

Water in the subsurface

(basic concepts)

Water in the subsurface (basic terms)

- ▶ groundwater
- ▶ water table
- ▶ capillary fringe (subsurface layer located above the water table, made of fine pores, where water is held by capillary forces)
- ▶ aquifer (confined / unconfined)
- ▶ aquitard
- ▶ vadose (unsaturated) zone
- ▶ phreatic (saturated) zone

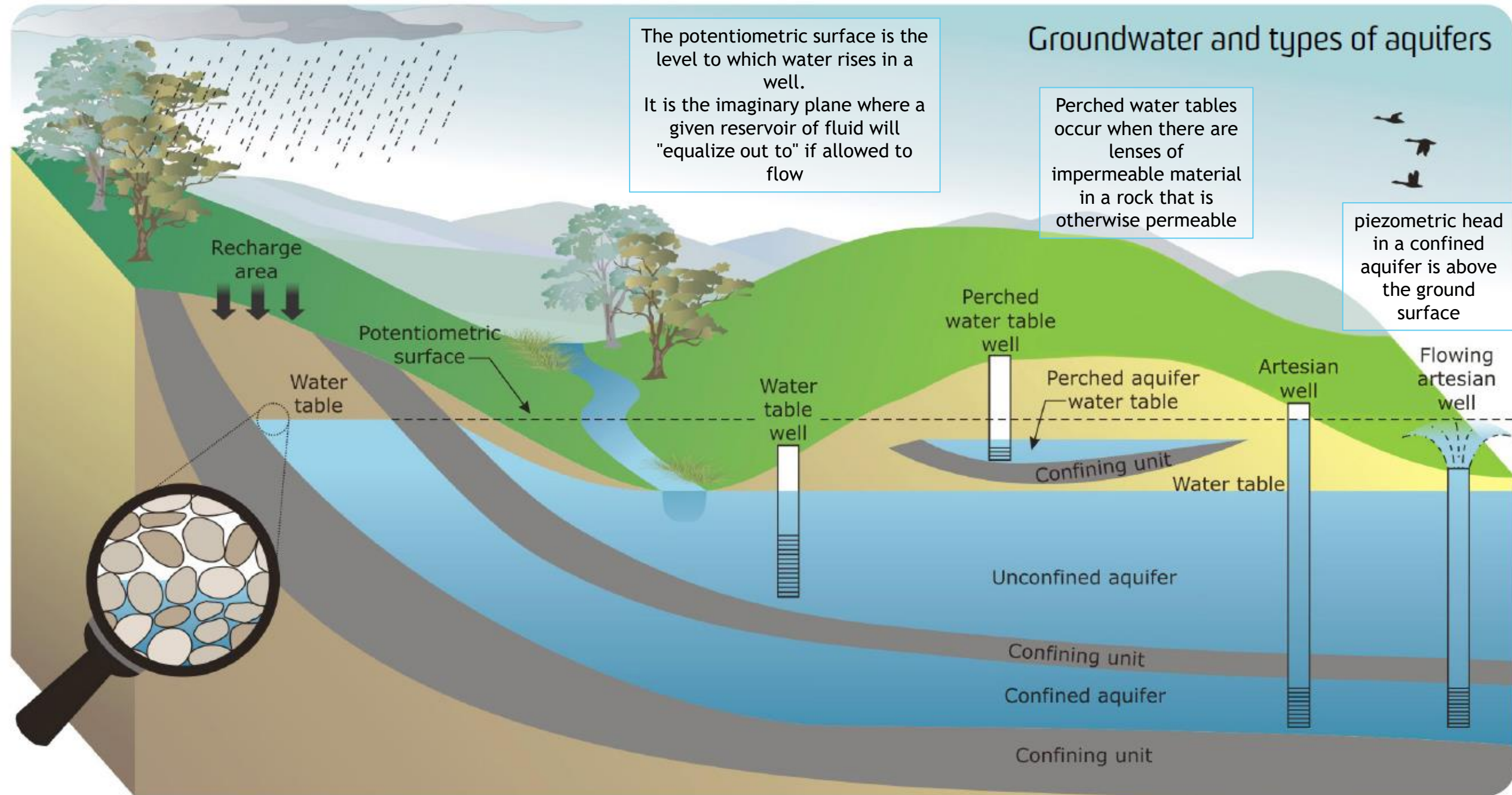
Groundwater and types of aquifers

The potentiometric surface is the level to which water rises in a well.

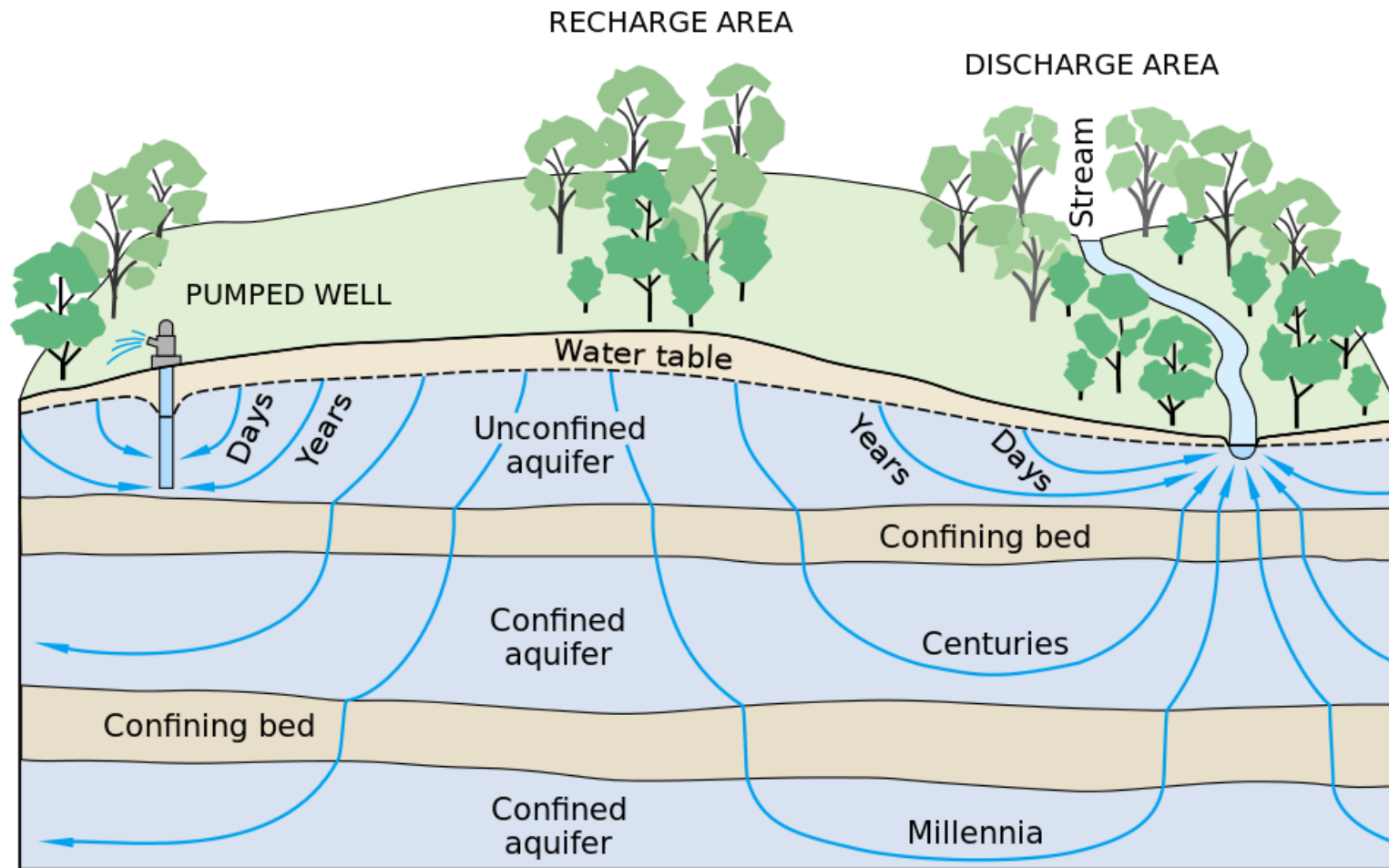
It is the imaginary plane where a given reservoir of fluid will "equalize out to" if allowed to flow

Perched water tables occur when there are lenses of impermeable material in a rock that is otherwise permeable

