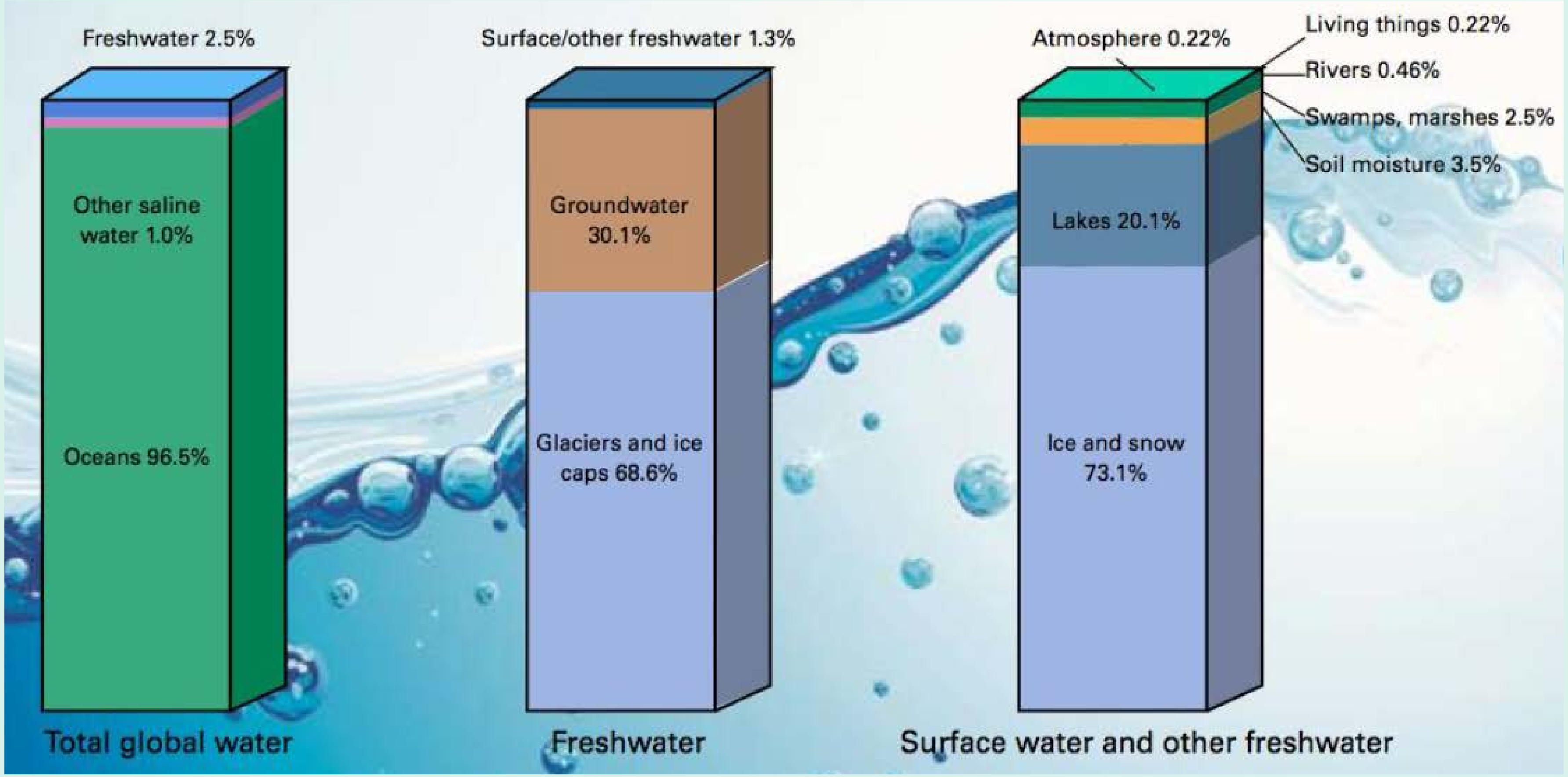
GROUNDWATER HYDROLOGY (HWRE 6034)

Objective: To introduce fundamentals of groundwater hydrology, groundwater assessment and groundwater development.

Chapter 1: Introduction

Definition of groundwater

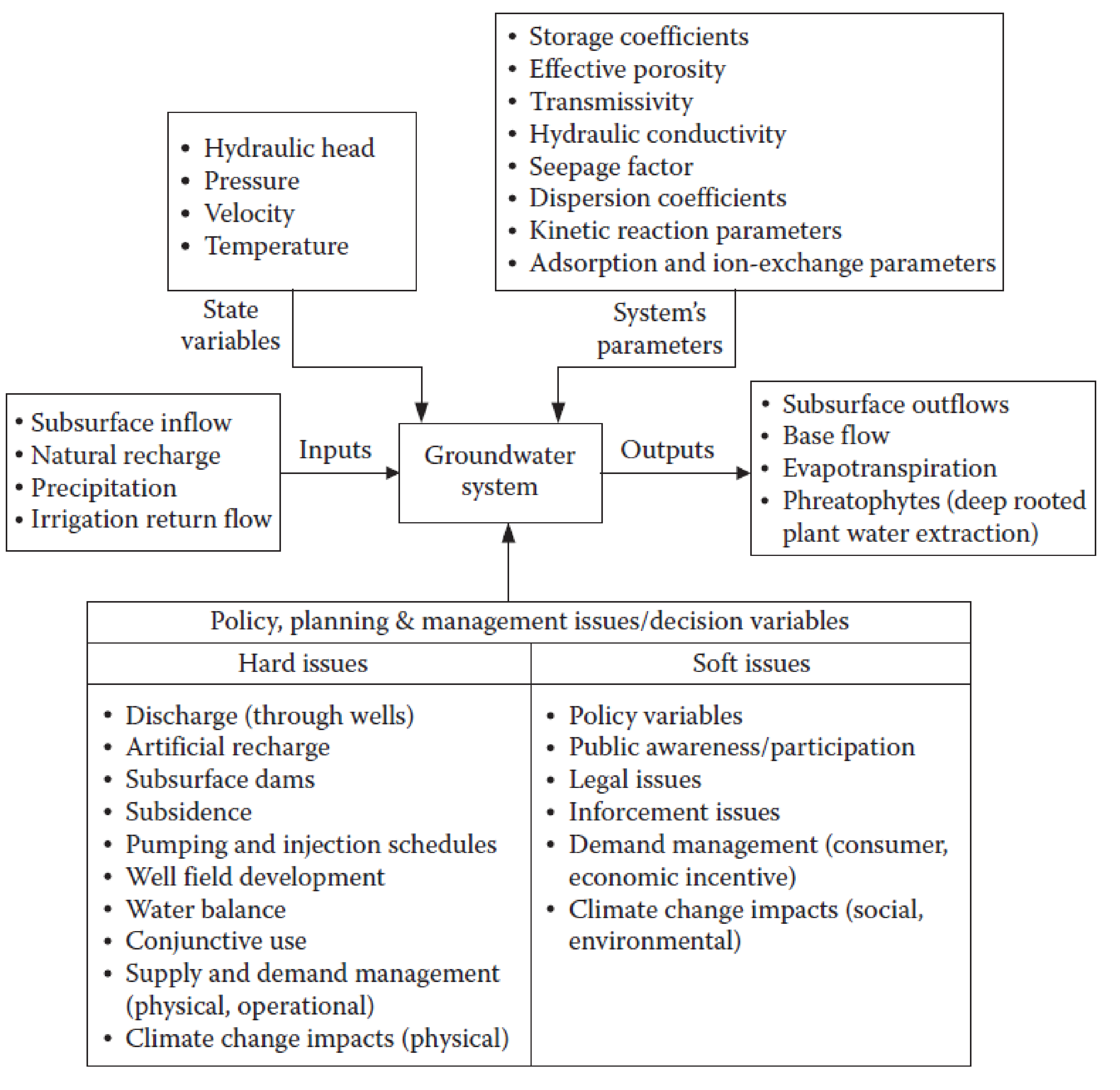
- Ground-water hydrology is the subdivision of the science of hydrology that deals with the occurrence, movement, and quality of water beneath the Earth's surface.



Introduction

- The groundwater system is a part of the hydrologic cycle and should be studied on a watershed scale.

- Combination of many elements and factors affecting groundwater, so related and connected, call for a holistic view to groundwater challenges within a hydrologic cycle.



Introduction

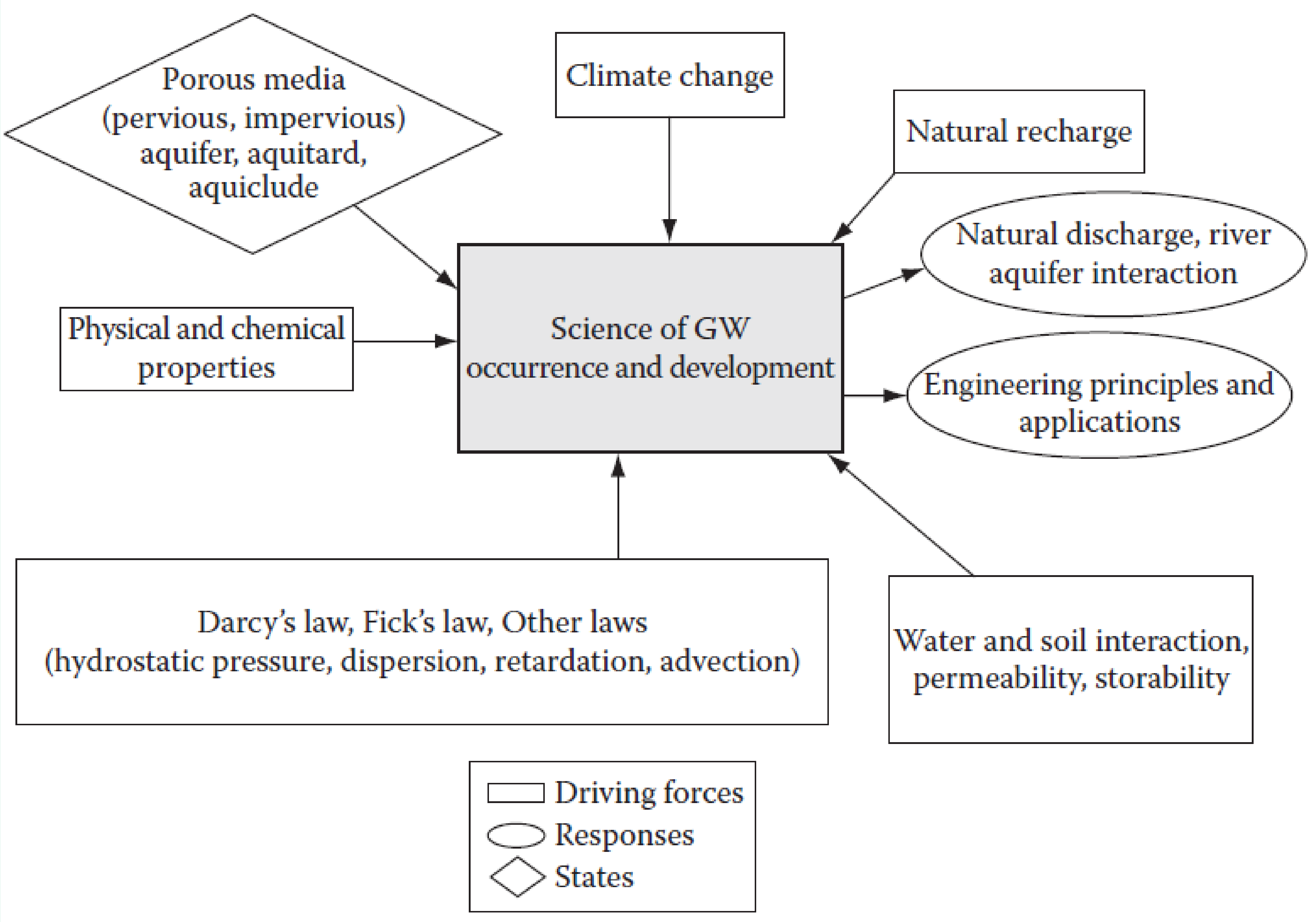


Figure. Science framework of groundwater (GW) occurrence (hydrogeology).

Introduction

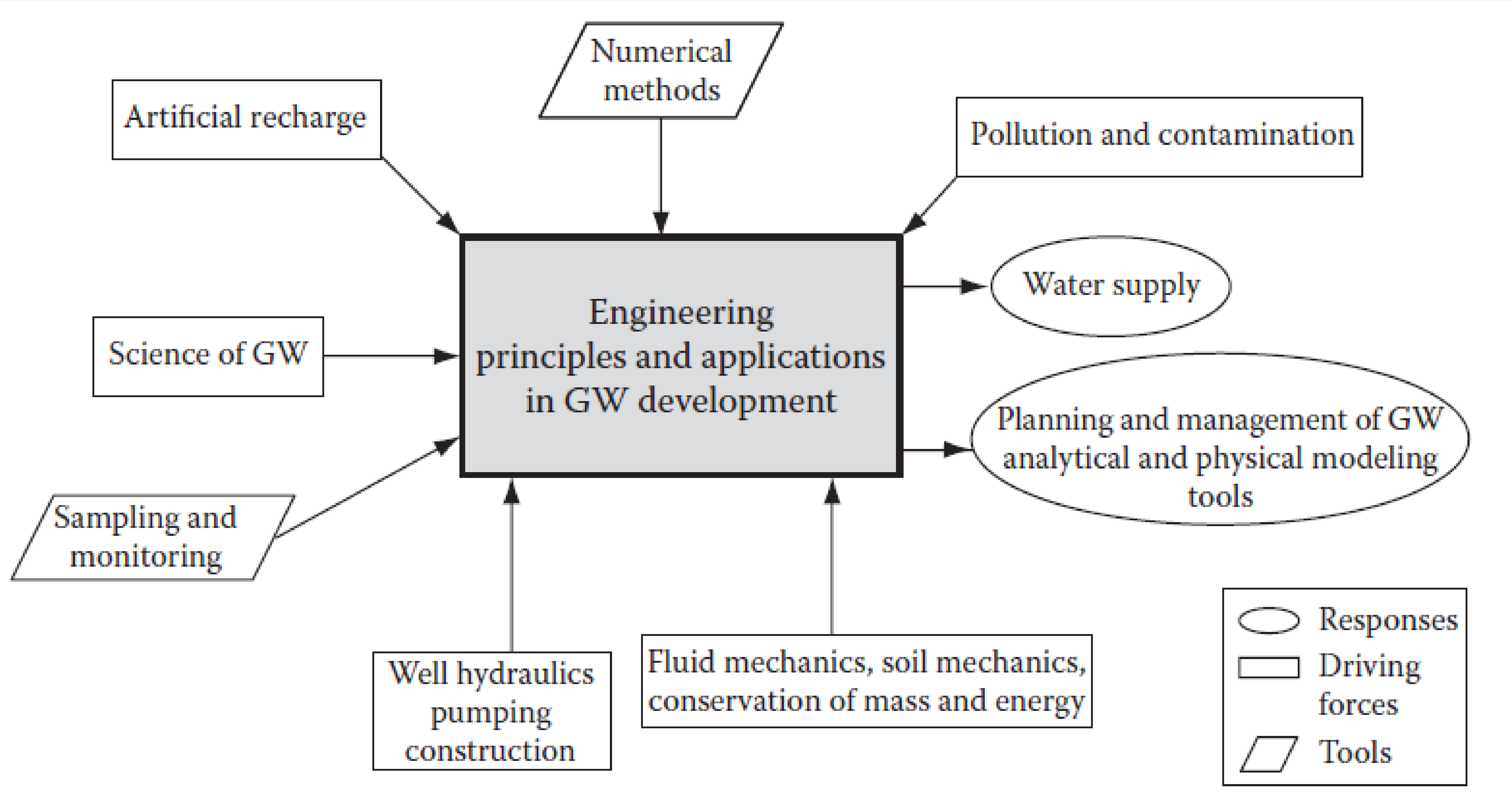


Figure. Basic engineering principles and applications in groundwater (hydrological and hydraulic design).

Chapter 1: Introduction

Groundwater is more vulnerable to pollution because

it is **invisible** to monitor and regulatory issues related to groundwater misuse,

and **act** of contaminating groundwater **are not easy to enforce**.

Planning for sustainable development of water resources means

- ✓water conservation,
- ✓waste and leakage prevention,
- ✓improved efficiency of water systems,
- ✓improved water quality,
- ✓water withdrawal and usage within the limits of the system,
- ✓water pollution within the carrying capacity of the streams, and
- ✓water discharge from groundwater within the safe yield of the system.

Chapter 1: Introduction

- It is not easy to determine and monitor the safe yield of the aquifers.
- Aquifer safe yields can not be enforced for many technical, operational, and political reasons.
- So the aquifers are subject to conditions of over expectation in many parts of the world especially in arid and semiarid regions.

- Groundwater is widely used for irrigation in countries with arid and semiarid climate.
- Fore example:
  - the total irrigated land by groundwater in the United States is 45%.
  - In Asia and Africa, more than 60% of land mass is irrigated by groundwater.

Chapter 1: Introduction

- Libya's irrigated farming is primarily from low-quality groundwater resources, several kilometers deep.
- Groundwater is by far the **most abundant source of freshwater** on continents outside Polar Regions, followed by ice caps, lakes, wetlands, reservoirs, and rivers.

- It is estimated that about 20% of global water withdrawals comes from groundwater (WMO, 1997).
- According to the UNEP, annual global freshwater withdrawal has grown from 3790 km^3 in 1995 to about 4430 km^3 in 2000.

Chapter 1: Introduction

- The share of groundwater is expected to increase at a slower rate due to already over drafted aquifers in many points of the world.
- There are many advantages in storage of groundwater compared to the surface storage:

  - ✓ Minimum evaporation losses—It is limited to
    - ✓ Groundwater close to the surface by capillary fringes
    - ✓ "Phreatophytes"—plants feed on capillary fringe
  - ✓ Quality may benefit from filtering action (however, may be too high in dissolved solids).
  - ✓ There is general improvement of water quality because of the porous media filtration of airborne and surface runoff contaminants and pathogens.
  - ✓ Outflow is gradual (good regulation in underground reservoir).

Advantages..

- ✓ No other missive structure such as dams is needed (however, may involve high pumping costs).
- ✓ Land use above the groundwater resources can be continued without change
  - ✓ (there is no submergence of houses, abstraction to infrastructure, and property development and agricultural development.

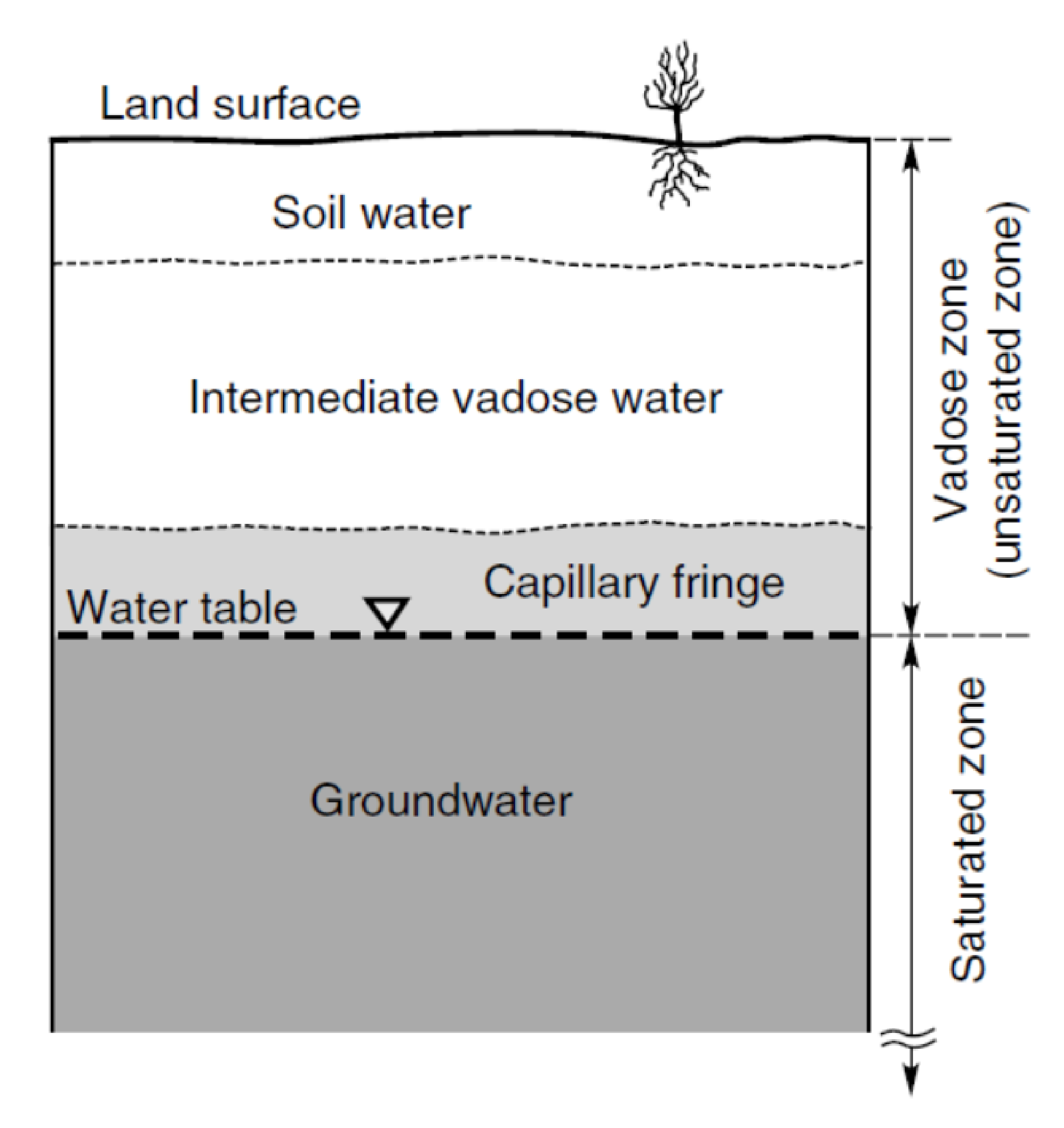
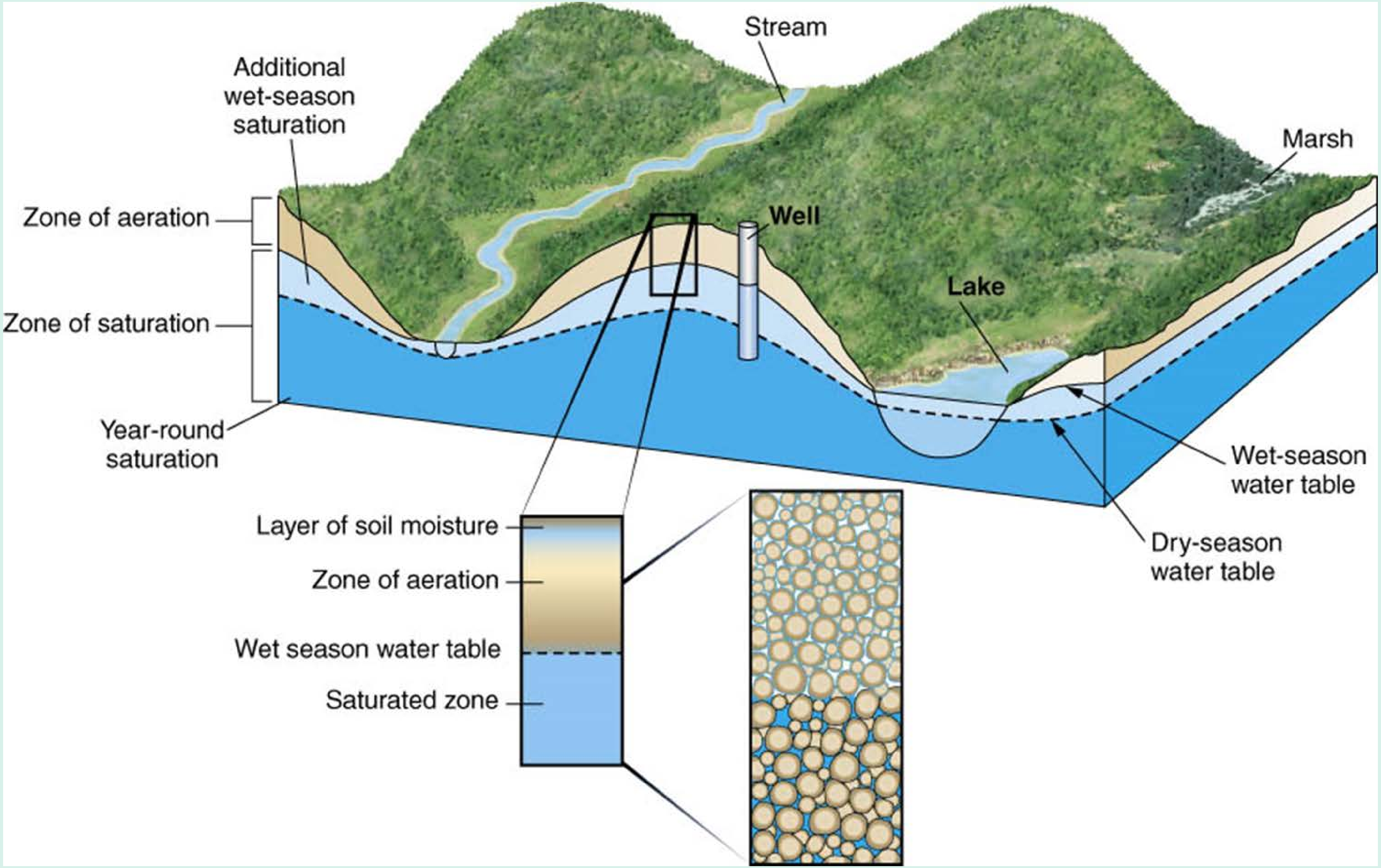


Figure 2. Hydro-geologic zones and types of water in the subsurface.


Stream
Additional wet-season saturation
Marsh
Zone of aeration
Well
Lake
Zone of saturation
Year-round saturation
Wet-season water table
Dry-season water table
Layer of soil moisture
Zone of aeration
Wet season water table
Saturated zone

Role of groundwater in hydrological cycle

- Inflow to the hydrologic system arrives as *precipitation*, in the form of rainfall or snowmelt.
- Outflow takes place as *streamflow* (or runoff) and as *evapotranspiration*, a combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants.
- Precipitation is delivered to streams both on the land surface, as *overland flow* to tributary channels; and by subsurface flow routes, as *interflow* and *baseflow* following *infiltration* into the soil.

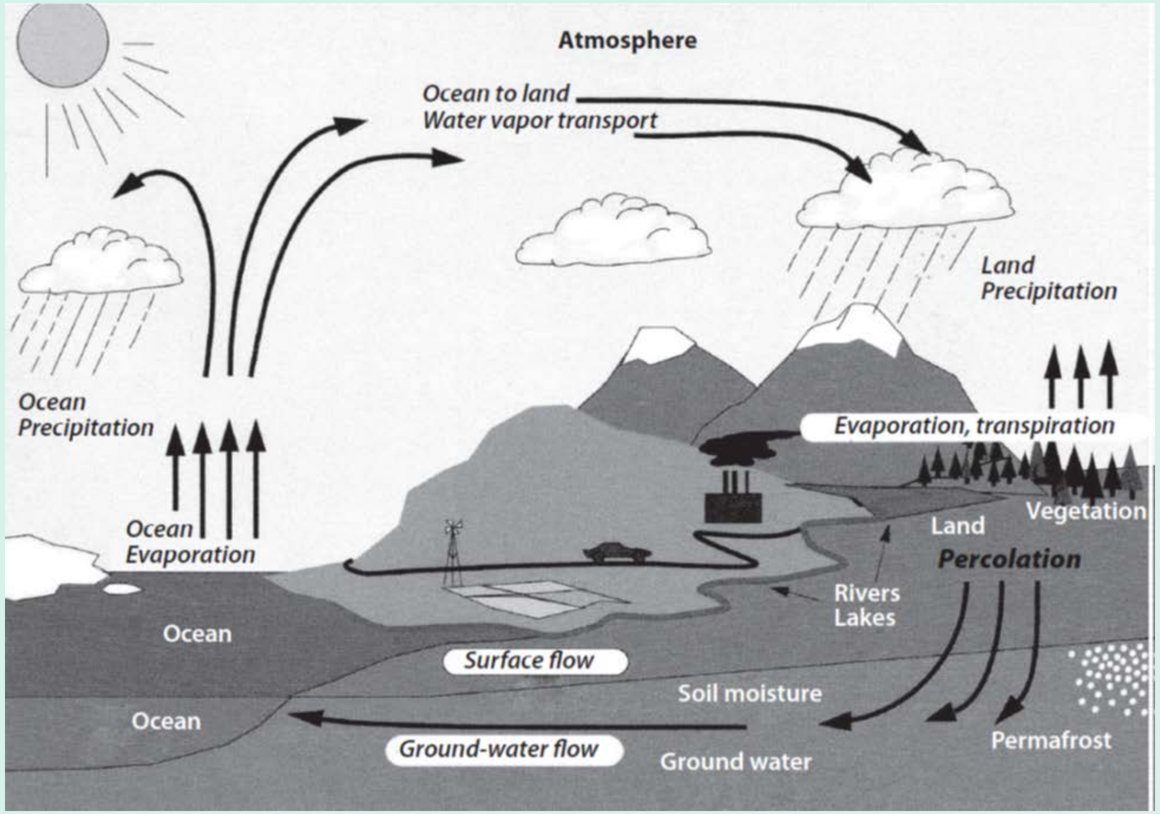


Figure 3. Pictorial representation of the global hydrological cycle

Role of groundwater in hydrological cycle

- The subsurface hydrologic processes are just as important as the surface processes.
- In fact, one could argue that they are more important,
  - for it is the nature of the subsurface materials that controls infiltration rates, and the infiltration rates influence the timing and spatial distribution of surface runoff.

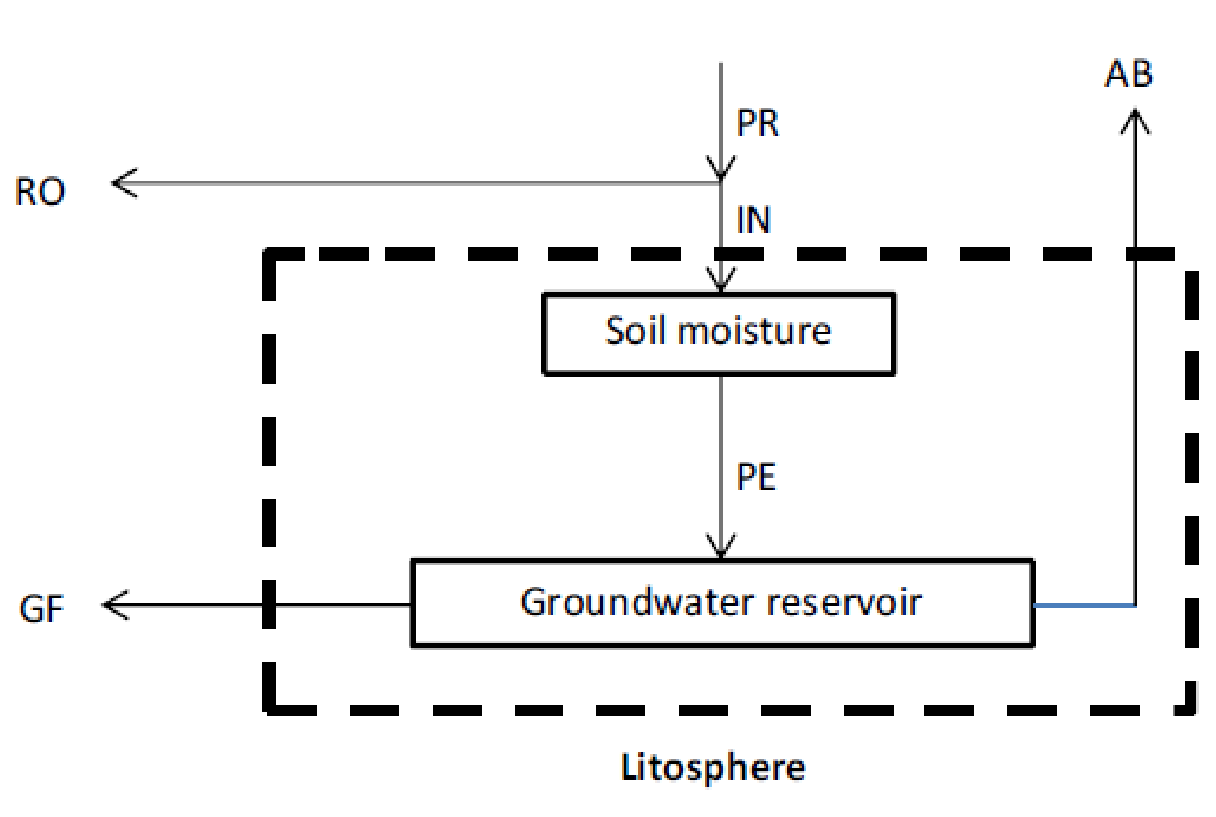


FIGURE 3. Subsurface hydrologic cycle parts.

PR, precipitation; IN, infiltration; PE, percolation; GF, groundwater flow; RO, runoff; AB, abstraction.

