ACC DAR Adapting to Climate Change in Coastal Dar es Salaam

Technical Workshop on Monitoring Seawater Intrusion in Coastal Groundwater

HYDROGEOLOGY OUTLINES AND SEAWATER INTRUSION THEORY AND MODELING

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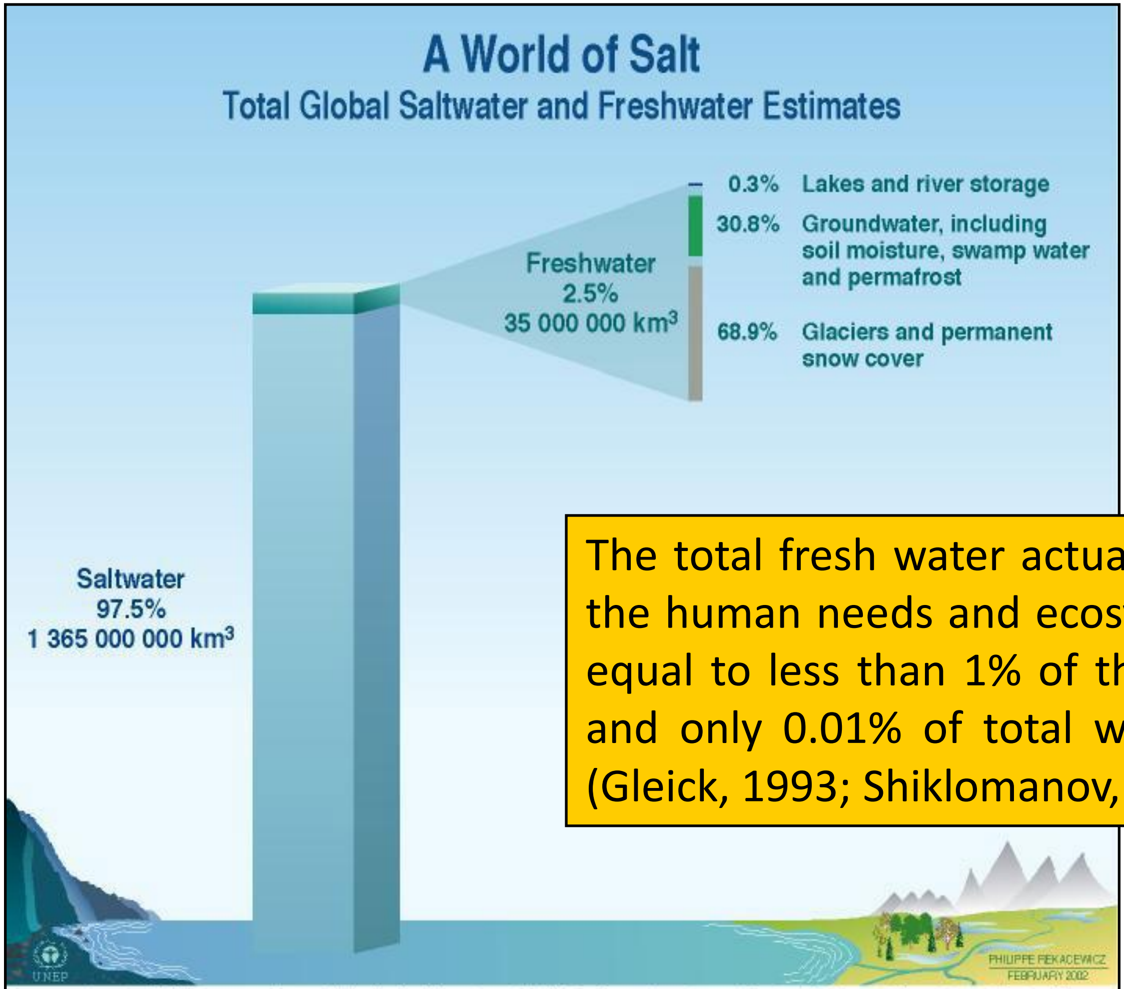
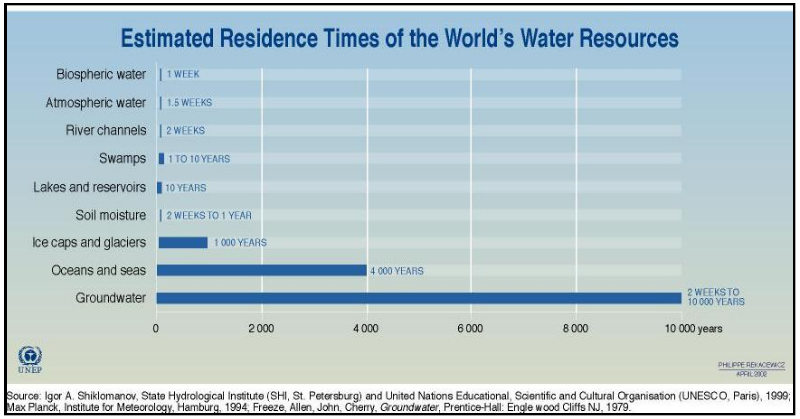
Water distribution on earth