piezometric head in a confined aquifer is above the ground surface



Time of water movement through the aquifer vary from days up to millennia

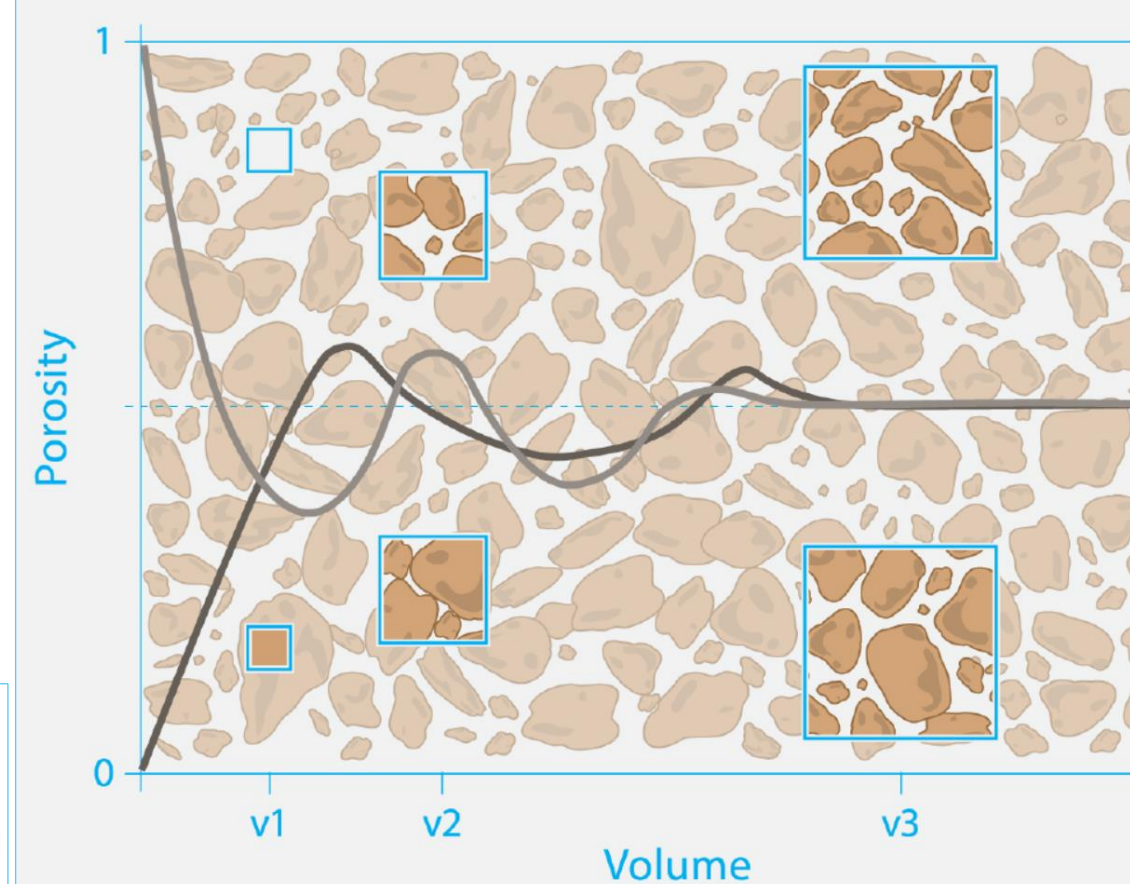
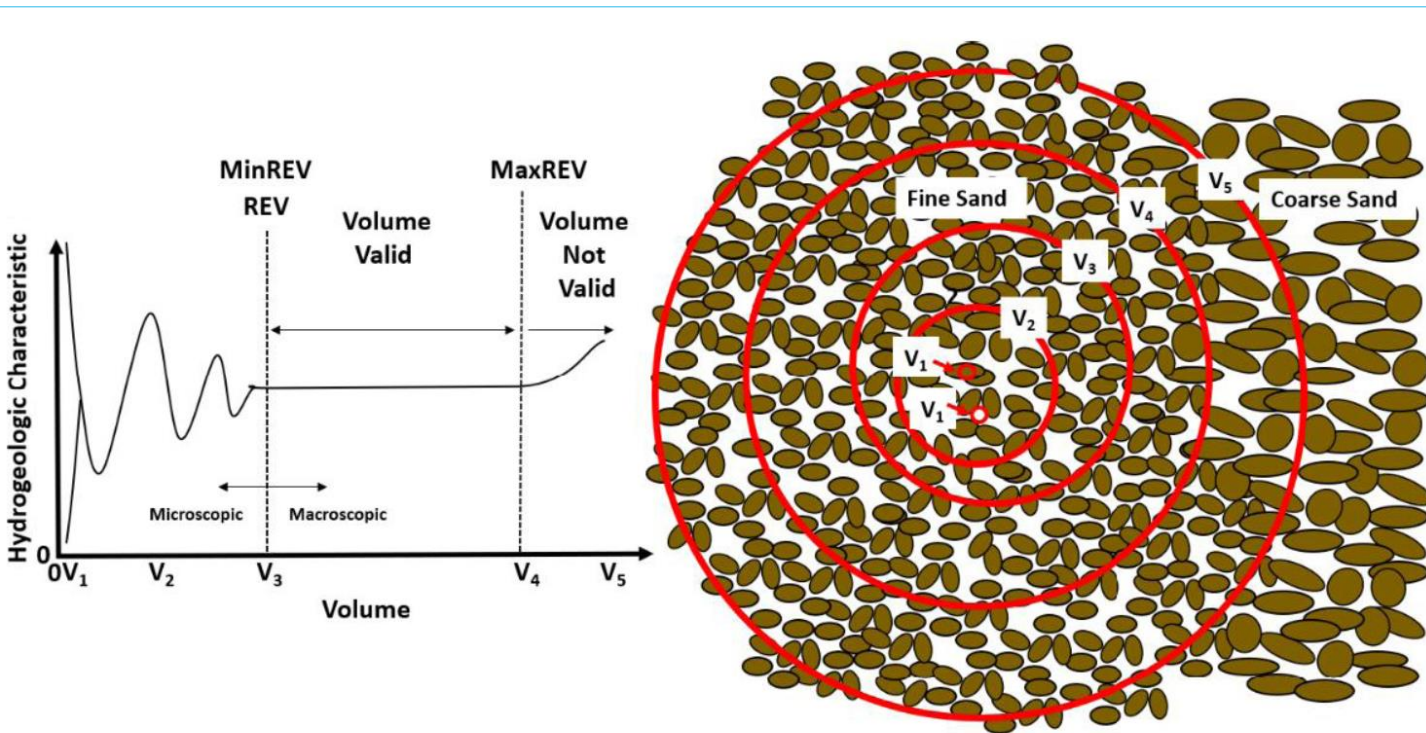


Water in the subsurface (basic terms)

- ▶ recharge: the replenishing of groundwater by rain, rivers, etc. (currently groundwater is being extracted at faster pace compared to recharge)
- ▶ permeability: a measure of the ease with which water can flow through a material; permeability $\leq$ hydraulic conductivity (both terms have been used often as synonyms)
- ▶ potentiometric surface: the level to which water rises in a well
- ▶ confining unit: a layer of low permeability material above a confined aquifer

Water in the subsurface (basic terms)

- ▶ Representative Elementary Volume (REV):
the smallest volume of a porous environment
at which properties are the same as the
properties of whole considered unit



Water in the subsurface (basic terms)

- ▶ total porosity vs. effective porosity; total volume of soil pores include also those that are not connected → from point of water/fluid movement these are useless; effective porosity include only interconnected pores

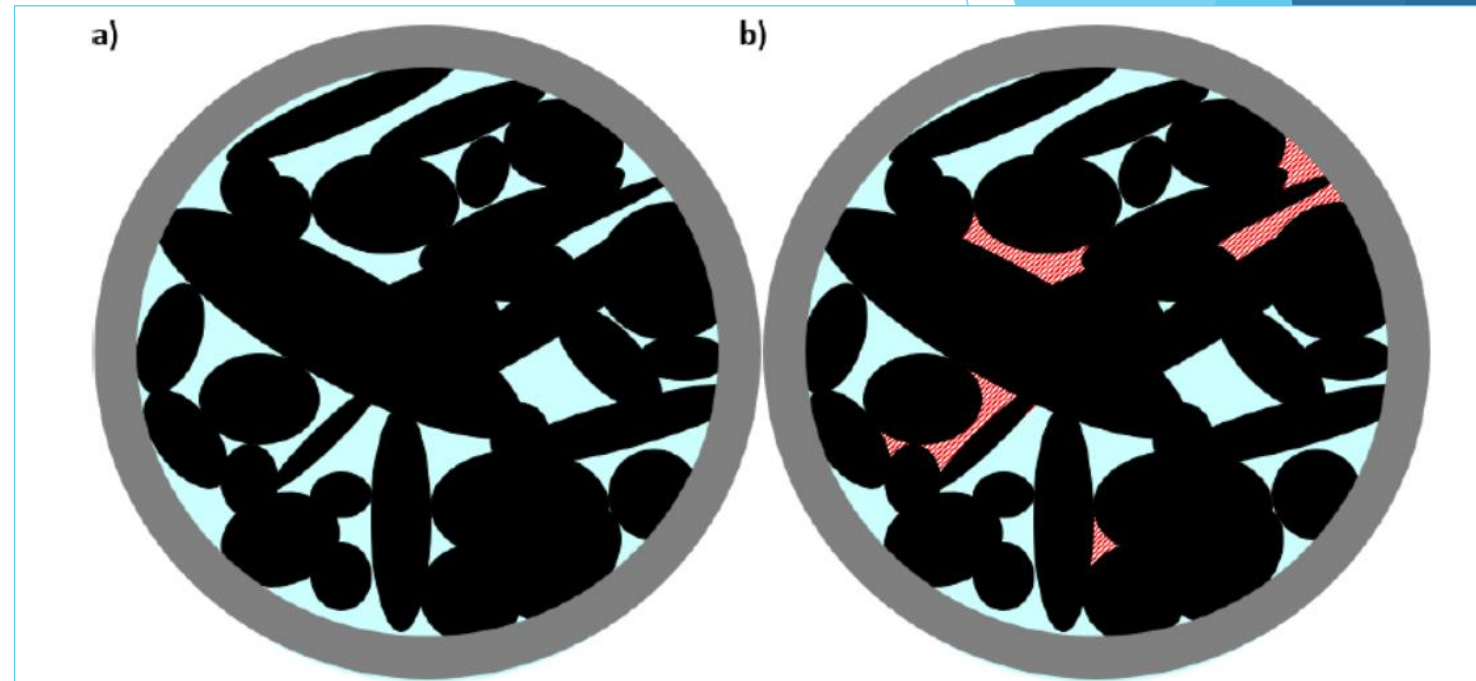


Figure 7 - Relationship between total porosity and effective porosity where the total sample volume, V_T , is represented by the area inside the gray circle. a) Water occupies all pore spaces (light blue spaces, V_V) and the total porosity is $n = V_V/V_T$; b) Some pore spaces are disconnected from other pores (red hatched spaces) and groundwater can only access the connected pore spaces (blue area, V_I), thus effective porosity is $n_e = V_I/V_T$.

Physical parameters of porous environment

Let's say we have 1 kg of moist sample taken in the field with a volume of 0.64 l; after drying at 105°C, the weight is reduced to 0.8 kg; assume that the density of the solid phase (ρ_s) (particles) is 2650 kg/m³; from the given data we can calculate the following:

- ▶ bulk density $\rho_b = M_s/V_t = 0.8 \text{ kg}/6.4 \cdot 10^{-4} \text{ m}^3 = 1250 \text{ kg/m}^3$
- ▶ porosity $f = 1 - \rho_b/\rho_s = 1 - 1250/2650 = 1 - 0.472 = 0.528$ or $f = V_f/V_t = (V_t - V_s)/V_t$
- ▶ void ratio $e = V_t/V_s = (V_t - V_s)/V_s = (6.4 - 3.02) \cdot 10^{-4} \text{ m}^3/3.02 \cdot 10^{-4} \text{ m}^3 = 1.12$
- ▶ mass water content $w = M_w/M_s = (M_t - M_s)/M_s = (1.0 - 0.8) \text{ kg}/0.8 \text{ kg} = 0.25 \rightarrow 25\%$
- ▶ volumetric water content $\theta = V_w/V_t = 2.0 \cdot 10^{-4} \text{ m}^3/6.4 \cdot 10^{-4} \text{ m}^3 = 0.3125 \rightarrow 31.25\%$
($V_w = M_w/\rho_w$ and $\rho_w \approx 1000 \text{ kg/m}^3$)
- ▶ volumetric ratio water/solid phase $v_w = V_w/V_s = 2.0 \cdot 10^{-4} \text{ m}^3/3.02 \cdot 10^{-4} \text{ m}^3 = 0.662$
- ▶ degree of water saturation $s = V_w/(V_t - V_s) = 2.0 \cdot 10^{-4} \text{ m}^3/(6.4 - 3.02) \cdot 10^{-4} \text{ m}^3 = 0.592$
- ▶ volume fraction filled with air $f_a = V_a/V_t = (6.4 - 2.0 - 3.02) \cdot 10^{-4} \text{ m}^3/6.4 \cdot 10^{-4} \text{ m}^3 = 0.216$

