



- *Well - a deep hole dug or drilled into the ground to obtain water from an aquifer*
  - *Wells in unconfined aquifers, water level before pumping is the water table*
  - *Water enters well from pore spaces within the surrounding aquifer creating a cone of depression*
  - *Water table can be lowered by pumping, a process known as drawdown*

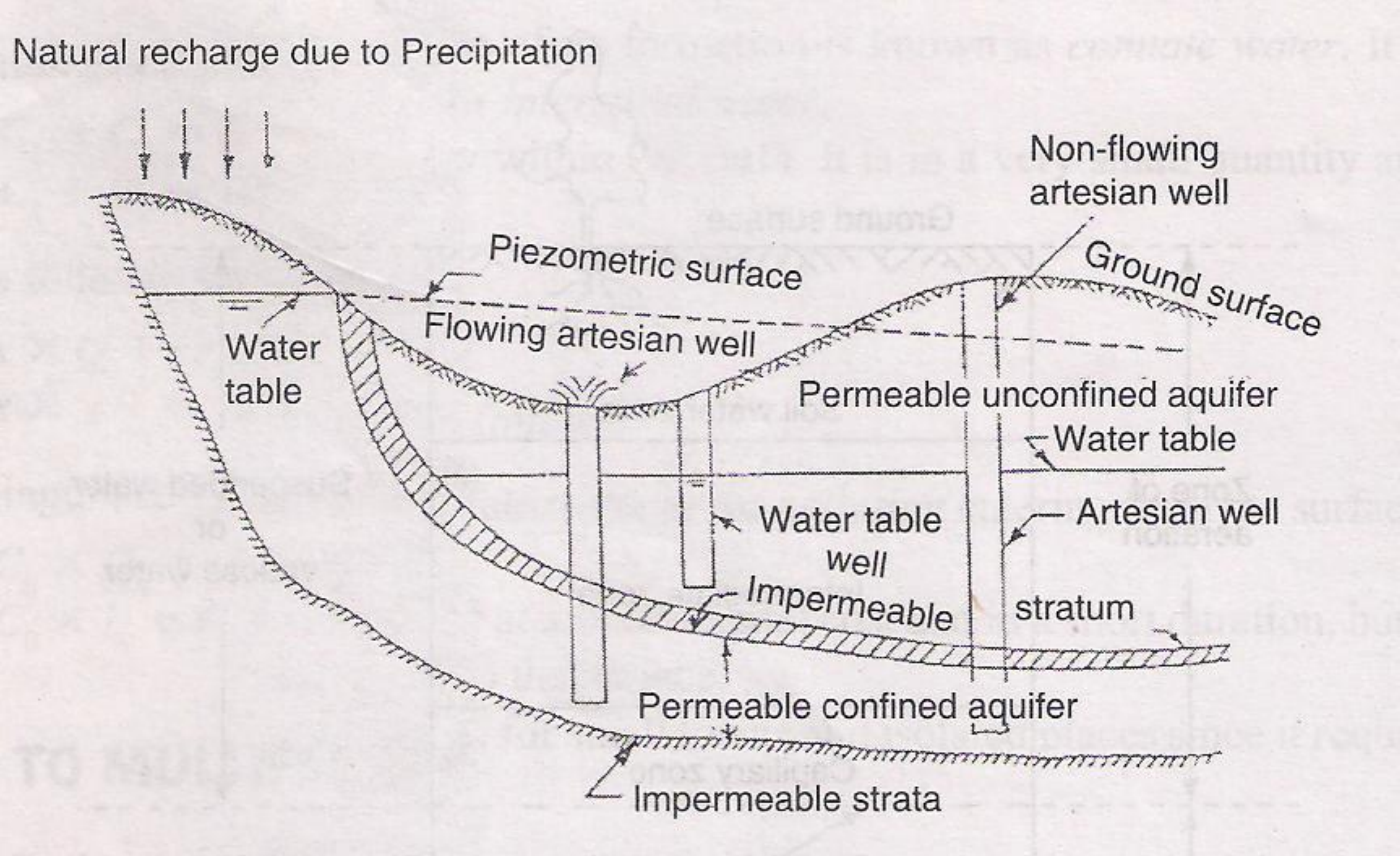


Recharge area
Water table well
Piezometric surface
Flowing well
Artesian well
Water table well
B
Water
Table
C
A
Unconfined layer
Confining layer
Confined aquifer
Impermeable strata