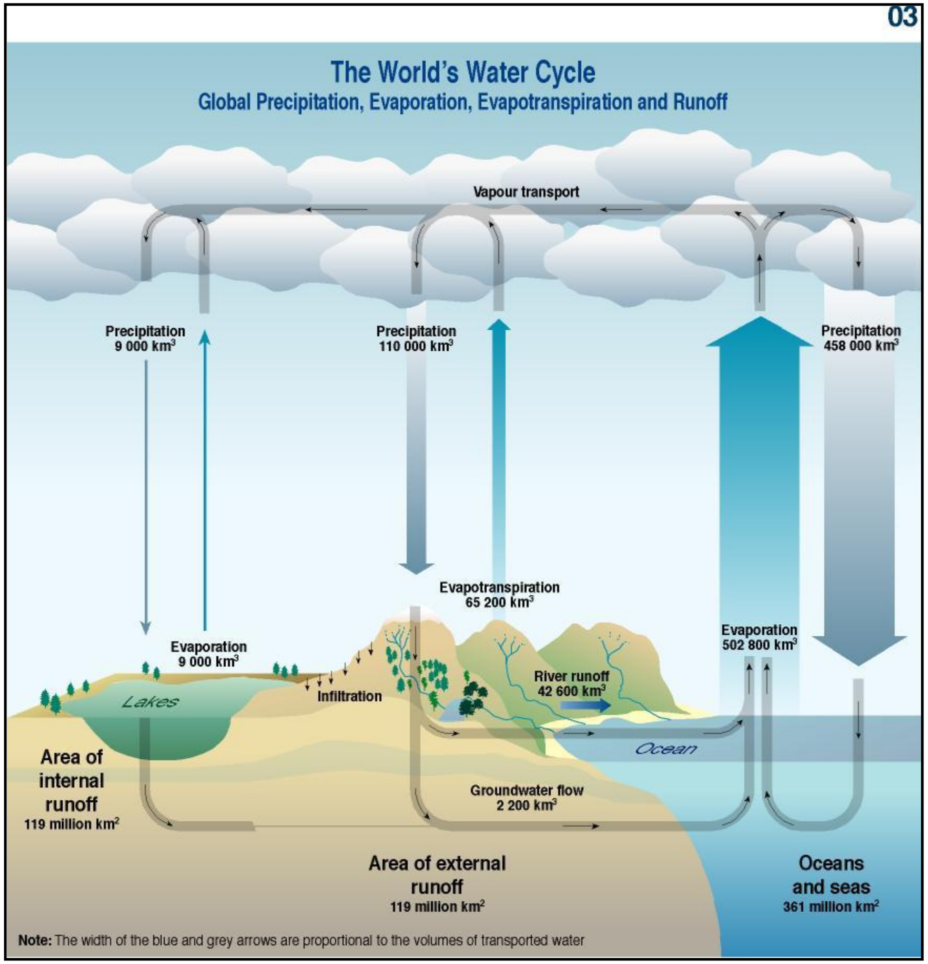


Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999.