Role of groundwater in hydrological cycle

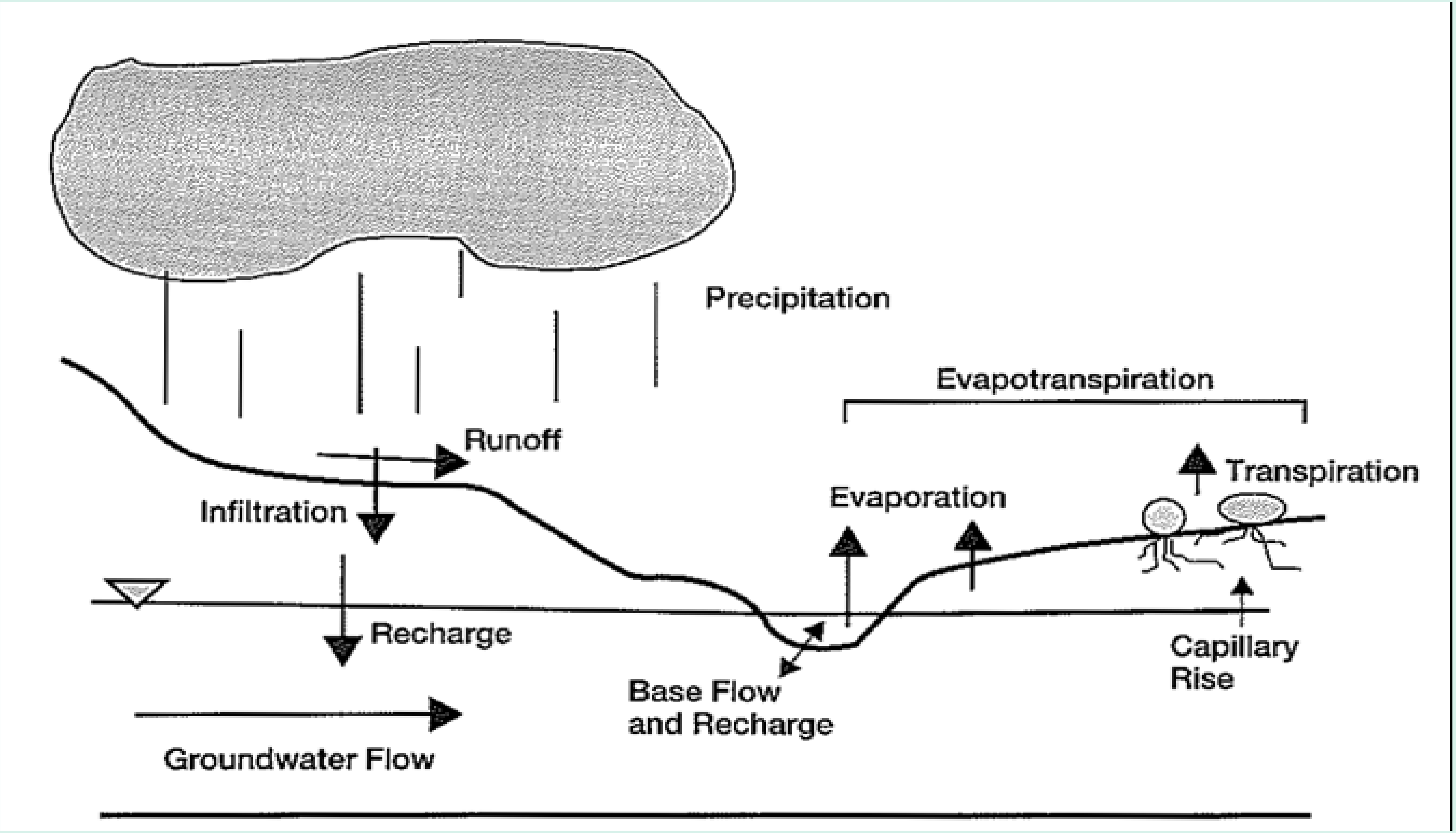
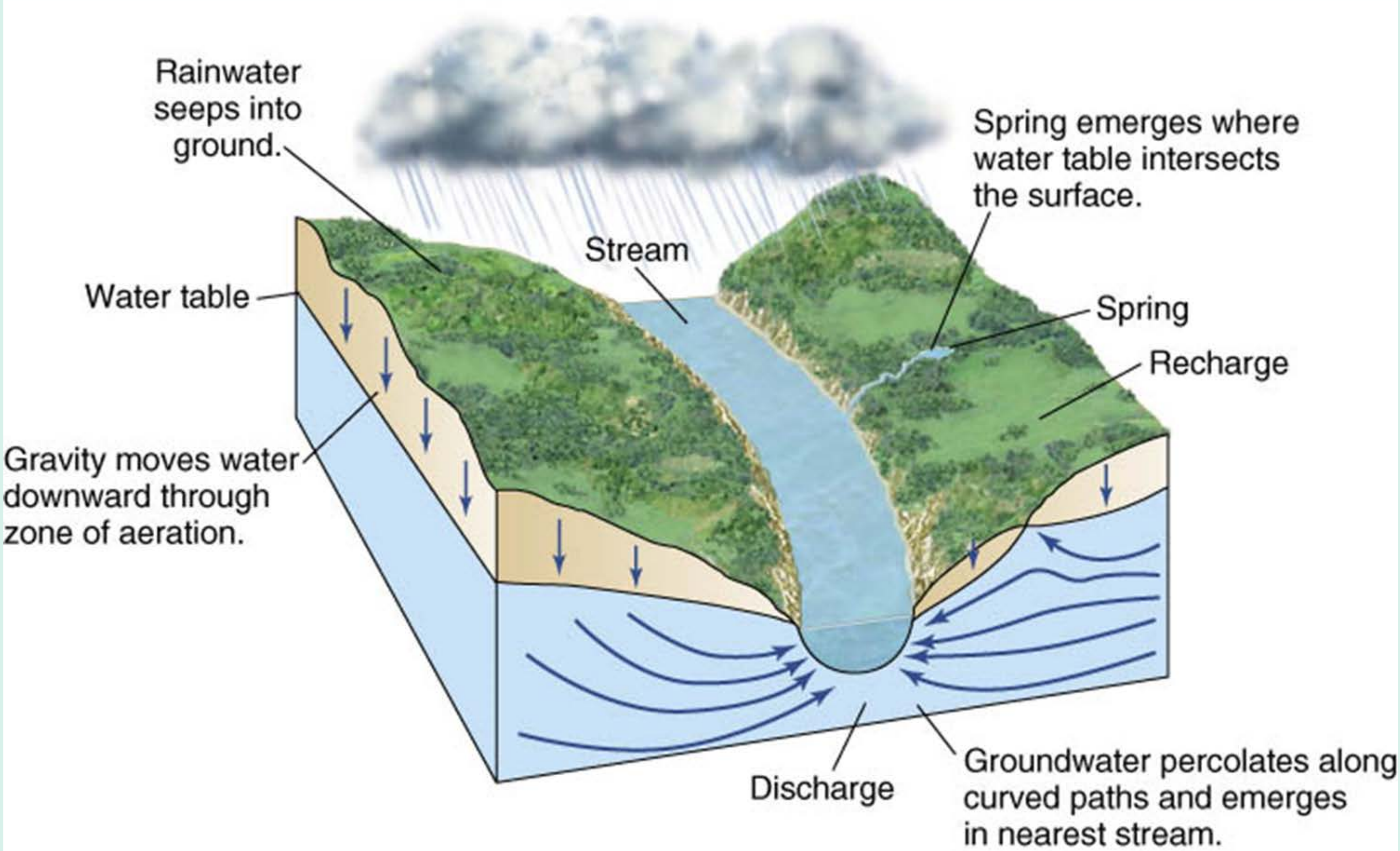
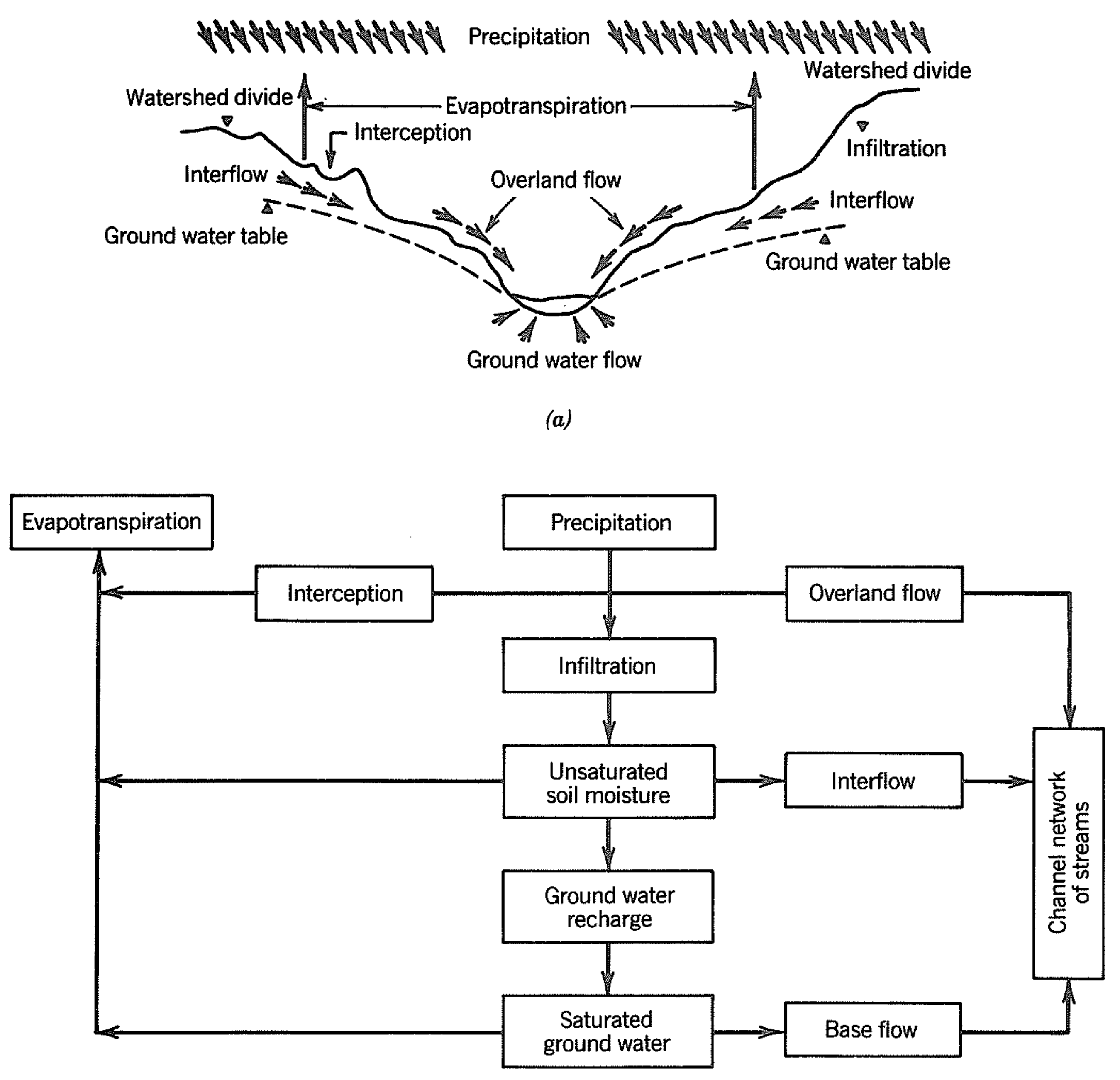


Figure. Schematic view of the hydrologic cycle

Role of groundwater in hydrological cycle



Role of groundwater in hydrological cycle



Role of groundwater in hydrological cycle

- Ground water is water under positive (i.e., greater than atmospheric) pressure in the saturated zone of earth materials.
- The water table is the fluctuating upper boundary of the ground-water zone at which pressure is atmospheric.
- Most water enters the ground-water reservoir when infiltrated water arrives at the water table as recharge;
  - recharge can also occur by horizontal or vertical seepage from surface-water bodies.

Role of groundwater in hydrological cycle

- Under natural conditions ground water eventually
  - discharges into rivers or lakes or, in coastal areas, directly into the ocean;
  - water can also leave the groundwater reservoir by moving upward from the water table into the capillary fringe and thence into the unsaturated zone, where it is subject to evapotranspiration.

- Ground water constitutes about 30% of the world's total fresh water and 99% of its total stock of liquid fresh water.

Role of groundwater in hydrological cycle

- As with all hydrologic stocks, ground water is in continual motion, albeit slow (typically much less than 1 m/d).

- The overall residence time for the global ground-water reservoir is about 235 yr;
  - for moderate to large-scale regional flow systems in various parts of the world residence time varies from a few years to 1,000 years or more.

- In spite of its slow pace, ground water is a crucial link in the hydrologic cycle because it is the source of most of the water in rivers and lakes.

Role of groundwater in hydrological cycle

- Ground water is also important as the direct source of water withdrawn for domestic water use, irrigation, and industrial uses worldwide.
- Concern about the quantity and quality of ground water is one of the major water-resource issues in many parts of the world.

- Groundwater is an important part of Earth's hydrologic cycle or movement of water between oceans, atmosphere, and land.
- Groundwater is derived mostly from percolation of precipitation and, to a lesser degree, from surface water streams and lakes that lose water to underlying aquifers.
- Groundwater from aquifers and aquitards discharges to fresh surface water bodies on land (streams, lakes, marshes) and to oceans.

Role of groundwater in hydrological cycle

- This discharge is either concentrated via springs and seeps, or directly into surface water bodies where it is normally not visible.
- The volume of groundwater stored and moving through aquifers and aquitards in the upper portion of Earth's crust is much larger than any other form of mobile freshwater on Earth, excluding glaciers and ice caps.

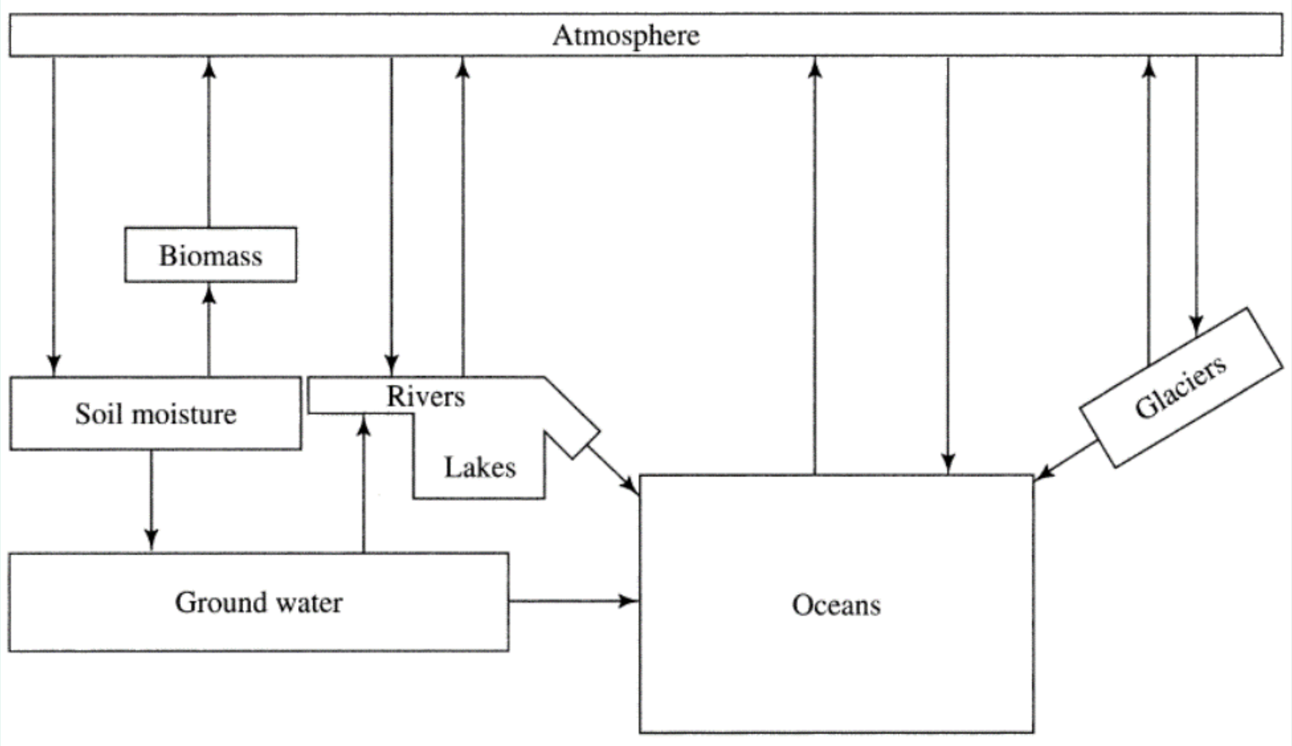


Figure 4. The principal storages (boxes) and pathways (arrows) of water in the global hydrologic cycle.

Role of groundwater in hydrological cycle

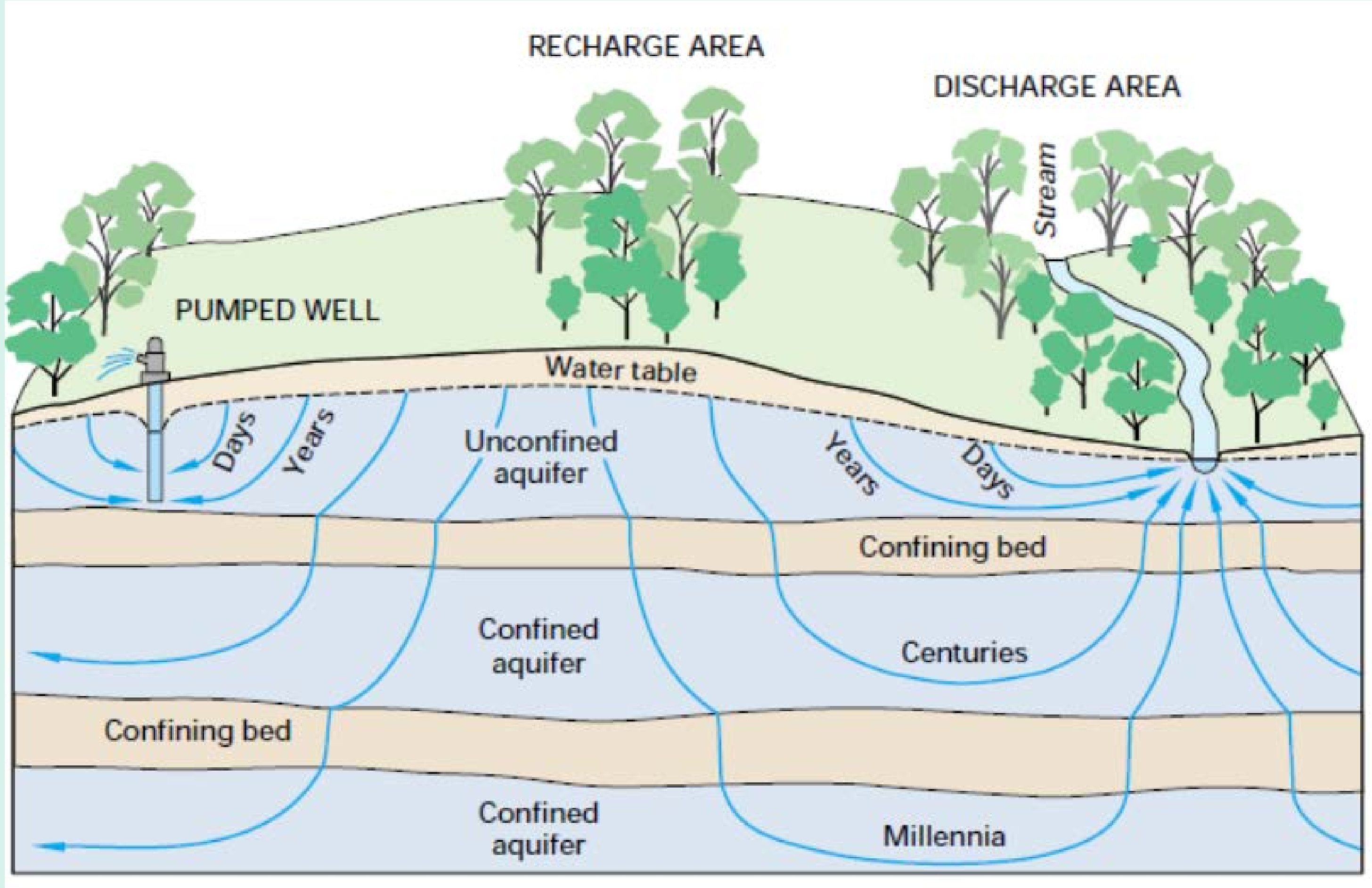


Figure 5. Ground-water flow paths vary greatly in length, depth, and travel time from points of recharge to points of discharge in the groundwater system.

- Groundwater is one of the main components of the environment that is less affected by short-term climate and hydrologic variability.
- According to a global model Water, 36% of the river runoff is formed by groundwater
    - so separating groundwater shares from surface water resource is not easy to assess.

Role of groundwater in hydrological cycle

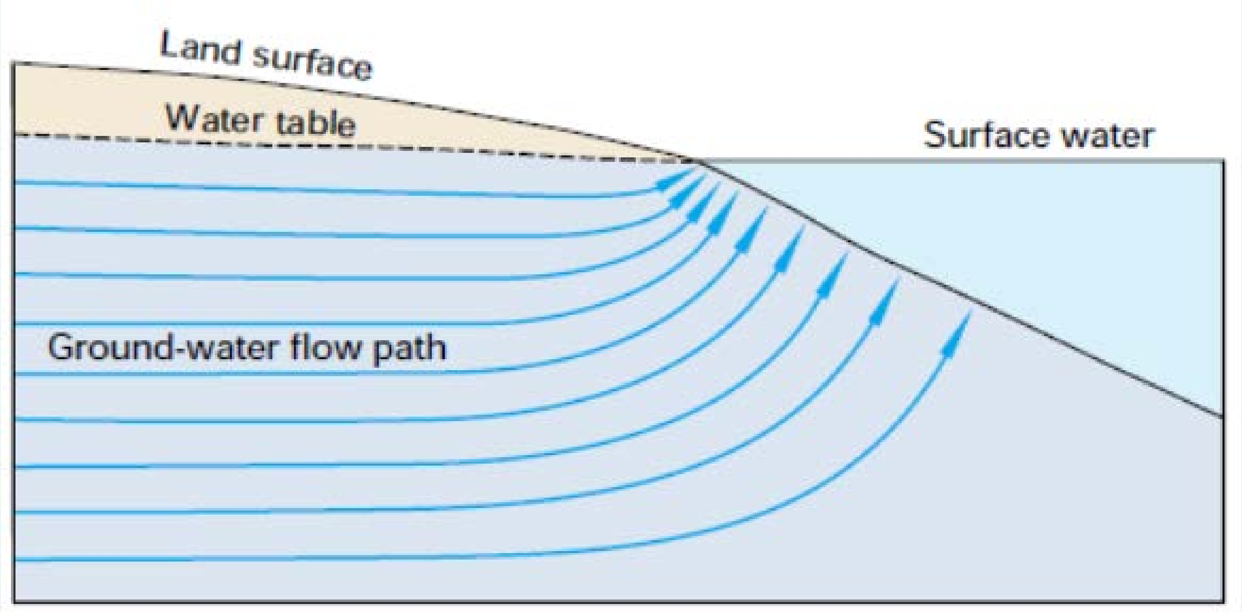


Figure 6. Ground-water seepage into surface water usually is greatest near shore.

- In flow diagrams such as that shown here, the quantity of discharge is equal between any two flow lines; therefore, the closer flow lines indicate greater discharge per unit of bottom area.

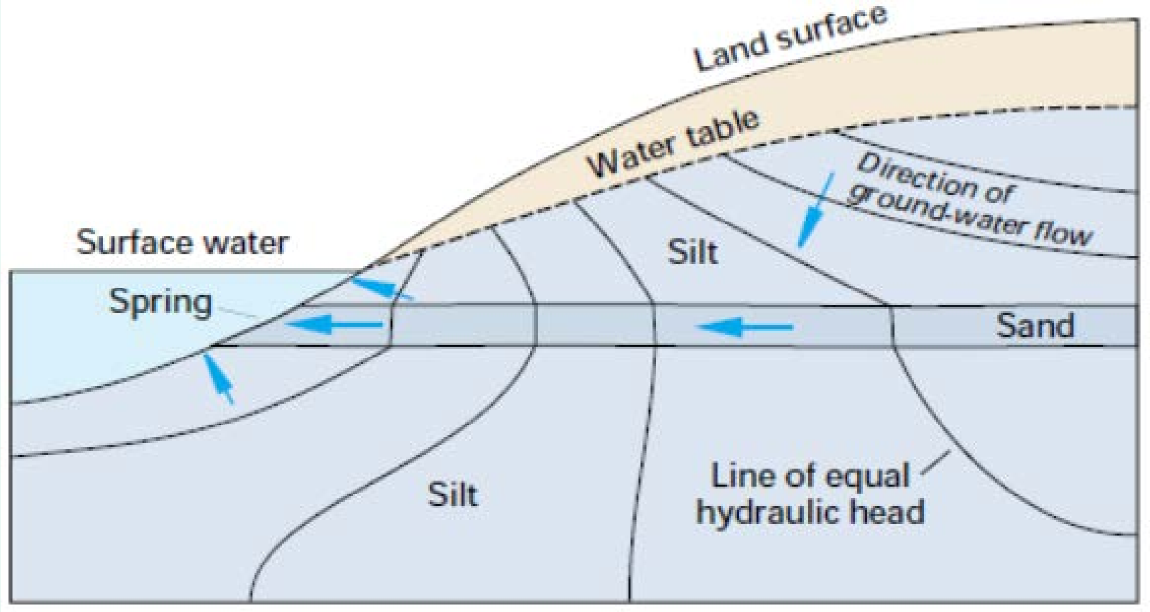


Figure 7. Subaqueous springs can result from preferred paths of ground-water flow through highly permeable sediments.

Groundwater bearing formations

- Most of the rocks near the Earth's surface are composed of both solids and voids.
- The solid part is, of course, much more obvious than the voids, but, without the voids, there would be no water to supply wells and springs .

- Water-bearing rocks consist either of unconsolidated (soil like) deposits or consolidated rocks .
- The Earth's surface in most places is formed by soil and by unconsolidated deposits
- The unconsolidated deposits are underlain everywhere by consolidated rocks .

Groundwater bearing formations

- Most unconsolidated deposits consist of material derived from the disintegration of consolidated rocks .
- The material consists, in different types of unconsolidated deposits, of particles of rocks or minerals ranging in size from fractions of a millimeter (clay size) to several meters (boulders) .

- Unconsolidated deposits important in ground-water hydrology include,
  - ✓in order of increasing grain size,
    - ✓clay, silt, sand, and gravel.

Groundwater bearing formations

- An important group of unconsolidated deposits also includes fragments of shells of marine organisms.
- Consolidated rocks consist of mineral particles of different sizes and shapes that have been welded by heat and pressure or by chemical reactions into a solid mass.

- Such rocks are commonly referred to in ground-water reports as bedrock.
- They include sedimentary rocks that were originally unconsolidated and igneous rocks formed from a molten state.

Groundwater bearing formations

- Consolidated sedimentary rocks important in ground-water hydrology include limestone, dolomite, shale, siltstone, sandstone, and conglomerate.
- Igneous rocks include granite and basalt .
- There are different kinds of voids in rocks, and it is sometimes useful to be aware of them.
- If the voids were formed at the same time as the rock, they are referred to as primary openings (2).
- The pores in sand and gravel and in other unconsolidated deposits are primary openings.
- The lava tubes and other openings in basalt are also primary openings

Groundwater bearing formations

- If the voids were formed after the rock was formed, they are referred to as secondary openings.
- The fractures in granite and in consolidated sedimentary rocks are secondary openings.
- Voids in limestone, which are formed as ground water slowly dissolves the rock, are an especially important type of secondary opening.

- It is useful to introduce the topic of rocks and water by dealing with unconsolidated deposits on one hand and with consolidated rocks on the other.
- However, many sedimentary rocks that serve as sources of ground water fall between these extremes in a group of semi-consolidated rocks.

Groundwater bearing formations

- These are rocks in which openings include both pores and fractures-in other words, both primary and secondary openings.
- Many limestones and sandstones that are important sources of ground water are semi-consolidated.

- The proportion of solids (particles) and voids (pores, fractures, solution cavities) in any rock body defines its worth for water storage and yield capability, i.e., its water release potentiality.
- Voids and solids are present in any rock mass as mutually exclusive combinations, which give the rock ability to store fluids (water, gas, oil, air) in the voids.

Groundwater bearing formations

- Rock masses may be potential reservoirs provided that the voids are interconnected.
- The term reservoir has a broad meaning and in general, it can be defined as “any material body, which can store and release fluid.”
- Reservoir does not necessarily mean that it can transmit water at demand levels.

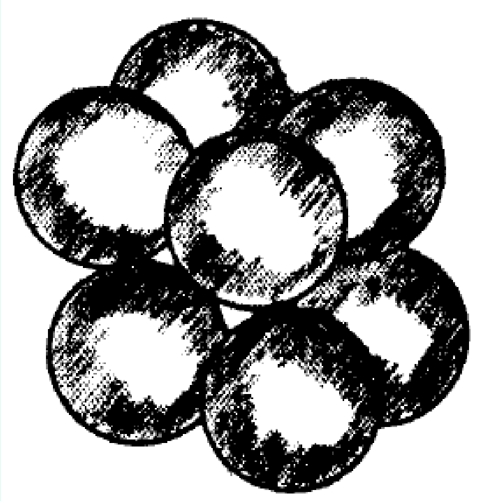
- The proportion of interconnected pores present in the whole bulk of the rock mass further defines the permeable or impermeable nature of the reservoirs.
- Clay being highly porous material falls into the category of reservoirs but it is not able to yield water at significant rates, so it is an impermeable reservoir.
- Depending on the genesis of voids as porous, fractured, or karstic, the geological formations are regarded as fluid (groundwater, oil, and gas) reservoir.

Groundwater bearing formations

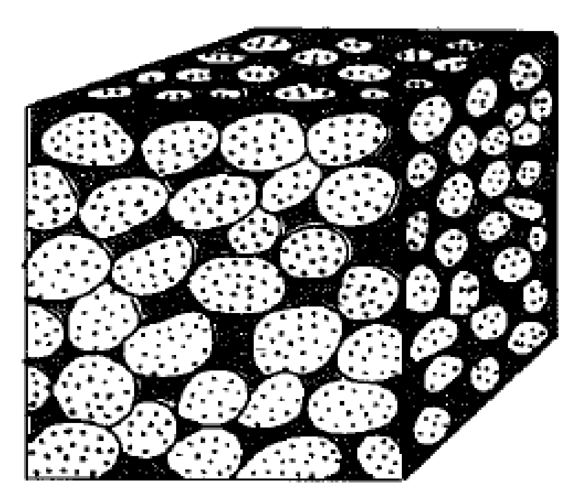
- The sedimentary rocks such as sandstone, clay, and limestone are potential groundwater reservoirs.
- The igneous and metamorphic rocks (if not fractured) like granite and gabbro are not significant groundwater reservoirs.
- Depending upon the geometrical interrelationships (size, shape, orientation, interconnection) among pore spaces, the permeable reservoirs are further classified into porous, karstic, and fractured media.
- Porous medium can be categorized broadly into fine- and coarse-grained formations.
- From volcanic rocks granite, granodiorite, diorite, and alkalic granite may have fair to good permeability related to the degree of weathering and fracturing.
- Groundwater recharge may take place after heavy rain in weathered zone.

Groundwater bearing formations

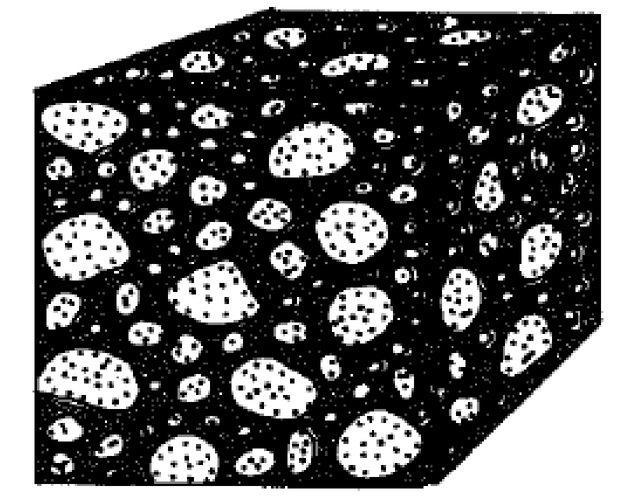
- The main storage appears in weathered and fractured zones.
- Basalt and andesite occur as top-cover rocks, and therefore, their potentiality as an aquifer cannot be high, and they cause high infiltration but low-evaporation losses.
- Basalt thickness may reach up to about 60–80 m and the underlying volcanic rocks may include water in fractures and weathered zones.
- The groundwater quality is expected to be good.



Porous material



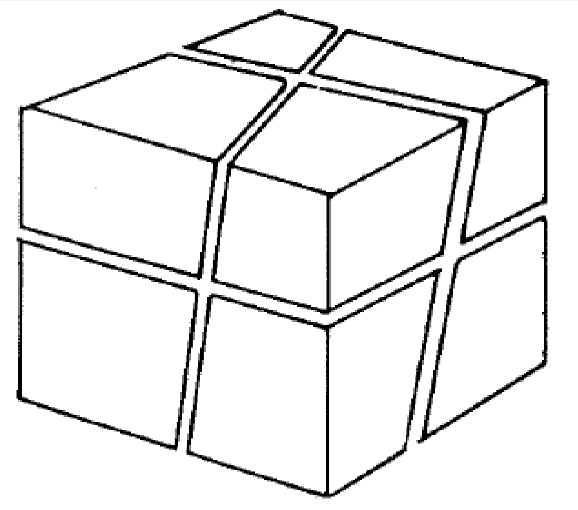
Well sorted sand



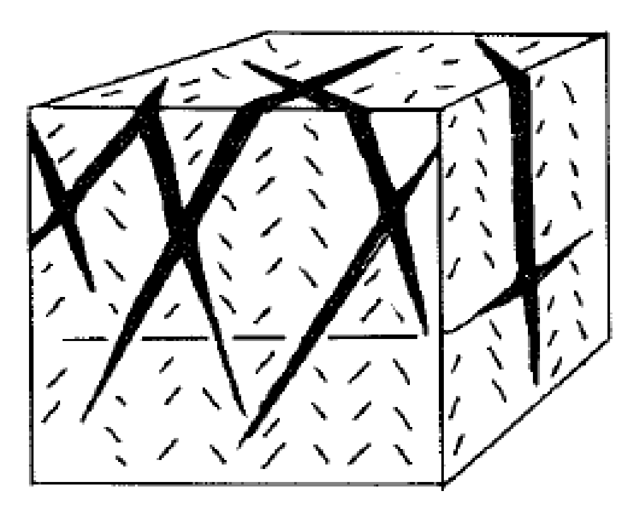
Poorly sorted sand

PRIMARY OPENINGS

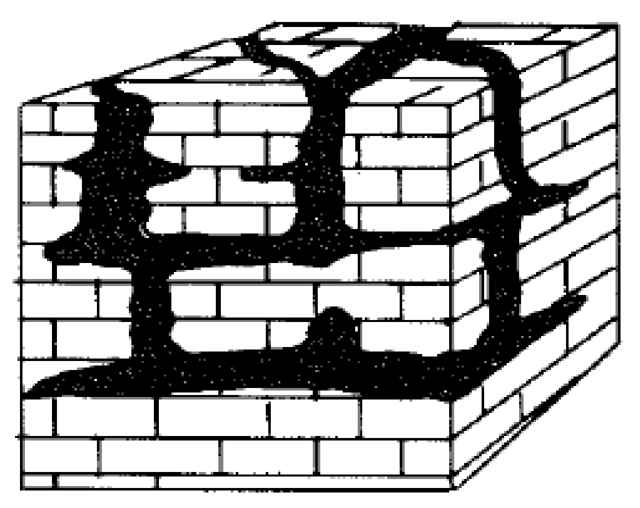
Groundwater bearing formations



FRACTURED ROCK



FRACTURES IN GRANITE



CAVERNS IN LIMESTONE

SECONDARY OPENINGS

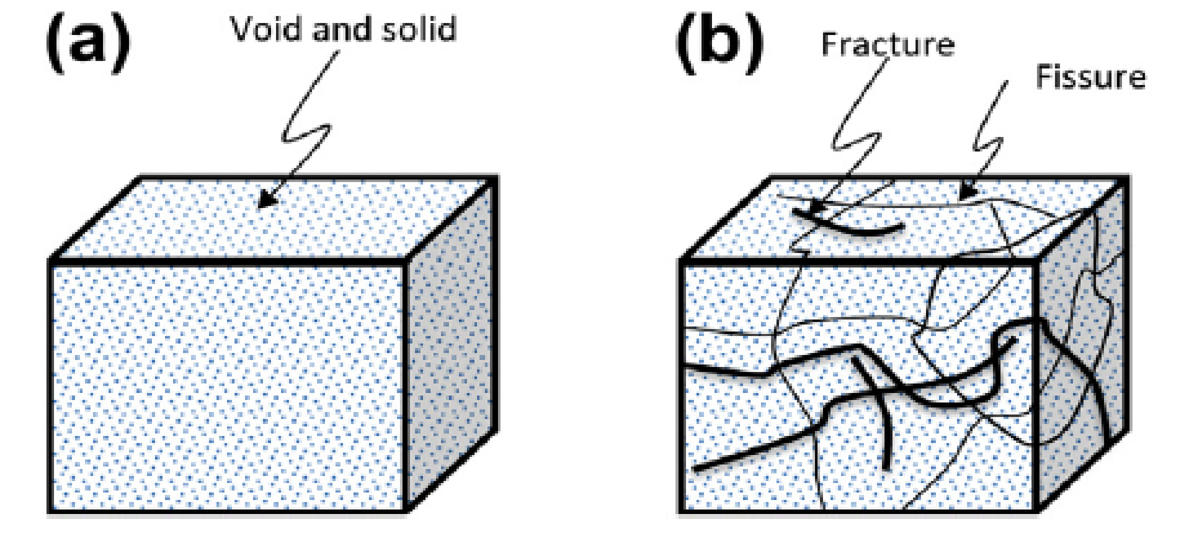


Figure: Porosity: (a) primary, (b) secondary.