WELLS

- **Artesian Well**
  - ✓ ***When a well is penetrated into a confined aquifer, water rises in the well to the level of local static or artesian head.***
  - ✓ ***"If the water level in the well is below the ground level, but remains above the local water table then it is known as artesian well." Its diameter is very small varying from 15 cms to 75 cms.***
- **Flowing Well**
  - ✓ ***"If the pressure in the confined aquifer water is such that under this pressure water will rise above the ground level" then it is known as flowing well.***

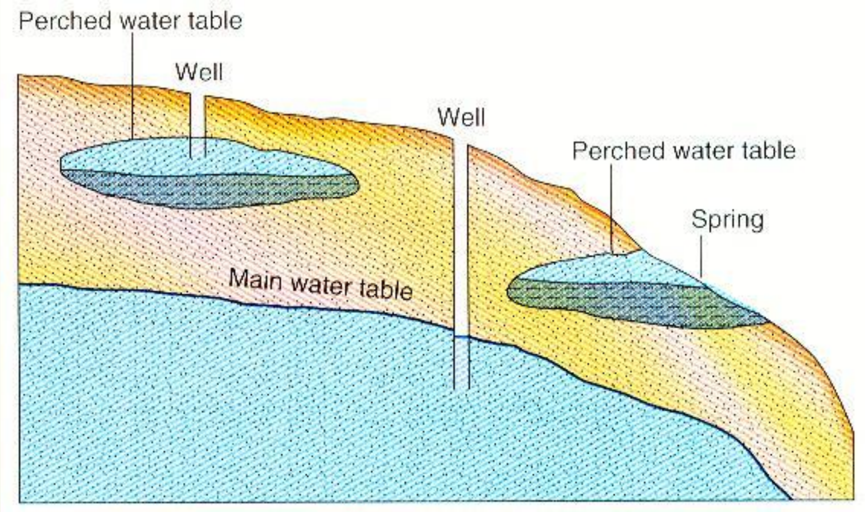
WELLS



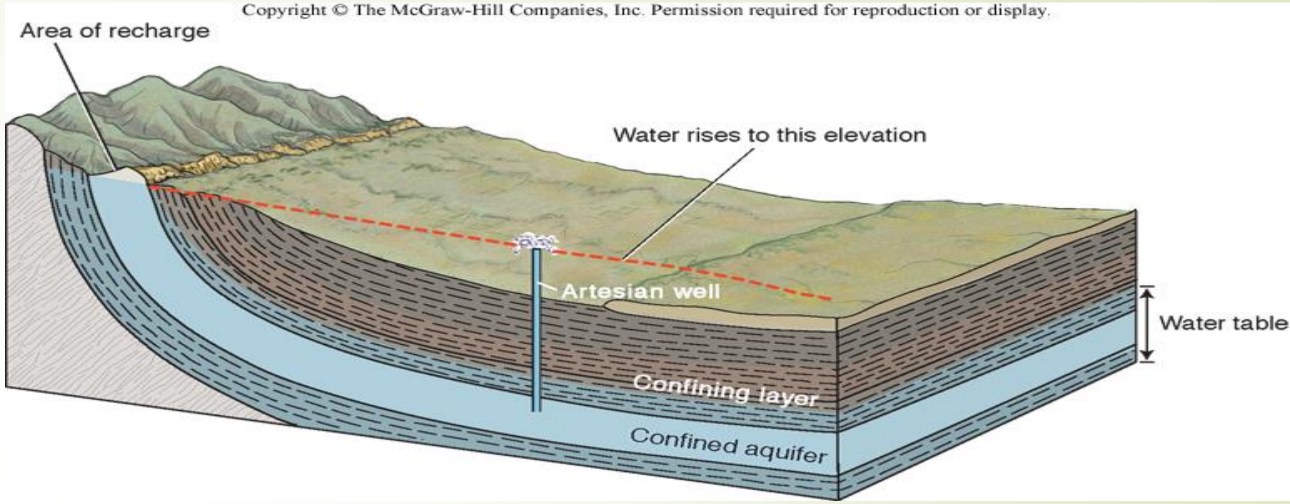
Natural recharge due to Precipitation
Non-flowing
artesian well
Piezometric surface
Ground surface
Flowing artesian well
Water
table
Permeable unconfined aquifer
Water table
Artesian well
Water table
well
Impermeable
stratum
Permeable confined aquifer
Impermeable strata