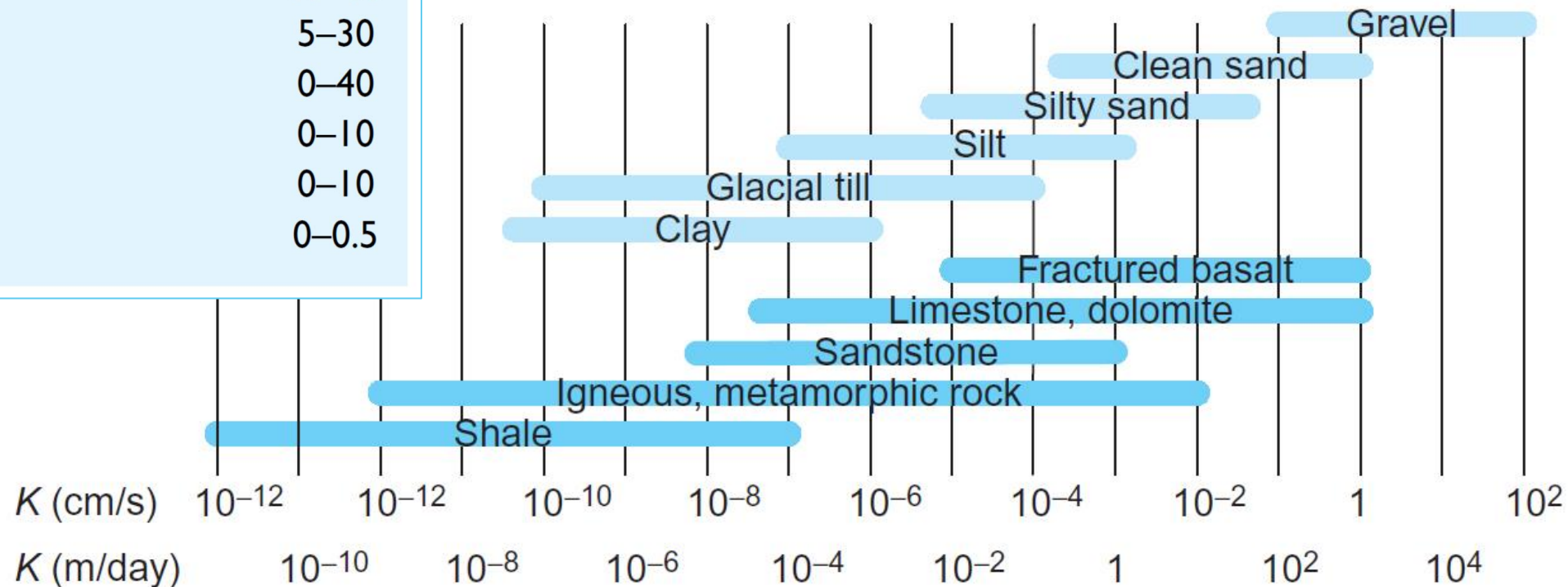
subscripts:
t → total
s → solid
w → water
a → air
f → pores

Water in the subsurface: porosity (n) and hydraulic conductivity (K)

Table 2.2 Typical Values of Porosity

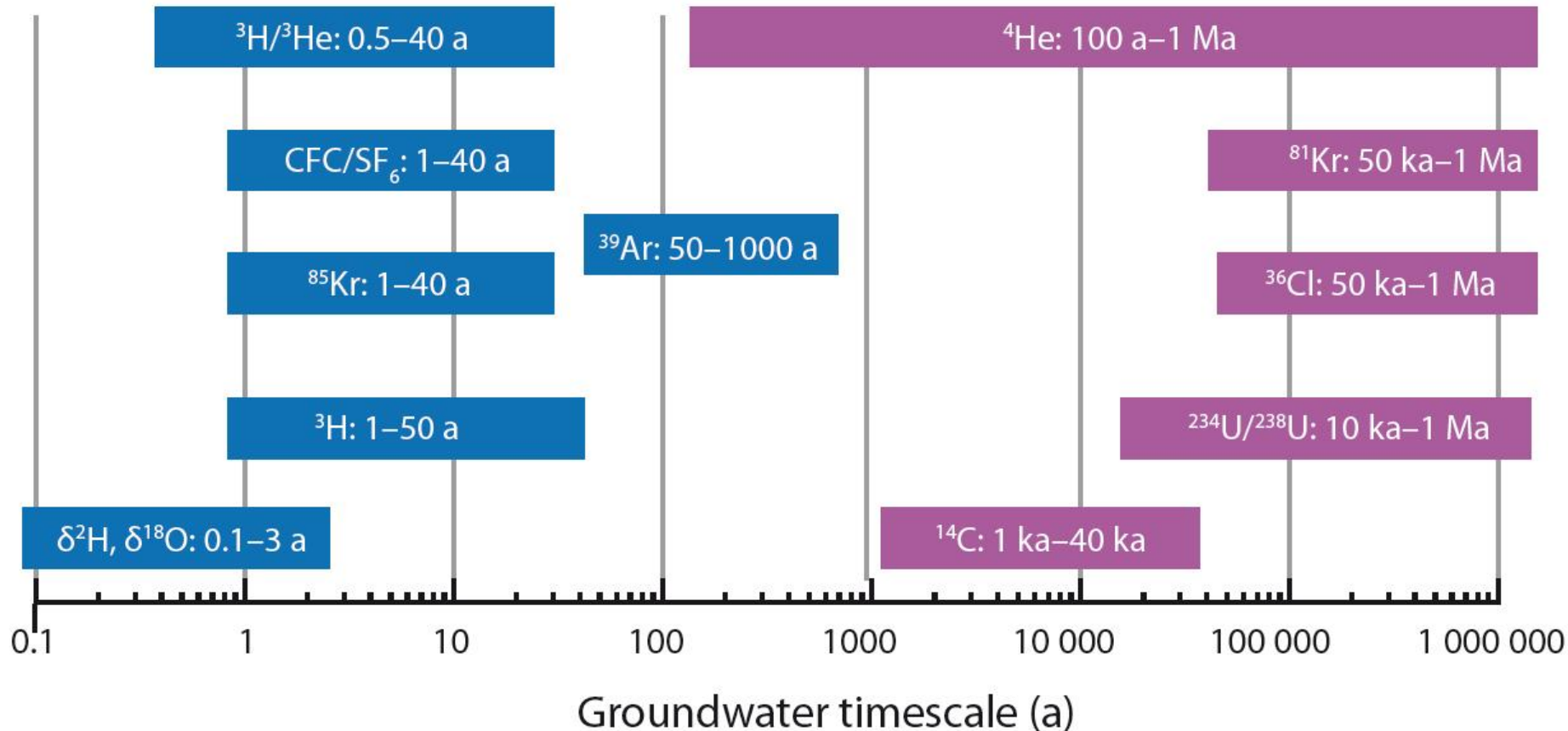
Material	n (%)
Narrowly graded silt, sand, gravel	30–50
Widely graded silt, sand, gravel	20–35
Clay, clay–silt	35–60
Sandstone	5–30
Limestone, dolomite	0–40
Shale	0–10
Crystalline rock	0–10
Massive granite	0–0.5

source: Groundwater Science Charles R. Fitts (2012)

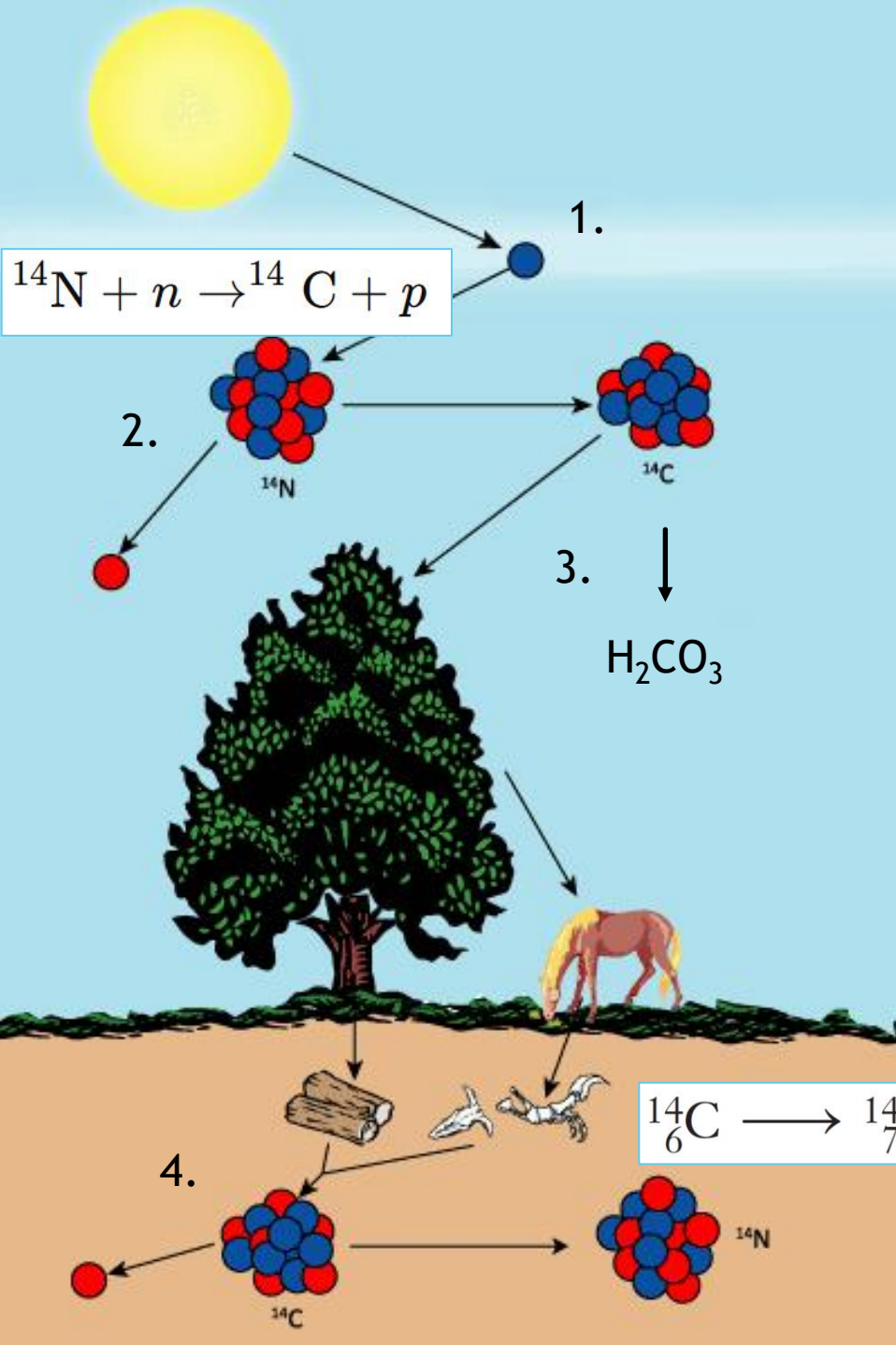


Velocity of water movement in the subsurface

- ▶ how do we distinguish the “old” water from “young” and what this concept means? and how do we know the recharge rates within the aquifers?
- ▶ use of radiometric methods



radiocarbon method (^{14}C dating - principle)