Occurrence of groundwater

- The definition of groundwater as the water contained beneath the surface in rocks and soil is conceptually simple and convenient, although the actual situation is somewhat complex.
- Water beneath the ground surface includes that contained in the soil, in the intermediate unsaturated zone below the soil, in the capillary fringe, and below the water table.
- The region between the soil and the water table is referred to as the unsaturated or the ***vadose*** zone.
- The unsaturated zone contains both air and water, while in the saturated zone all of the voids are filled with water.
- The ***water table***, the boundary between the unsaturated and saturated zones, is often misused as a synonym for groundwater.
- To be precise, it represents the upper surface of groundwater, where hydraulic pressure is equal to atmospheric pressure.

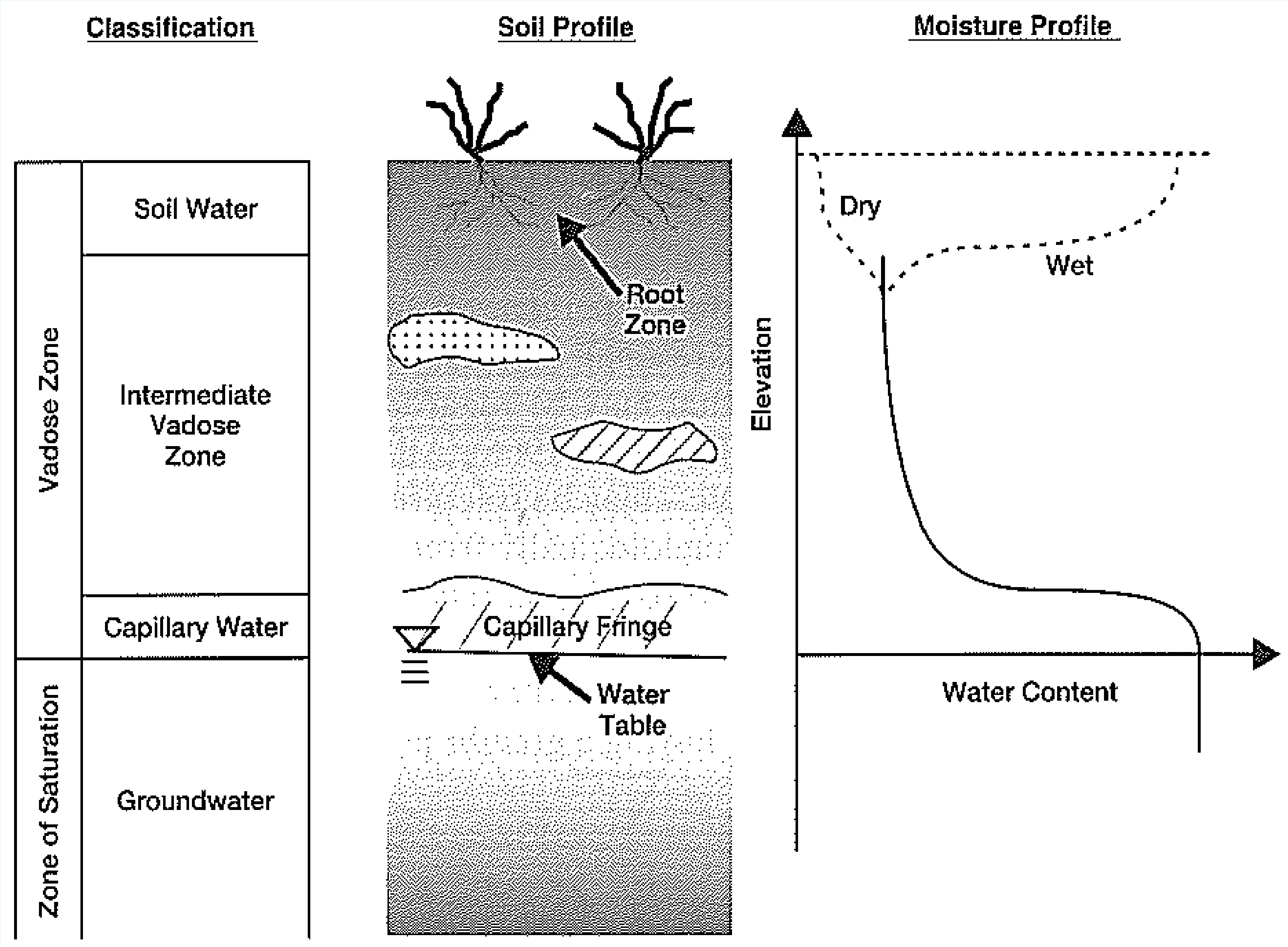


Figure. Vertical distribution of water content and classification system

Occurrence of groundwater

- The water level encountered in an idle well, or in a well a long time after any water was pumped from it, is the same level as the water table.
- Therefore, groundwater refers only to water in the saturated zone below the water table, and the total water column beneath the Earth's surface is usually called subsurface water.
- The saturated and unsaturated zones are hydraulically connected, and the position of the water table fluctuates seasonally in response to recharge from rainfall and also as a result of groundwater abstraction.
- Geological formations having pore spaces that are saturated and permit easy movement of the groundwater are called ***aquifers***.
- Materials through which water can pass easily are said to be *permeable*, and those that scarcely allow water to pass through, or only with difficulty, are termed *impermeable* or *semi-permeable*, respectively.

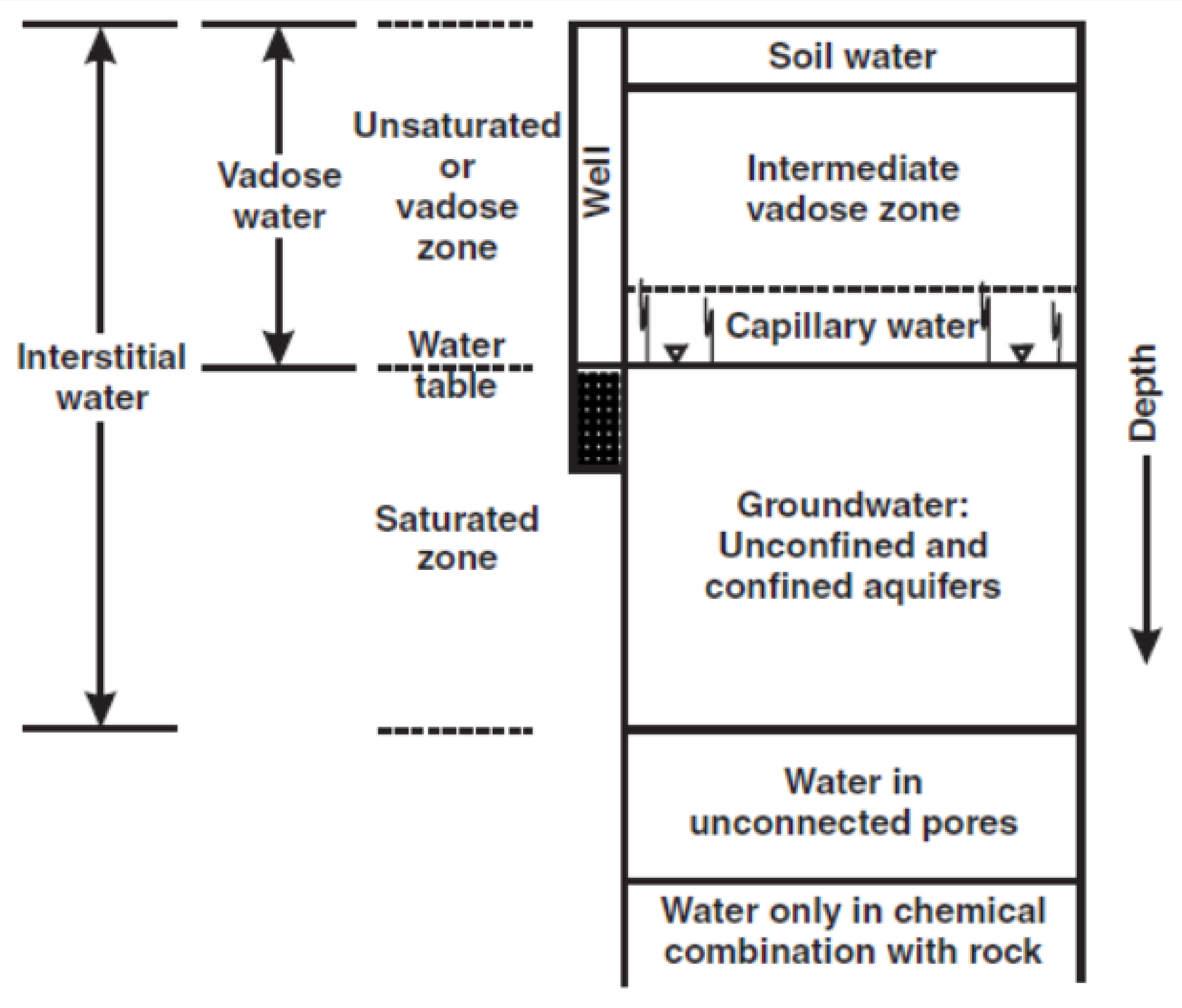


Figure 8. Schematic sketch for defining various zones of subsurface water.

Aquifer formations

- Aquifer formations and groundwater flow systems are typically the result of a long and complex history of geological and hydrogeological processes.
- Aquifers exhibit a more or less strong spatial variability.
- Not only hydraulic conductivity and porosity but also the mineral composition of the solid aquifer material varies spatially.

- Aquifers are also the field for microbial life, which is important for the quality of groundwater.
- Some amounts of groundwater occur in most geological formations because nearly all rocks in the uppermost part of the Earth's crust possess openings called pores or voids.

Aquifer formations

Geologically, rock formations can be subdivided into three main types:

- *Sedimentary rocks* are formed by deposition of weathered rock material, usually under water in lakes, rivers, and in the sea.
- In unconsolidated granular materials, such as sands and gravels, voids constitute the pore spaces between the grains.

- These may become consolidated physically by compaction due to the overburden of earth materials and chemically by cementation, to form typical sedimentary rocks such as
  - sandstone, limestone, and shale, that have considerably reduced void spaces between the grains.

Aquifer formations

- *Igneous rocks* are formed from molten magma rising from great depths and subsequent cooling to form crystalline rocks either below the ground or on the land surface.
- It includes granites and basalts.
- Most igneous rocks are **highly consolidated** and usually have **few void** spaces between the grains.

- *Metamorphic rocks* are formed by deep burial, compaction, melting, and alteration of other rocks during periods of intense geological activity in the past.
- Metamorphic rocks, such as gneisses and slates, are normally well consolidated with few void spaces in the matrix between the grains.

Aquifer formations

- In the highly consolidated rocks, such as
  - ✓lavas, gneisses, and granites, the only void spaces may be **fractures**.
- These fractures may be **completely closed** or
  - ✓may have **limited interconnected** openings of relatively narrow aperture.

- Weathering and associated decomposition of igneous and metamorphic rocks
  - ✓may significantly **increase the void spaces** in the rock matrix as well as in the fractures.

Aquifer formations

- Fractures may enlarge to become open fissures as a result of
    - ✓dissolution by the chemical action of flowing groundwater or infiltrating rainwater.

- Limestone (largely made up of calcium carbonate) and evaporates (composed of gypsum and other salts) are particularly susceptible to active dissolution,
    - ✓which can produce caverns,
    - ✓swallow holes, and
    - ✓other features characteristic of karstic aquifers.

Aquifer formations

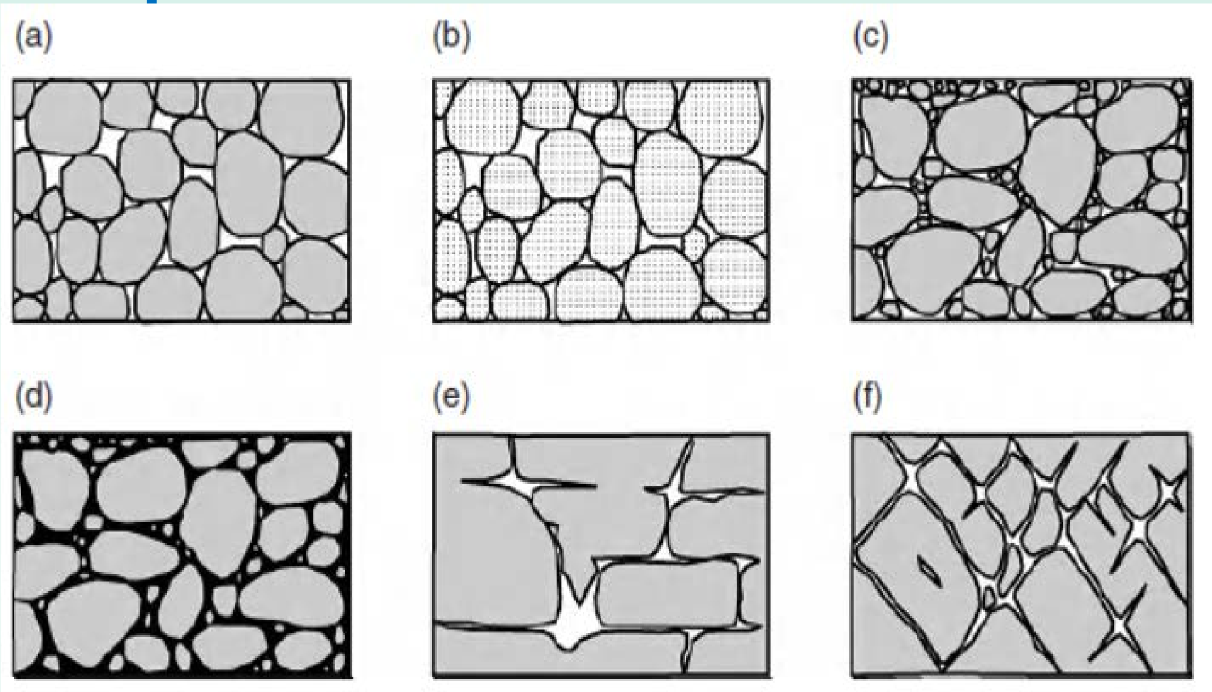


Figure. Texture and porosity of typical aquifer forming rocks/sedimentary deposits.

Primary porosity: (a) Well-sorted unconsolidated sedimentary deposits with high porosity.

(b) Well-sorted sedimentary deposit comprising pebbles that may themselves be porous, making the deposit as a whole highly porous.

(c) Poorly-sorted sedimentary deposits having low porosity.

(d) Sedimentary deposits with primary porosity reduced by secondary deposition of mineral matter (cementing material) between the grains.

Secondary porosity: (e) Rock with porosity increased by dissolution due to chemical action of infiltrating (or flowing) water. (f) Rock with porosity increased by fracturing.

Aquifer formations

- In hydrology rock types are usually classified on the basis of their potential to bear and transmit water, into four broad groups:
    i. unconsolidated materials;
    ii. porous sedimentary rocks;
    iii. porous volcanic rocks; and
    iv. fractured rocks.
- In unconsolidated materials, water is transported through the primary openings in the rock/soil matrix.
- Consolidation is a process where loose materials become compacted and coherent.
- Sandstones and conglomerates are common consolidated sedimentary rocks formed by compaction and cementation.

Aquifer formations

- Carbonate rocks (i.e. limestone and dolomite) are sedimentary rocks that are formed by chemical precipitation.
- Water is usually transported through secondary openings in carbonate rocks that are **progressively enlarged over time**
    - ✓ by dissolution of rock by the action of carbonic acid contained in water which arises from dissolution of atmospheric carbon dioxide.
- Movement of water through volcanics and fractured rock is dependent upon the **interconnection** and **density of flow pathways**.
- An *unconfined aquifer* contains a phreatic surface (water table) as the upper boundary that fluctuates in response to recharge and discharge.

Classification of aquifers

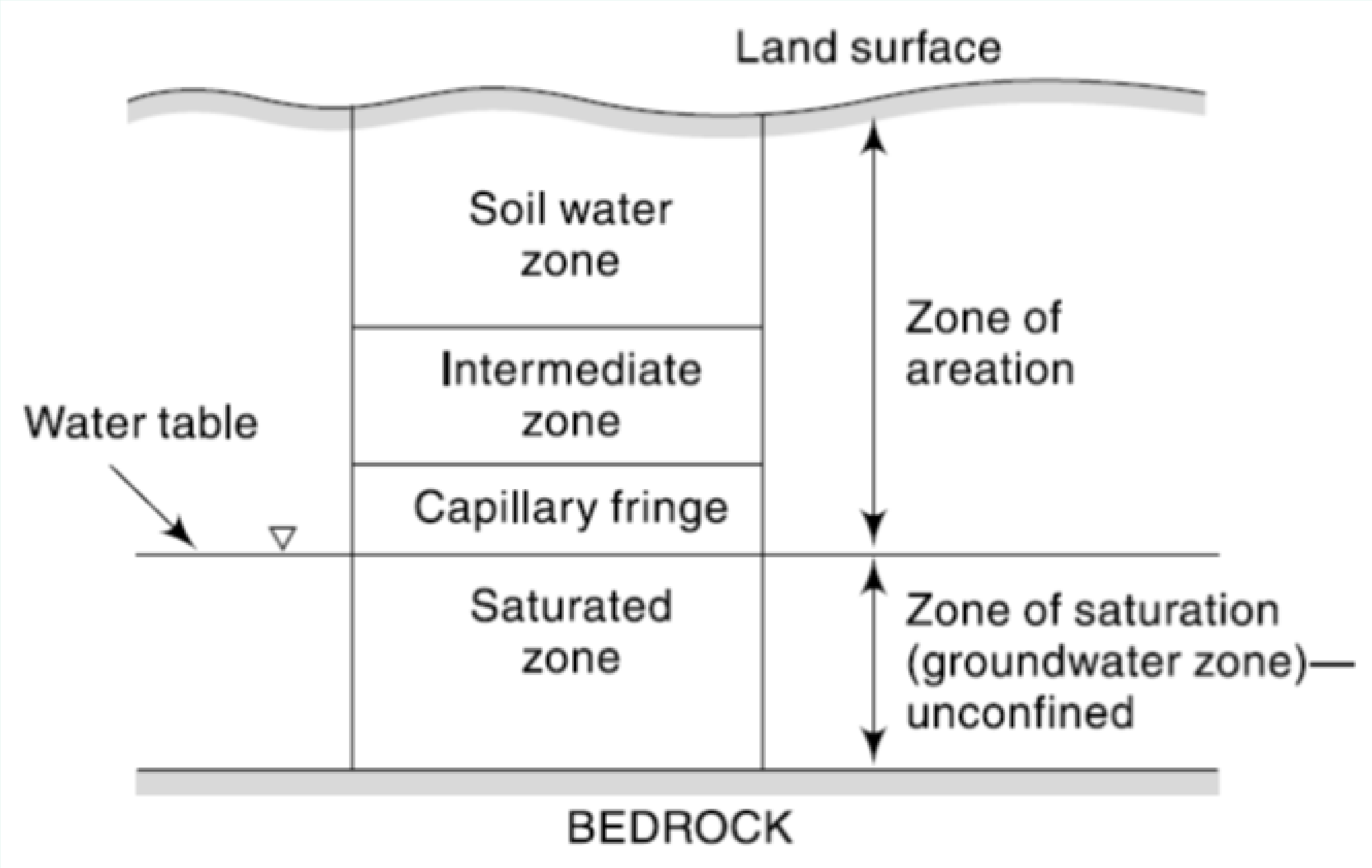


Figure. Classification of Subsurface Water

Classification of aquifers

Zone of Aeration:

- The soil pores are only partially saturated with water.
- The space between the land surface and the water table marks the extent of this zone.
- The soil moisture in the zone of aeration is of importance in agricultural practice and irrigation engineering

- The zone of aeration has three subzones.
    - Soil water zone
    - Capillary fringe
    - Intermediate zone

Classification of aquifers

Saturated Formation

- All earth material from soil to rocks have pore spaces.
- Although these pores are completely saturated with water below the water table, from the groundwater utilization aspect
    - only such material through which water moves easily and hence can be extracted with ease are significant.
- On this basis the saturated formations are classified into four categories:
    - Aquifers
    - Aquitards
    - Aquiclude, and
    - Aquifuge

Classification of aquifers

Aquifer: An aquifer is a saturated formation of earth material which *not only stores water but yields it in sufficient quantity*.

- Thus an aquifer transmits water relatively easily due to its high permeability.
- Unconsolidated deposits of sand and gravel form good aquifers.

Aquitard: It is a formation through which *only seepage is possible* and thus the yield is insignificant compared to an aquifer.

- It is partly permeable. Example: a sandy clay.
- Through an aquitard appreciable quantities of water may leak to an aquifer below it.

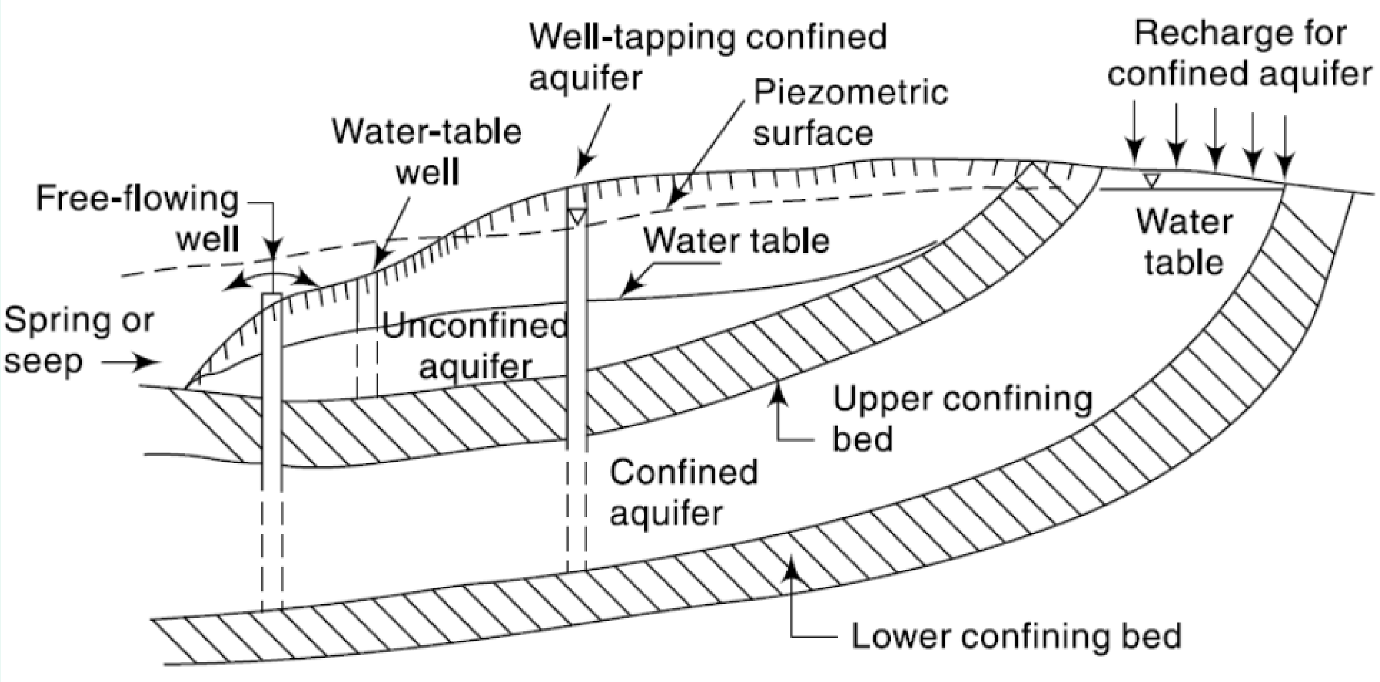
Aquiclude: It is a geological formation which is essentially impermeable to the flow of water.

- It may considered as closed to water movement even though it may contain large amount of water due to its high porosity. Example: Clay

Classification of aquifers

Aquifuge: It is a geological formation which is neither porous nor permeable.

- There are no interconnected openings and hence it cannot transmit water.
- Massive compact rock without any fractures is an aquifuge.



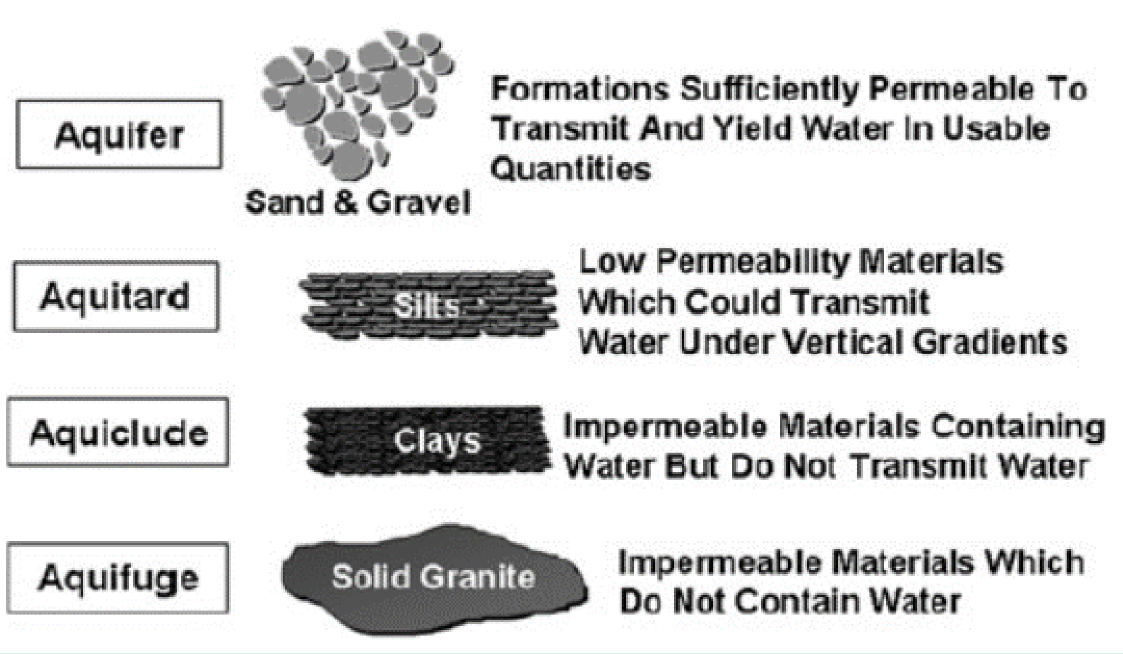


Figure. Confined and Unconfined Aquifers

Classification of aquifers

- If the pressure in a confined aquifer is such that the potentiometric surface is above ground level,
  - ✓then a borehole drilled into the aquifer **will overflow**.
- Recharge to confined aquifers is predominantly from areas where
  - ✓the confining bed is **breached** either by an erosional unconformity,
  - ✓fracturing, depositional absence, or
  - ✓from the outcrop region known as the ‘recharge area’.
- For a phreatic aquifer, which is the first unconfined aquifer formed below the surface,
  - ✓the recharge is from all over the ground surface and so potentiometric surface and water table coincide.

Classification of aquifers

- A special type of unconfined aquifer, where a groundwater body is separated above the water table by a layer of unsaturated material, is called a *perched aquifer*.
- A perched aquifer occurs when
  - ✓water moving down through the unsaturated zone encounters an impermeable formation.
- Clay lenses in sedimentary deposits often have shallow perched water bodies overlying them.
- Wells tapping perched aquifers generally **yield small quantities of water temporarily**,
  - ✓which may be used for domestic water supply for individual households or small communities.

Classification of aquifers

- For groundwater development, unconfined aquifers are often favored because
  - their much **higher storage coefficient** makes them more efficient for exploitation than confined aquifers.
- Unconfined aquifers, being shallower, are **cheaper to drill** and require **less energy to pump** out water.

- Thus, occurrence and movement of groundwater are controlled by
  - ✓the geological environment in which they occur,
  - ✓the geometric arrangement of different formations, and
  - ✓by the hydraulic conditions prevailing in the subsurface.

Classification of aquifers

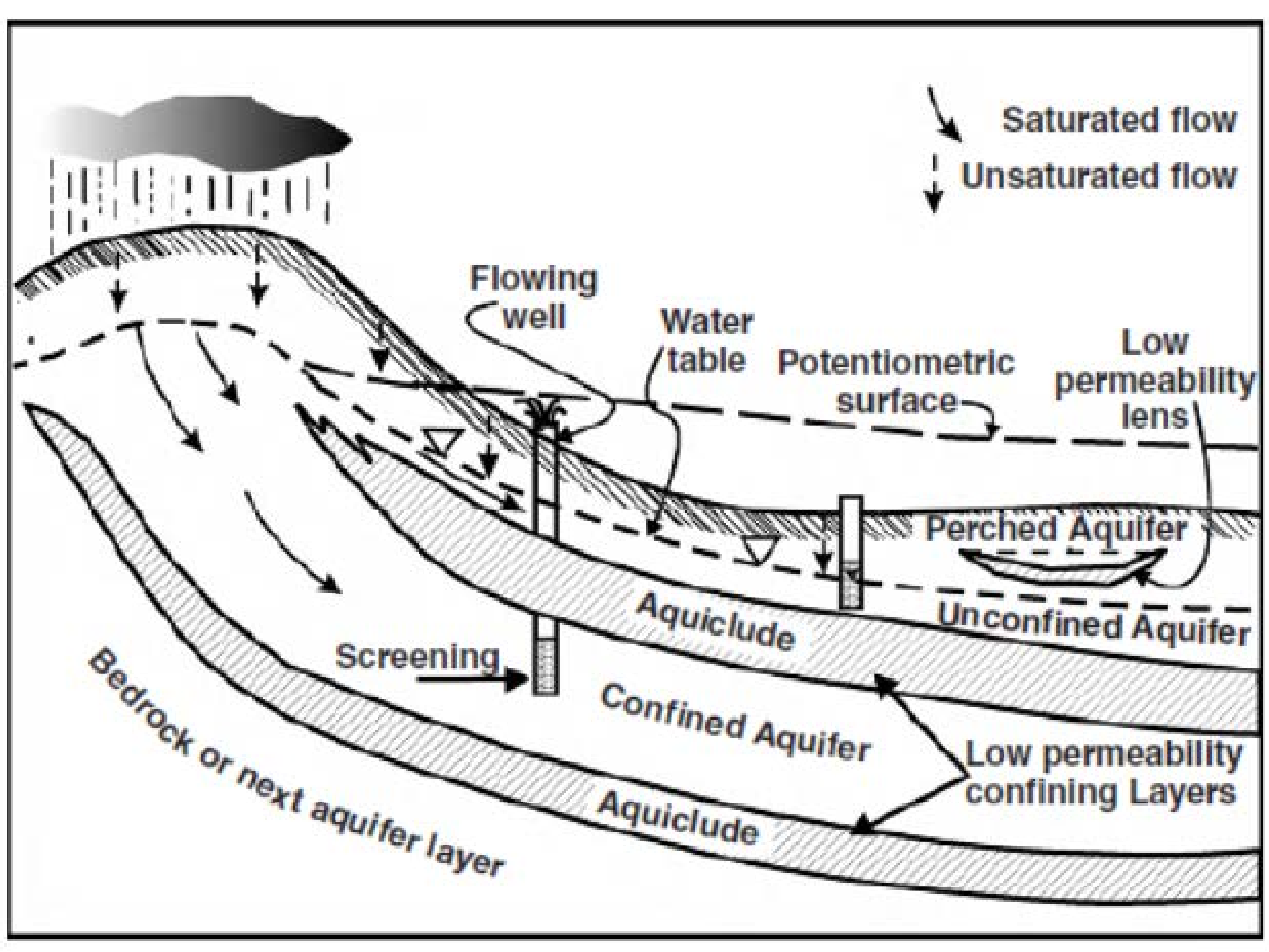


Figure. Schematic cross-section showing unconfined and confined aquifers and the confining beds called either aquicludes or aquitards, depending on their permeability.