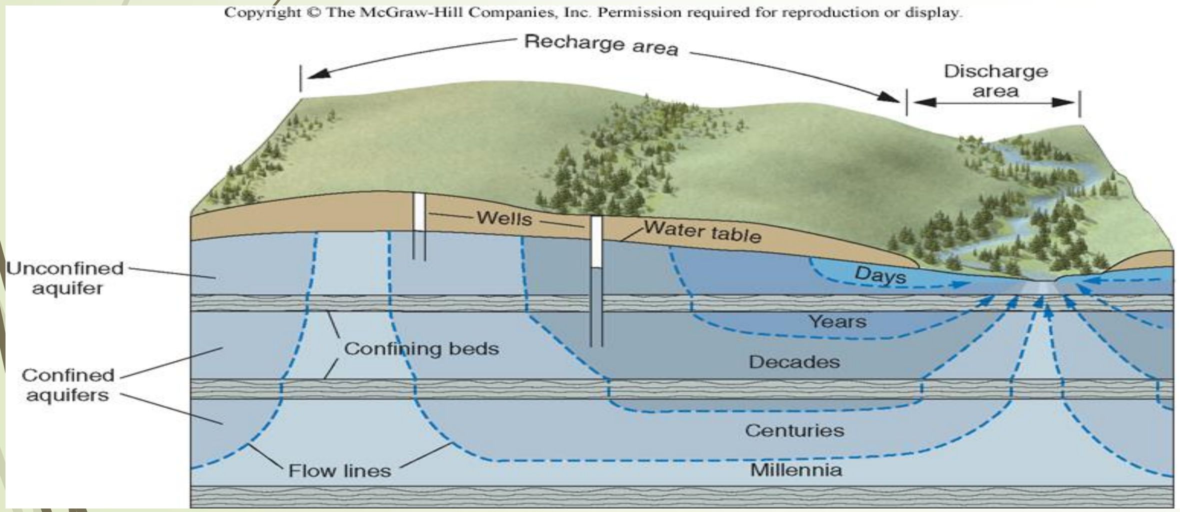
PERCHED AQUIFERS

- ***Perched water table: the top of a body of ground water separated from the main water table beneath it by a zone that is not saturated***