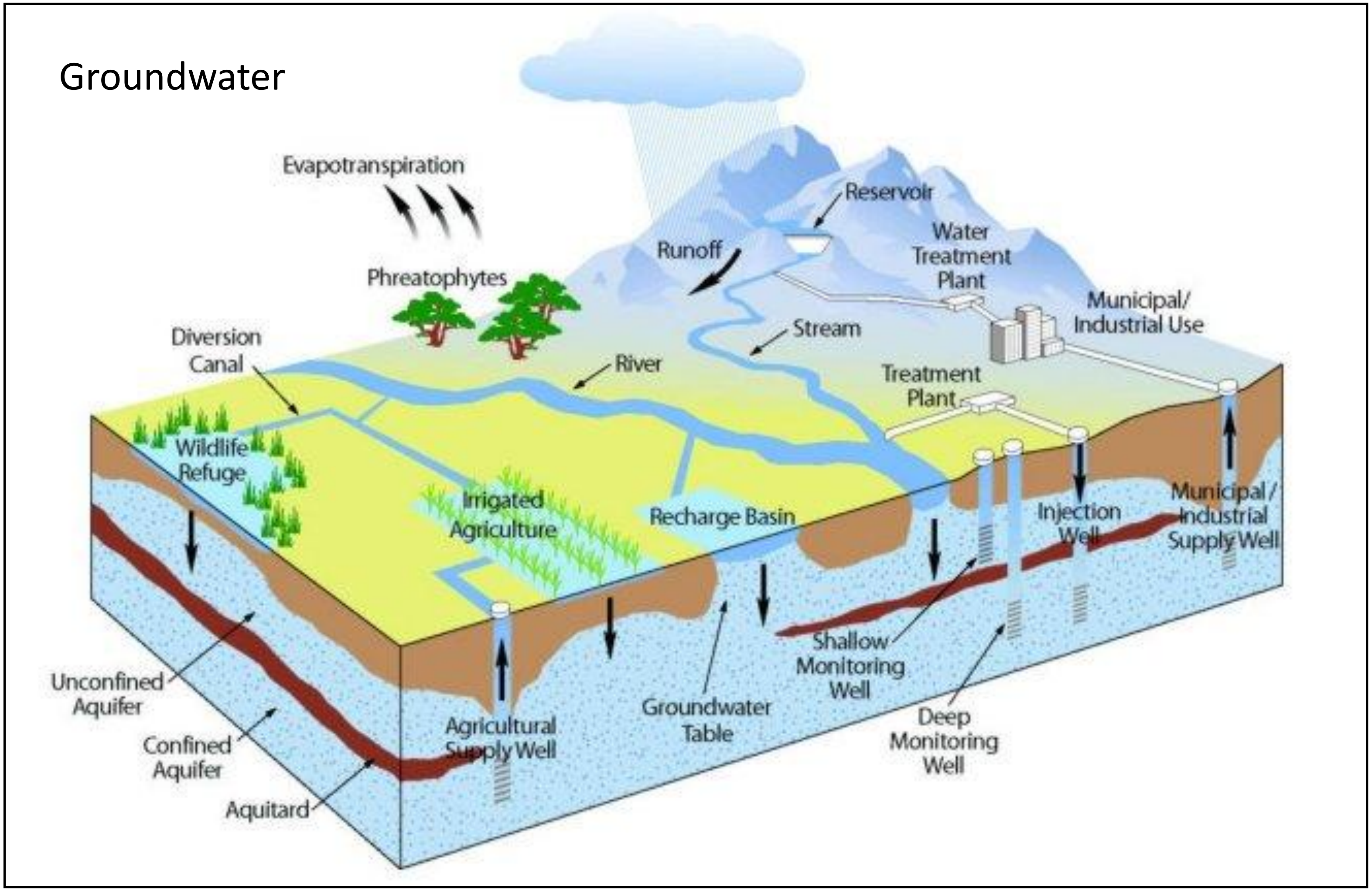
The total fresh water actually available and accessible to the human needs and ecosystems is about 200 000 km3, equal to less than 1% of the total of existing freshwater and only 0.01% of total water resources on the planet (Gleick, 1993; Shiklomanov, 1999).