1. interaction of cosmic rays with the atmosphere results in neutron radiation

2. neutrons reacts with ^{14}N nucleus, which releases proton and as a result ^{14}C is formed

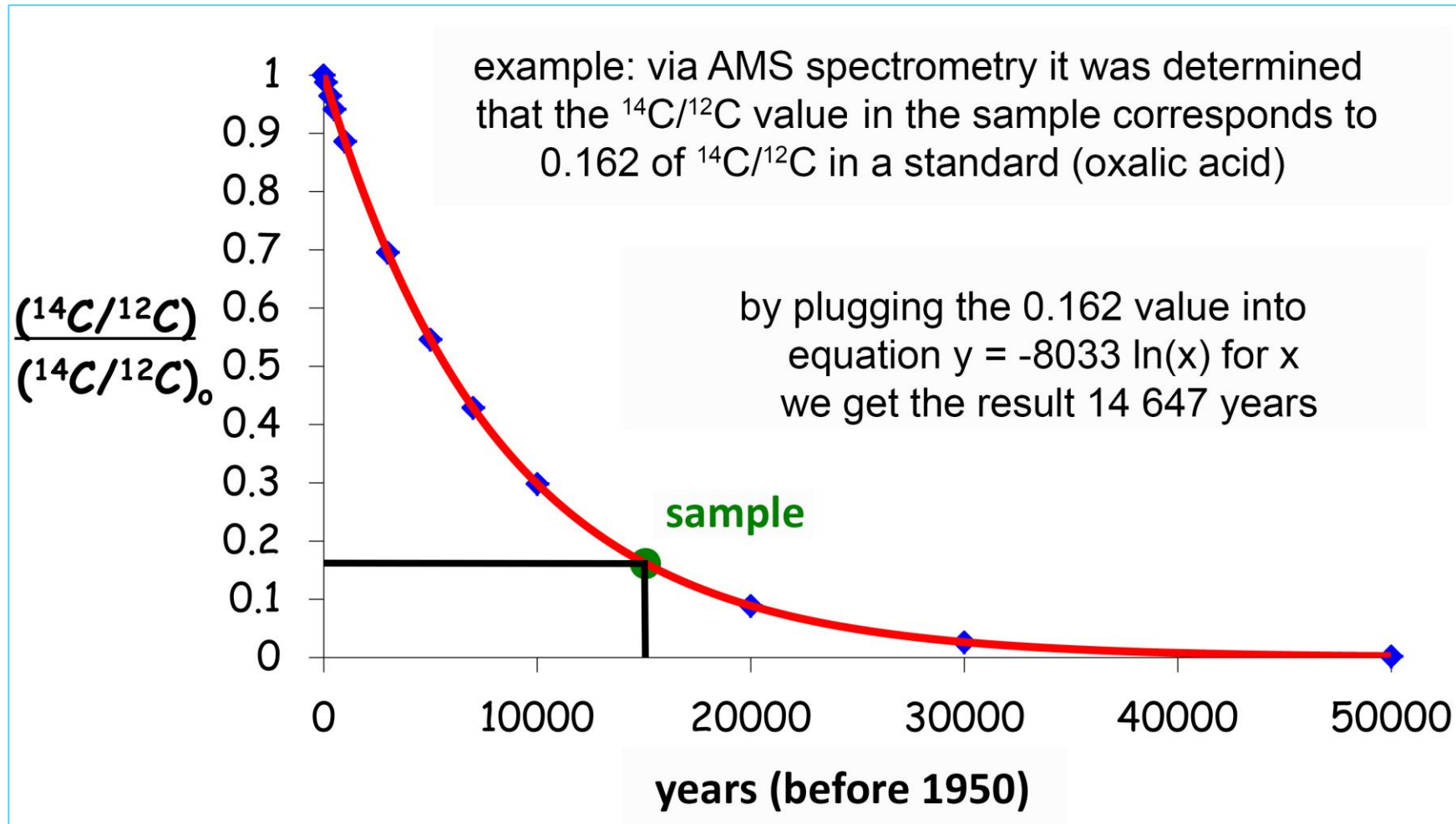
3. ^{14}C bound in CO_2 is being either assimilated by plants via photosynthesis or it reacts with water in atmosphere to form H_2CO_3 which falls on Earth's surface as precipitation

4. ^{14}C bound in CO_2 , organic matter, or carbonate decays/transforms to ^{14}N , which is accompanied by release of antineutrino; as antineutrino is released neutron turns into

The nuclei of ^{14}C are radioactive and decay with a half-life of $5,700 \pm 30$ years

Radiometric methods

▶ radiocarbon (^{14}C) dating



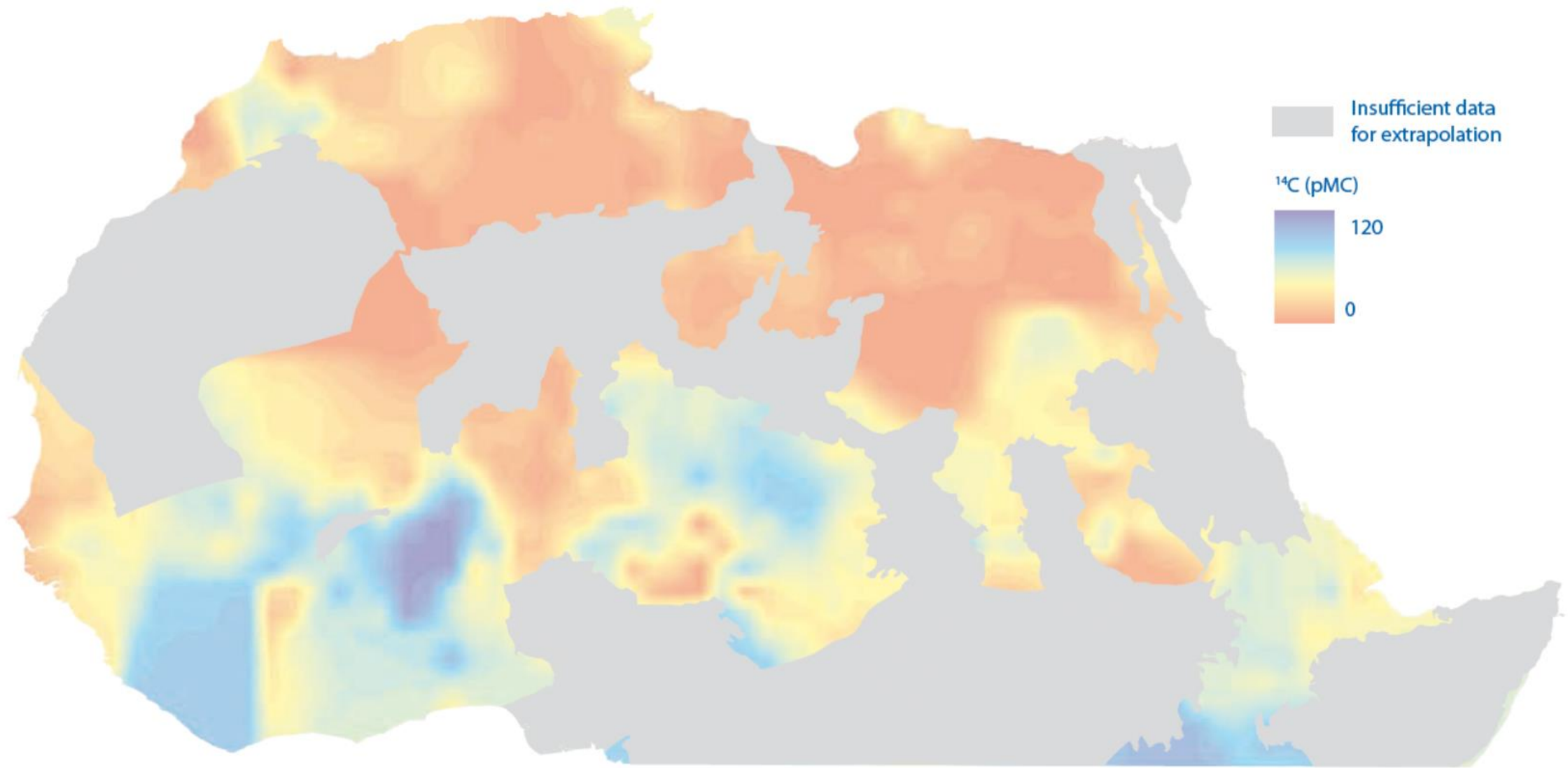
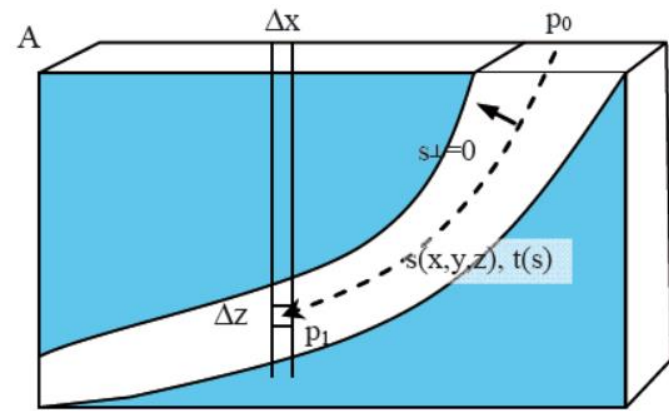


FIG. 1.2. Distribution of ^{14}C in groundwater in northern Africa.

source: Isotope methods for dating old groundwater. 2013, International Atomic Energy Agency.

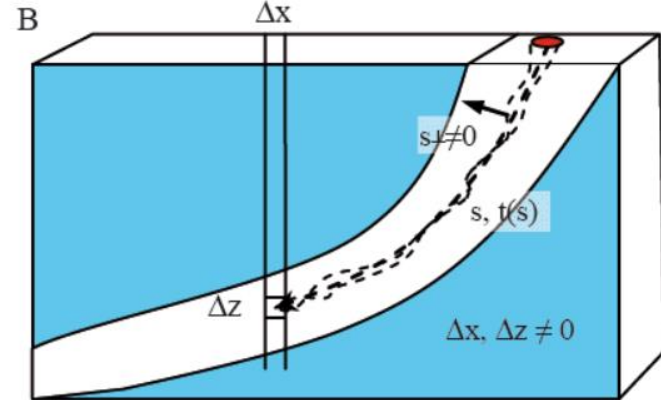
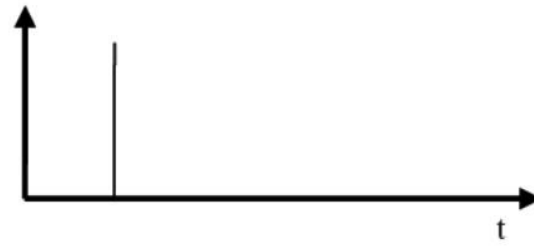
Groundwater dating - levels of complexity:

- what if the groundwater at position (x,y,z) was under the influence of dispersive mixing?
- what if the groundwater arrived at position (x,y,z) via flow from two (or more) similar but not identical entryway sources?
- how does multicomponent mixing impact the interpretation of an 'idealized groundwater age'?