Classification of aquifers

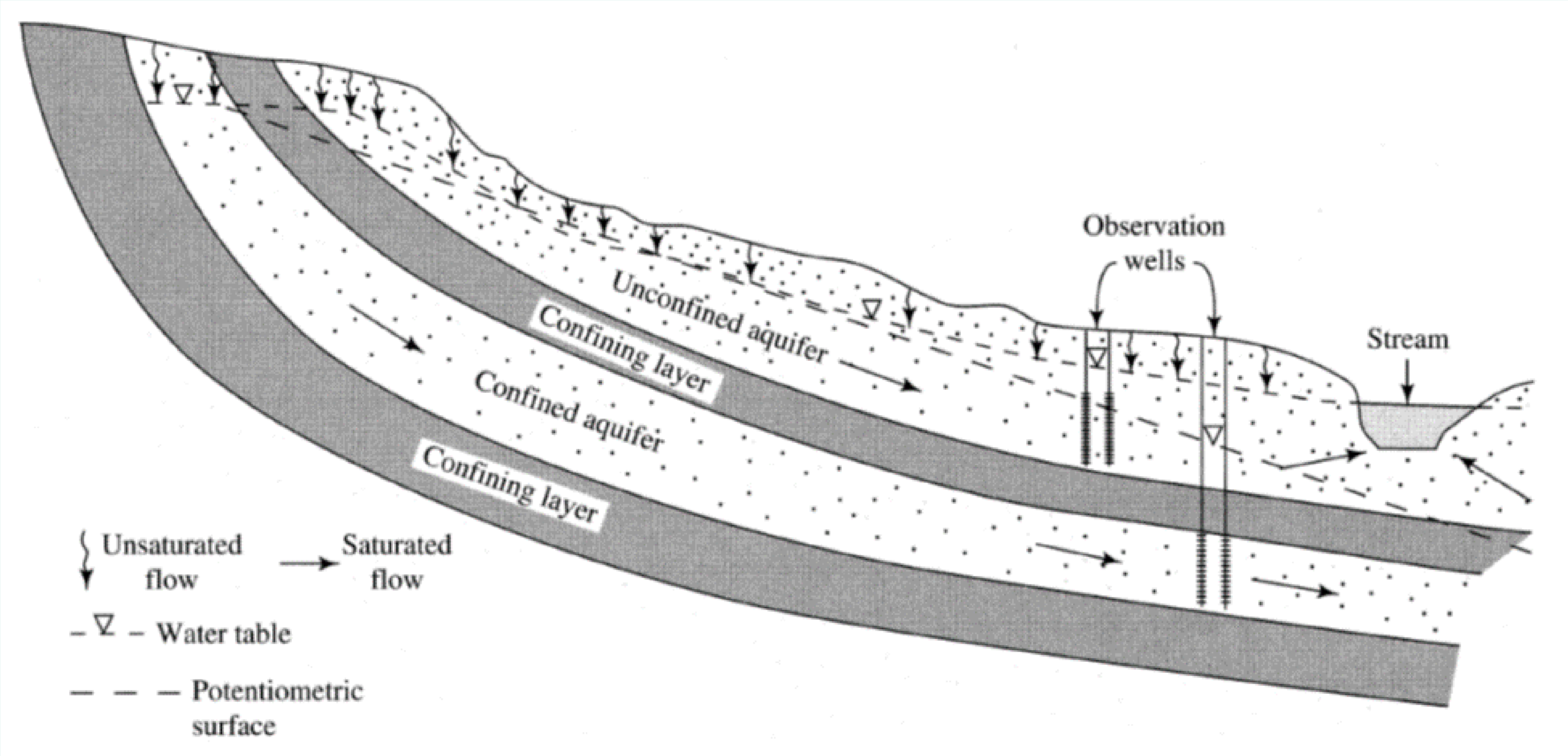


Figure. Schematic cross-section showing unconfined and confined aquifers and the confining beds called either aquicludes or aquitards, depending on their permeability.

Classification of aquifers

- By definition, in a confined aquifer, the elevation of the hydraulic head **exceeds** the top of the aquifer.
- In an artesian aquifer, the hydraulic head exceeds the elevation of the ground surface.
- The water level elevation recorded in a piezometer penetrating a confined aquifer defines the *piezometric* or *potentiometric surface*.

- In an artesian aquifer where the piezometric surface exceeds the land surface, *flowing wells* may result.
- Unconfined or phreatic aquifers have an upper surface, known as the *water table* or *phreatic surface*, which is at atmospheric pressure

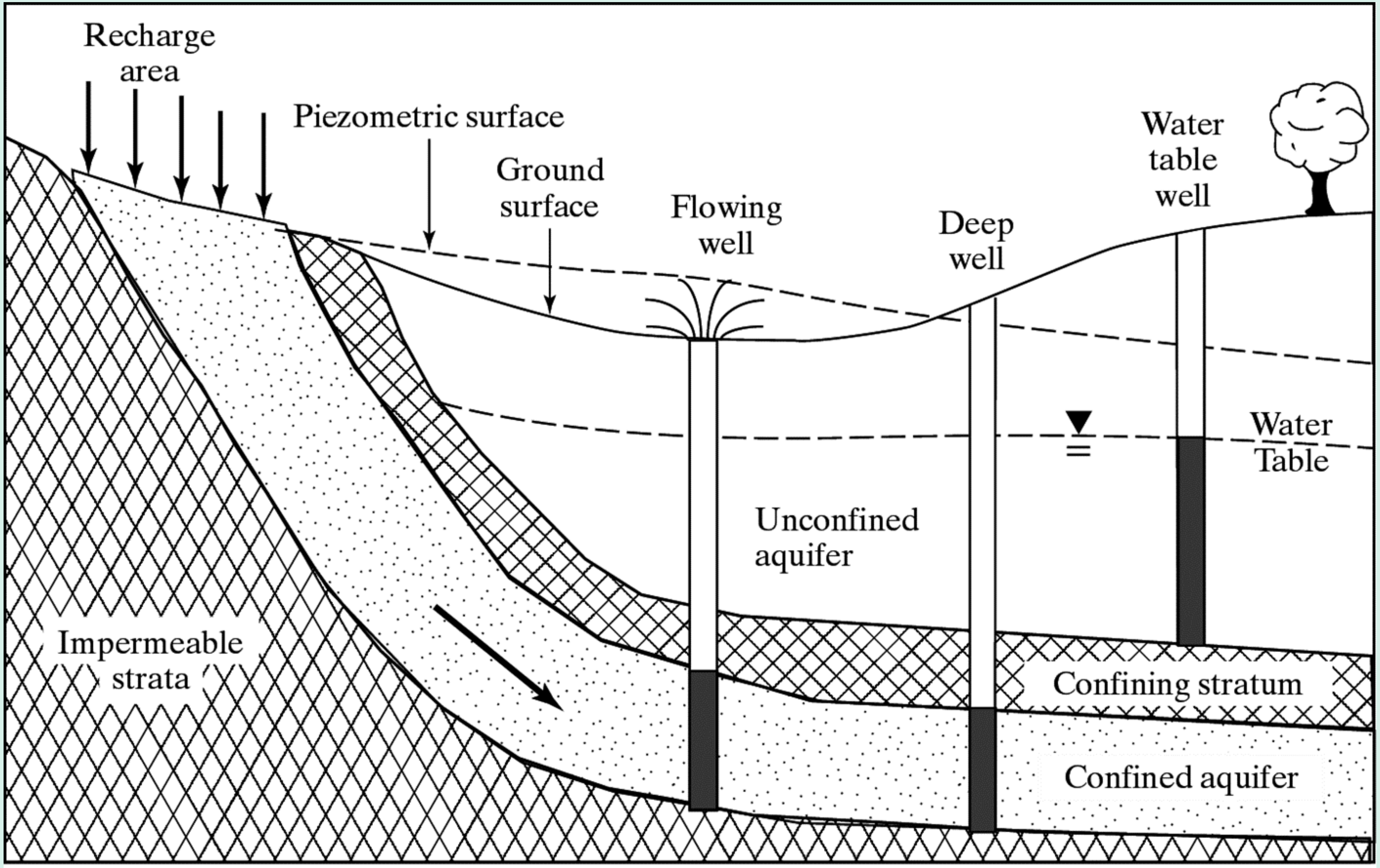
Classification of aquifers

- Semiconfined or leaky aquifers result when the upper or lower confining layer is sufficiently permeable to allow flow of water between it and overlying or underlying aquifers.
- Flow among aquifers occurs when the piezometric head in one unit is either higher or lower than the head in an adjacent unit.

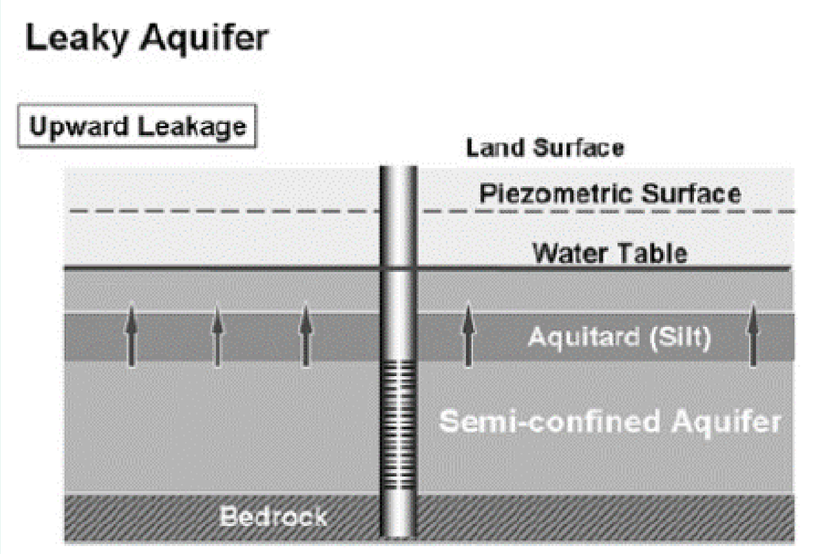
- This inter-aquiferflow, or leakage, may represent a significant portion of aquifer recharge or loss.
- Leakage is usually a transient phenomenon, as in the case of leakage induced by pumping or natural fluctuations in recharge.

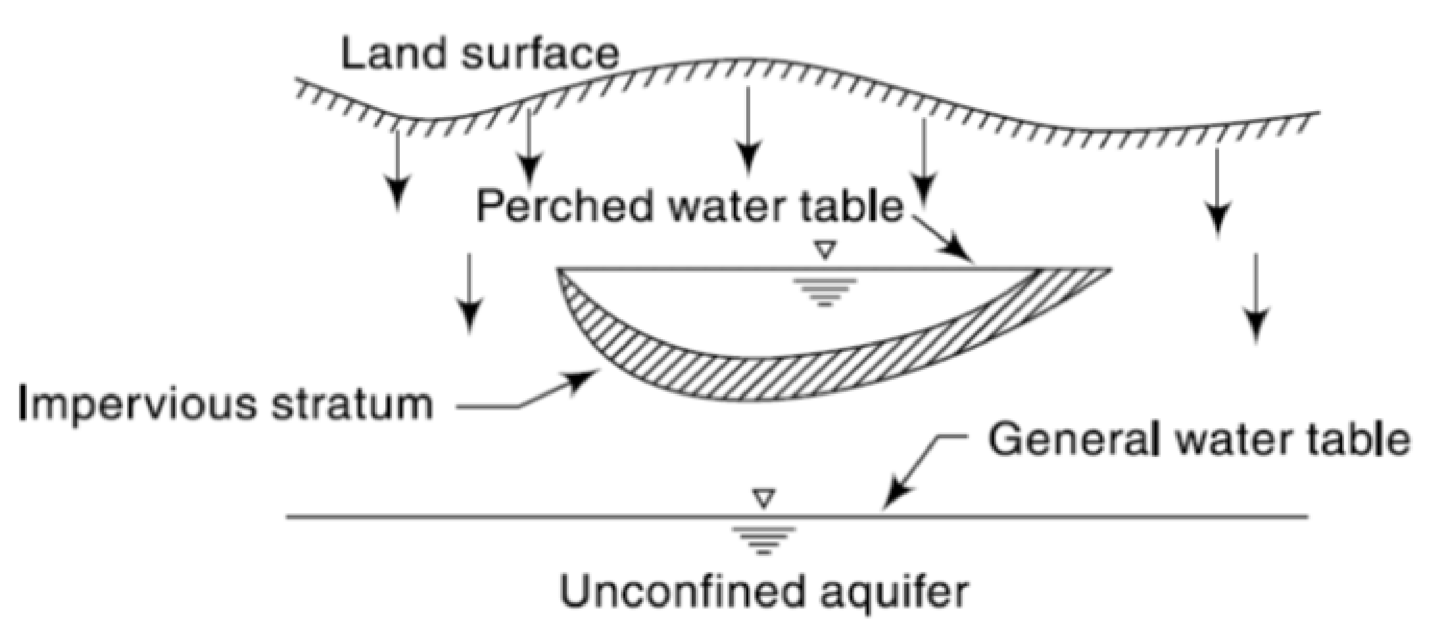
Classification of aquifers

- A confined aquifer is called a leaky aquifer if either or both of its confining beds are aquitards.

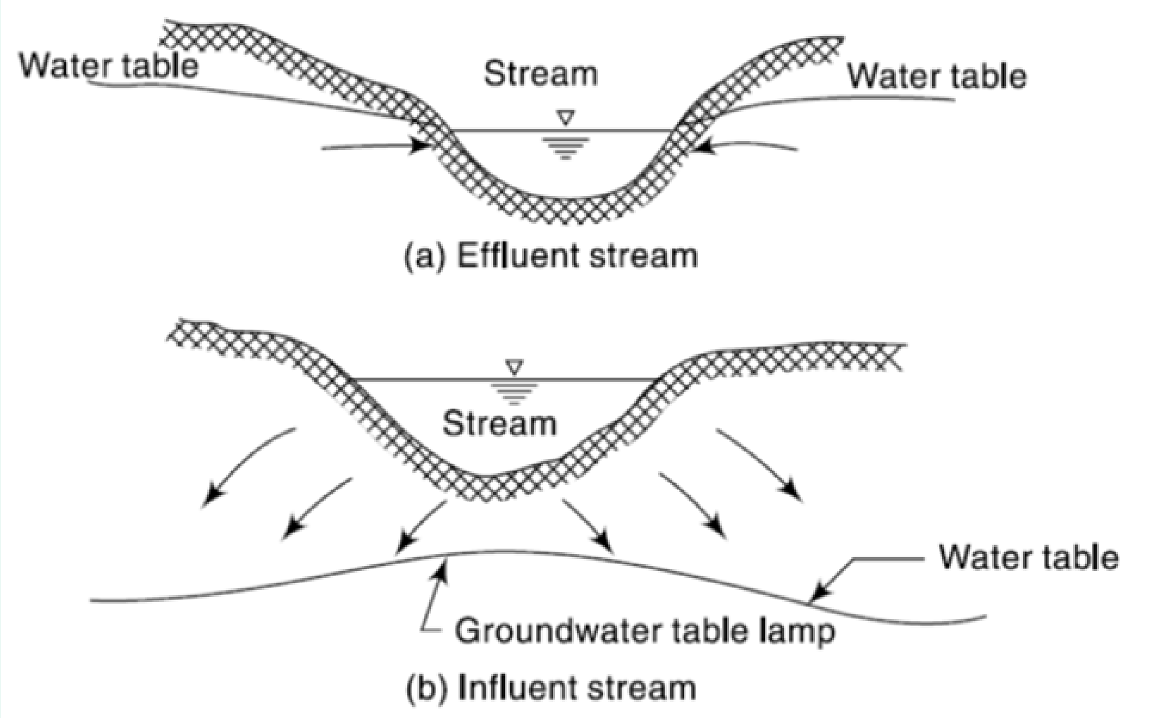


Classification of aquifers



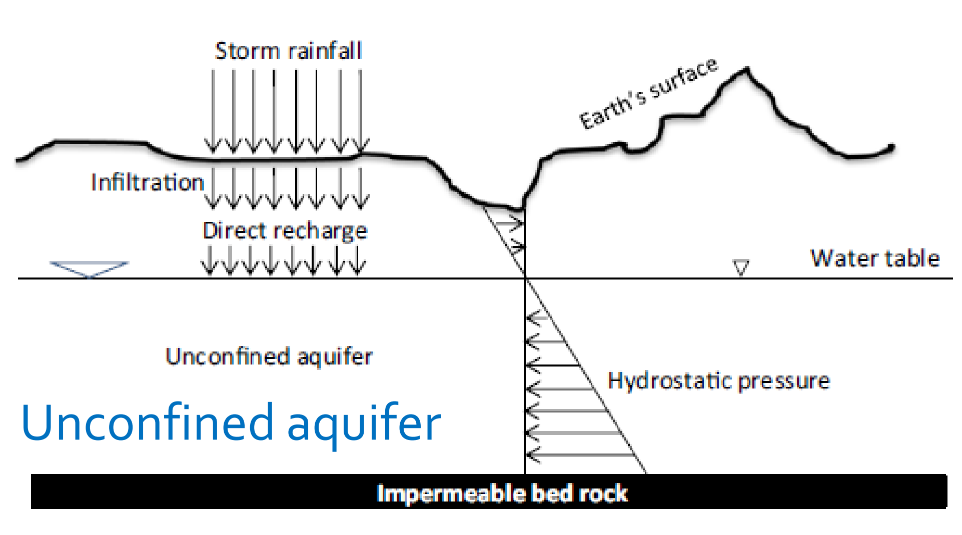


Perched Water Table

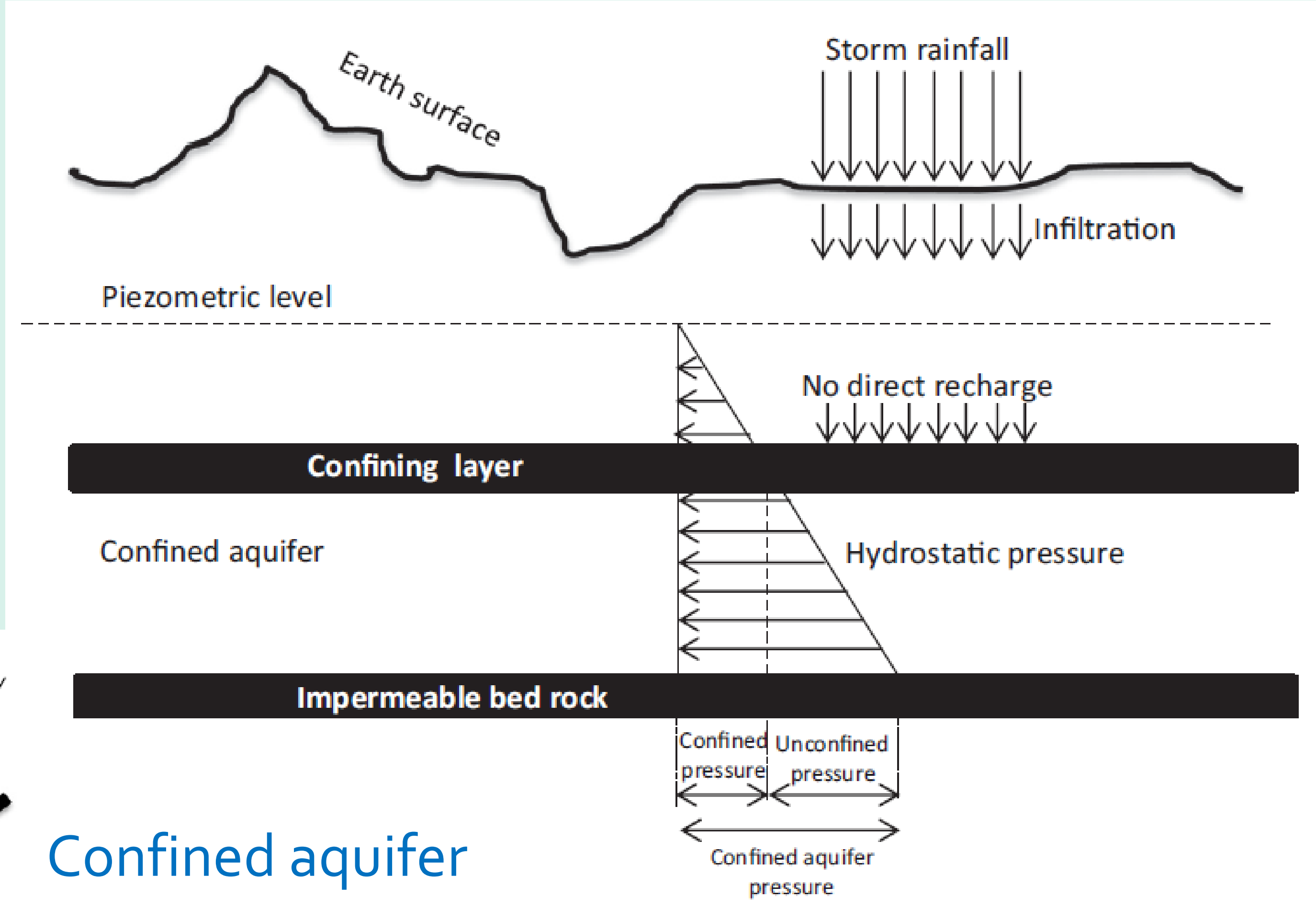


Effluent and Influent Streams

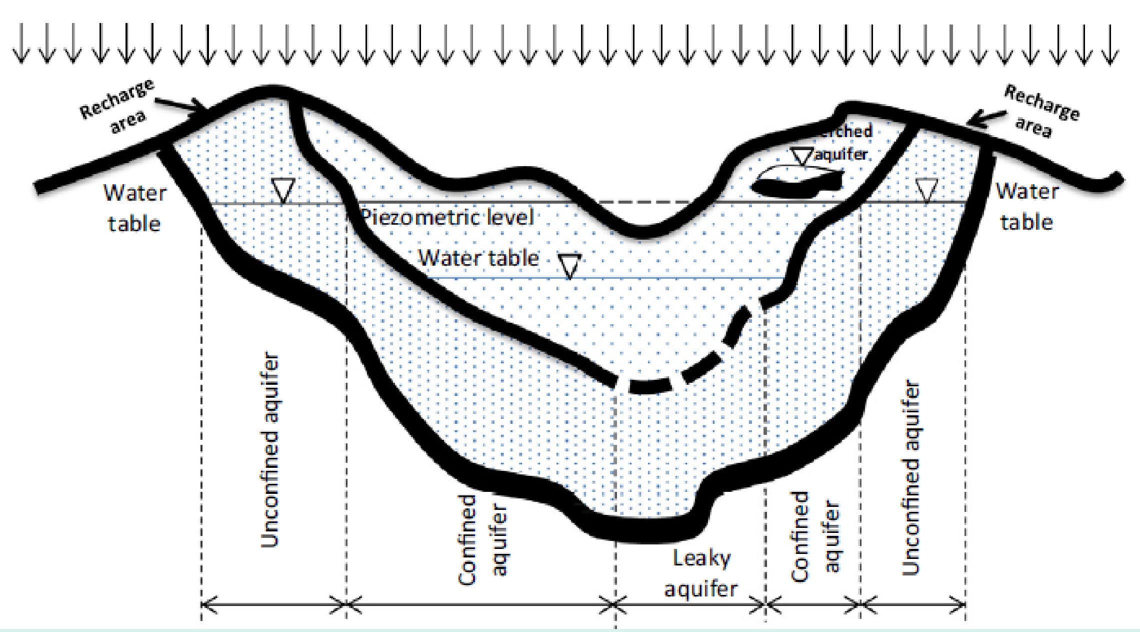
Classification of aquifers



Unconfined aquifer

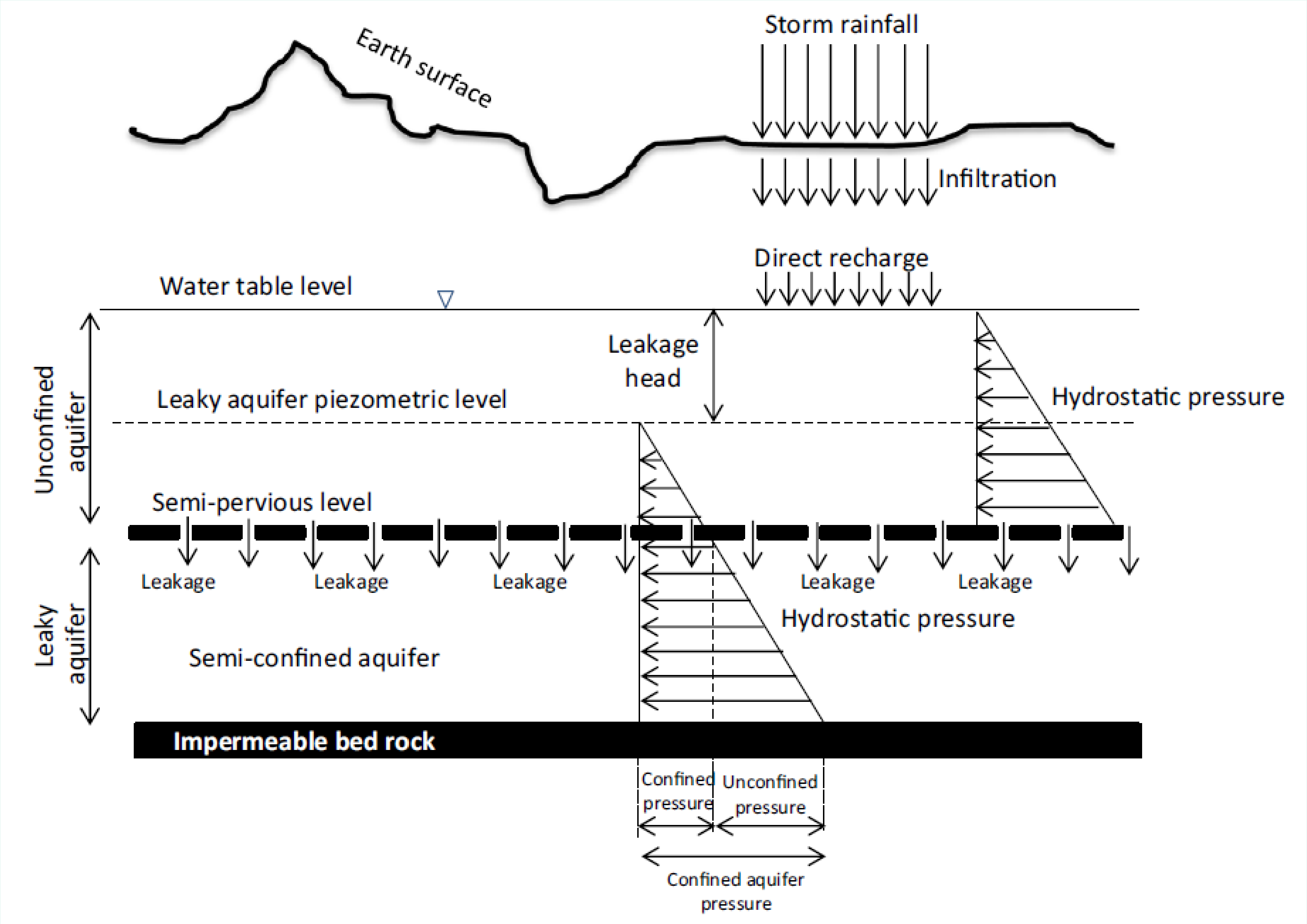


Confined aquifer



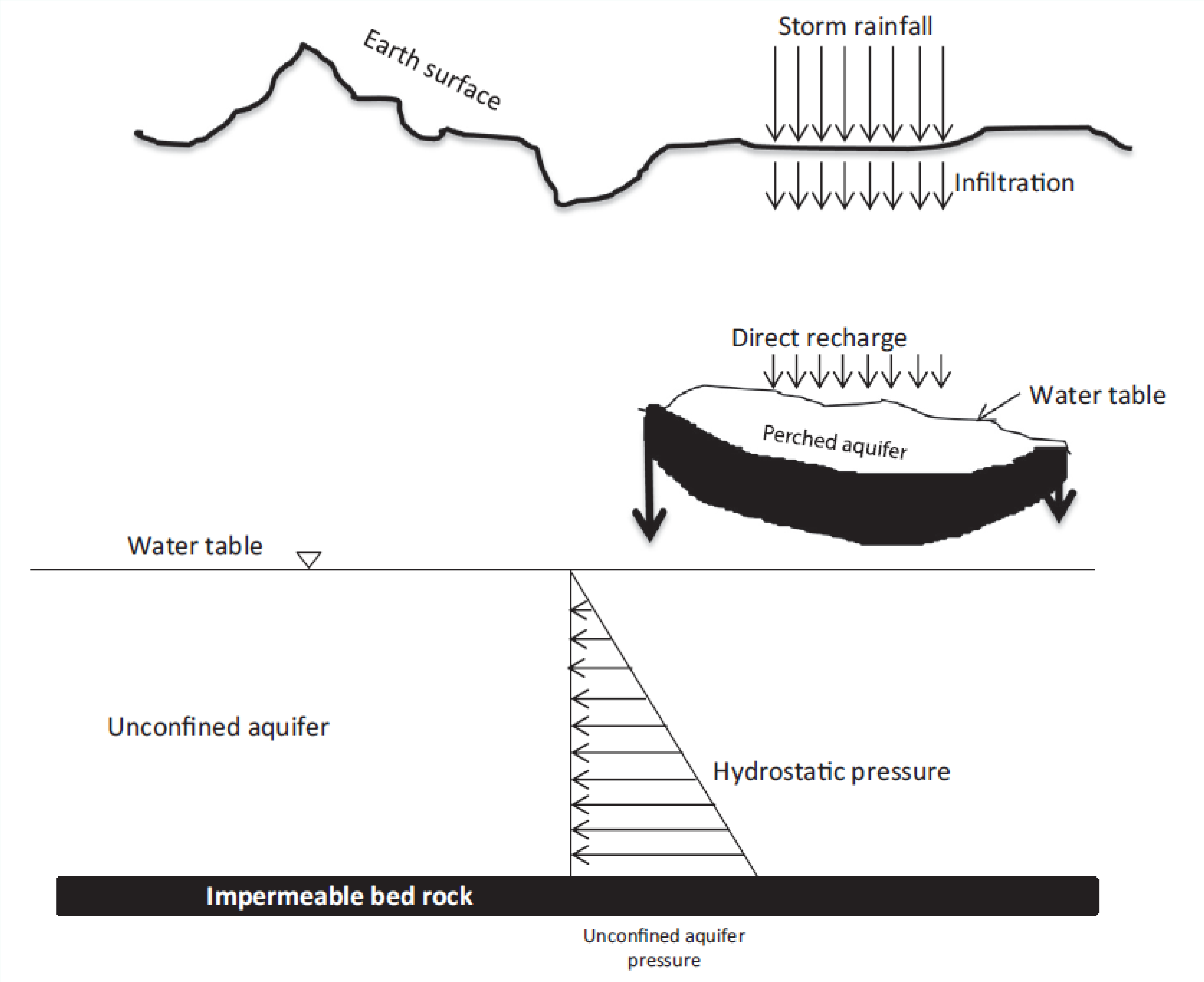
Composite aquifer.

Classification of aquifers



Leaky aquifer.

Classification of aquifers



Perched aquifer.

Flow and Storage Characteristics of Aquifers

Aquifer Parameters:

- In practice, the most essential work is **aquifer parameter determination**.
- The following parameters are necessary for any groundwater **exploration**, **quantity** and **management** studies:

  - ✓Porosity,
  - ✓Specific yield and retention,
  - ✓Hydraulic conductivity (coefficient of permeability),
  - ✓Transmissibility (transmissivity),
  - ✓Storage coefficient and specific storage.

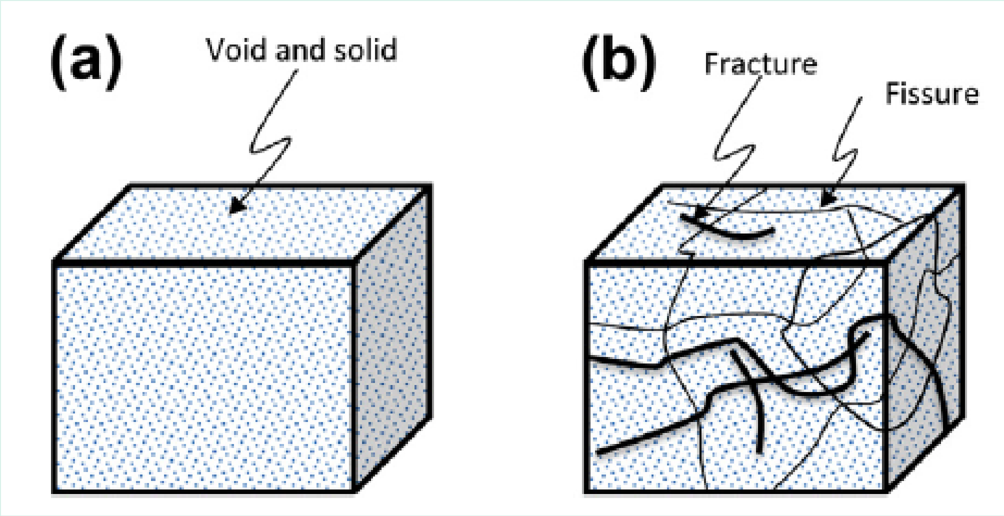
Flow and Storage Characteristics of Aquifers

Porosity

- Porosity, n, is the capacity of a rock mass to accommodate fluid.
- It is defined as the ratio of void volume, V_V, to the total volume, V_T of the rock body as,

$$n = \frac{V_V}{V_T}$$

- In practical terms, it indicates **void volume percentage**.
- Porosity formation during the time of diagenesis is called primary porosity.
- Any change in this porosity due to post processes such as faulting, fracturing, folding and jointing, and solution activity generates secondary porosity



Flow and Storage Characteristics of Aquifers

Porosity

- *Effective porosity* is that portion of the total void space of a porous material that is capable of **transmitting fluid** and it is almost similar to the *specific yield*.
- Porosity is the primary rock property that is used in groundwater reservoir evaluations and assessments.

It helps to evaluate various reservoir properties such as,

1. Available fluid volumetric calculation in the reservoirs,
2. Fluid saturation degree calculation,
3. Geologic characterization of the reservoir.

Flow and Storage Characteristics of Aquifers

- In ground-water hydrology, porosity tells us the maximum amount of water that a rock can contain when it is saturated.
- However, it is equally important to know that **only a part of this water is available** to supply a well or a spring.

- Hydrologists divide water in the groundwater storage into the part that will drain under the **influence of gravity** (called **specific yield,** *available for groundwater pumping*) and
  - the part that is **retained** as a film on rock surfaces and in very small openings (called **specific retention**)
    - by adhesion and capillary forces.