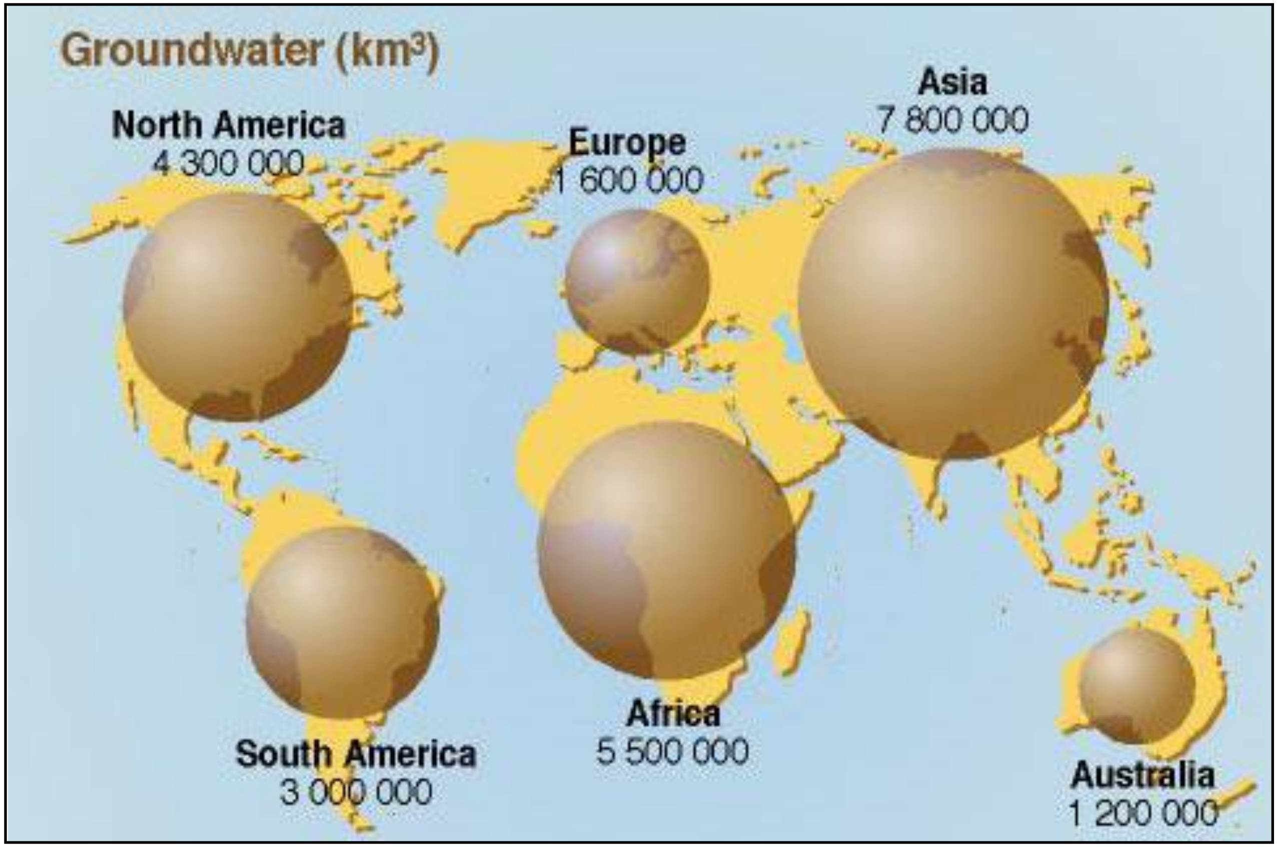
The water cycle





Groundwater





Groundwater is the most abundant source of fresh water, followed by lakes, rivers and wetlands: Represent over 90% of available freshwater (Boswinkel, 2000). About 1 and a half billion people depend on groundwater for drinking water needs (WRI, UNEP, UNDP, World Bank, 1998).
The overall picture of withdrawals and consumption of underground water on a global scale is not yet known, but it is estimated that approximately the underground withdrawal can be estimated at about 600-700 km3