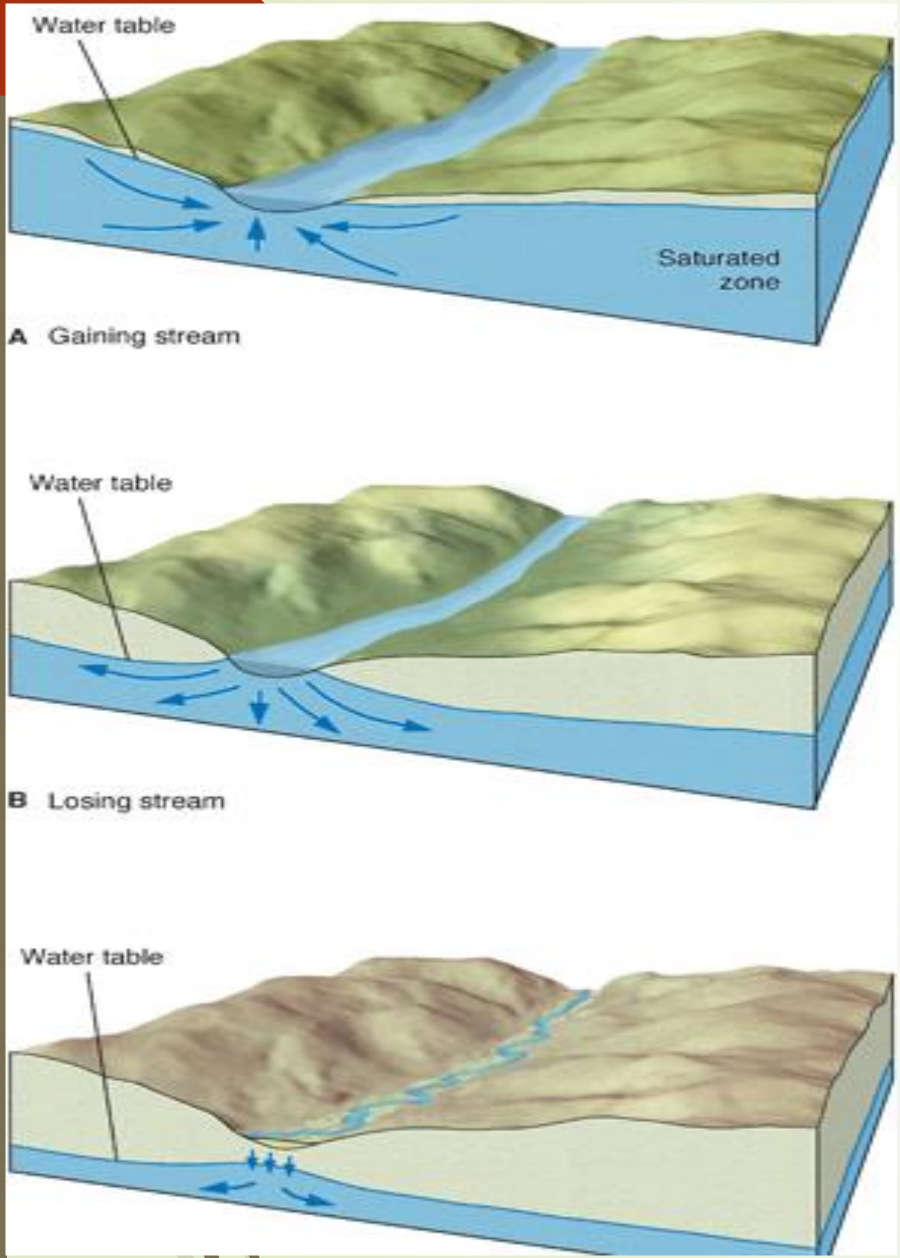
Artesian Wells





❖ ***Water may rise to a level above the top of a confined aquifer, producing an artesian well***

Springs and Streams



- ❖*Spring - a place where water flows naturally from rock or sediment onto the ground surface*
- ❖*Gaining streams - receive water from the saturated zone*
  - ➢*Gaining stream surface is local water table*
- ❖*Losing streams - lose water to the saturated zone*
  - ➢*Stream beds lie above the water table*
  - ➢*Maximum infiltration occurs through streambed, producing permanent "mound" in the water table beneath dry channel*

GROUNDWATER MOVEMENT

HYDRAULIC HEAD / FLUID POTENTIAL = h (length units)