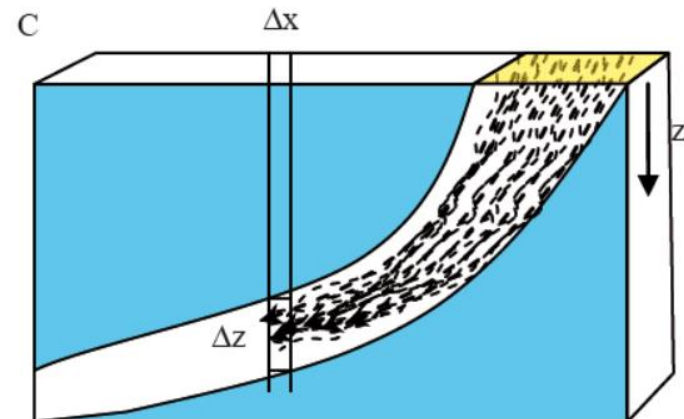
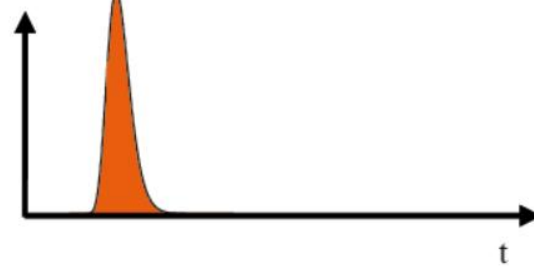


Idealized groundwater age A_{id}

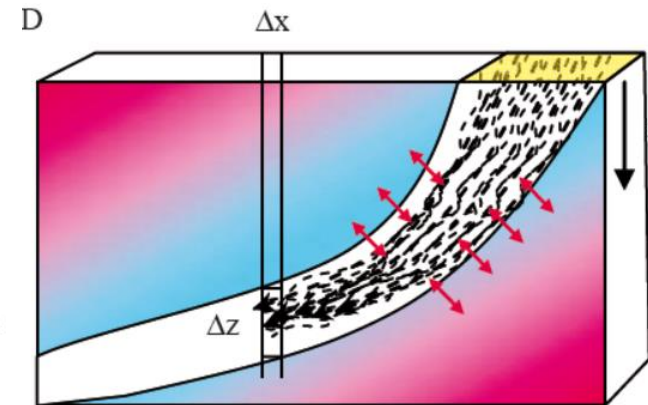
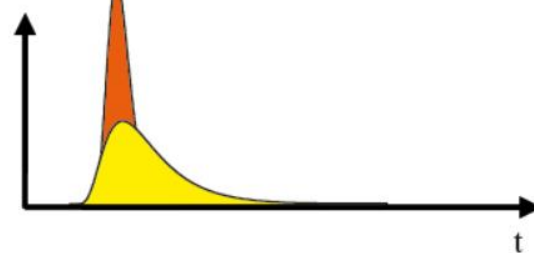
$$\lim_{\Delta z \rightarrow 0, \Delta x \rightarrow 0} \Delta t(p_1 - p_0) = A_{id}$$



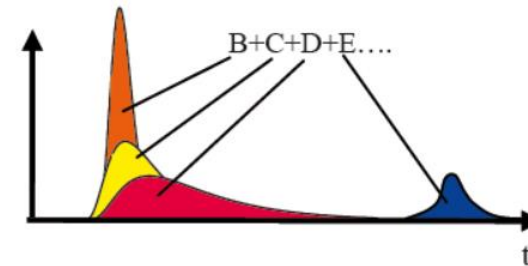
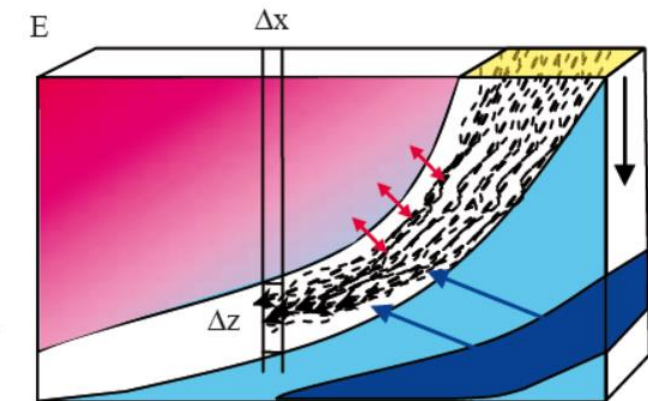
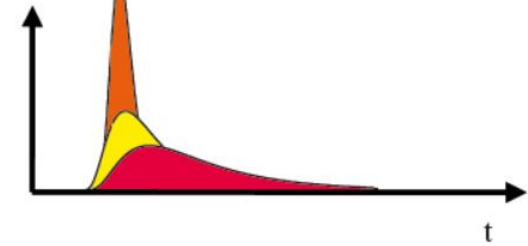
Frequency distribution of idealized groundwater ages