Hydrological water balance

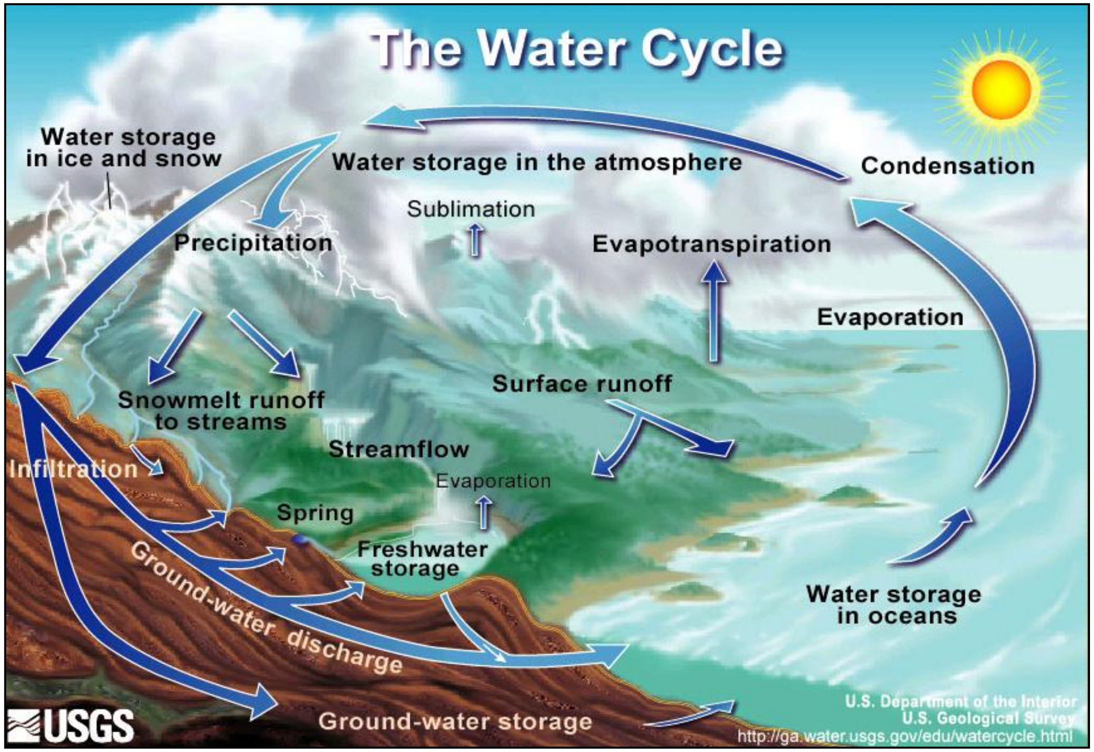
$$R = ET + I + Ro$$

R = Rainfall

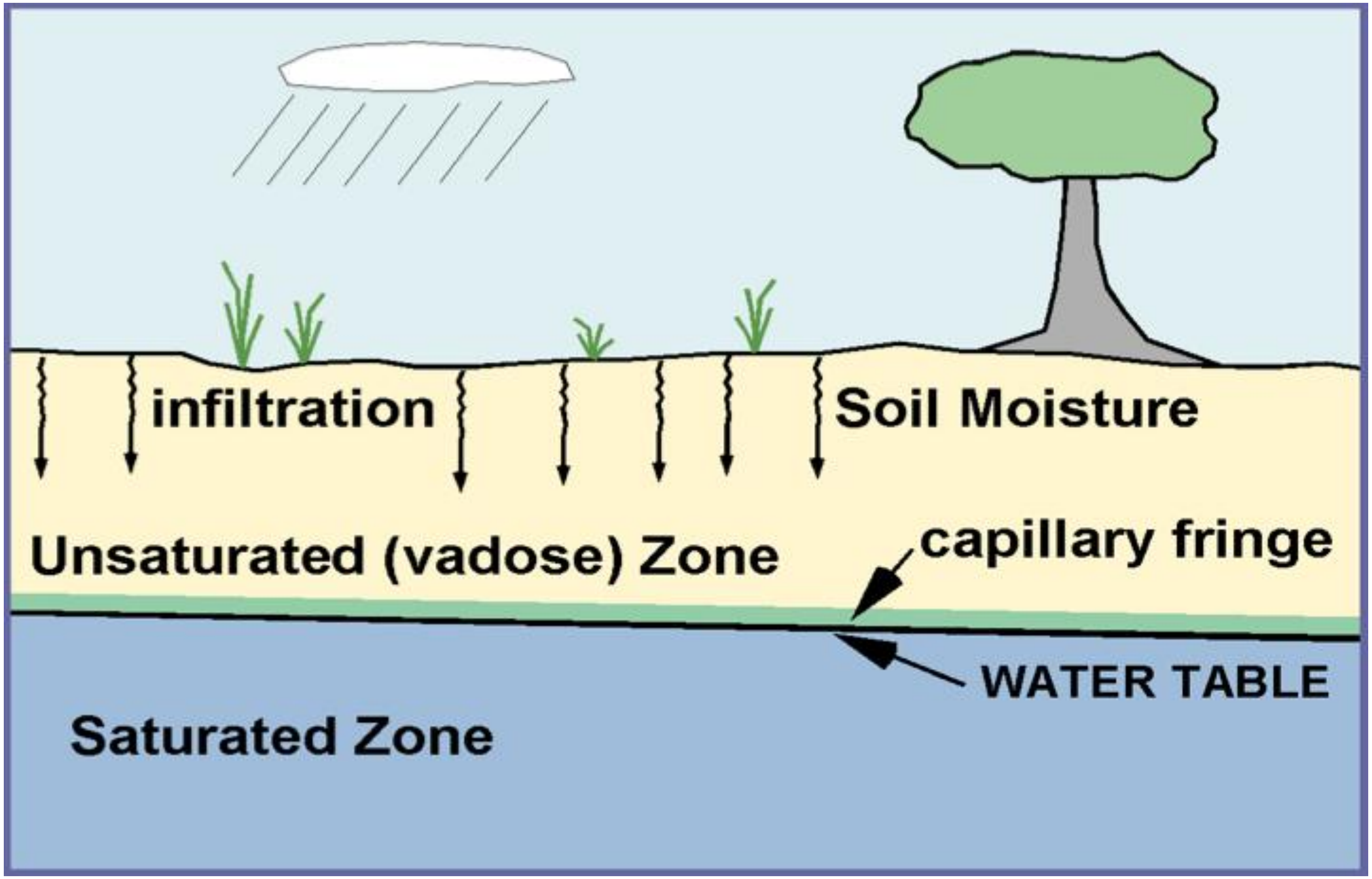
ET = Evapotranspiration

Ro = Runoff

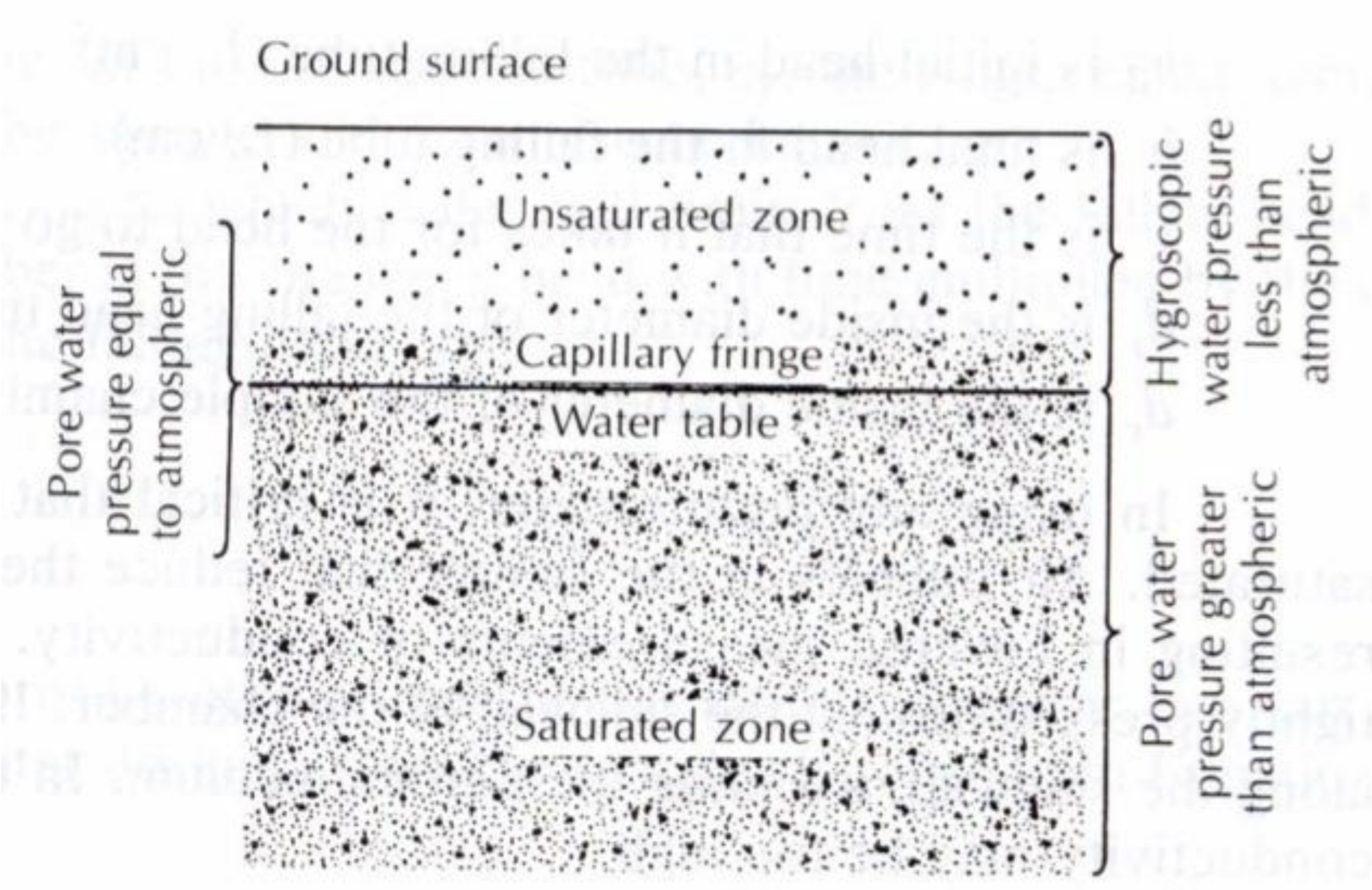