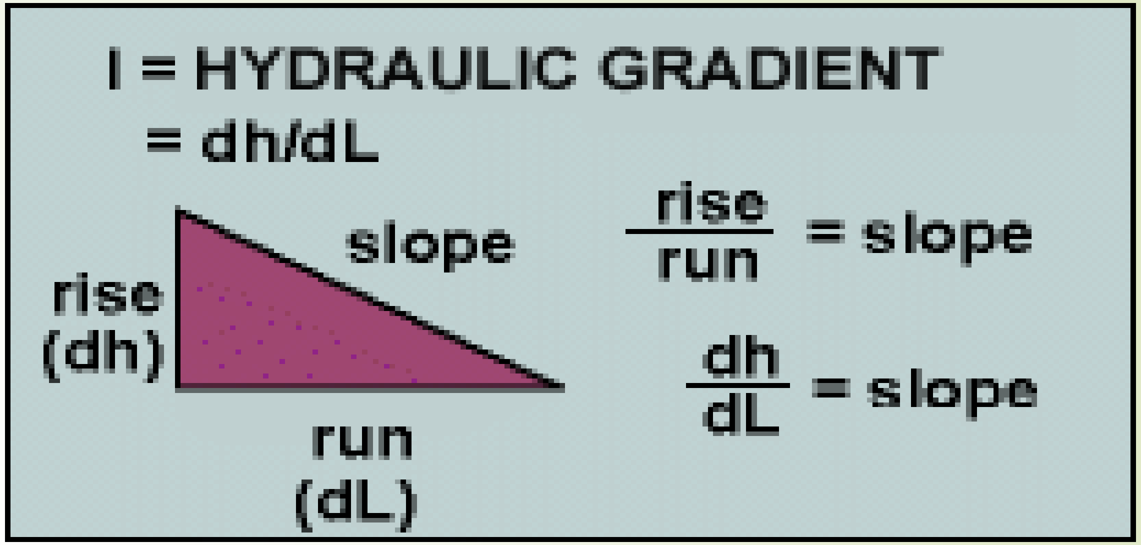
- ***Measure of energy potential (essentially is a measure of elevational/gravitational potential energy)***
- ***The driving force for groundwater flow***
- ***Water flows from high to low fluid potential or head (even if this means it may go "uphill"!)***
- ***Hydraulic head is used to determine the hydraulic gradient***

GROUNDWATER MOVEMENT

- *Hydraulic head = the driving force that moves groundwater.*
- *The hydraulic head combines fluid pressure and gradient, and can be though of as the standing elevation that water will rise to in a well allowed to come to equilibrium with the subsurface.*
- *Groundwater always moves from an area of higher hydraulic head to an area of lower hydraulic head. Therefore, groundwater not only flows downward, it can also flow laterally or upward.*