Porosity values of different rock materials are shown in Table below

Sediment Classification	Porosity (%)
Well-sorted sand and gravel	25–50
Mixed sand and gravel	20–35
Mixed sand and gravel	20–35
Glacial till	10–20
Silt	35–50
Clay	40–70
Karst limestone	5–50
Calcaireoolitique	3–20
Marble	0.1–0.2
Schist	1–10
Dolomite	3–5
Granite	0.02–15
Gypsum	3–4
Basalt	0.1–12
Fractured basalt	5–15
Sandstone	5–30
Shale	0–10
Fractured crystalline rock	0–10
Dense crystalline rock	0–5

Flow and Storage Characteristics of Aquifers

Specific Yield and Retention

- Specific yield is the amount of water that can be extracted under the gravitation force, and specific retention **cannot be separated from the grain surfaces** because the fluid is attached to grain surfaces due to adhesion forces.
- Specific yield tells how much water is **available for man's use**, and specific retention tells how much water **remains in the rock** after it is drained by gravity . Thus,

$$n = S_y + S_r$$

$$S_y = \frac{V_d}{V_t} \qquad S_r = \frac{V_r}{V_t}$$

where

n is porosity, S_y is specific yield, S_r is specific retention,

V_d is the volume of water than drains from a total volume of V_t ,

V_r is the volume of water retained in a total volume of V_t, and

V_t is total volume of a soil or rock sample.

Flow and Storage Characteristics of Aquifers

Specific Yield and Retention

- The specific yield, S_y, is the storage term used directly for unconfined aquifers.
- It is defined as the drainable water volume, V_d, from storage per unit surface area of the aquifer per unit decline in the water table.

- This definition implies that it is a dimensionless quantity (m^3/m^2m).
- The porosity is the combination of specific yield and specific retention, S_r, and they complement each other, $n = S_y + S_r$
- Specific yield is useful to define part of porosity referring only to the movable (abstractable) water in the rock.
  - ✓ Usually $0.01 < S_y < 0.3$.

Specific Yield and Retention

- It is also known as effective porosity in engineering.

- High Sy values are indicative that the water is released from the storage of unconfined aquifers by dewatering of the pores,
  - ✓ while in confined aquifers the release of water is due to secondary causes such as expansion of water and compaction of aquifer.

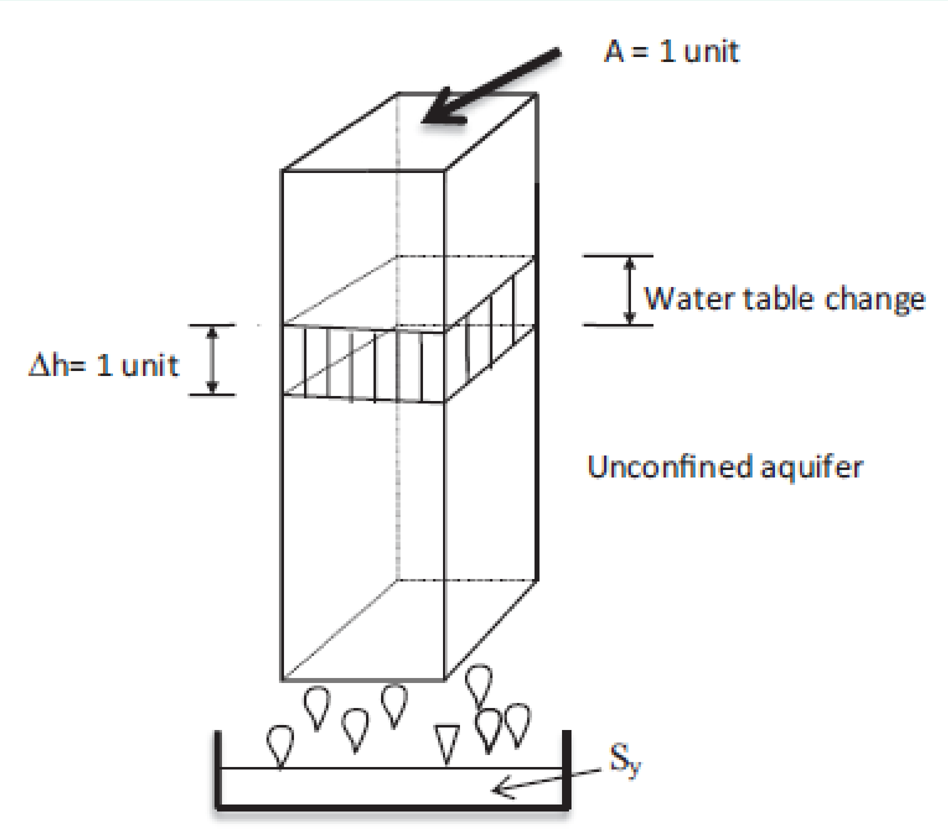


Figure. Specific-yield definitions.

- The same yield from unconfined aquifers can be obtained with less head changes over less-extensive areas when compared to confined aquifers.

Specific Yield and Retention

- Many researchers (soil scientists, hydrologists, water engineers) need to define the amount of water that a soil can hold against gravity.
- This is the specific retention, Sr, capacity.
- It is also essential for plant-water-use calculations.
- The term “field capacity” was introduced as “the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased.”

- In the light of the previous sentences, one can conclude that field capacity is equivalent to specific retention.
- Its definition is slightly more satisfying than that presented for Sr.

Specific Yield and Retention

- Depending on the material type, the percentages of Sy and Sr vary within n.
- The major role in the ratio of such contribution is played by the particle surface area.
- The smaller the average grain size the larger is the surface area of the medium.
- Larger surface areas attract more water, and accordingly, their specific retention values are greater.

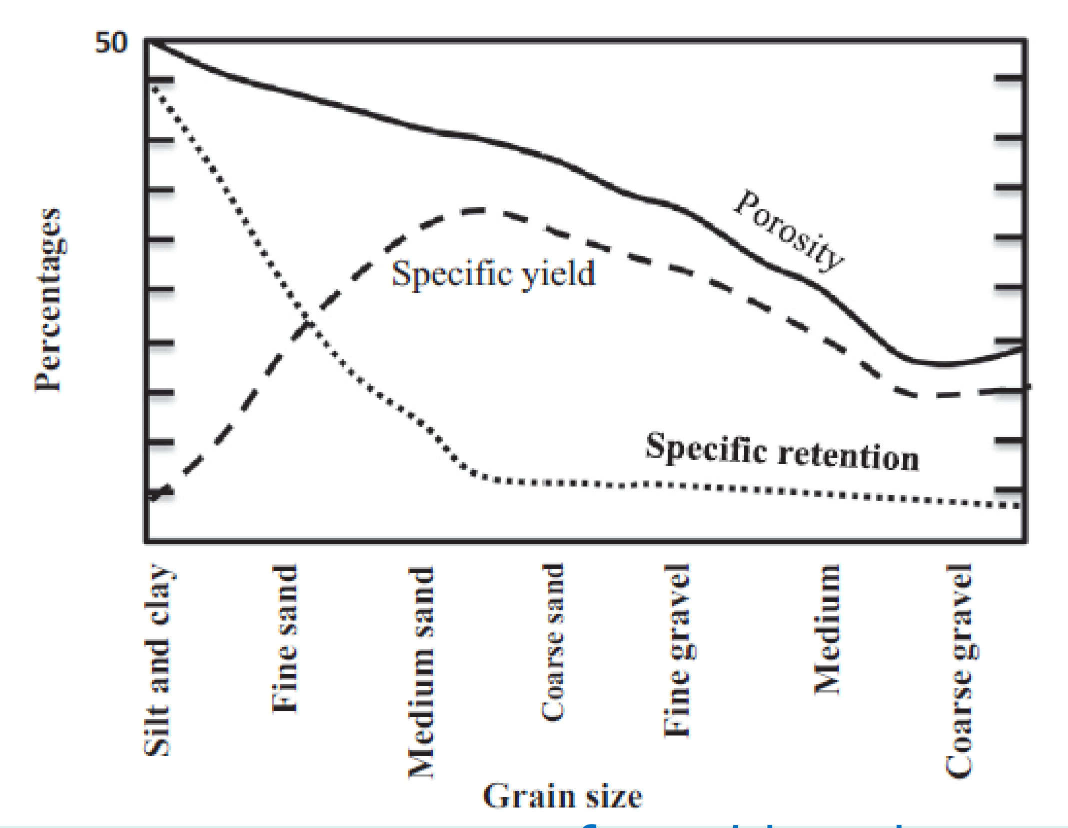


Table. Representative Porosity, Specific Yield, and Specific Retention Values

Grain Size	Material	Porosity (%)	Specific Yield (%)	Specific Retention (%)
Very fine	Clay	50	2	48
Fine	Sand	25	22	3
Course	Gravel	20	19	1

Figure. Porosity, specific yield, and retention relations.

Specific Yield and Retention

- In hydrogeological studies, the specific yield concept is **more important** than porosity, since
  - the porosity does not give any clue of water abstraction from aquifers.
- For instance, in igneous rocks, porosity is not more than 2% but they yield all the available water in their voids up to approximately 100%.
- On the contrary, clays have the maximum porosity but they yield less than 5% of stored water.

Table. Sediment Specific Yield (Johnson, 1967)

Material	Minimum	Average	Maximum
Clay	0	0.02	0.05
Sand clay	0.03	0.07	0.12
Silt	0.03	0.18	0.19
Fine sand	0.10	0.21	0.28
Medium sand	0.15	0.26	0.32
Coarse sand	0.20	0.27	0.35
Gravelly sand	0.20	0.25	0.35
Fine gravel	0.21	0.25	0.35
Medium gravel	0.13	0.23	0.26
Coarse gravel	0.12	0.22	0.26

The specific yield percentages are given for unconfined aquifers in unconsolidated sedimentary

Specific Yield and Retention

- If a granular material with an average porosity of 30% exists below the water table, its voids are saturated containing 30% water per unit volume.
- If the water table is lowered, the soil will eventually give up about two-thirds of its water, equivalent to 20% of the total volume.
- The remaining 10% water by volume is held by surface tension.
- In hydrological terminology, one says that the specific yield is 0.2 and specific retention is 0.1.

Specific Yield and Retention

Example 1: An aquifer with an area of 7 km² experiences a head drop of 0.85 m after 8 years of pumping. If the pumping rate is 5.5 m³/day, determine the specific yield of the aquifer.

Solution: $S_y = \frac{V_w}{A\Delta h} = \frac{Q\Delta t}{A\Delta h} = \frac{5.5\ m^3/day*8\ years*365\ day/year}{7.5\ km^2*10^6\frac{m2}{km^3}*0.85\ m} = \frac{20440}{5.525*10^6} = 2.7*10^{-3}$

Example 2: A soil sample has a volume of 180 cm³. The volume of voids in the sample is estimated equal to 67 cm³. Out of the volume of voids, water can move through only 45 cm³. Determine the porosity, specific porosity, specific retention, and specific yield of the soil. What is the area of the aquifer, which the sample was taken from, if pumping at rate 6.0 m³/day causes 1.0 m head drop in the aquifer in 5 years?

Solution: $n = \frac{V_w}{V_t} = \frac{67}{180} = 0.37$, $\tilde{n} = \frac{V_{wm}}{V_T} = \frac{45}{180} = 0.25$

$S_r = n - \tilde{n} = 0.37 - 0.25 = 0.12$

$S_y = n - S_r = 0.37 - 0.12 = 0.25$

$$A = \frac{V_w}{S_y\Delta h} = \frac{Q\Delta t}{S_y\Delta h} = \frac{6.0\frac{m^3}{day}*5\ year*365\ day/year}{0.25*1.00\ m} = \frac{10950\ m^3}{0.25\ m} = 43800\ m^2$$

Specific Yield Determination Methods

- Specific yield plays key role in many hydrogeological and engineering works, and therefore, **its accurate determination is important**.
- For this purpose, there are different field and laboratory works .
- Specific yield is very significant for unconfined aquifers and **groundwater recharge** calculations.

  - UNCONFINED AQUIFER TEST METHODS
  - VOLUME-BALANCE METHOD
  - WATER-BUDGET METHODS

Hydraulic Conductivity

- Hydraulic conductivity is one of the parameters, which tells about the **transmission properties** of an aquifer.
- It depends upon the specific yield (effective porosity) of the aquifer, which means the degree of interconnection of the pores.
- It can be defined as the volume of water per unit time passing through per unit cross-sectional area of the aquifer under the effect of unit hydraulic gradient.
- Its dimension is $[L^3/T/L^2]$ but generally written as L/T, which is equivalent to the velocity dimension in physics.

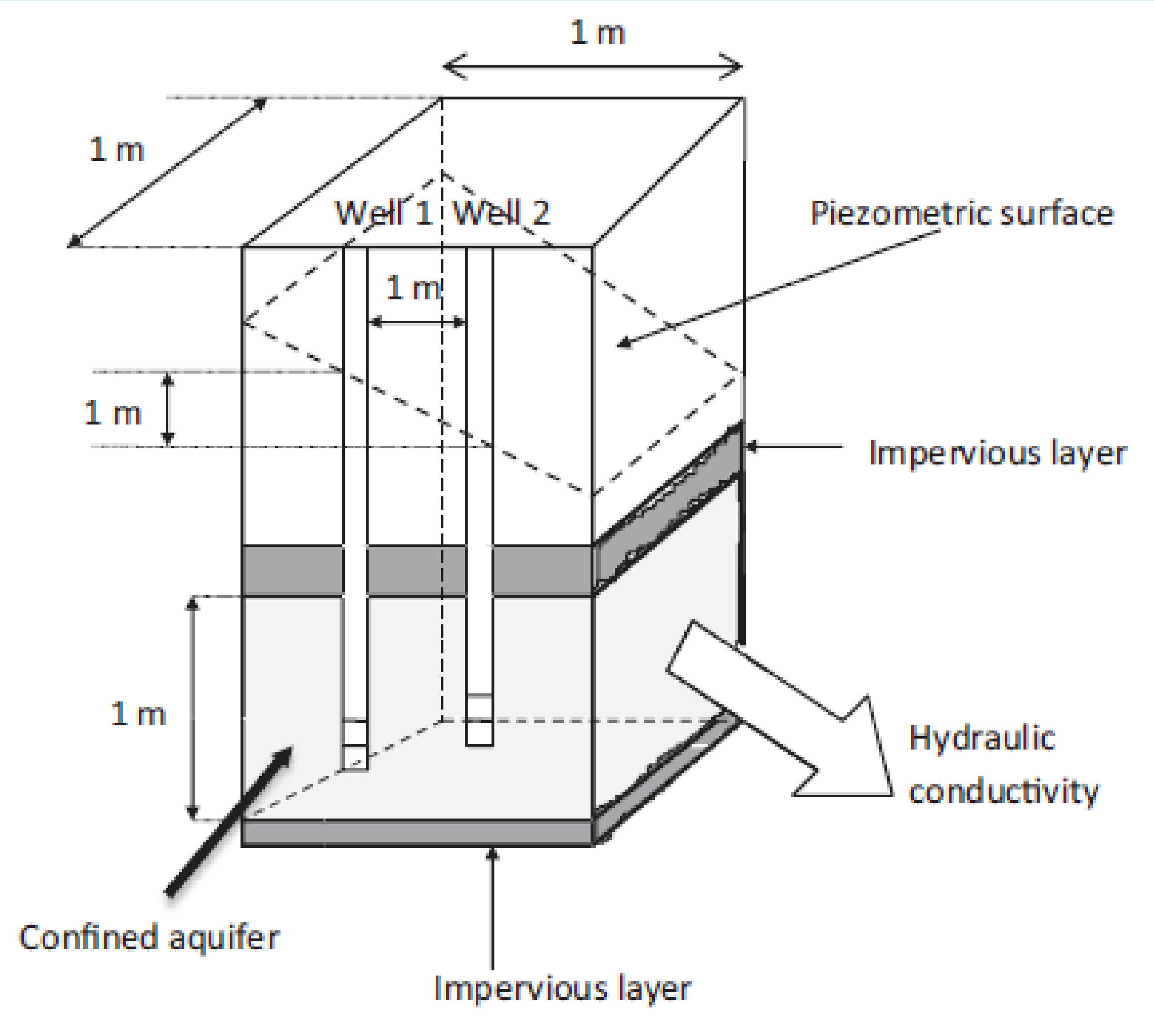
- Under the light of this definition, one can write notationally the hydraulic conductivity,

  K, as, $K = Q/Ai$

where Q is the discharge, A is the cross-sectional area, and i is the hydraulic gradient.

Hydraulic conductivity is a property that describes the ease with which water can move through the interconnected void spaces.

Hydraulic Conductivity



Definition of hydraulic conductivity.

Permeability can be defined as the capacity of a rock for transmitting a fluid (water, oil, gas) and it is also a measure of the relative ease with which a porous medium can transmit a liquid.

The main factors that affect the permeability are:

1. Textural features such as voids, grain size, distribution and shapes, and gravel packing,
2. Clay type, distribution, and amount,
3. Secondary porosity,
4. Reactive fluids,
5. Turbulent (high-velocity) flow,
6. Overburden pressure.

Hydraulic Conductivity

- Hydraulic conductivity is not only different in different types of rocks but may also be **different from place to place** in the same rock.
- If the hydraulic conductivity is essentially the same in any area, the aquifer in that area is said to be **homogeneous**.
- If, on the other hand, the hydraulic conductivity differs from one part of the area to another, the aquifer is said to be **heterogeneous**.
- Hydraulic conductivity may also be different in different directions at any place in an aquifer.
- If the hydraulic conductivity is essentially the same in all directions, the aquifer is said to be **isotropic**.

Hydraulic Conductivity

- If it is different in different directions, the aquifer is said to be **anisotropic** .
- Although it is convenient in many mathematical analyses of ground-water flow to assume that aquifers are **both homogeneous** and **isotropic**, such aquifers are **rare**.
- The condition most commonly encountered is for hydraulic conductivity in most rocks and especially in unconsolidated deposits and in flat-lying consolidated sedimentary rocks to be larger in the horizontal direction than it is in the vertical direction .

TABLE. Hydraulic Conductivity for Unconsolidated and Hard Rocks

Medium	K (m/day)
UNCONSOLIDATED DEPOSITS	
Clay	1–5
Fine sand	5–20
Medium sand	$20–10^2$
Coarse sand	$10^2–10^3$
Gravel	$5–10^2$
Gravel and gravel mixes	$10^3–10^{-1}$

Hydraulic Conductivity Calculation by Tracer

Three wells, W1, W2, and W3, are at various horizontal distances from each other as in Figure below.

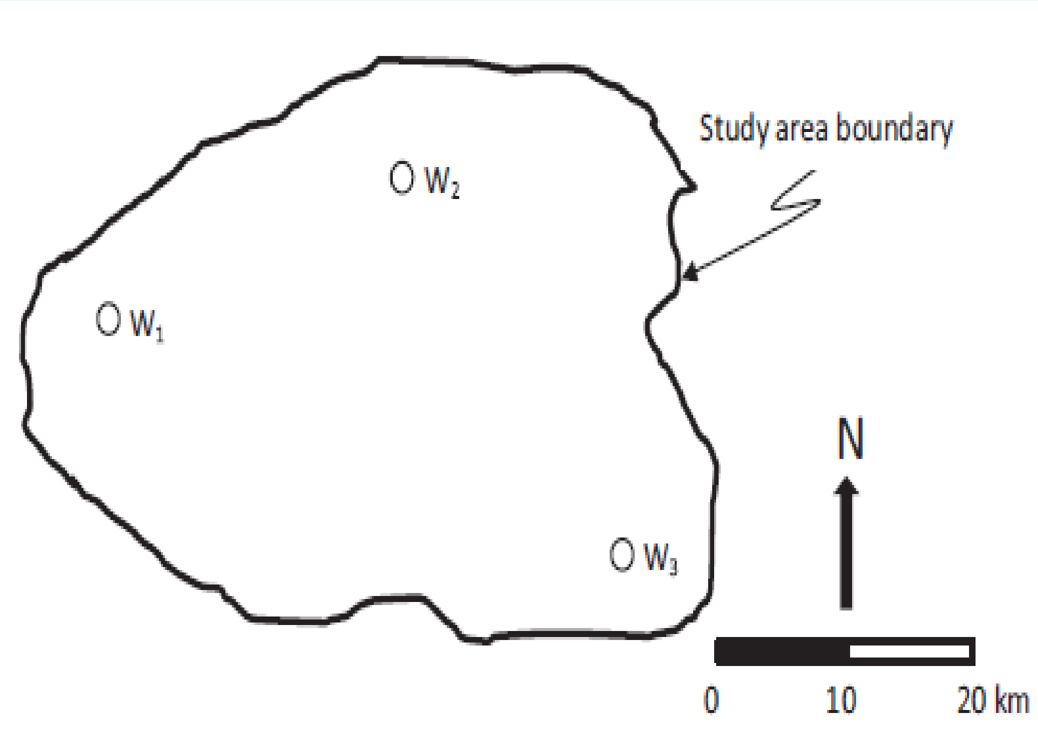
The hydraulic heads (piezometric levels) in these wells are 212, 202 and 198 m, respectively.

The horizontal distance between W1 and W2 (W1 and W3) is 65 m (136 m).

A tracer like potassium permanganate is dropped at well number W1 and after 48 and 25 min it reached W2 and W3, respectively.

So what can one say about the hydraulic conductivity of the aquifer?

Make necessary interpretations.

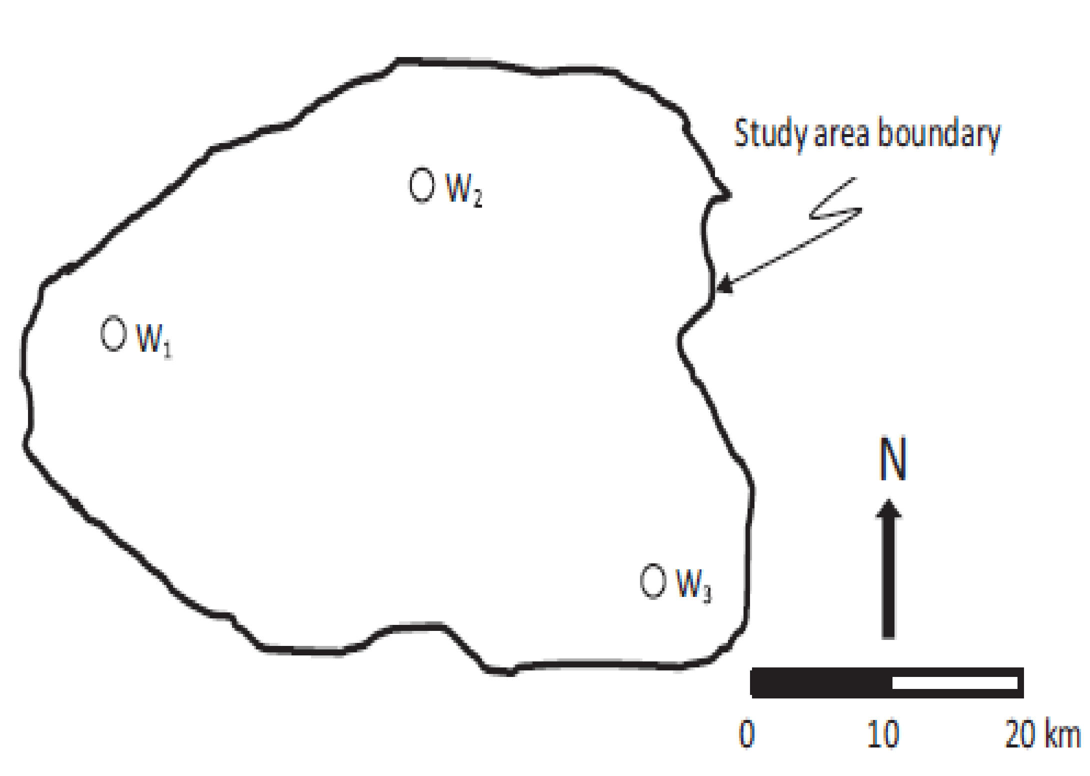


Hydraulic Conductivity Calculation by Tracer

Solution

The groundwater flow is from W1 toward W2 and W3, because the hydraulic head at W1 is the highest. It is first necessary to calculate the hydraulic gradient between well pairs (W1, W2) and (W1, W3). The first pair has the hydraulic gradient as (212−202)/65 = 0.154 and the other (212−198)/136 = 0.103.

If the aquifer is homogeneous and isotropic with uniform thickness, then the hydraulic conductivity between W1 and W2 is more than between W1 and W3, hence, under the given conditions groundwater flows faster from W1 to W2 than from W1 to W3.



Specific Storage and Storage Coefficient

- The volume of water stored in a saturated porous medium per unit volume of medium equals the porosity.
- However, the actual volume of water in a unit volume of porous medium may change in response to *changes in head*; these changes are reflected in the values of the **specific storage** and the **specific head**.

- Consider a small unit area (say 1 m^2) on the earth's surface above an aquifer.
- When the hydraulic head in the aquifer increases or decreases, water is taken into or released from storage.
- The increase or decrease in *volume of water* stored beneath the *unit area* per unit increase or decrease in *head* is the **specific storage** of the aquifer.

Transmissivity

Various definitions of transmissivity as it stands in the groundwater hydraulics literature fall into one of the following categories:

1. The rate of flow under unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer (Kruseman and de Ridder, 1990),

2. The ratio at which water of prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of the properties of the liquid, the porous media, and the thickness of the porous media (Todd, 1980).
3. The product of the thickness of the aquifer and the average value of the hydraulic conductivity (Freeze and Cherry, 1979),

Transmissivity

- The rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient

- A common unit in hydrogeology

$Q = -KA(\Delta h/l)$ $\quad\quad$ $A = b \times w$

$Q = -K(b \times w)(\Delta h/l)$ $\quad\quad$ divide both sides by w

$Q/w = -K(b)(\Delta h/l)$ $\quad\quad$ divide both sides by $-\Delta h/l$

$Q/w/(-\Delta h/l) = Kb$

$$T = Kb$$

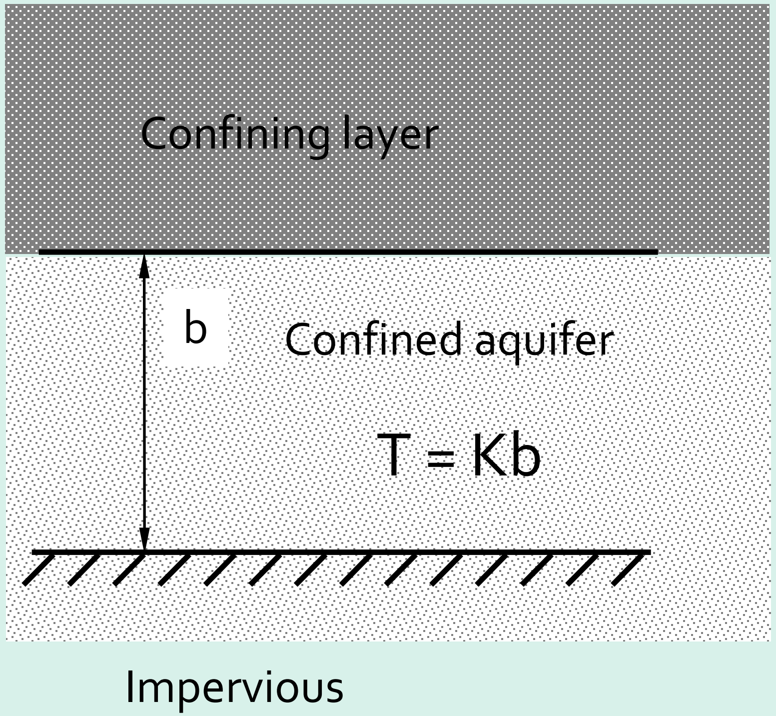
- ***K*** **is the hydraulic conductivity**
- ***b*** **is the aquifer thickness**

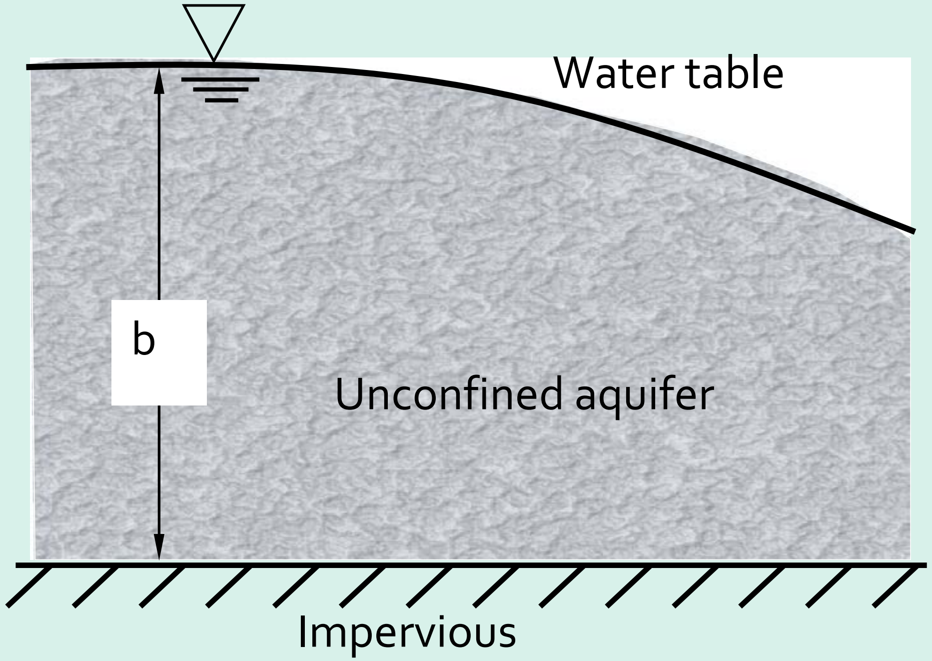
Transmissivity

- Transmissivity is well defined for the analysis of well hydraulics in a **confined aquifer** in which the flow field is essentially horizontal and two-dimensional, in which b is the (average) thickness of the aquifer between upper and lower confining layers

- It is, however, **not well defined in unconfined aquifer** but is still commonly used.
- In this case, the saturated thickness is the **height of the water table above the top of the underlying aquitard** (impervious layer) that bounds the aquifer

Schematic representation of the definition of transmissivity





(Adapted from Freeze and Cherry, 1979)

Note that transmissivities greater than 0.015 m^2/s represent good aquifers for water well exploitation (Freeze and Cherry, 1979).

Transmissivity

- Transmissivity is different from hydraulic conductivity in that it **includes the whole saturation thickness**, b, of the aquifer while K is defined for unit saturation thickness only.
- Potentiality implies **extraction possibilities of groundwater** from the aquifers.
- In groundwater movements instead of hydraulic conductivity **transmissivity must be adopted** for objective decisions.

- Logically, **high transmissivity** values imply **high potentiality**.
- Transmissivity is the amount of water that moves horizontally through a unit width of a saturated aquifer in result to a unit change in gradient.

Transmissivity

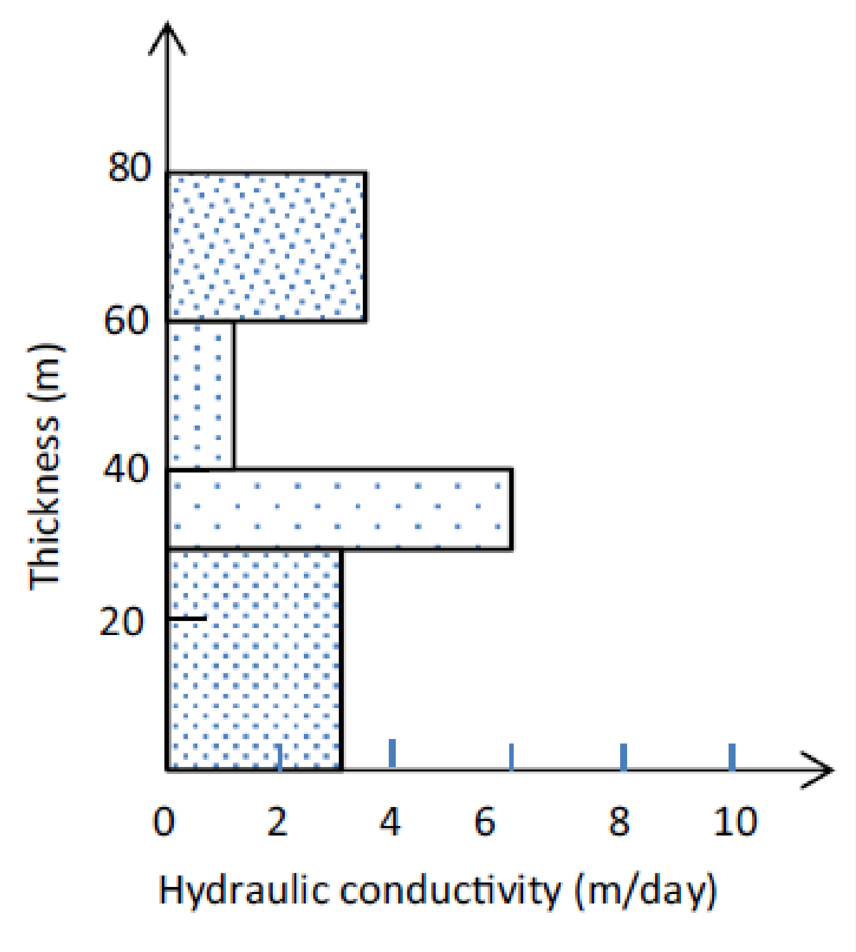
- Transmissivity is usually reported in units of square meters per day.
- For multi-layer aquifers, the transmissivity is calculated as follows:

$$T = \sum_{i=1}^{n} T_i$$

Example.

Heterogeneous Media Transmissivity Calculation

If the hydraulic conductivity variation in an aquifer is given as in Figure, then calculate its transmissivity along the same depth.



Transmissivity

Solution

For transmissivity calculation, water level is visualized to increase steadily from 0 to 80 m. Hence, the transmissivity values will be added on each other. The transmissivity calculations are achieved along the following four steps.

1. If the aquifer is saturated up to 30 m, then the transmissivity is $T_{30} = 30 * 3 = 90\ m^2/day$.
2. If saturation reaches to 40 m, then additional transmissivity will come from the second layer as $10 * 6 = 60\ m^2/day$. Hence, total transmissivity is $T_{40} = T_{30} + 60 = 90 + 60 = 150\ m^2/day$.
3. Likewise, in the case of 60 m saturation, additional transmissivity is $20*1= 20\ m^2/day$.

Addition to the previous step leads to $T_{60}= T_{40}* 20= 150* 20 = 170\ m^2/day$.

Transmissivity

4. Finally additional 20 m rise in the saturation level leads to additional transmissivity of 20 * 4 = 80 m^2/day. The total transmissivity becomes T80 = T60 * 80 = 170 + 80 = 250 m^2/day.

In real field studies, however, most aquifers consist of a combination of different geological layers of varying hydraulic conductivities with different thicknesses.