I = Direct Infiltration



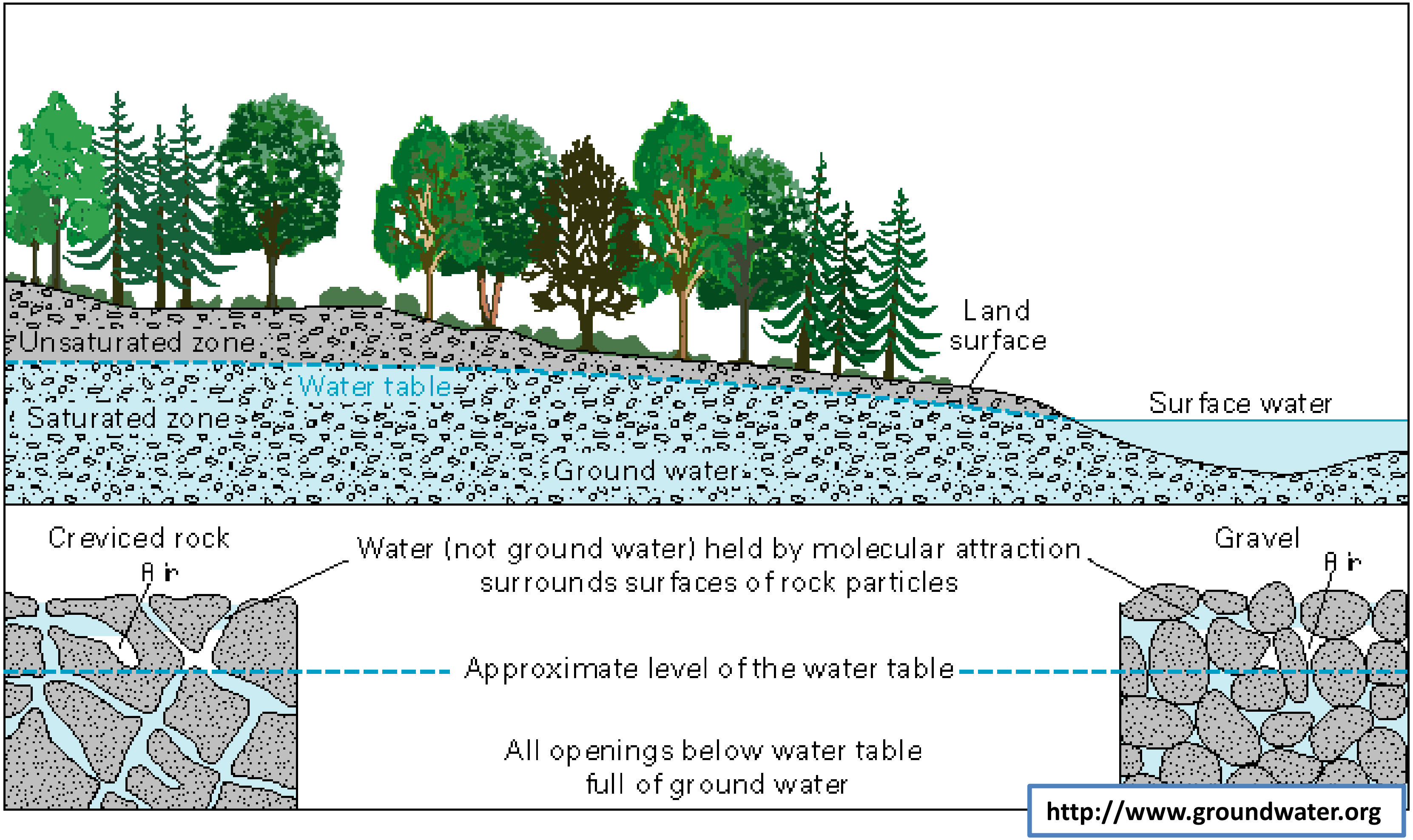
Take a look to what happens to the waters after they infiltration into soil.



Sature / Unsatured (Vadose) zone

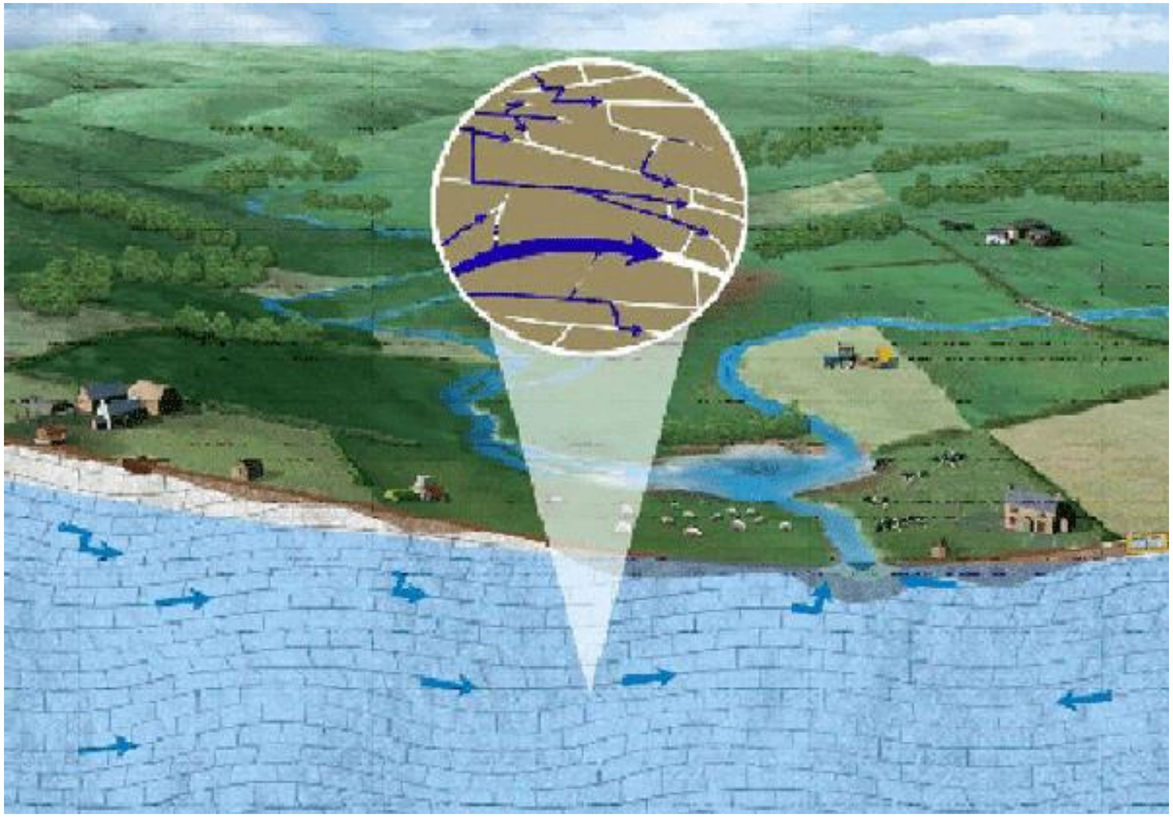


Sature / Unsatured (Vadose) zone



Aquifer concepts

An aquifer is a geological formation with such properties as to permit the accumulation and the flow of significant amounts of groundwater.