GROUNDWATER MOVEMENT

General Concepts

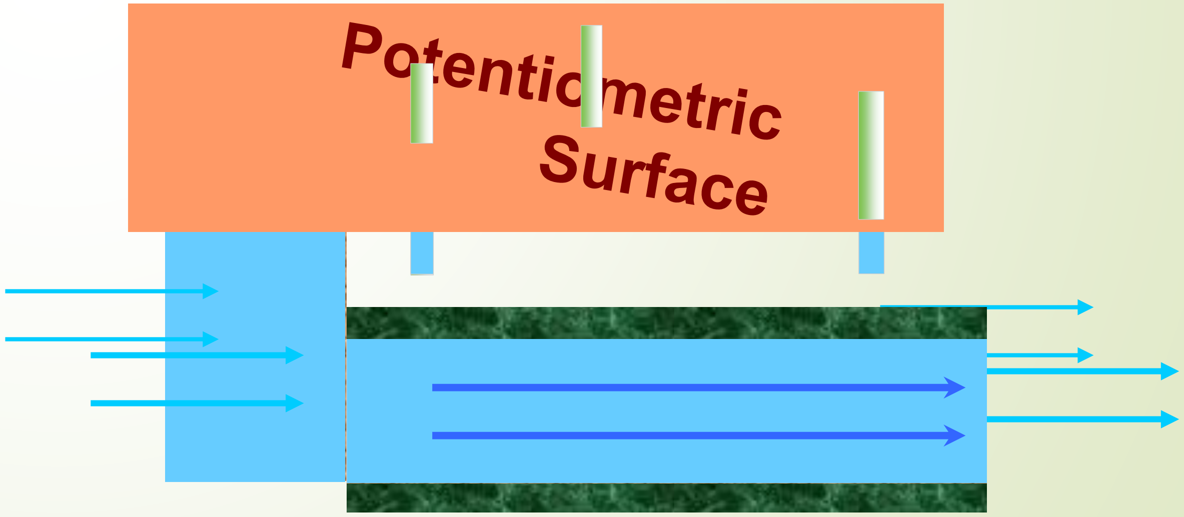


- ***Hydraulic gradient for an unconfined aquifer = approximately the slope of the water table.***
- ***Porosity = fraction (or %) of void space in rock or soil.***
- ***Permeability = Similar to hydraulic conductivity; a measure of an earth material to transmit fluid, but only in terms of material properties, not fluid properties.***
- ***Hydraulic conductivity = ability of material to allow water to move through it, expressed in terms of m/day (distance/time). It is a function of the size and shape of particles, and the size, shape, and connectivity of pore spaces.***

S. Hughes, 2003

DARCY'S LAW

- ❖ *What controls:*
  - ❖ *How much groundwater flows?*
  - ❖ *How fast groundwater flows?*
  - ❖ *Where groundwater flows?*

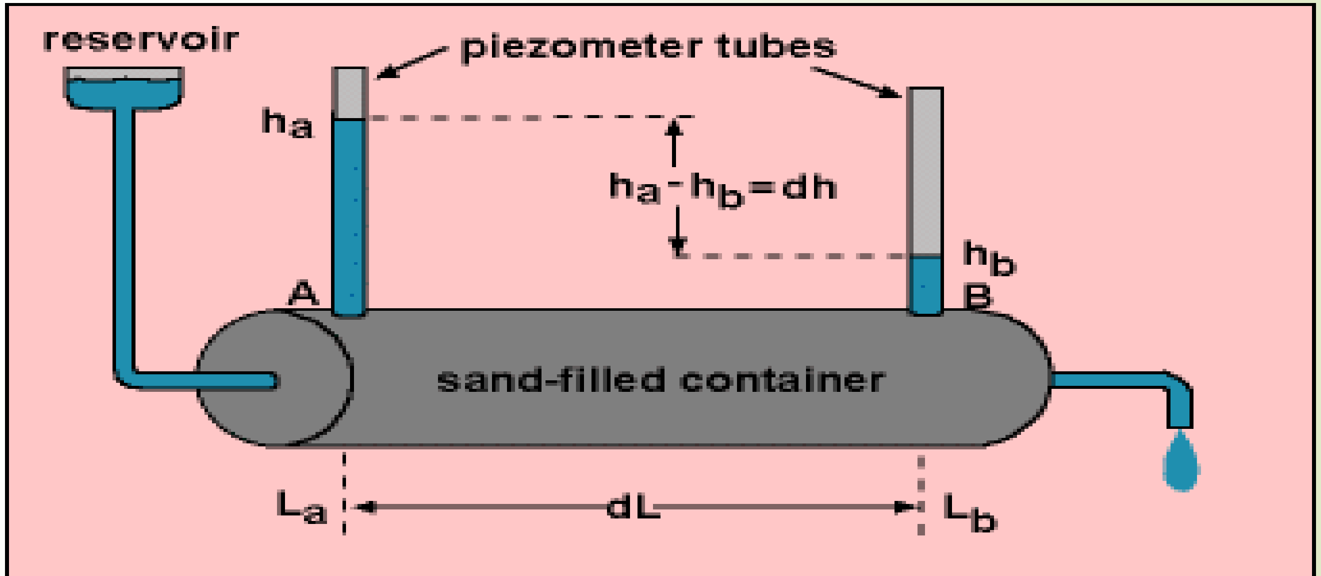


GROUNDWATER MOVEMENT -- DARCY'S LAW

Q = KIA -- Henry Darcy, 1856, studied water flowing through porous material. His equation describes groundwater flow.