- The transmissivity must be worked out by calculating the contribution of each layer.
- **Specific capacity** is defined as the ratio of discharge to the drawdown in a well.
- It is discharge per unit drawdown and usually expressed in (l/min)/m.
- It provides a measure for well behavior and productivity.
- Wells are productive provided that small drawdowns are coupled with high discharges.
- The bigger the specific capacity the better is the well.

Specific capacity

- The specific capacity value of a well is not constant but dependent on time.
- It is a function of aquifer parameters, hydraulic conductivity, transmissivity, and the storage coefficient.
- Logically, for the same discharge it is directly proportional to the transmissivity but indirectly related to storativity.

Table: Specific Capacity Well Classification

Specific Capacity (l/min/m)	Well Productivity Classification
>300	High
300–30	Moderate
30–3	Low
3–0.3	Very low
<0.3	Negligible

Table: Aquifer Potentiality

Transmissivity (m^2/day)	Potentiality Description
$T < 5$	Negligible
$5 < T < 50$	Weak
$50 < T < 500$	Moderate
$T > 500$	High

Specific Storage and Storage Coefficient

- The mechanisms relating changes in head and changes in storage, and the relative magnitudes of these changes, differ for unconfined and confined aquifers (Figure below).

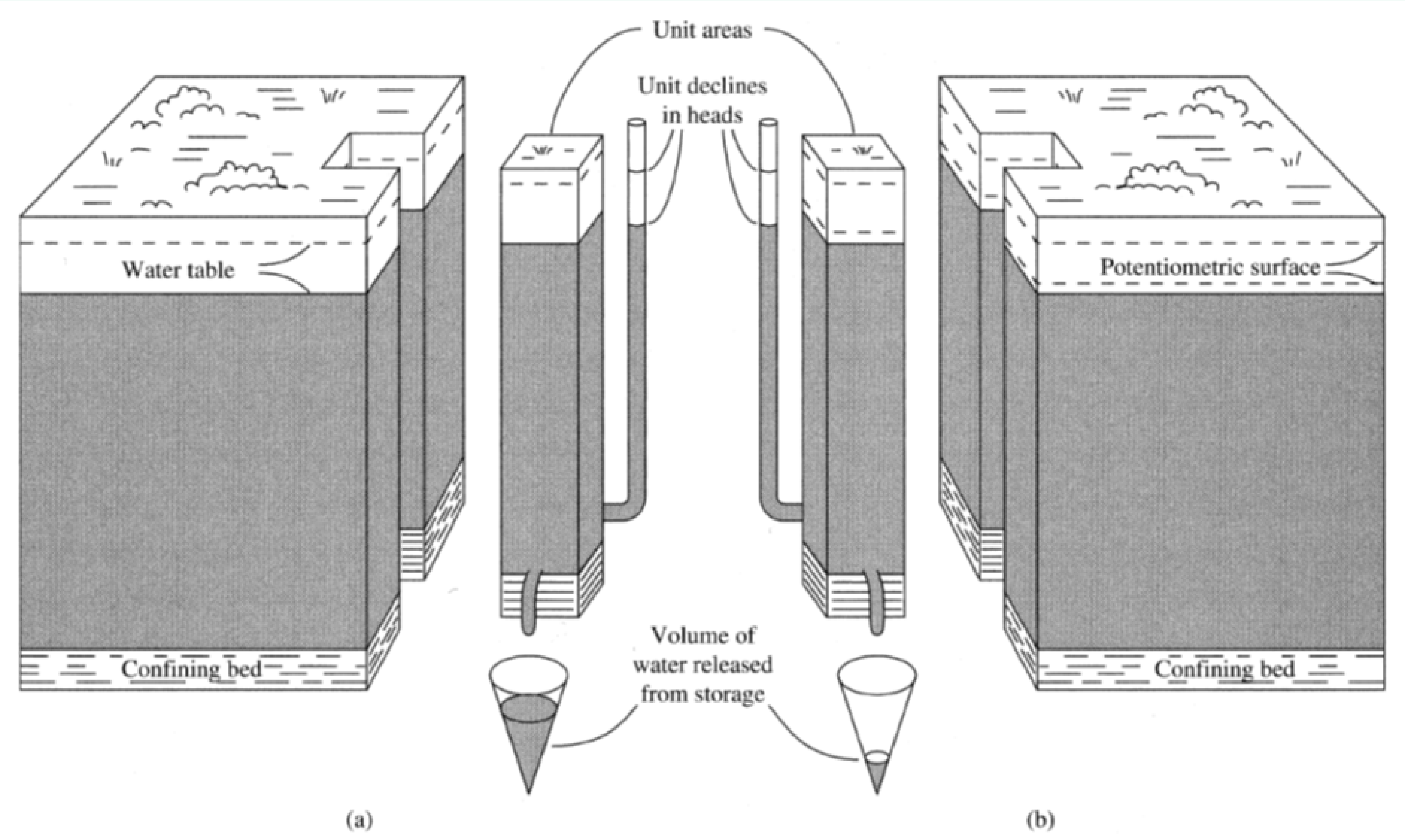


Figure. Definition of storativity in (a) unconfined and (b) confined aquifers.

Specific Storage (Ss)

- Specific storage (specific storativity), S_s (1/L)
- **Definition:** the amount of water released from (or added to) storage per unit decline (or unit rise) in hydraulic head from unit volume of *saturated* aquifer .

$$S_s = \frac{\Delta V_{water}}{V_{aquifer} \times \Delta h}$$

- **Storativity (Storage coefficient), S**: is the amount of water released from (or added to) storage per unit decline (or unit rise) in hydraulic head normal to the unit surface area of saturated aquifer
- Similar to transmissivity, storativity is developed primarily for the analysis of well hydraulics in a confined aquifer

$$S = \frac{\Delta V_{water}}{A_{aquifer} \times \Delta h} = S_s b$$

b is the saturated thickness of the aquifer

- **Storativity of a confined aquifer:** Water is released from a confined aquifer via
  - Expansion of water due to decline of hydraulic head
  - Release of pore water due to compaction of soil skeleton that is again induced by the decline of hydraulic head
- In general, storage coefficients for a confined aquifer are small, in the range of 0.005 to 0.00005 (Freeze and Cherry, 1979)

Storativity of an unconfined aquifer: Water is released in unconfined aquifer via primary release:

storage from the decline of water table, which is generally known as specific yield, S_y Secondary release: the expansion of water and expel of water from aquifer compaction

$S = S_y + hS_s$, h is the saturated thickness of the unconfined aquifer .

The usual range of S_y is 0.01 ~ 0.30.

Specific Storage and Storage Coefficient

- In an unconfined aquifer, a change in head produces a change in the volume of water in the medium.
- A decrease in head is reflected in the lowering of the water table and a concomitant decrease in water content of the portion of the aquifer through which the water table descends and in the overlying unsaturated zone.

- The opposite occurs for an increase in head.
- The amount of water-content change is characterized by the **specific yield**, S_y, defined as the volume of water released per unit surface area per unit decline of water table.
- The relative volume of water retained in the portion of the aquifer experiencing a head decline is the specific retention, S_r.

Specific Storage and Storage Coefficient

- The water remaining in the portion of the medium experiencing a water-table decline is held by surface tension against gravity, so specific retention is essentially identical to field capacity.
- Recall also that soil drainage is not instantaneous, and many days may be required for water content to decline to S_r in a draining aquifer.

Porosities, Specific Yields, and Specific Retentions of Geologic Materials.[a]

Material	Porosity			Specific Yield			Specific Retention		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
Unconsolidated Alluvial Deposits									
Clay	0.34	0.42	0.57	0.01	0.06	0.18	0.25	0.38	0.47
Silt	0.34	0.46	0.61	0.01	0.20	0.39	0.03	0.28	0.45
Fine sand	0.26	0.43	0.53	0.01	0.33	0.46	0.03	0.08	0.43
Medium sand	0.29	0.39	0.49	0.16	0.32	0.46	0.01	0.04	0.18
Coarse sand	0.31	0.39	0.46	0.18	0.30	0.43	0.05	0.07	0.18
Fine gravel	0.25	0.34	0.39	0.13	0.28	0.40	0.00	0.07	0.17
Medium gravel	0.24	0.32	0.44	0.17	0.24	0.44	0.01	0.07	0.15
Coarse gravel	0.24	0.28	0.37	0.13	0.21	0.25	0.03	0.09	0.14

Specific Storage and Storage Coefficient

- In a confined aquifer, a decrease in head is reflected in a lowering of the piezometric surface, but the aquifer beneath the unit surface area remains saturated.
- In this case, the decrease of storage accompanying the head decrease is due to:

1. compaction of the aquifer as part of the weight of the overlying material is transferred from the liquid to the solid grains, resulting in an increase in effective stress and a slight decrease in porosity and

2. expansion of the water due to the lowered pressure.

- The changes are reversed for an increase in head.
- The most prominent characteristic of a confined aquifer is that as the water is withdrawn the aquifer remains fully saturated.

Specific Storage and Storage Coefficient

- Storage coefficient depends upon
    - the whole saturation thickness of the aquifer and
    - the division of storativity by saturation thickness, m, is called specific storage, S_S.
- Storativity involves no dimensions, while
- S_S has the dimension of inverse length (L1).

- Physically, S_S is described as the volume of water that a unit volume of aquifer takes into storage or releases from storage under a unit decline in hydraulic head.

Specific Storage and Storage Coefficient

- The ability of an aquifer to store water is one of the most important hydraulic properties.
- The groundwater in rest is under the influence of gravity and hydrostatic pressure.
- The former is the combined weight of solid and water above a horizontal area at any depth in the aquifer.
- The changes are reversed for an increase in head.

Lithology Types	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}
Rock without fissures	7.46×10^{-7}

Specific Storage and Storage Coefficient

- The amount of water taken into or released from groundwater reservoir under unit change in the piezometric level and unit horizontal area is the definition of storage coefficient, which is also called as storativity.
- Any fall (rise) in the piezometric level implies the release (intake) of water from the groundwater reservoir storage.
- The word storativity (storage coefficient), S, is used especially for the storage properties of confined aquifers and interchangeably with specific yield for unconfined aquifers.
- It is defined as the volume of water that an aquifer releases from storage per unit surface area of the aquifer per unit decline in the hydraulic head normal to that surface.

Specific Storage and Storage Coefficient

- The most distinctive characteristic of confined aquifers is that as the water is withdrawn the aquifer remains fully saturated.
- The overburden is supported partly by the solid grains and partly by the pressure of the water.
- Removal of water from the aquifer occurs at the cost of pressure drop, and therefore, more overburden must be taken by the solid grains, which results in slight compression leading to consolidation of the layer.

- Meanwhile, a slight expansion of water takes place.
- In unconfined aquifers, the volume of water derived from expansion of the water and compression is negligible.
- Expansion of water is relatively smaller than compression of the aquifer, and accordingly, the storage coefficient is smaller than unconfined aquifers.

Hydraulic Head

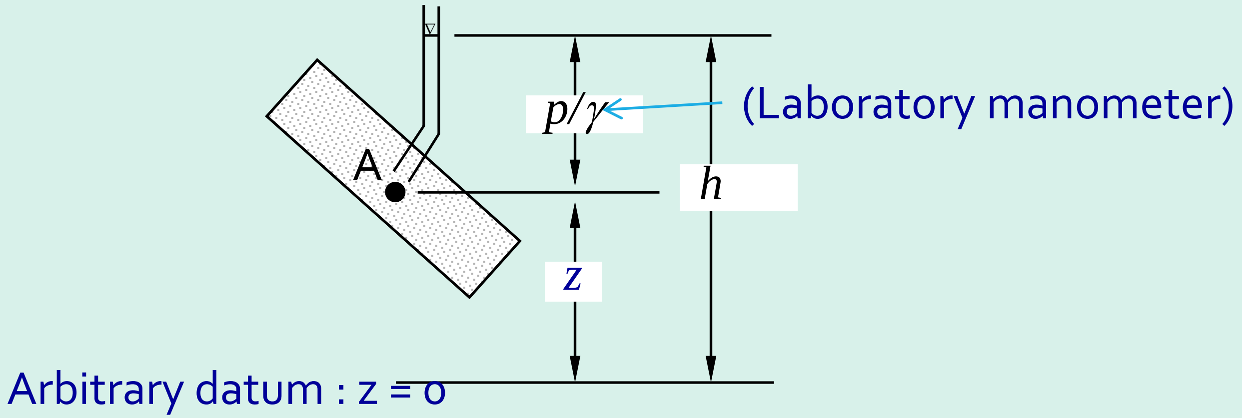
- Hydraulic head, h (L): For incompressible fluids (density is a constant) it is the sum of potential energy and pressure energy **per unit weight** of water. Sum of elevation head (z) and pressure head (p/γ)

$$h = \frac{p}{\gamma} + z \qquad (2)$$

$$[h] = \frac{energy}{weight\ of\ water} = \frac{Nm}{N} = m$$

$$\frac{p}{\gamma} = \frac{p}{\rho g} = \frac{N/m^2}{(Kg/m^3)(m/s^2)} = \frac{Nm}{N} = m$$

$$[z] = \frac{Potential\ Energy}{Weight\ of\ Water} = \frac{Nm}{N} = m$$



Schematic of hydraulic head, pressure head, and elevation (potential) head

Example: Specific yield and Storage Coefficient

A confined aquifer has 346 km^2 areal extent with saturation and confining layer thicknesses as 125 m and 12 m, respectively. Various field tests indicated that the average storativity coefficient is $1.9 * 10^{-4}$ and the aquifer material has a specific yield of 0.18. The initial piezometric level is at 73 m above the confining layer. If there is 128 m drop in the piezometric level, then what amount of water is taken from the aquifer? Discuss the aquifer situation, in general.

Solution

A relevant figure for the exposition of the case is given in Figure where all the relevant values are shown. The aquifer is confined initially, but after a long period of withdrawal the initial piezometric level falls to 128 m, which causes this aquifer to behave as an unconfined aquifer.

Example: Specific yield and Storage Coefficient

The unconfined aquifer starts after 73 + 12 = 85 m fall from the initial piezometric level. This means that until 85 m drop from the initial piezometric level the aquifer is under confined conditions and for the remaining 128 – 85 = 43 m the unconfined aquifer case prevails. First, the water volume, Vco, which comes from the confining condition, can be calculated according to Equation (a) as,

$Vco = 1.9 * 10^{-4} * 346 * 10^{6} * 85$

$= 558.8 * 10^{6} m^{3}$

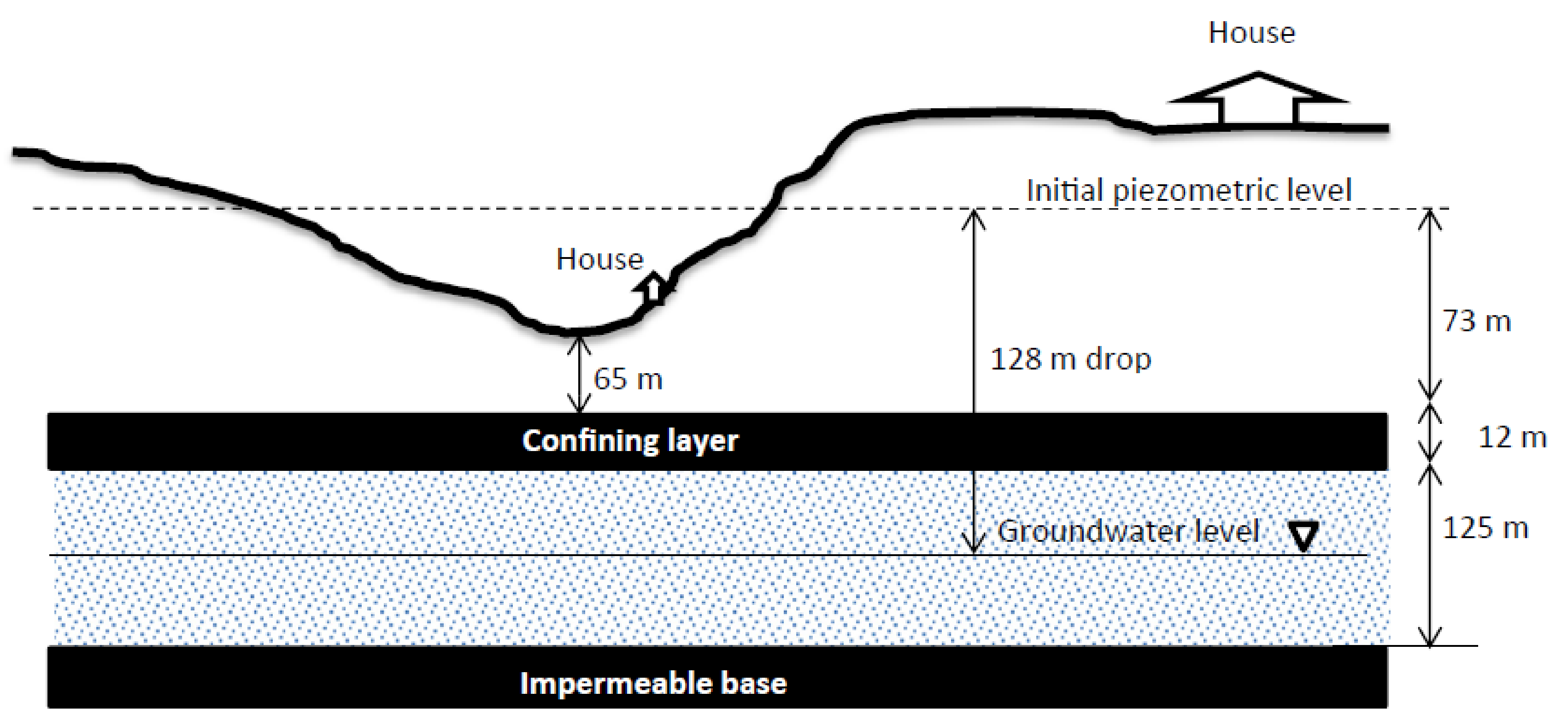


Figure: Aquifer composition.

Example: Specific yield and Storage Coefficient

- Depending on piezometer (water table) fall, Δh, released water volume, Vw, can be calculated by the use of the storage coefficient, S, and the plan area, A, of the aquifer as follows:

  Vw = SAΔh   equation (a)

- The hydraulic head drop within the unconfined condition is 43 m and the use of specific yield value in the same equation yields the unconfined aquifer water volume, Vun, as,

$$V_{un} = 0.18 \times 346 \times 10^6 \times 43 = 2678.0 \times 10^6 m^3$$

- Drilling any well in the valley gives rise to flowing well condition and the house may be affected due to groundwater inundation.

Example: Hydraulic Head Drop and Abstractable Water

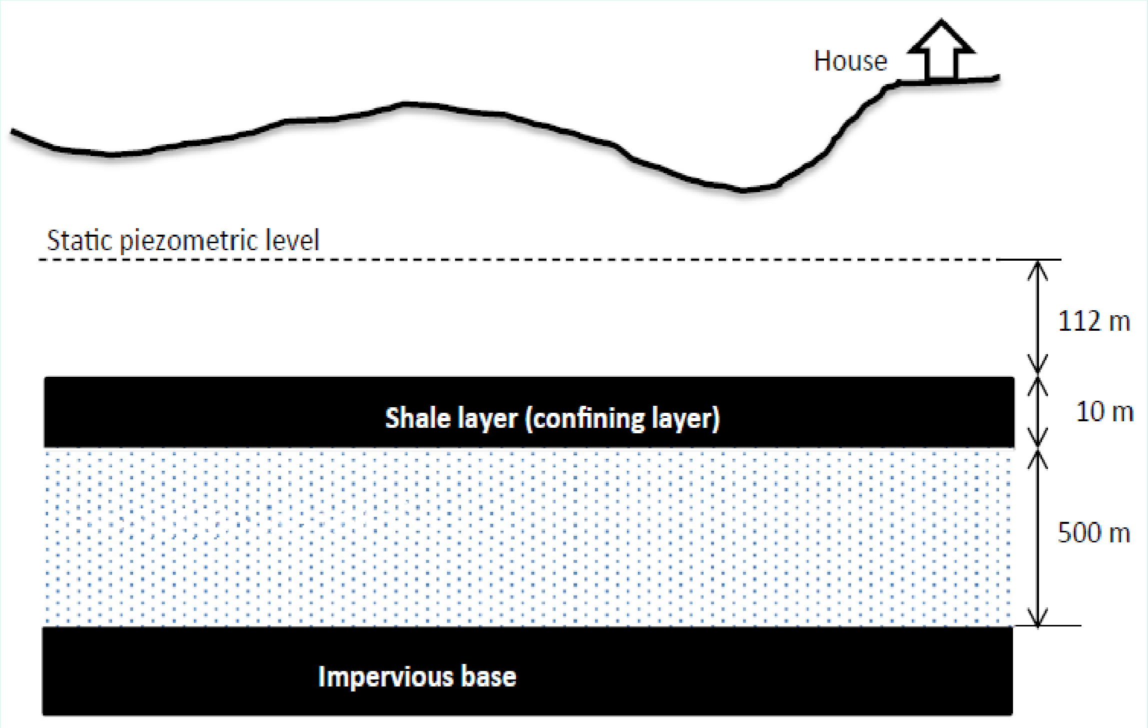
An extensive (500 km^2) sandstone aquifer of thickness 500 m is overlain by 10 m shale layer and the static piezometric level is 622 m above the upper bedrock surface. The aquifer material has a storage coefficient equal to $3.7*10^5$. If $1.2*10^6$ m^3 water should be withdrawn from this aquifer by a set of wells, then what would be the amount of piezometric level fall? Will the aquifer remain in the confining state?

Solution

Again, the drawing of the given configuration is helpful for imagination of the given quantities and configuration in Figure. If the drop in the static piezometric level is indicated as unknown by Δh, then similar to the previous example, the total volume of the drop space from Eq. (a) is, $V_T = 3.7 \times 10^{-6} \times 500 \times 10^6 \times \Delta h$

This volume must be equal to the volume withdrawn, and therefore, one can write that

$$3.7 \times 10^{-5} \times 500 \times 10^6 \times \Delta h = 1.2 \times 10^6$$



Example: Hydraulic Head Drop and Abstractable Water

from which one can obtain Δh = 64.86 m. Since this is less than the confining pressure level of 122 m, the aquifer remains under the confining condition. This means that $1.2 * 10^6$ m^3 of water is withdrawn due to the water compressibility only.

Example: Specific Retention and Storativity

In an unconfined aquifer there is about 6.7 m drop in the water table. The aquifer area is 8 km^2. The aquifer material is composed of sand with porosity 0.37 and specific retention 0.10.

1. Calculate the specific retention. 2. Calculate the volume change in the aquifer storage.

Solution

$$n = S_y + S_r \tag{2.5}$$

1. The porosity is composed of specific yield and specific retention summation as in Eq. (2.5).

The necessary arrangement in this equation gives,

$S_y = n – Sr = 0.37 – 0.10 = 0.27$

2. The change in water volume is given by Equation (a), and the substitution of convenient numerical values into this equation gives,

$V_w = 0.27 * 8 * 10^6 * 6.7 = 1.45 * 10^7$ m^3

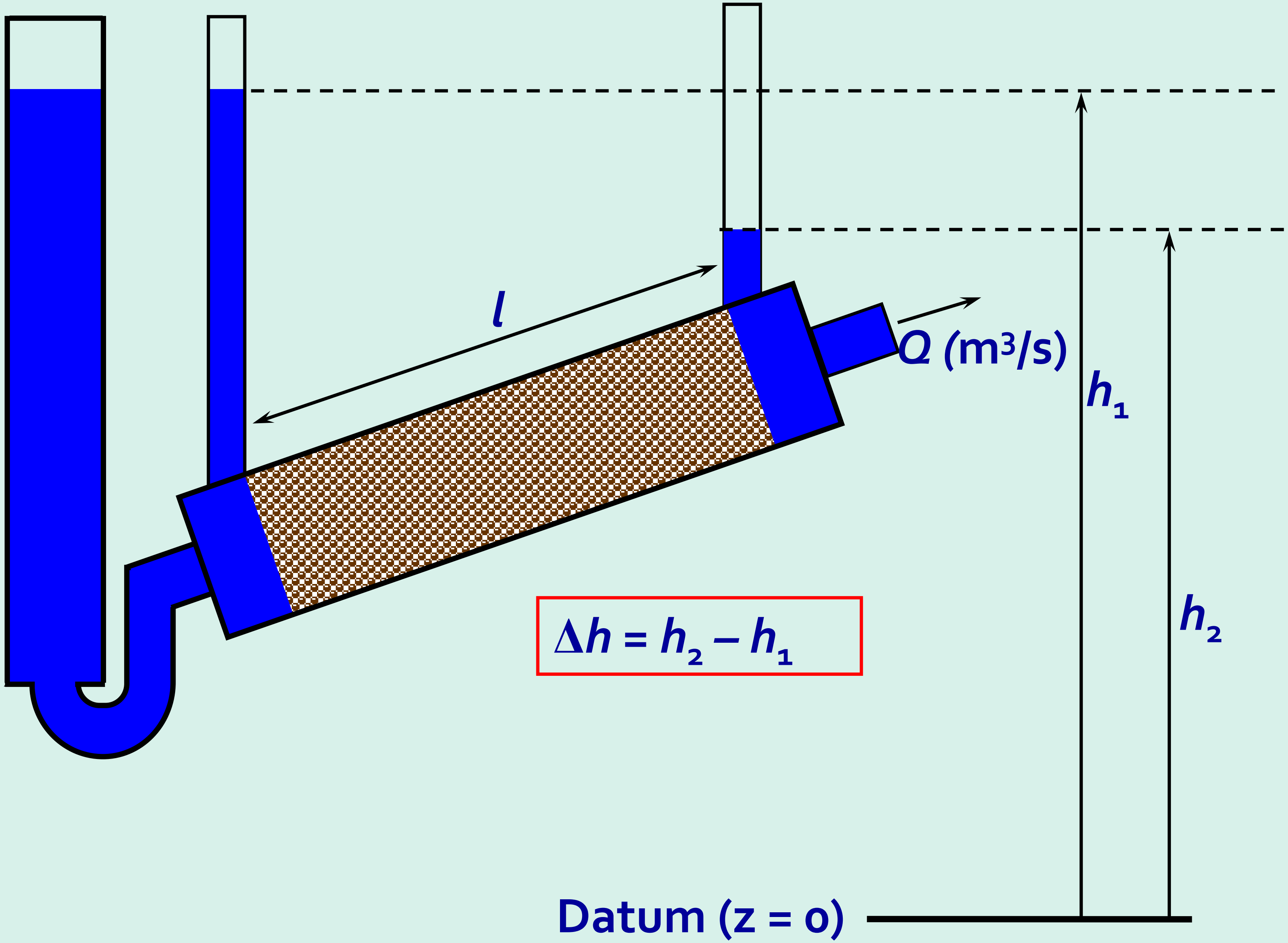
DARCY'S LAW

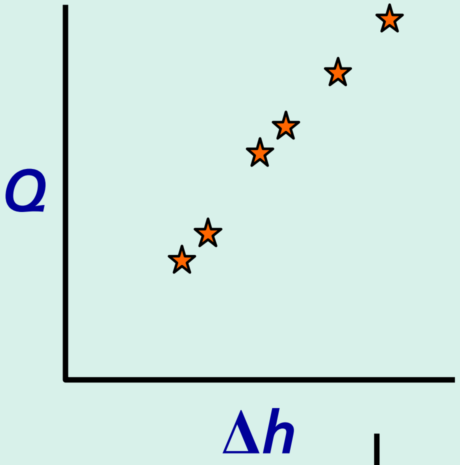
- Darcy (1856) suggested his law after a series of experimental studies.
- He performed experiments to deduce the nature of flow laws in saturated porous media.
- His simple experimental setup is shown in Figure in which he used sand as a medium and water as a fluid.
- The water flow is possible under the hydraulic head, Δh.
- Herein, rational and logical rules will be used for the Darcy's law.
- Logically, groundwater filter velocity, V_f, is directly proportional to the hydraulic gradient, i =Δh/ΔL.

Hence, in general, one can write the proportionality relationship as,

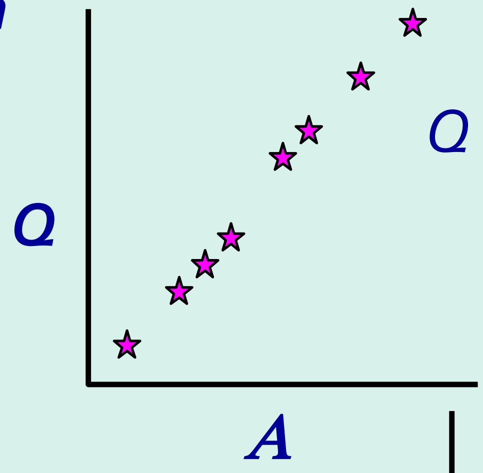
$$V_f \ \alpha \ \frac{\Delta h}{\Delta l}$$

Darcy's experiment, 1856

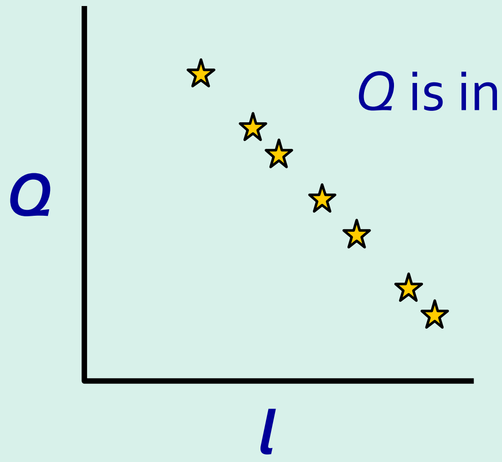




Q is proportional to **Δ*h***



Q is proportional to sample cross sectional area, *A*



Q is inversely proportional to sample length, *l*

DARCY'S LAW

- Combine and insert a constant of proportionality

  $Q = -KA(\Delta h/l)$

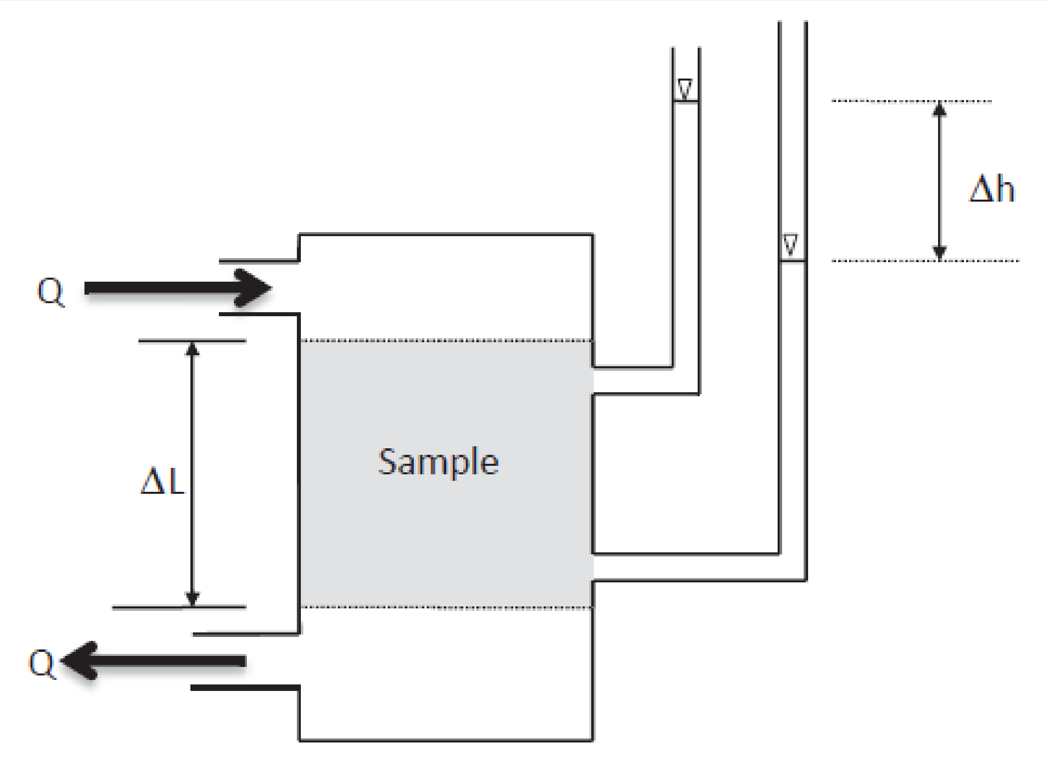
  - ✓A = sample cross-sectional area [m²]
    - ✓perpendicular to flow direction
  - ✓K = hydraulic conductivity [m/s]
  - ✓ $\Delta h/l$ = hydraulic gradient [-]
- Sometimes written as $Q/A = q = -K(\Delta h/l)$
  - ✓Where q = specific discharge
- Hydraulic gradient often written as a differential, dh/dl

DARCY'S LAW

- Herein, α shows the proportionality sign. In order to convert this proportionality into an equation form, it is necessary to import a constant, K, which yields, $V_f = K\frac{\Delta h}{\Delta l}$
- This is the logical derivation of Darcy's law.
- The hydraulic gradient is dimensionless and the proportionality constant has the same unit as the velocity.
- It is equivalent to the groundwater velocity per unit hydraulic gradient.
    - K should reflect the medium feature for fluid flow.
- In general, the more is the interconnected void percentage in the flow cross-section, the bigger will be the K value.
- This again logically implies that the coarser the grains in a porous medium the bigger is the K value.

DARCY'S LAW

- Logic cannot tell numerical values, and therefore, determination of K value requires field or laboratory experiments.
- In groundwater literature, K is referred to as the permeability of hydraulic conductivity.
- If one considers the product of Equation above by unit cross-sectional area, then it is the amount of discharge that passes from the unit area.