Frequency distribution of idealized groundwater ages

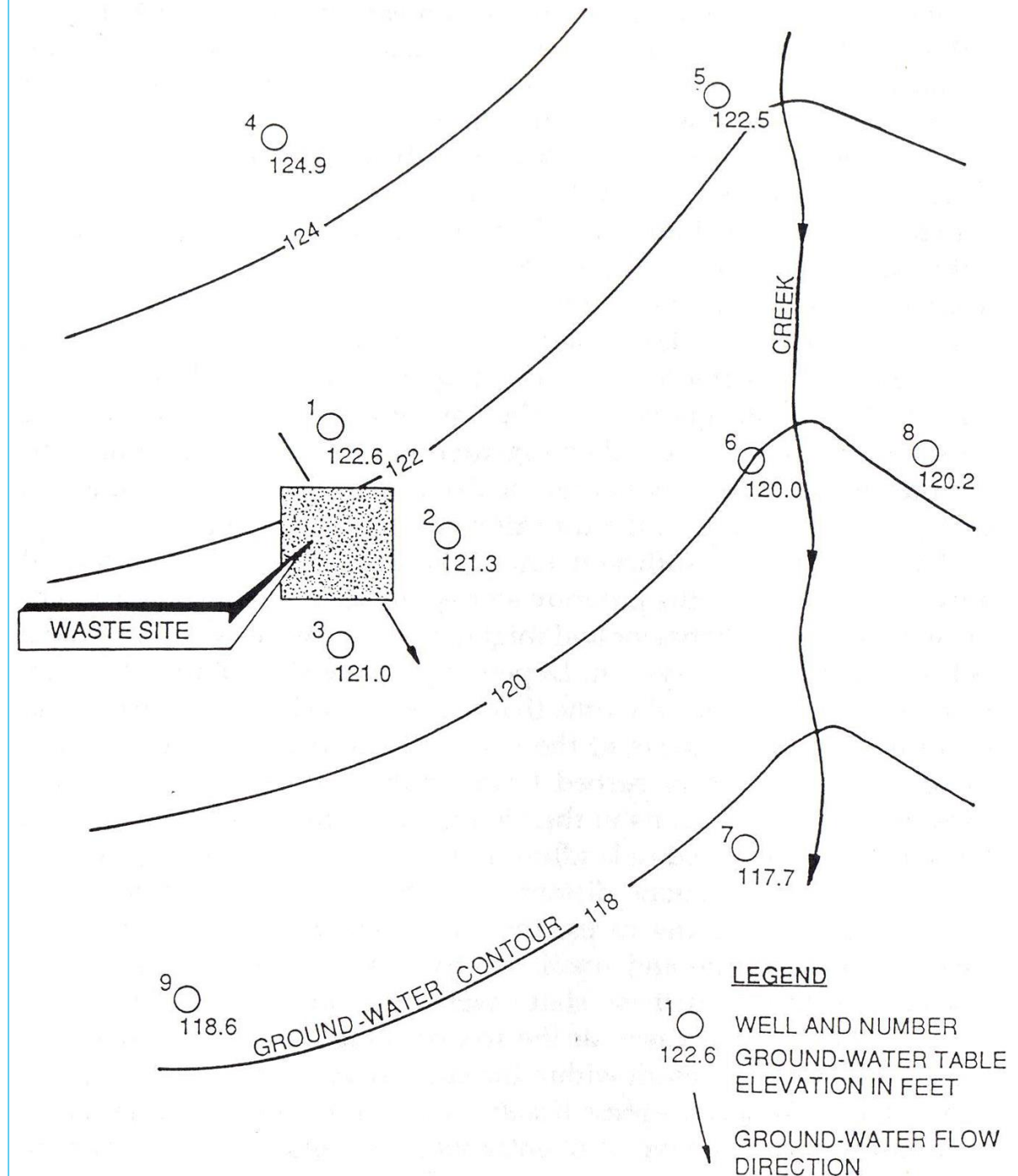


Frequency distribution of idealized groundwater ages



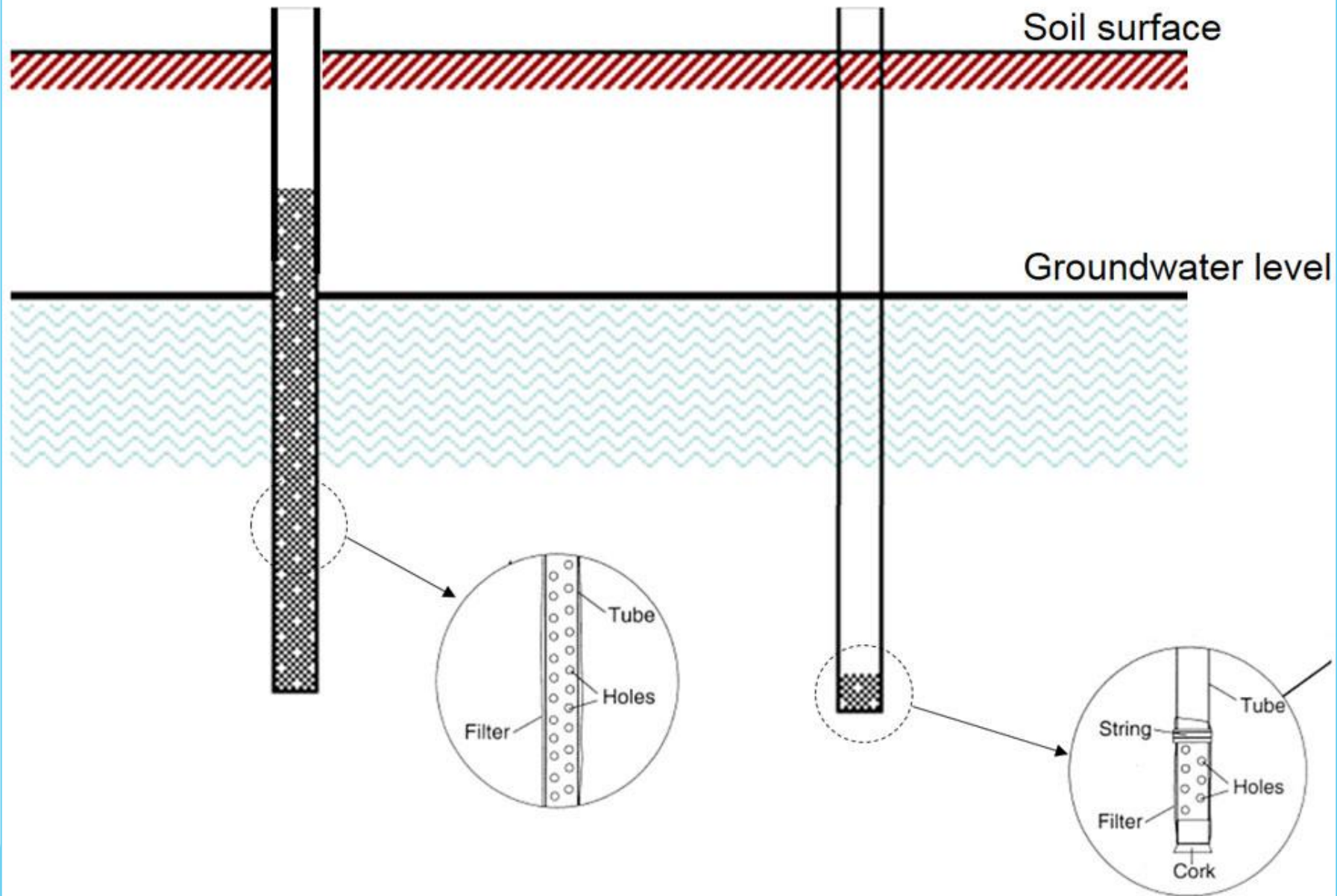
Similarly as in case of other geospatial data, location (depth) of water table may be visualized by contours / isolines

direction of water flow:
higher hydraulic head $\rightarrow$ lower hydraulic head



Observation well

Piezometer



Water in the subsurface (energy and hydraulic head)

- ▶ Water flows from one place to another in response to uneven distributions of mechanical energy within the water body
- ▶ Water always flows from regions with higher mechanical energy towards regions with lower mechanical energy
- ▶ The mechanical energy in water can take on three forms:
 1. Elastic potential energy (is gained by compressing water)
 2. Gravitational potential energy (is achieved by lifting water to higher elevation)
 3. Kinetic energy (stems from the velocity of water)
- ▶ This is implemented in Bernoulli equation, which describes the mechanical energy E of water (in $J = kg\ m^2/sec^2 = Nm$) with mass m , pressure P , elevation z , volume V , and velocity v

$$E = PV + mgz + \frac{1}{2}mv^2$$

Water in the subsurface (energy and hydraulic head)

- ▶ the energy predicted by Bernoulli eq. can be thought of as the work required to compress, elevate, and accelerate a mass m of water to its current state from a reference state where $P = z = v = 0$
- ▶ similar/analogous eq. form of the energy equation is the energy per mass of water, a quantity termed the fluid potential ϕ by Hubbert (1940):
- ▶ for analysis of water flow, a more convenient parameter is energy per weight of water. Taking eq. on the right and dividing each term by the weight of water mg gives a new quantity called the hydraulic head h :

$$\begin{aligned}\phi &= \frac{E}{m} \\ &= \frac{P}{\rho_w} + gz + \frac{v^2}{2}\end{aligned}$$

$$h = \frac{E}{mg} = \boxed{\frac{P}{\rho_w g}} + \boxed{z} + \boxed{\frac{v^2}{2g}}$$

pressure head

elevation head

velocity head

Water in the subsurface (basic terms)

- ▶ **hydrostatics:** deals with the characteristics of water at rest
- ▶ **hydrodynamics:** water movement

- hydrodynamics, in contrast, studies fluids in motion; it deals with kinetic energy, momentum, and flow
- example of equation (Bernoulli) relevant in this regard:

$$\frac{P}{\rho g} + \frac{v^2}{2g} + z = \text{constant along a streamline}$$

- shows how pressure energy (potential), kinetic energy, and gravitational potential energy are interconverted as water moves
- it involves both kinetic and potential energy, but focuses on their interaction and transformation in motion

- hydrostatics is primarily concerned with potential energy and how it manifests as pressure distribution in fluids at rest
- the key concept is pressure variation due to gravity, which is directly linked to potential energy.
- the concept is implemented in equation:

$$\frac{dP}{dz} = -\rho g$$

- P is pressure, ρ is fluid density, g is gravitational acceleration, and z is elevation

Water in the subsurface (properties and processes)

- ▶ spatial and temporal variability of the properties in porous system creates difference(s) in water potential → water flow
- ▶ porosity (effective porosity)
- ▶ hydraulic head
- ▶ degree of water saturation
- ▶ water conductivity:
 1. saturated: stable in time, may change in space based on aquifer parameters; significantly controlled by effective porosity (pores that are connected from hydraulic viewpoint)
 2. unsaturated: variable, characteristic for soils and vadose zone in general

In groundwater systems, water moves because of differences in hydraulic head (h), which is a measure of energy per unit weight of water

$$h = z + \frac{P}{\rho g}$$

z is elevation head (gravitational potential energy), $P/(\rho g)$ pressure head (pressure potential energy)

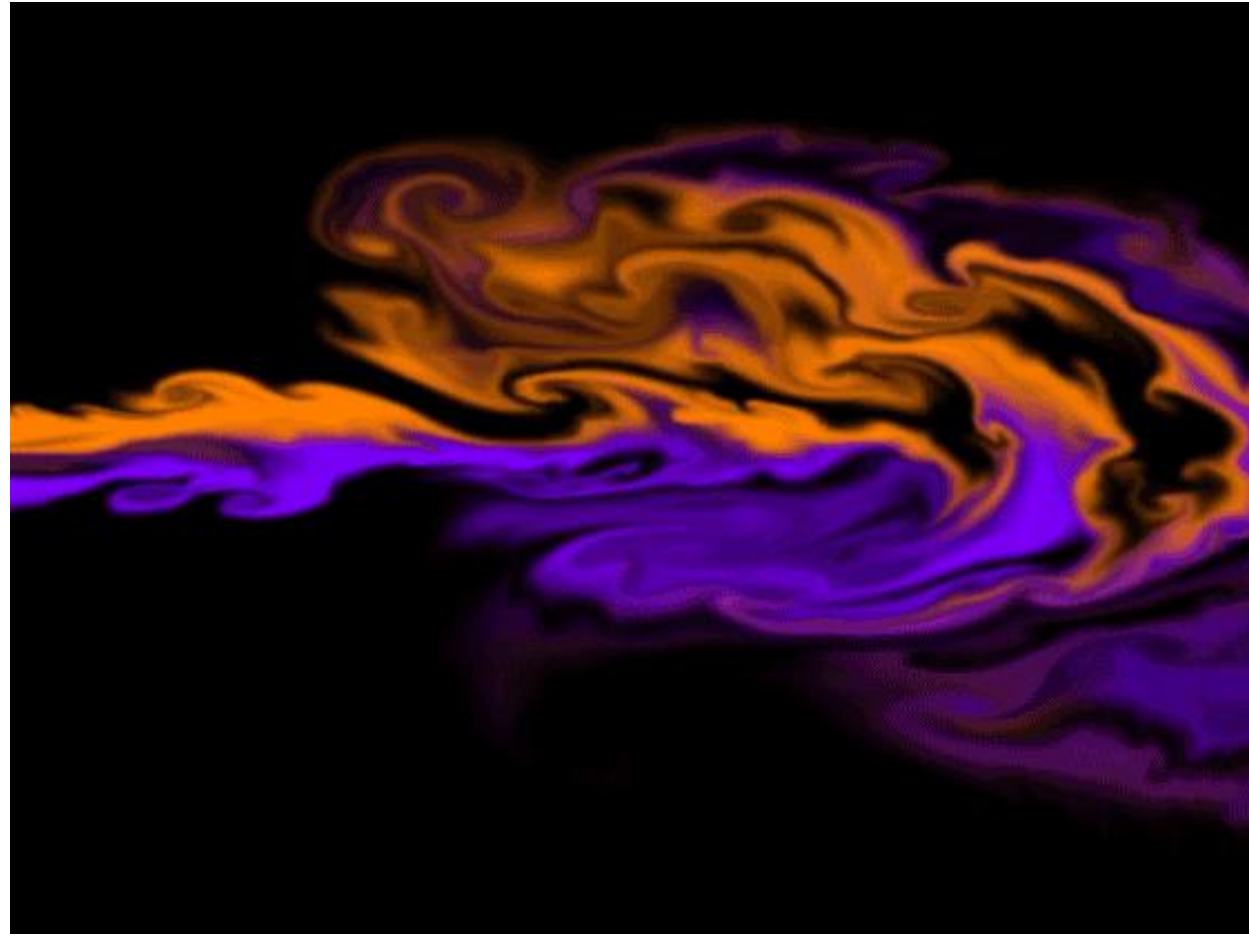
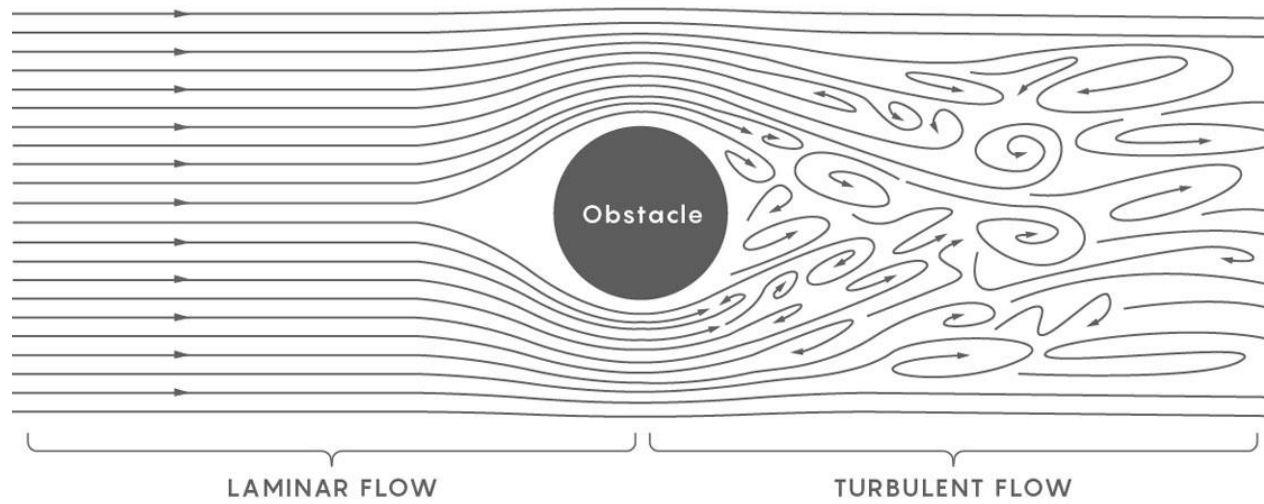
Water flows from higher total potential energy (head) to lower total potential energy (head).