Darcy's experiment:

- *Water is applied under pressure through end A, flows through the pipe, and discharges at end B.*
- *Water pressure is measured using piezometer tubes*



Horizontal pipe demonstrating Darcy's experiment

- *Hydraulic head = dh (change in height between A and B) Flow length = dL (distance between the two tubes)*
- *Hydraulic gradient (I) = dh / dL*

S. Hughes, 2003

Groundwater Movement

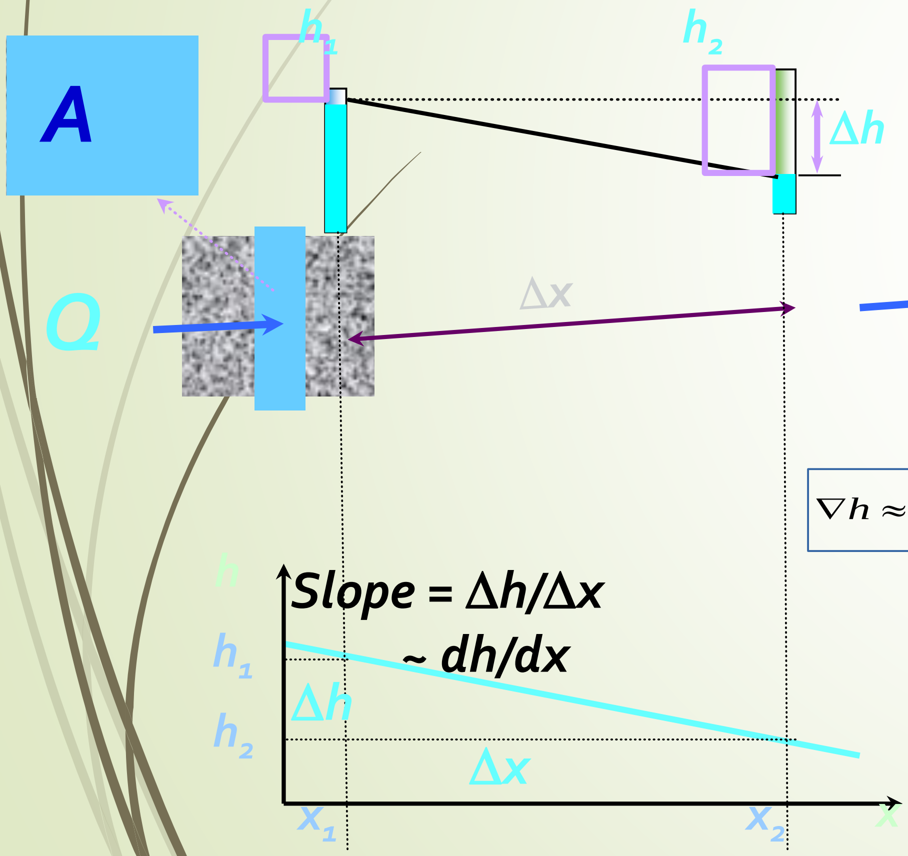
Porosity and hydraulic conductivity of selected earth materials

Material	Porosity (%)	Hydraulic Conductivity (m/day)
Unconsolidated		
Clay	45	0.041
Sand	35	32.8
Gravel	25	205.0
Gravel and sand	20	82.0
Rock		
Sandstone	15	28.7
Dense limestone or shale	5	0.041
Granite	1	0.0041

Darcy's Law

Henry Darcy's Experiment (Dijon, France 1856)

Darcy investigated ground water flow under controlled conditions



$$\boxed{Q \propto \Delta h, \quad Q \propto 1/\Delta x, \quad Q \propto A}$$

Q: Volumetric flow rate [$L^{3/T}$]

A: Cross Sectional Area (Perp. to flow)

K: The proportionality constant is added to form the following equation:

$$\boxed{\nabla h \approx \frac{\Delta h}{\Delta x}}$$ *: Hydraulic Gradient*

$$\boxed{Q \propto A\frac{\Delta h}{\Delta x} \quad \Rightarrow \quad Q = -K\,A\frac{\Delta h}{\Delta x}}$$

K units [L/T]

LIMITATIONS OF DARCY'S LAW

- ***Flow is Laminar.***
- ***Reynolds Number defined as $N_R = v\,D/\nu$, where v = velocity, D= A representative length and ν = kinematic viscosity of the fluid is <5.***
- ***The soil media is isotropic (K independent of direction).***
- ***Soil is homogeneous.***