DARCY'S LAW

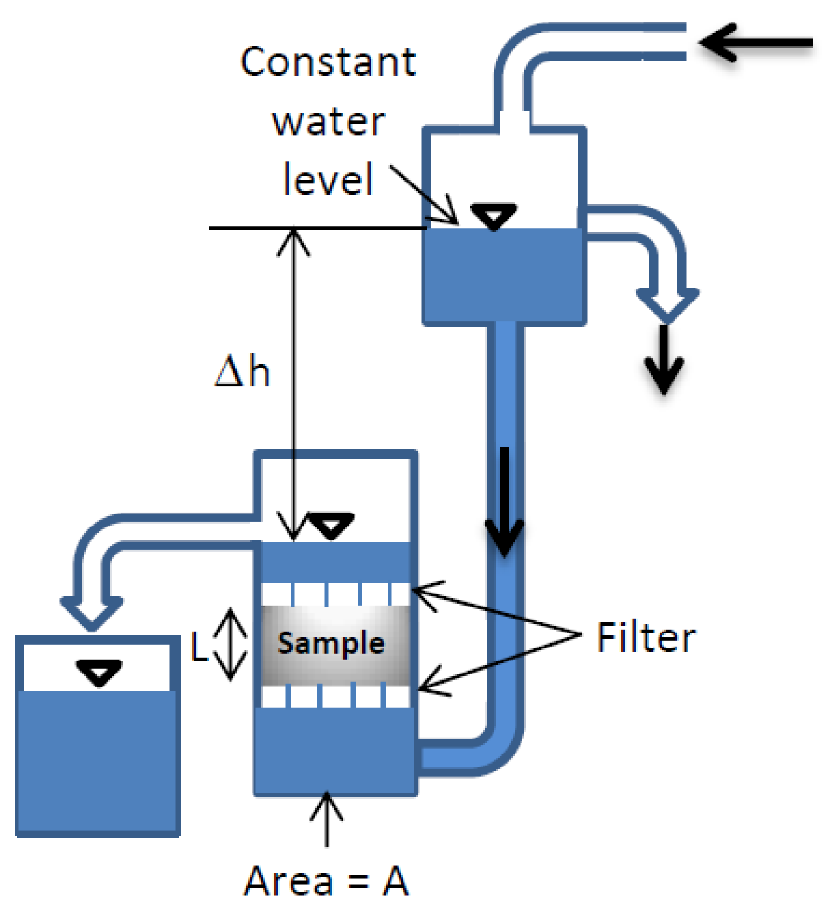
- This is named as the specific discharge, q.
- Darcy succeeded in formulating an empirical relationship among different variables as volumetric flow rate through
  - a homogeneous and isotropic media,
  - perpendicular to the unit cross-sectional area,
    - which is directly proportional to the hydraulic gradient.

$$q = \frac{Q}{A} = K\frac{\Delta h}{\Delta l}$$

in which Q is the discharge through the cross-sectional area, A, perpendicular to the flow direction, K is the proportionality constant known as the hydraulic conductivity of the medium, and $\Delta h/\Delta l$ is the hydraulic gradient.

Constant Head Pereameter

Example: As shown in figure below, a constant head permeameter, similar to Darcy's experiment, has a soil sample of 30 cm length with the cross-sectional area equal to 100 cm^2. As 0.1 cm^3/s discharge goes through this soil sample, the hydraulic head falls 9 mm. Calculate the hydraulic conductivity of the soil.



Constant head permeameter.

Solution

Permeameters are used for hydraulic conductivity measurements in the laboratory.

The given quantities with usual notations are as follows.

The length of soil sample : $L = 30$ cm

The cross-sectional area : $A = 100\ cm^2$

Head fall : $\Delta h = 9$ mm

Discharge : $Q = 0.1\ cm^3/s$

Constant Head Pereameter

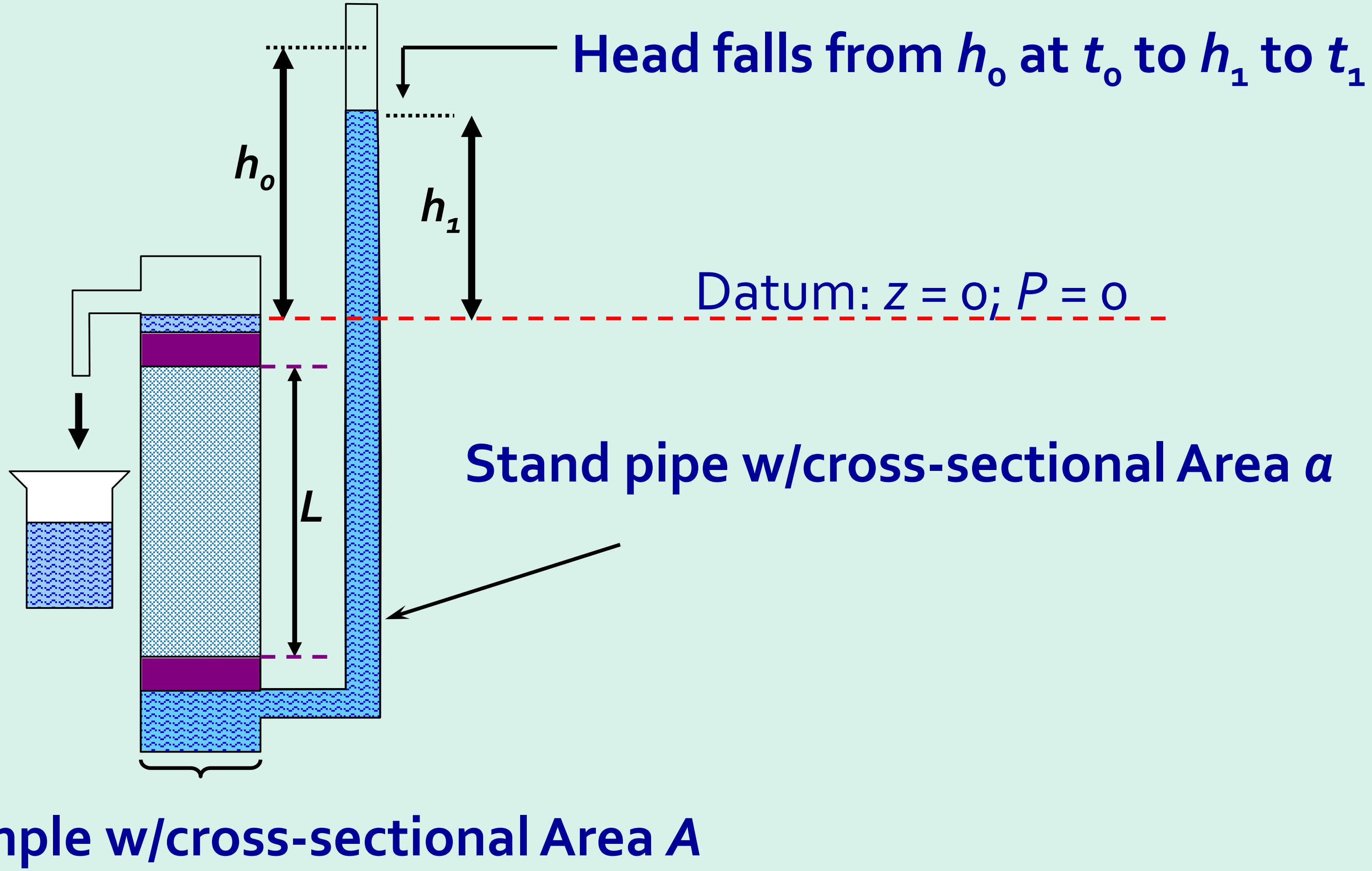
The velocity of the flow is $V = Q/A = 0.1/100 = 0.0001$ cm/s.

The slope of the piezometer line is $i = \Delta h/L = 0.9/30 = 0.03$.

The substitution of these values into basic Darcy's law yields the hydraulic conductivity of the soil as,

$$K = V/i = 0.0001/0.03 = 3.3*10^{-2} \text{ cm/s}$$

Measuring K
Falling Head Permeameter



Falling Head Permeameter Analysis

- Apply to fine grained soils
  - Constant head permeameter test inaccurate, lengthy

- Mass balance – standpipe

  $Q = dV/dt = a\,(dh/dt)$

- Darcy's Law – sample

  $Q = -KA_{xs}(h/L)$

- Set Q equal

  $a\,(dh/dt) = -KA_{xs}(h/L)$

Set datum at outlet
Therefore, $h_{outlet} = 0$ and
$\Delta h = h_{outlet} - h = -h$

At $t = t_o$
$\Delta h = h_{outlet} - h_o = -h_o$

At $t = t_1$
$\Delta h = h_{outlet} - h_1 = -h_1$

Falling Head Permeameter Analysis

- Combine mass balance and Darcy's Law

  $a\,(dh/dt) = -KA(h/L)$

- Separate variables and integrate

$$-\int_{h_o}^{h_1} \frac{dh}{h} = \frac{KA}{aL} \int_{t_o}^{t_1} dt \qquad \ln\frac{h_o}{h_1} = \frac{KA\,(t_1 - t_o)}{aL}$$

$$K = \frac{aL}{A\,(t_1 - t_o)} \ln\frac{h_o}{h_1}$$

Falling Head Permeameter Test Design

Example: Solve for time =
$$K = \frac{aL}{A\ (t_1 - t_o)} \ln \frac{h_o}{h_1}$$

- Trial Design:
  - L = 10 cm
  - A = 10 cm^2
  - Stand pipe a = 0.5 cm^2
  - h_o = 20 cm; h_1 = 19 cm
  - $K = 10^{-3}$ cm/sec (~ fine sand with silt)
- Time =
$$t_1 - t_o = \frac{0.5 \times 10}{0.001 \times 10} \ln \frac{20}{19} = 25.6 \text{ s}$$

Heterogeneity and Anisotropy

- Transmission properties of the aquifers are related to hydraulic conductivity, K, of the geological materials.
- It may show **variations at different points** in a geologic formation or along **different directions at the same point**.
- The former is called **heterogeneity** and the latter is referred to as **anisotropy**.

- The presence of heterogeneities and anisotropies in geological materials is an indication of the scale of variation in terms of time and space, and geological processes are responsible for the fabrication of these materials.
- A reservoir medium is regarded as an anisotropic domain if its basic hydraulic properties are dependent on direction.

Heterogeneity and Anisotropy

- An isotropic medium where permeability is equal in all directions in an aquifer is a theoretical assumption, which is used for the simplification of governing groundwater equation analytical solutions in porous media.
- This assumption is considered valid both in large-scale hydrology and comparatively in small-scale flow through permeable sediments.
- On the contrary, natural sediments are all anisotropic in their simplest modes, where vertical hydraulic conductivity is different from horizontal conductivity.
- Heterogeneity is the property of the aquifer medium where hydraulic conductivity is different in one place from that measured in another.
- It is observed through many field studies that natural sediments have both anisotropy and spatial heterogeneity which affect both the pattern and rates of porous medium flow.

Heterogeneity and Anisotropy

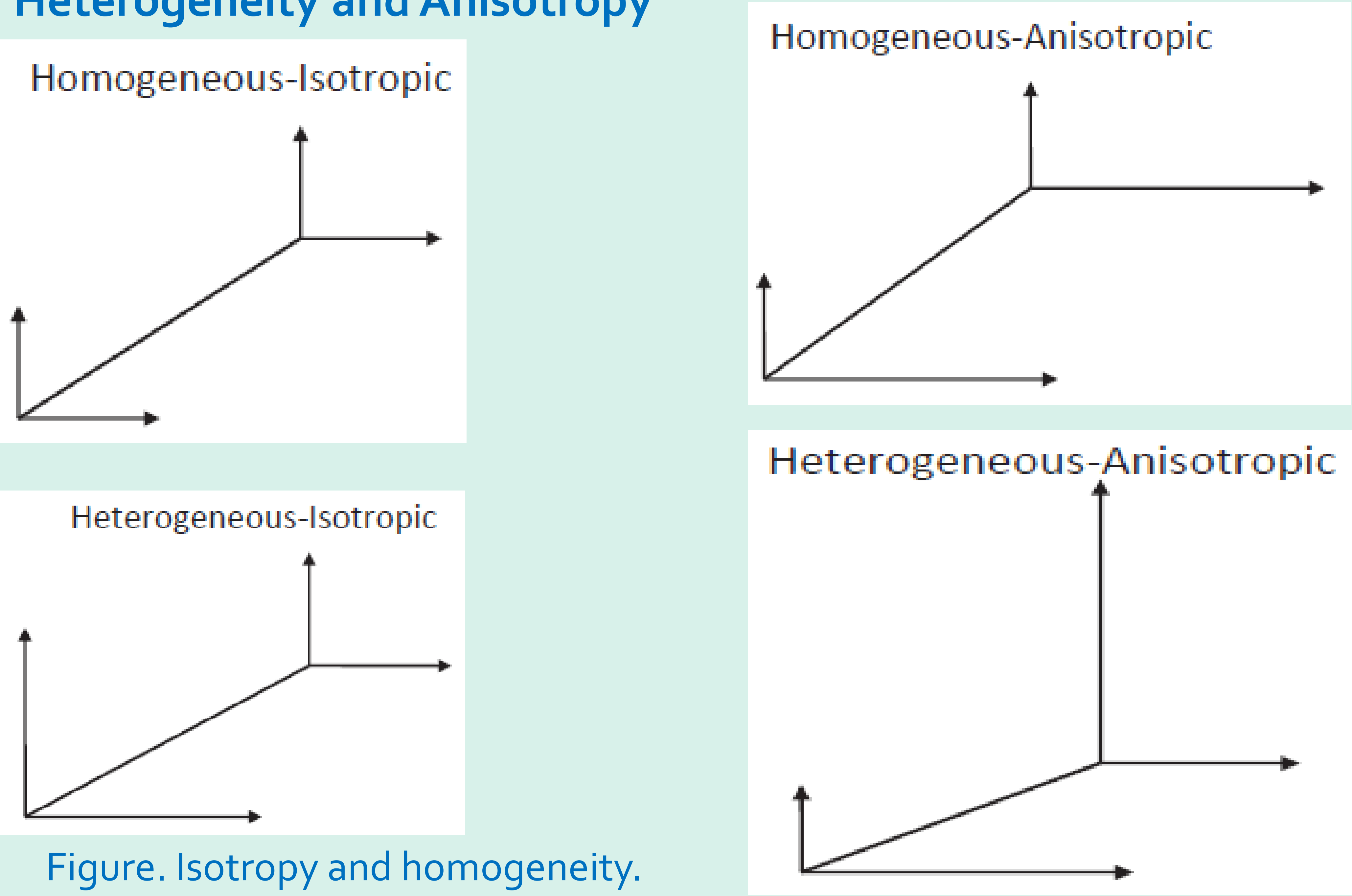


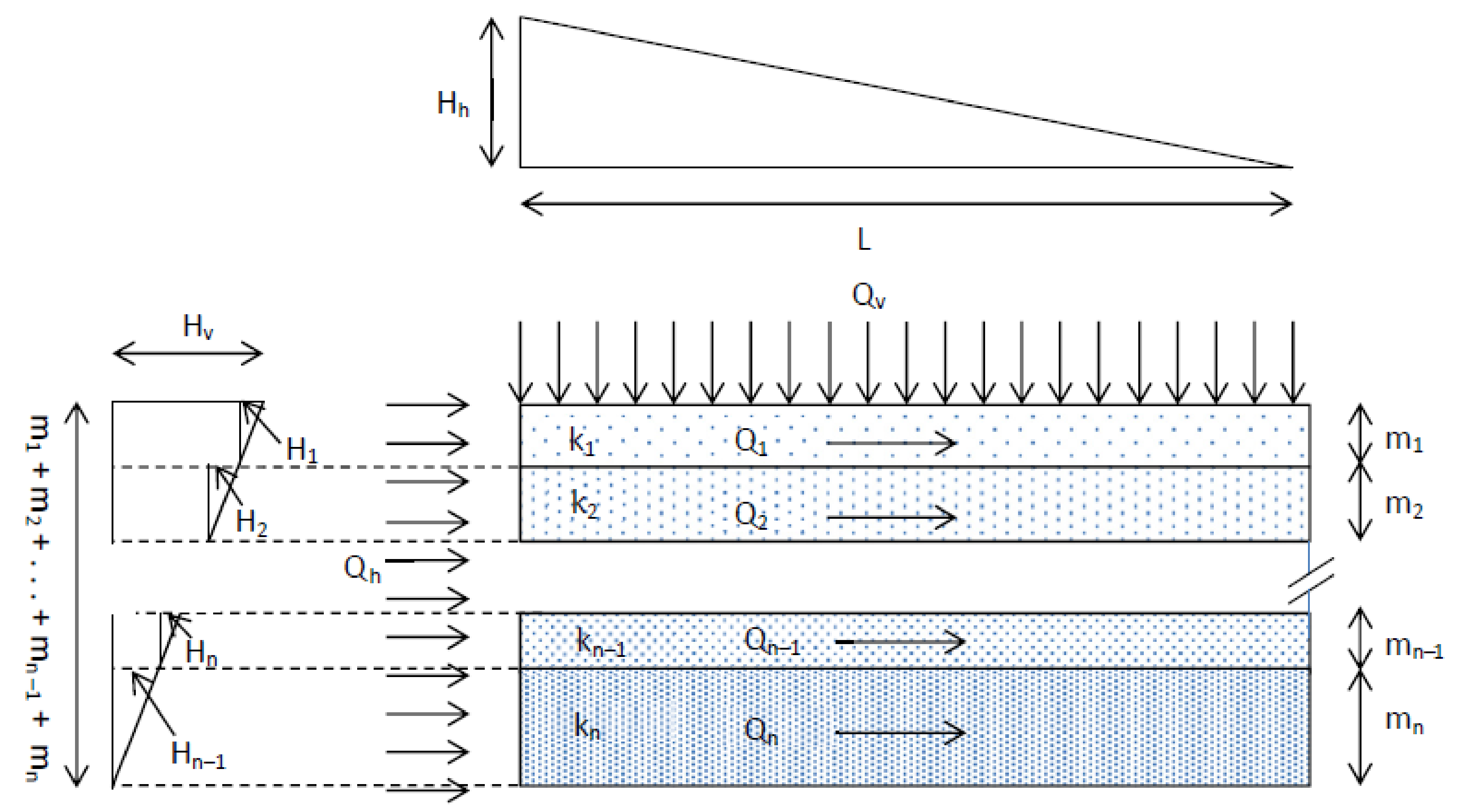
Figure. Isotropy and homogeneity.

Heterogeneity and Anisotropy

The general definition of transmissivity has been given already by Equation below. Let the thicknesses and hydraulic conductivities be m_1, m_2, m_3, ., m_n and k_1, k_2, k_3, .,k_n, respectively, where n is the number of different layers in a multiple aquifer such as in Figure below.

If the transmissivity changes vertically with thickness, K(z), then the transmissivity will be the summation along the thickness as,

$$T = \int_{bottom}^{top} K(z)dz$$



Heterogeneity and Anisotropy

First, the horizontal flow from left to the right is considered with total discharge, Q. Since no water is gained or lost in passing through the various layers, the principle of continuity leads to,

$$Q_h = Q_1 + Q_2 + \ldots + Q_n$$

For unit width (W = 1) of the aquifer cross-section, the individual discharges can be written by considering Darcy's law as,

$$\begin{aligned} Q_1 &= k_1 m_1 i_1 \\ Q_2 &= k_2 m_2 i_2 \\ \vdots \; &\; \vdots \\ Q_n &= k_n m_n i_n \end{aligned}$$

Horizontal flow in each layer has the same hydraulic gradient, and hence, the substitution of these equations into the previous one gives,

$$Q_h = (k_1 m_1 + k_2 m_2 + \ldots + k_n m_n) i_h$$

Substitution of this equation into the specific discharge expression (q) yields,

$$q = \frac{Q}{A} = K \frac{\Delta h}{\Delta l}$$

$$q_h = \frac{k_1 m_1 + k_2 m_2 + \ldots\ldots k_n m_n}{m_1 + m_2 + \ldots\ldots m_n} i_h$$

Heterogeneity and Anisotropy

which means that the horizontal hydraulic conductivity, k_h, for the section considered is,

$$k_h = \frac{k_1 m_1 + k_2 m_2 + \ldots\ldots k_n m_n}{m_1 + m_2 + \ldots\ldots m_n}$$

This last expression implies that horizontal hydraulic conductivity is the weighted average of the individual hydraulic conductivities with layer thicknesses being the weights. It is interesting to notice that if the layers have the same thicknesses, then Equation above takes the form as,

$$k_h = \frac{k_1 + k_2 + \ldots\ldots k_n}{n}$$

where n is the number of layers. This last expression implies that only in the case of equal layer thicknesses, the average hydraulic conductivity is equivalent to the arithmetic average of hydraulic conductivities.

Heterogeneity and Anisotropy

As a second case, let us consider vertical flow for which the overall hydraulic gradient is equal to the summation of the individual hydraulic heads divided by the total thickness

$$i_v = \frac{H_v}{m} = \frac{H_1 + H_2 + \dots\dots + H_n}{m_1 + m_2 + \dots\dots + m_n}$$

Each layer allows passage of the same total vertical discharge Q_v, and therefore, the specific discharge in each layer, q_v, is the same. The application of Darcy's law in each layer gives the individual head losses as,

$$H_1 = \frac{m_1}{k_1} q_v$$
$$H_2 = \frac{m_2}{k_2} q_v$$
$$\vdots \quad \vdots$$
$$H_n = \frac{m_n}{k_n} q_v$$

Substitution on Equation above yields,

$$q_v = \frac{m_1 + m_2 + \dots\dots m_n}{\frac{m_1}{k_1} + \frac{m_2}{k_2} + \dots\dots \frac{m_n}{k_n}}$$

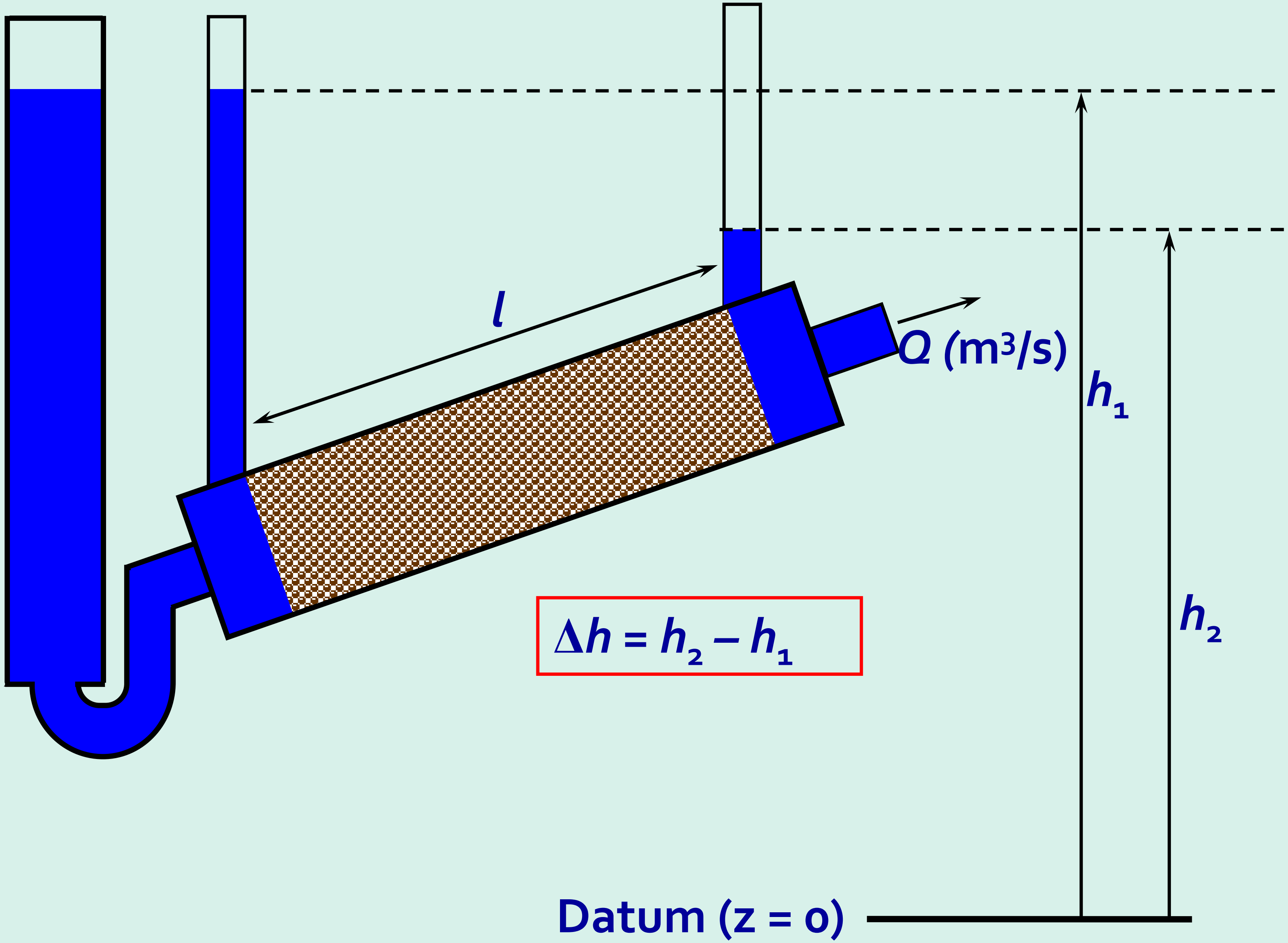
which is tantamount to saying that the vertical hydraulic conductivity, k_V, is,

$$k_V = \frac{m_1 + m_2 + \dots\dots + m_n}{\frac{m_1}{k_1} + \frac{m_2}{k_2} + \dots\dots + \frac{m_n}{k_n}}$$

Heterogeneity and Anisotropy

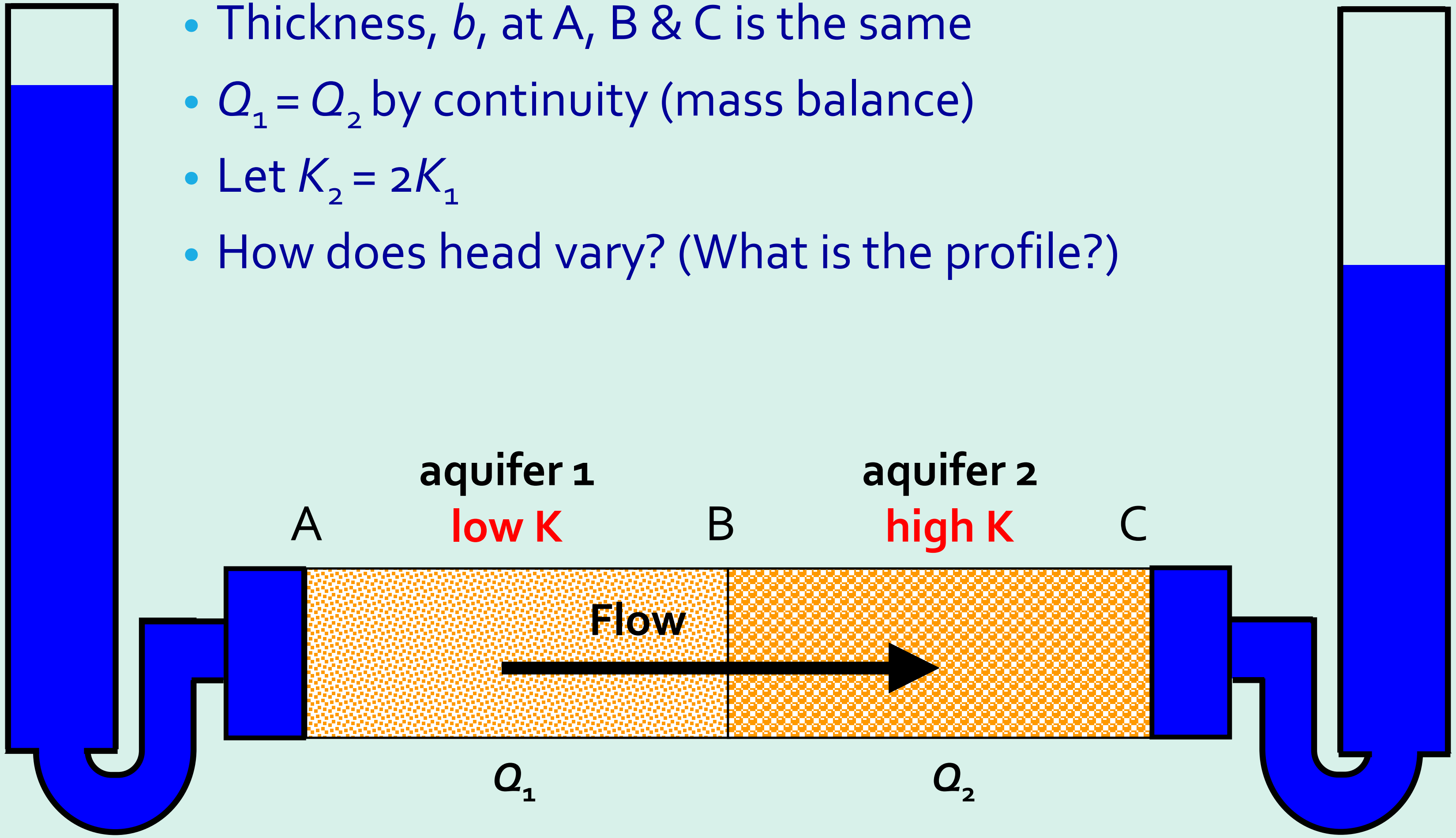
- Most frequently, multiple layers occur in the sedimentary rocks.
- In fact, they are often anisotropic with respect to hydraulic conductivity because they contain grains which are not spherical but elongated in one direction.
- During deposition, these grains settle with their longest axes more or less horizontally and this usually causes the horizontal hydraulic conductivity to be greater than vertical conductivity in a single layer.
- However, when many layers are considered then the bulk hydraulic conductivity of sediments is usually much greater than the vertical counterpart.
- It is also true for alluvial deposits, which are usually constituted by alternating layers or lenses of sand and gravel on occasional clays.

Darcy's experiment, 1856



Effect of *K* on Change in Head Gradient

- Length, *L*, from A to B and B to C is same
- Width, *w*, ⊥ to the page is constant
- Thickness, *b*, at A, B & C is the same
- $Q_1 = Q_2$ by continuity (mass balance)
- Let $K_2 = 2K_1$
- How does head vary? (What is the profile?)



Head Profile (Effect of *K*)

- By continuity, $Q_1 = Q_2$
- Write Darcy's Law

$$-K_1 A_1 (\Delta h/l)_1 = -K_2 A_2 (\Delta h/l)_2$$

- Cancel like terms, *A*, *l*
- Substitute $K_2 = 2K_1$

$$K_1 \Delta h_1 = K_2 \Delta h_2 = 2K_1 \Delta h_2$$

- Cancel K_1; therefore,

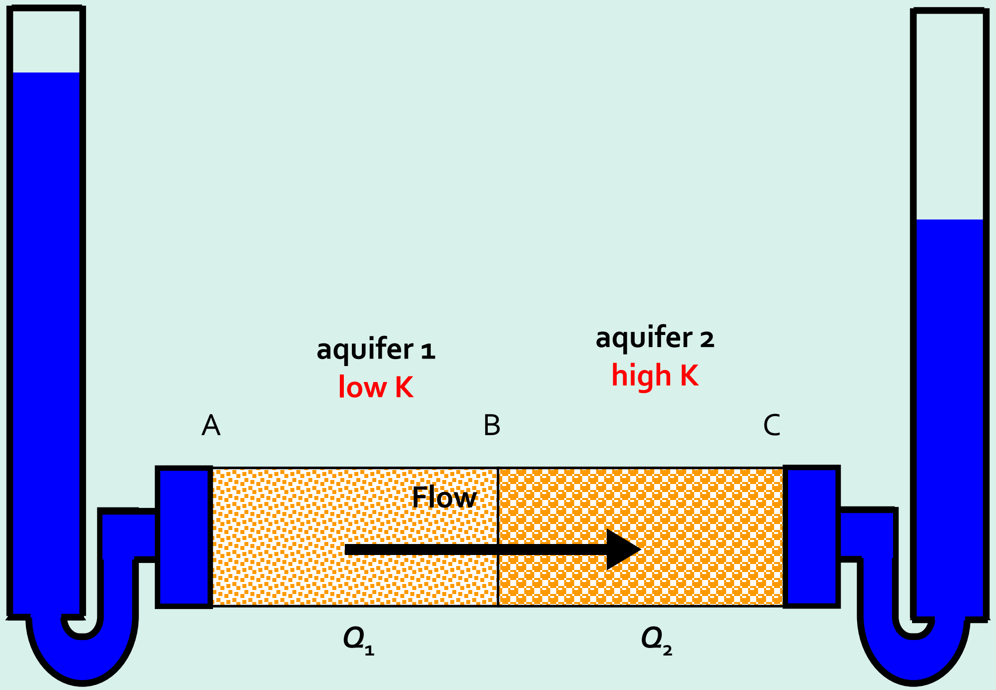
$$\Delta h_1 = 2\,\Delta h_2$$

- Determine Δh_1 and Δh_2

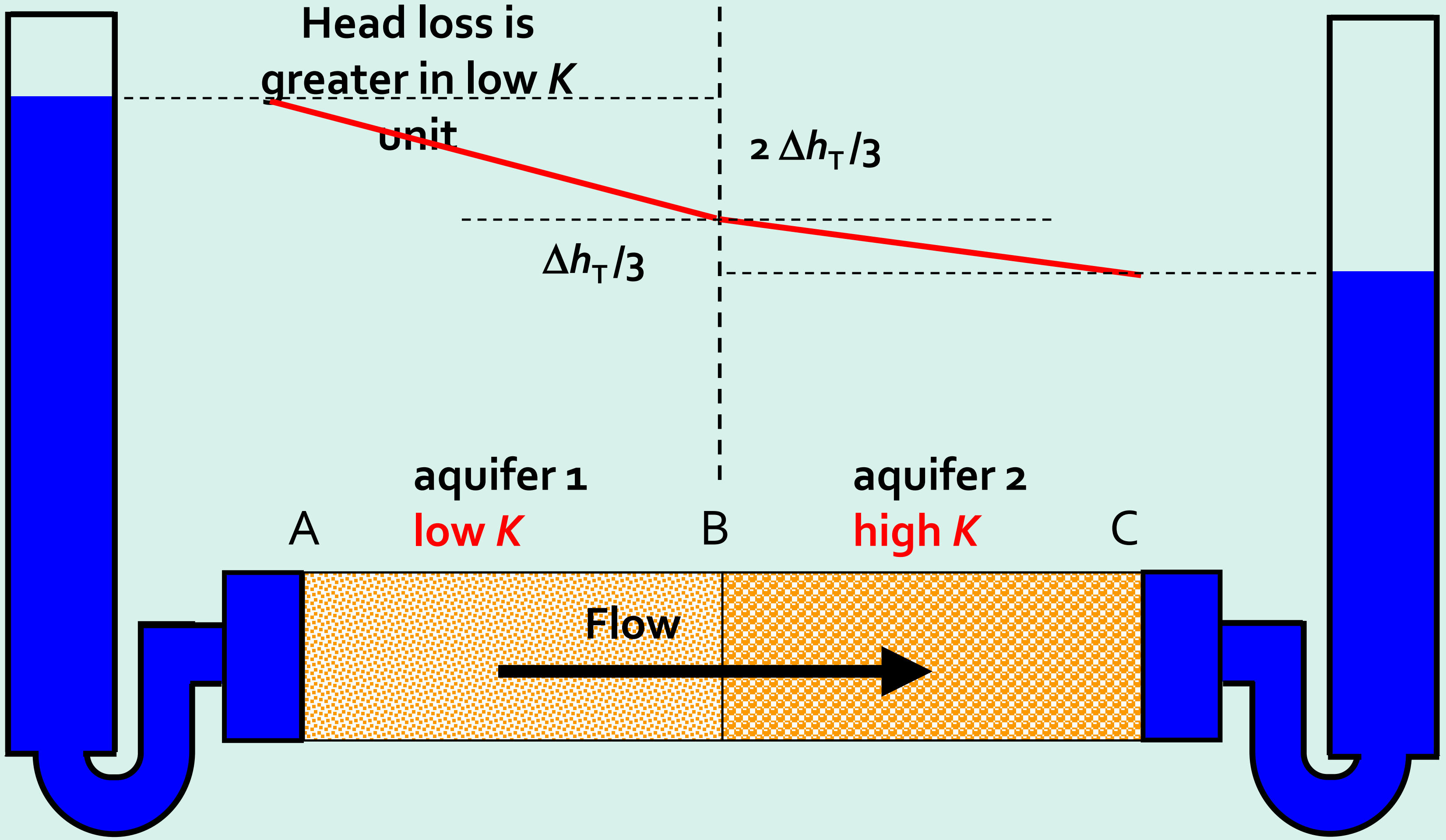
$$\Delta h_T = \Delta h_1 + \Delta h_2 = 2\,\Delta h_2 + \Delta h_2 = 3\,\Delta h_2$$