The kinetic energy term in groundwater flow is usually negligible (because flow velocities are very small), but the gradients in potential energy indeed drive the motion.

Water in the subsurface - water flow

- ▶ laminar → in straight tubes with smooth surface (straight flow direction and stable velocity)
- ▶ turbulent → when an abrupt change in hydraulic (water potential) gradient occurs; velocity and flow direction varies over relatively short distances

turbulent flow:

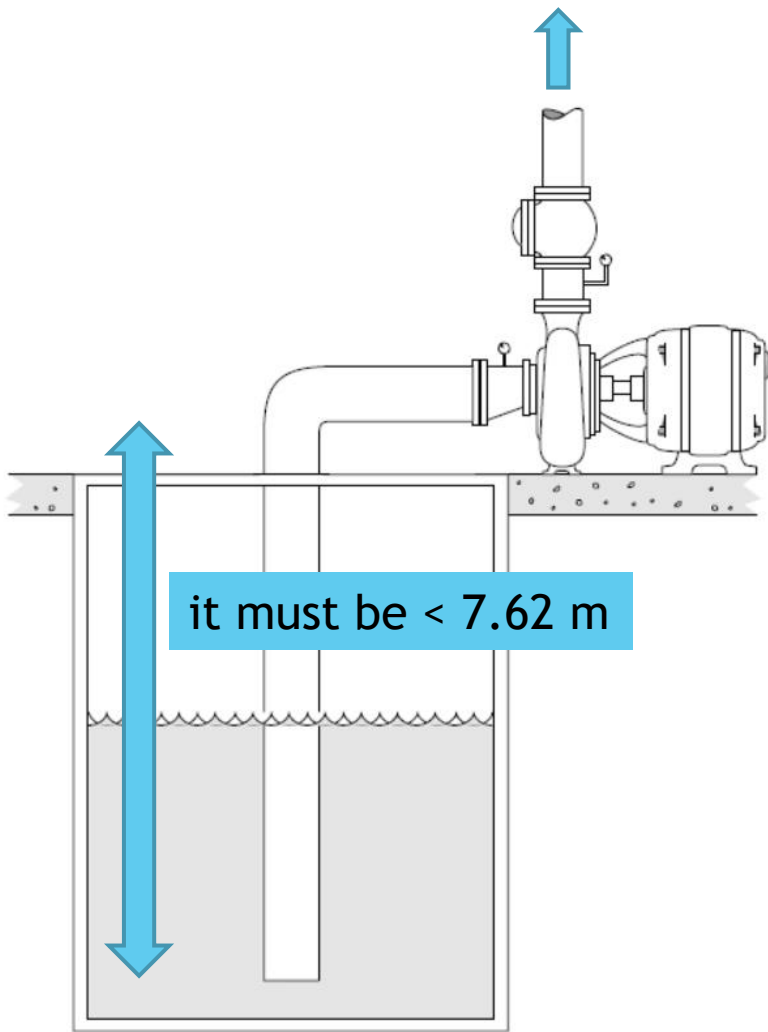


Water in the subsurface - effect of scale

- ▶ smaller scale (mm to m) → effect of capillary and osmotic forces is important
- ▶ larger scale ($> m$) → effect of gravity become very significant; thermal gradient of Earth's heat affect water movement at large scales

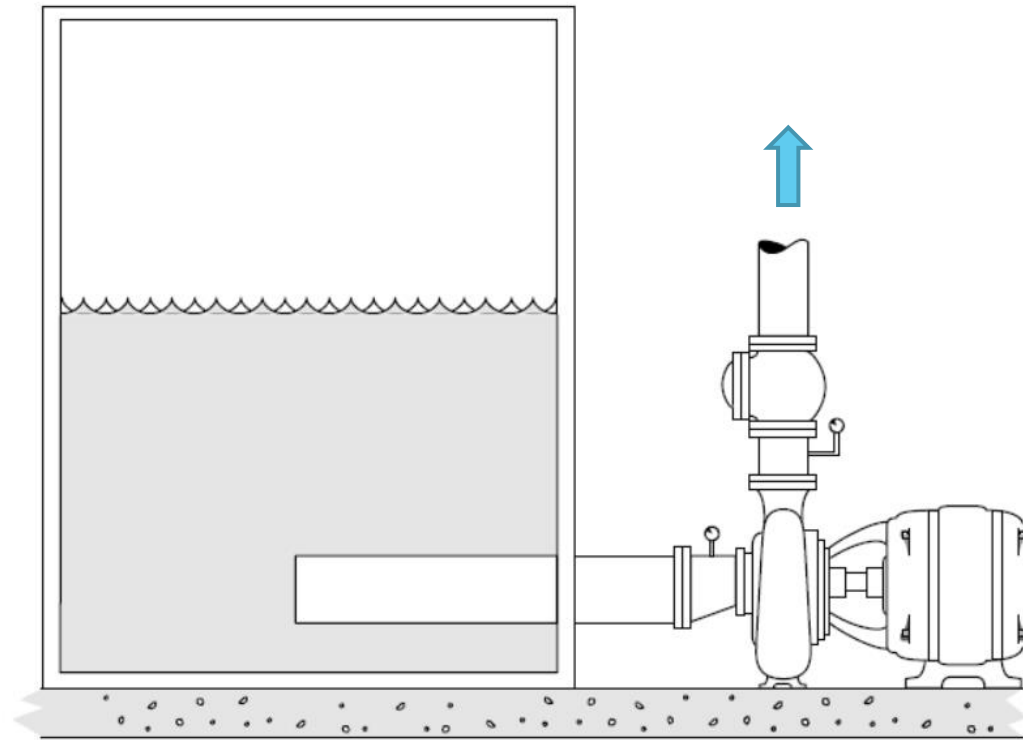
Pumping systems (general info)

- ▶ priming → filling the pump with water; otherwise, pump will not work
- ▶ a suction can lift water to a theoretical maximum of 9.75 m; the practical depth limit for suction pumps is however even smaller ≈ 7.62 m
- ▶ if we want to overcome the 7.62 m level (transport the water from depth > 7.62 m), the pump must be located at the bottom of the well or water reservoir → “push” water upwards (instead of “pulling it from above”)
- ▶ cavitation: the condition occurring in centrifugal pumps, where vapor bubbles are formed in a flowing liquid when the pressure of the liquid falls below its vapor pressure; once the bubbles reach an area where the pressure is above vapor pressure, the bubbles collapse thereby creating small areas of high temperature and emitting shock waves; cavitation is undesirable because it can damage the impeller, cause noise and vibrations, and decrease pump efficiency.