$$\Delta h_2 = \Delta h_T / 3$$

$$\Delta h_1 = 2\,\Delta h_T / 3$$

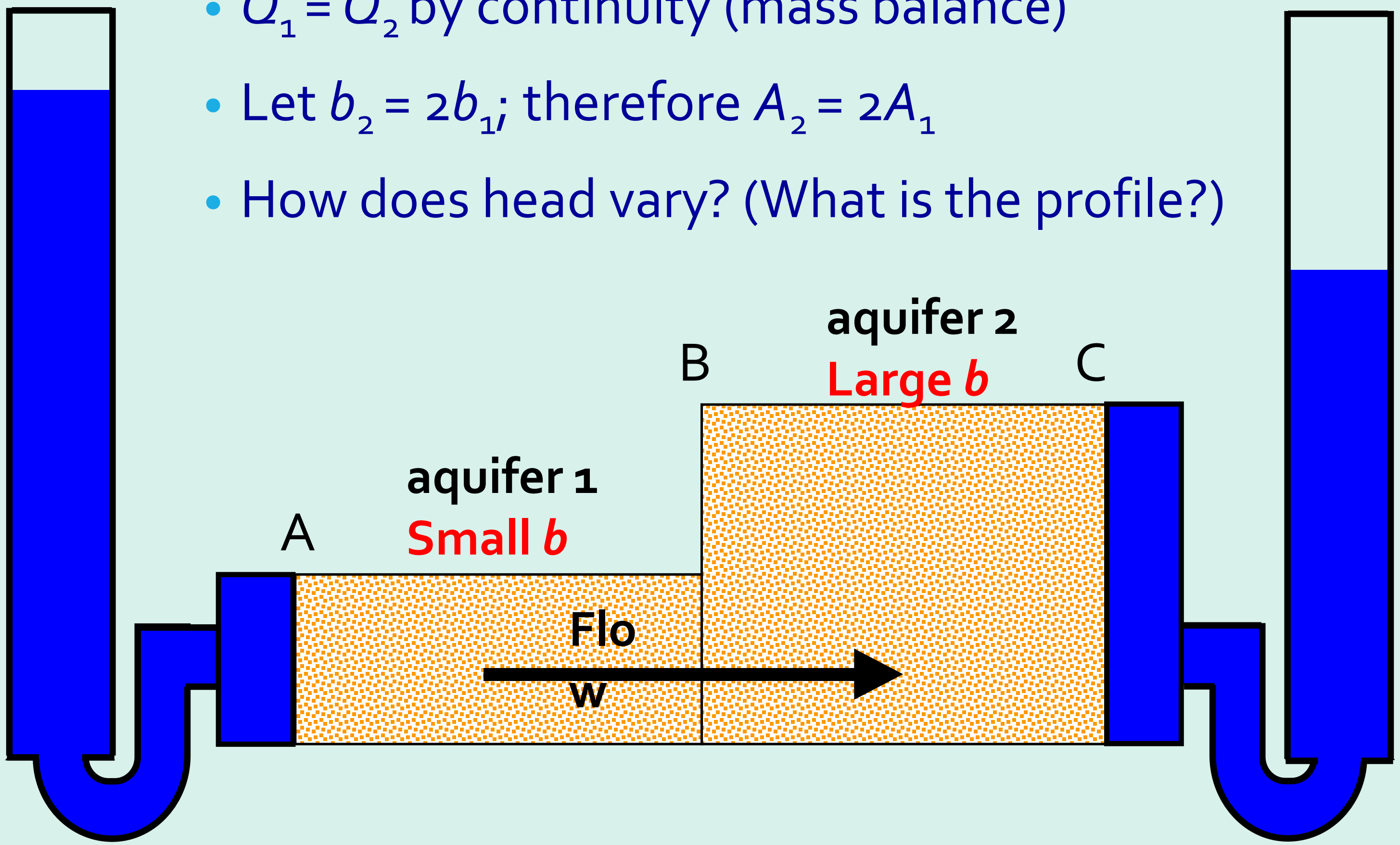


Change in K can cause Change in Head Gradient



Effect of *b* on Change in Head Gradient

- Length, *L*, from A to B and B to C is same
- Width, *w*, ⊥ to the page is constant
- Hydraulic conductivity, *K*, is the same
- $Q_1 = Q_2$ by continuity (mass balance)
- Let $b_2 = 2b_1$; therefore $A_2 = 2A_1$
- How does head vary? (What is the profile?)



Head Profile (Effect of *b*)

- By continuity, $Q_1 = Q_2$
- Write Darcy's Law

$$-K_1 A_1 (\Delta h/l)_1 = -K_2 A_2 (\Delta h/l)_2$$

- Cancel like terms, substitute $A_2 = 2A_1$

$$A_1 \Delta h_1 = A_2 \Delta h_2 = 2A_1 \Delta h_2$$

- Therefore,

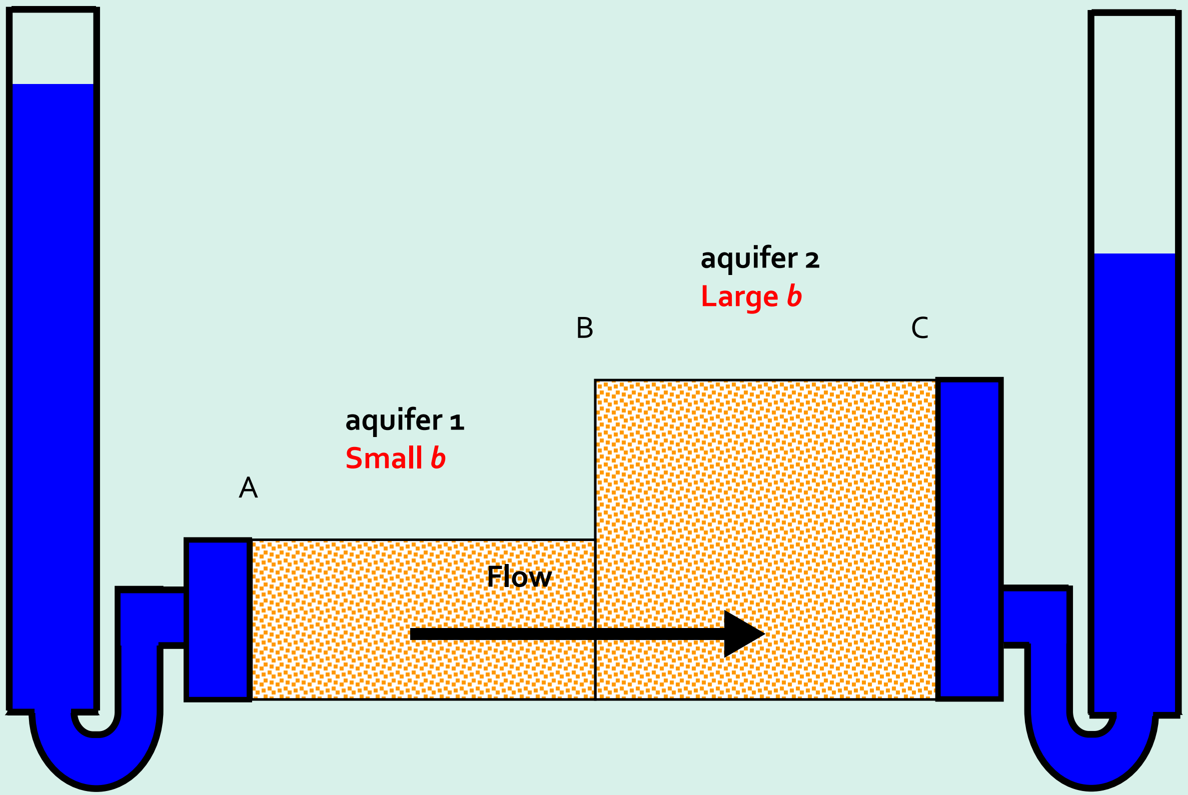
$$\Delta h_1 = 2\,\Delta h_2$$

- Determine Δh_1 and Δh_2

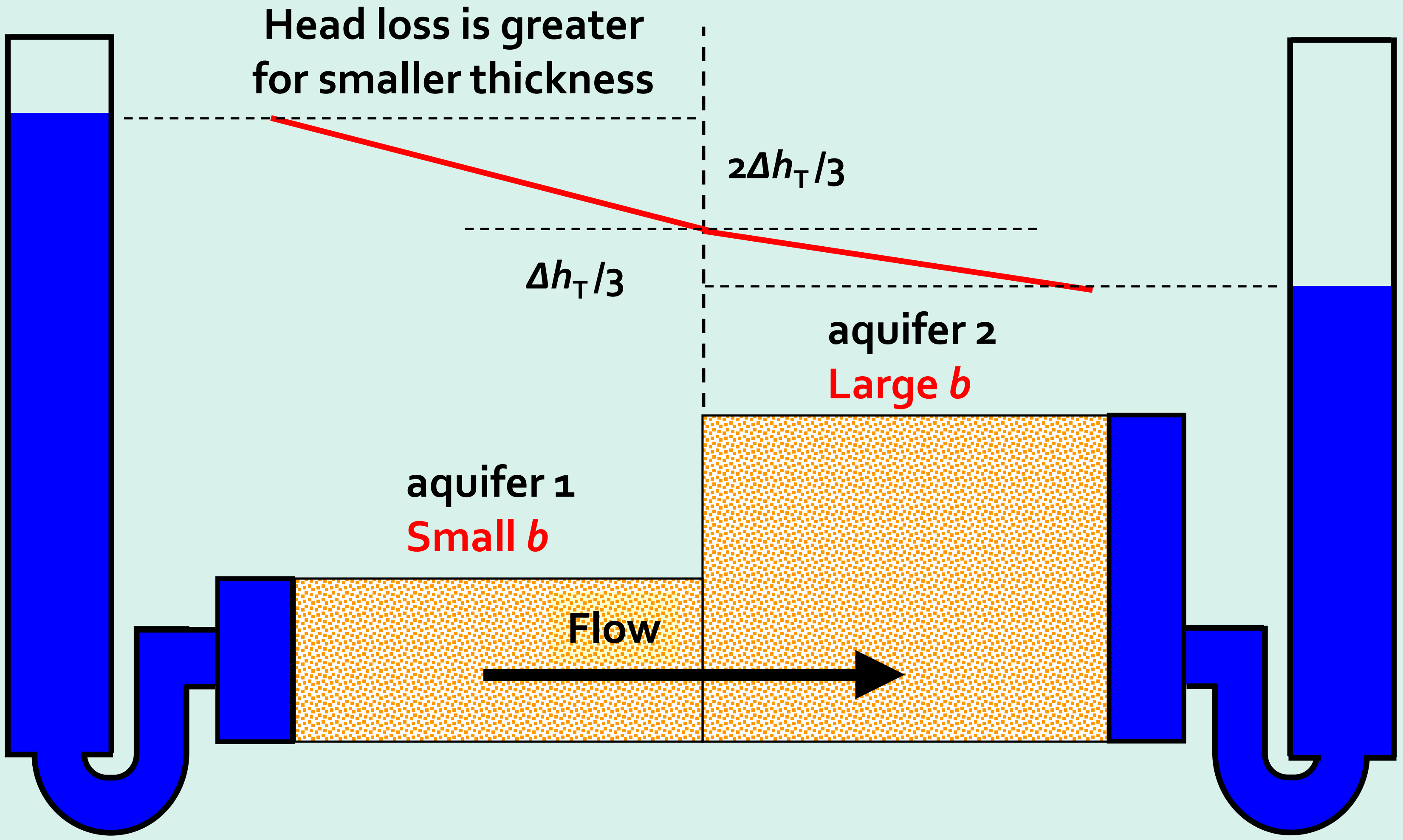
$$\Delta h_T = \Delta h_1 + \Delta h_2 = 2\,\Delta h_2 + \Delta h_2 = 3\,\Delta h_2$$

$$\Delta h_2 = \Delta h_T / 3$$

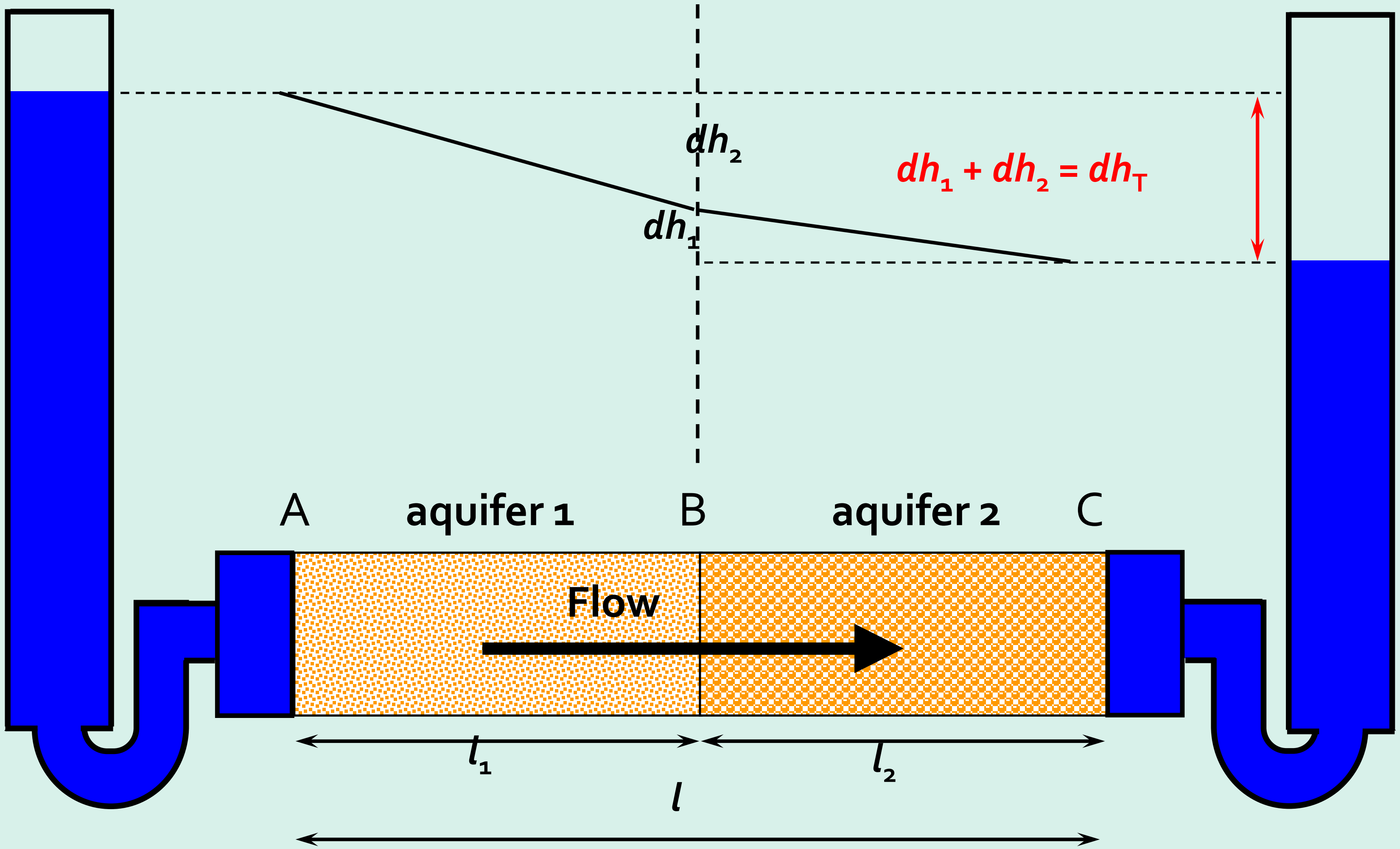
$$\Delta h_1 = 2\,\Delta h_T / 3$$



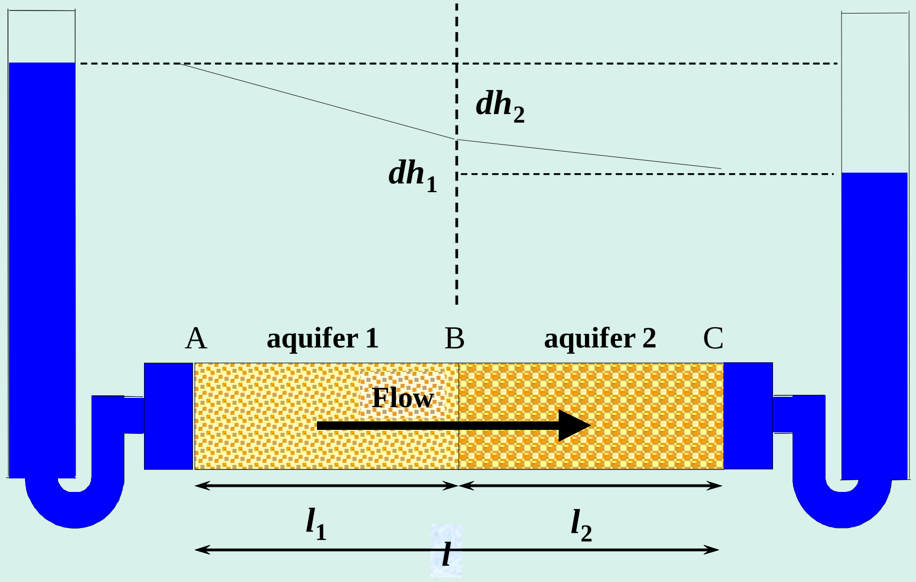
Changes in *b* can cause Changes in Head Gradient



Flow Across Layers – Effective *K*



- **Continuity: $Q_1 = Q_2$**
- **Head: $dh_1 + dh_2 = dh_T$**
- **Flow path: $l_1 + l_2 = l$**
- **Darcy's Law – solve for K_{eff}**



$$Q = K_{eff} A \frac{dh_T}{l} = K_{eff} A \frac{dh_1 + dh_2}{l_1 + l_2}$$

$$K_{eff} = \frac{Q(l_1 + l_2)}{A(dh_1 + dh_2)}$$

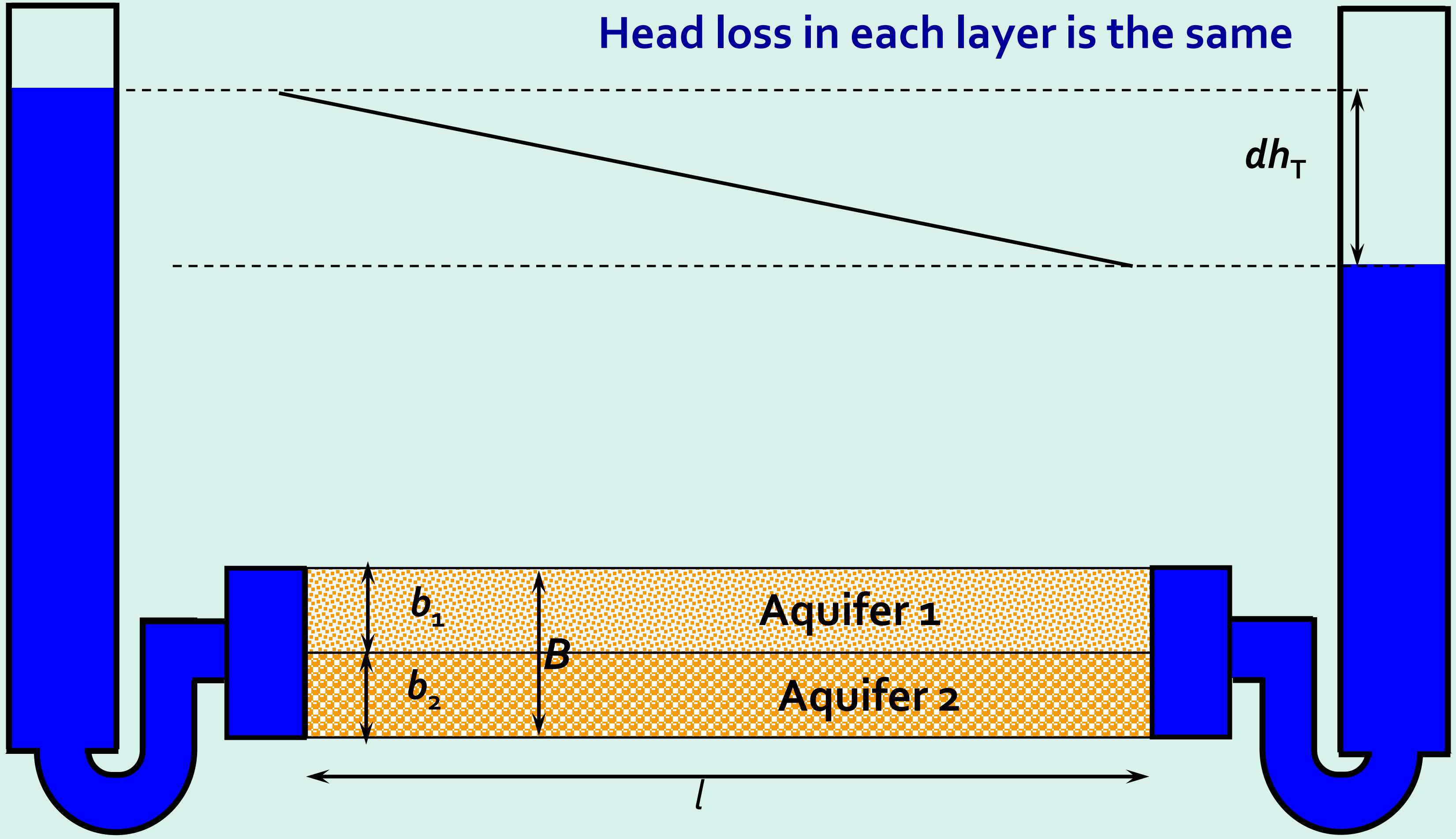
- **Darcy's Law – solve for dh_1 and dh_2**

$$Q = K_1 A \frac{dh_1}{l_1} \qquad dh_1 = \frac{Q l_1}{A K_1}$$

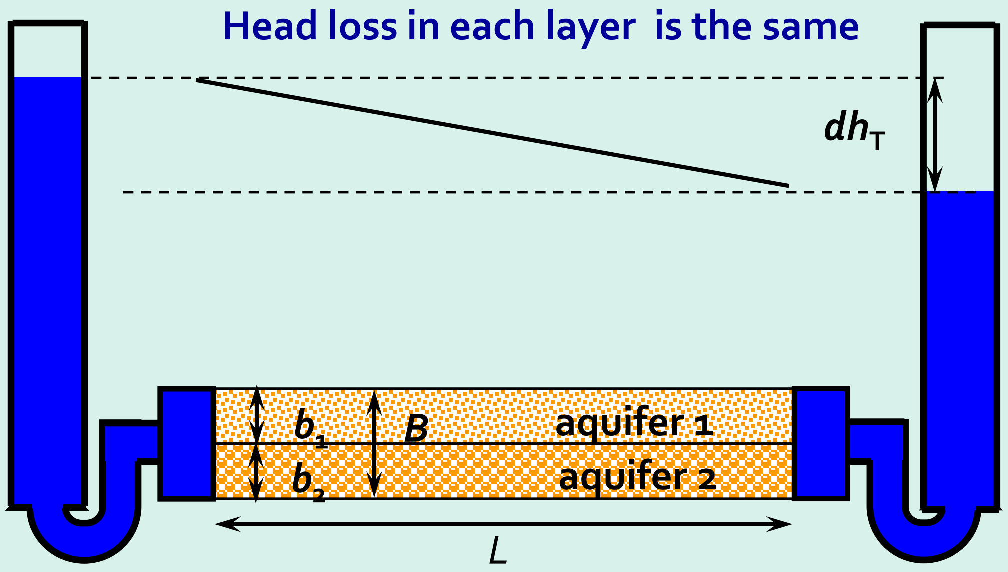
- **Substitute**

$$K_{eff} = \frac{(l_1 + l_2)}{\left[\frac{l_1}{K_1} + \frac{l_2}{K_2}\right]} = \frac{l}{\left[\frac{l_1}{K_1} + \frac{l_2}{K_2}\right]}$$

Flow Along Layers – Effective *K*



- Continuity: $Q_1 + Q_2 = Q_T$
- Head: $dh_1 = dh_2 = dh_T$
- Flow area: $b_1 w + b_2 w = A$
- Darcy's Law – solve for K_{eff}



$$Q_T = K_{eff}(b_1 + b_2)w\frac{dh_T}{L} \qquad K_{eff} = \frac{Q_T L}{(b_1 + b_2)w\,dh_T}$$

- Darcy's Law – solve for Q_1

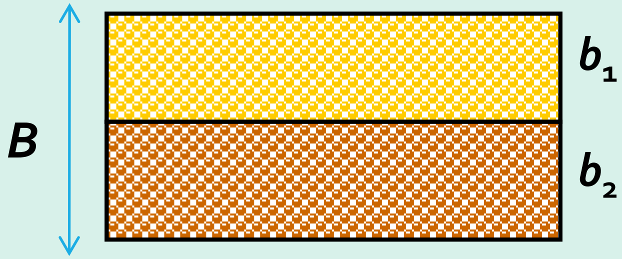
$$Q_1 = K_1 b_1 w \frac{\Delta h_T}{l}$$

- Substitute $Q_1 + Q_2 = Q_T$

$$K_{eff} = \frac{K_1 b_1 + K_1 b_1}{(b_1 + b_2)} = \frac{K_1 b_1 + K_2 b_2}{B}$$

Vertical vs Horizontal *K*

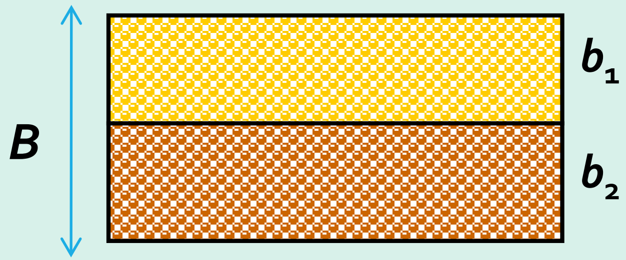
- Vertical flow – across layers
- Horizontal flow – along layers
- Example
  - $K_1 = 1$ and $K_2 = 100$ m/d
  - $b_1 = 2$ and $b_2 = 2$ m
- Find K_{eff} for horizontal and vertical flow



Vertical vs Horizontal *K*

- Vertical flow – across layers

$$K_{eff} = \frac{(b_1 + b_2)}{\left[\frac{b_1}{K_1} + \frac{b_2}{K_2}\right]} = \frac{4}{\left[\frac{2}{1} + \frac{2}{100}\right]} = 1.98\,[\text{m/d}]$$

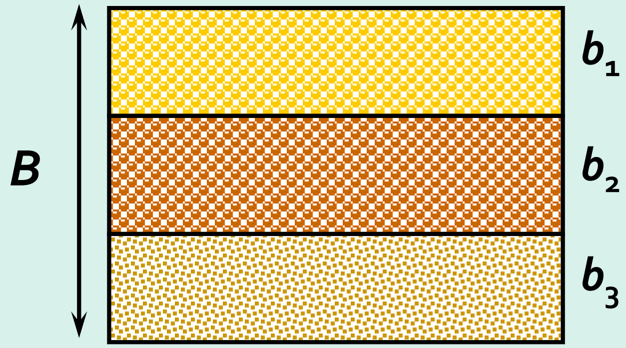


- Horizontal flow – along layers

$$K_{eff} = \frac{K_1 b_1 + K_1 b_1}{(b_1 + b_2)} = \frac{1 \times 2 + 100 \times 2}{4} = 50.5\,[\text{m/d}]$$

Vertical vs Horizontal *K*

- Vertical effective conductivity is dominated by the layer having the lowest *K*
- Horizontal effective conductivity is dominated by the high *K* layer
- Horizontal effective *K* is much larger than the vertical effective *K*



Example: Heterogeneity Assessment

- In an area five field tests are carried out each with transmissivity and storativity coefficients as in Table below. According to 5% relative error definition, the aquifer might be classified into different sets.

1. Is this aquifer homogeneous from storativity point of view?
2. Is it homogeneous from transmissivity point of view?
3. Which group of wells is homogeneous from storativity side?
4. Which group of wells is homogeneous from transmissivity side?
5. Which group of wells is homogeneous from both parameter sides?

Well Number	W1	W2	W3	W4	W5
Storativity ($\times 10^{-3}$)	1.3	2.4	2.75	8.72	2.3
Transmissivity (m^2/day)	136	129	147	70.1	59.8

Example: Heterogeneity Assessment

Solution

For the solution, it is necessary to consider the maximum and minimum parameter values as in Table below.

The relative error percentages are defined herein as the absolute value of difference between the maximum and minimum divided by the maximum and the result multiplied by 100.

The result is the relative error percentage as in the last column of Table below.

Well Number	Max.	Min.	Relative Error (%)
Storativity ($\times 10^{-3}$)	8.72	1.3	85.0
Transmissivity (m^2/day)	147	59.8	60.0

Example: Heterogeneity Assessment

1. Since the relative error is 85%, the aquifer does not have regional storativity homogeneity.
2. Since the relative error is 60%, the aquifer does not have regional transmissivity homogeneity.
3. For this purpose, the following matrix of relative error percentages is prepared for the storage coefficients.

There is only one case less than 5%, which is between W_2 and W_5. So, one can conclude that at 5% relative error levels of W_2 and W_5 have similarities.

	W2	W3	W4	W5
W1	45.8	52.7	85.1	43.5
W2		12.7	72.5	4.2
W3			68.6	15.8
W4				73.6

Example: Heterogeneity Assessment

4. Similar relative error matrix is prepared by taking into consideration the transmissivity pairs.

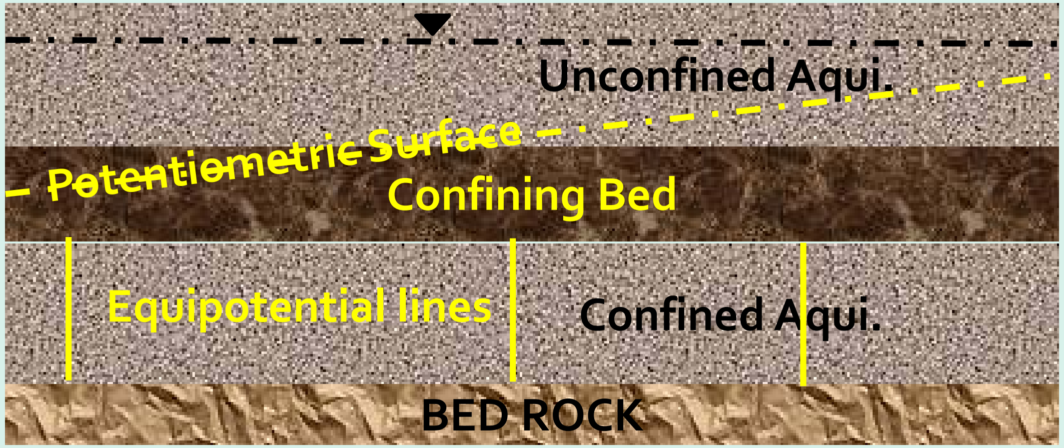
- From transmissivity point of view at 10% level wells W_1, W_2, and W_3 make a homogeneous group.

	W2	W3	W4	W5
W1	5.1	7.5	48.6	56.0
W2		12.2	43.3	50.9
W3			52.3	59.3
W4				14.7

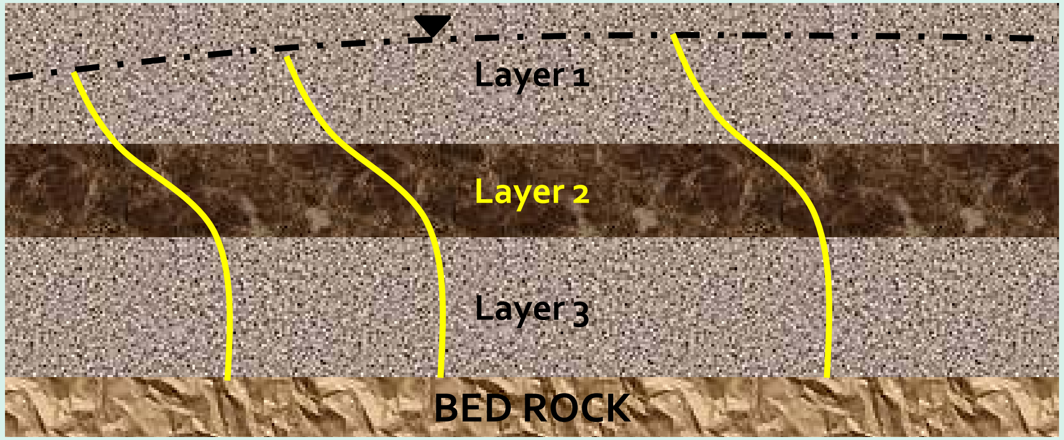
Conceptual views of groundwater

- Two conceptual views of groundwater:
  - Aquifer system view point
  - Flow system view point
- The aquifer view point:
  - Is based on the concept of confined and unconfined aquifers.
  - Is especially suited to analysis of flow to pumping wells
  - Is the basis for many analytical solutions including those of Theim, Theis and Jacob.
  - The groundwater flow assumed to be strictly horizontal through aquifers and strictly vertical through confining beds.
  - Is used to simulate two dimensional horizontal flow.
- In the flow system view point equipotential lines pass through all geologic units, both aquifers and confining beds.

The geologic system



The aquifer System view point



The flow system view point