it must be < 7.62 m

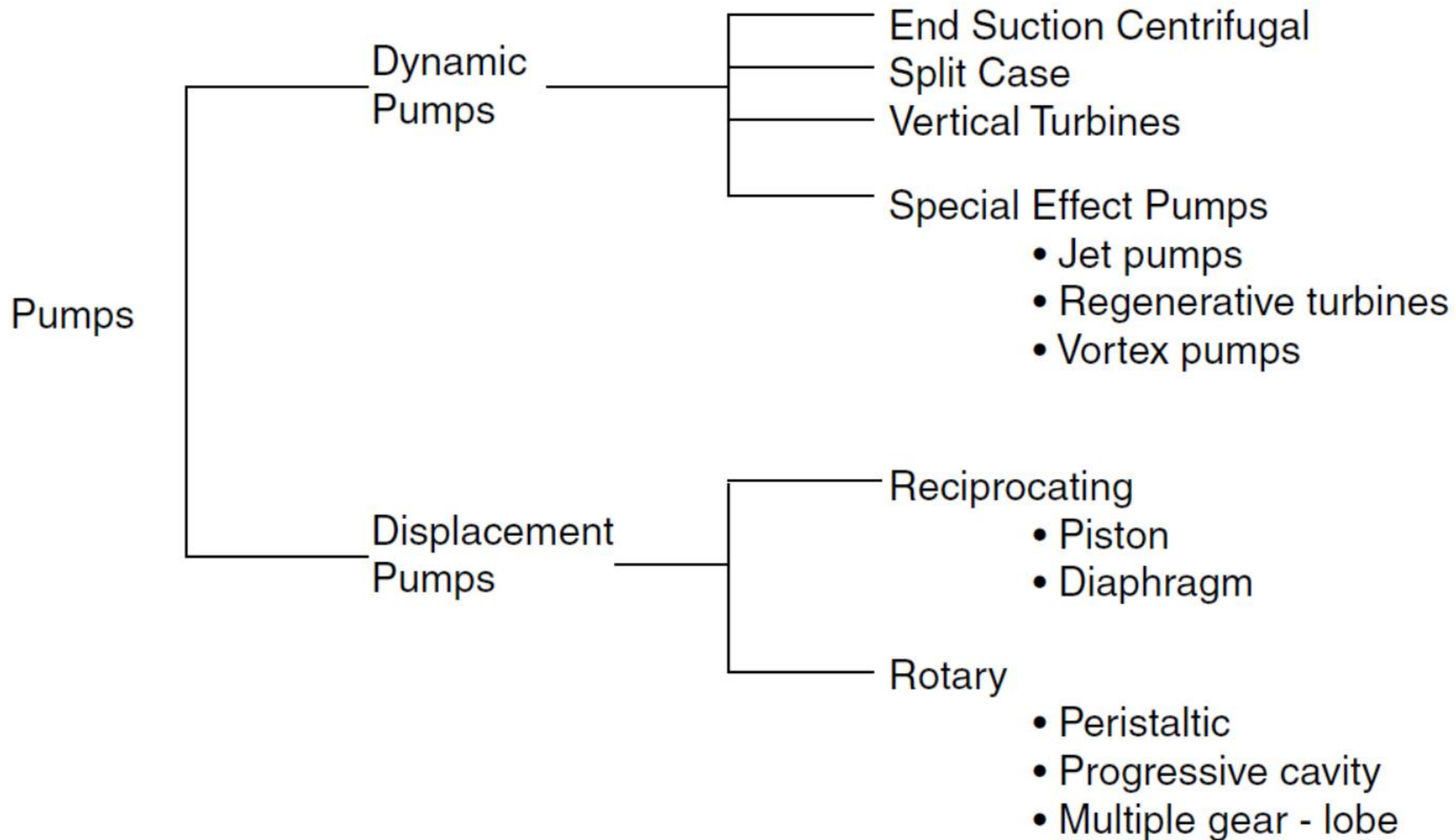
Suction lift



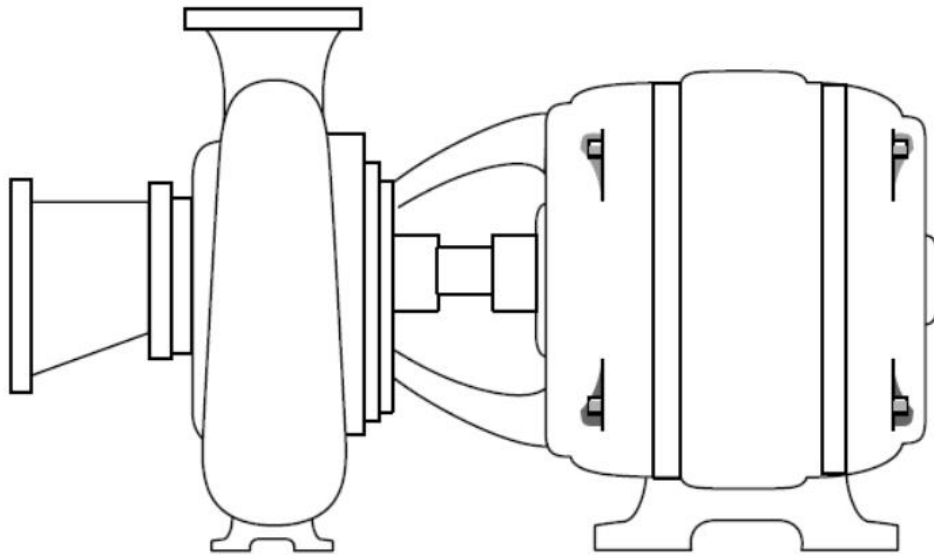
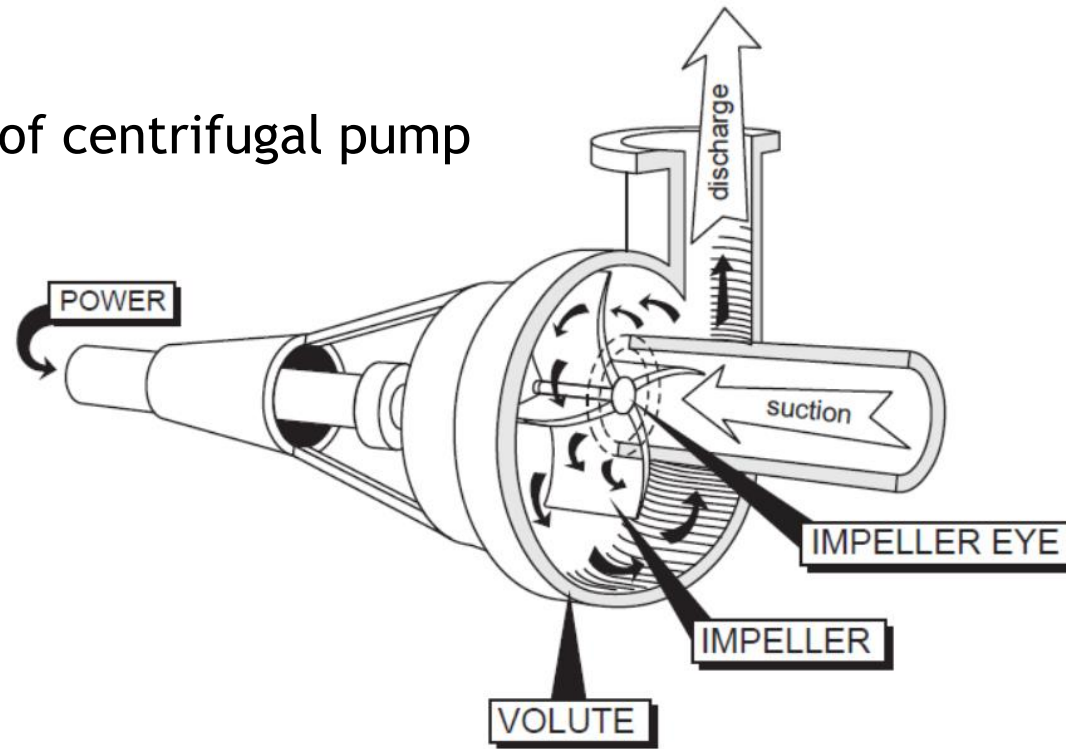
Suction head

Pumps (types)

- ▶ dynamic pumps: transport large volumes in situations where change in flow rate is not a problem; as the discharge pressure on a pump is increased, quantity of pumped water is decreased, an example is the centrifugal pump (frequently used type)
- ▶ displacement pumps: relatively small but precise volumes are transported; will not change pumped volume with change in discharge pressure; examples: diaphragm pump or peristaltic



general scheme of centrifugal pump



End suction centrifugal

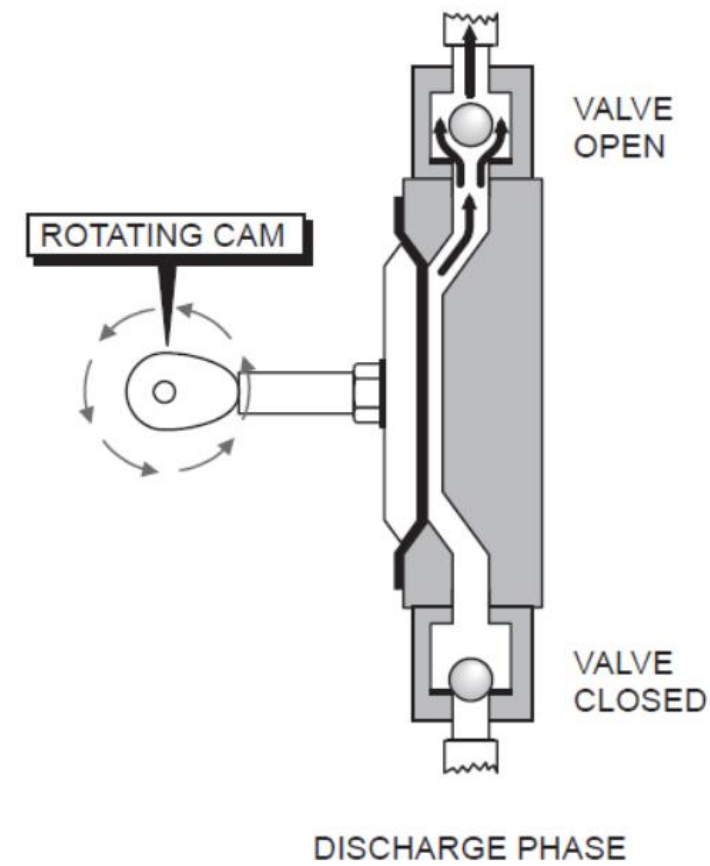
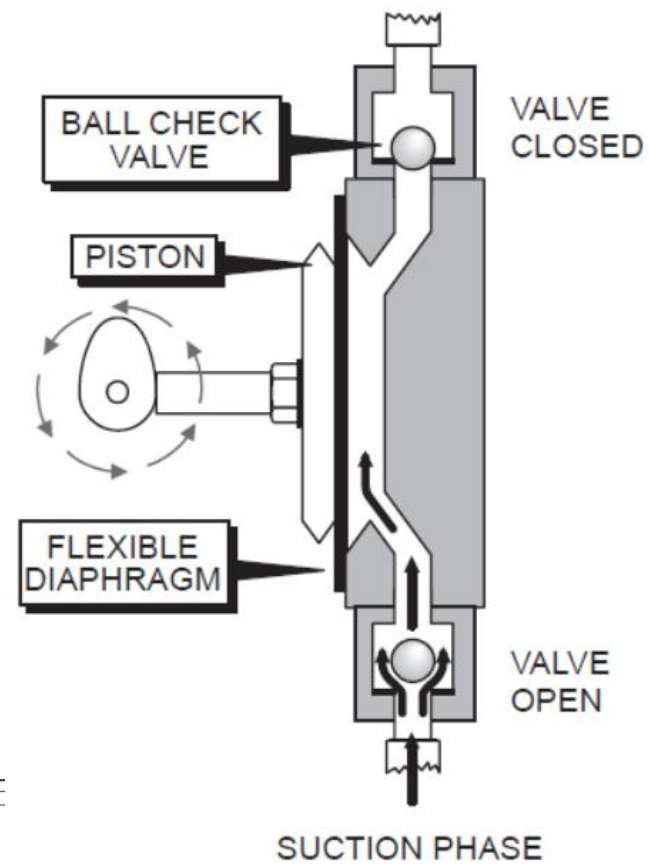
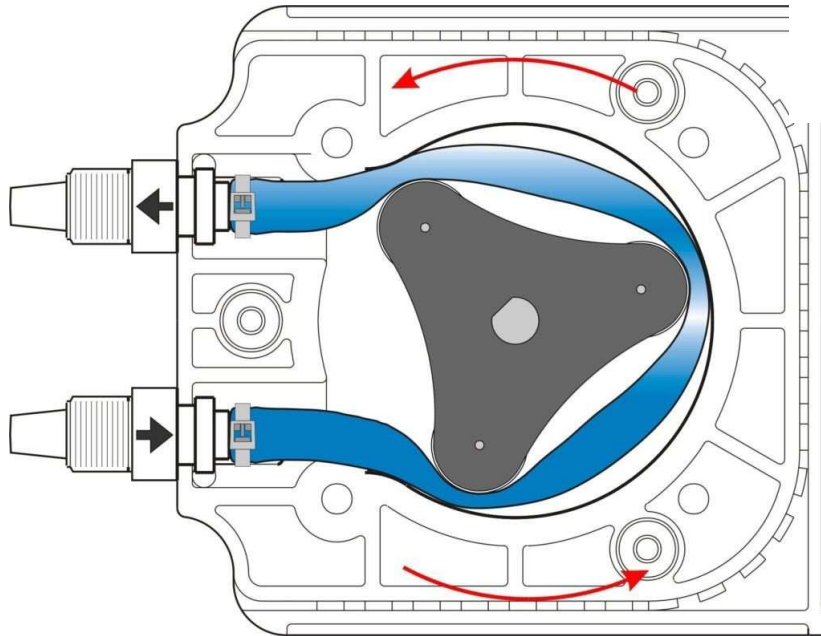
← very common type: end suction centrifugal pump

1. submersible turbine



More examples:

2. peristaltic pump



3. diaphragm pump

Aquifer (water) storage: confined vs. unconfined

- ▶ when water is pumped from a well in an unconfined aquifer, the pores are being drained and the volume of pores located near the well that was previously filled with water are being progressively filled by air
- ▶ in contrast, when water is pumped from a confined aquifer, air does not enter the pores, rather the water pressure is relieved and the geologic layers compact, because the high-water pressure that has been supporting the particles now decreased significantly
- ▶ the response to pumping propagates outward much more rapidly in confined aquifers as compared to unconfined aquifers
- ▶ important consequence → an equal decline of water levels in an unconfined aquifer will yield far more water than that of a confined aquifer
- ▶ in some regions of the world where large volumes of groundwater have been pumped from a confined aquifer, there has been significant compaction of geologic formations → sinking of the land surface (Central Valley, California)