Hydrogeological properties

- **POROSITY**
- The percentage of pore volume or void space, or that volume within rock that can contain fluids.

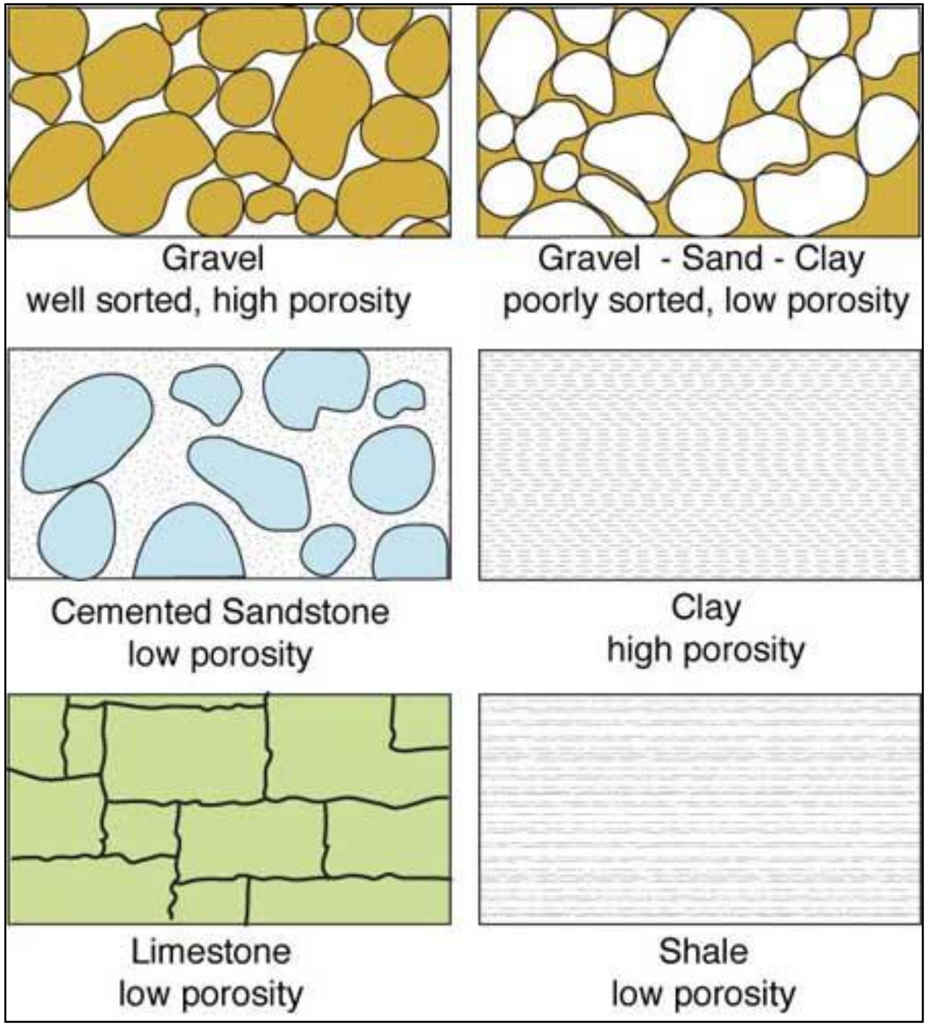
$$n = \frac{Vv}{Vt}$$

where V_V is the volume of void-space (such as fluids) and V_T is the total or bulk volume of material, including the solid and void components.

Porosity is a fraction between 0 and 1, typically ranging from less than 0.01 for solid granite to more than 0.5 for peat and clay. It may also be represented in percent terms by multiplying the fraction by 100.

Hydrogeological properties

POROSITY



Hydrogeological properties

- **HYDRAULIC CONDUCTIVITY**
- The hydraulic conductivity of a soil is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient.

The term coefficient of permeability is also sometimes used as a synonym for hydraulic conductivity.

The hydraulic conductivity depends on the soil grain size, the structure of the soil matrix, the type of soil fluid, and the relative amount of soil fluid (saturation) present in the soil matrix.
The important properties relevant to the solid matrix of the soil include pore size distribution, pore shape, tortuosity, specific surface, and porosity.
In relation to the soil fluid, the important properties include fluid density, , and fluid viscosity

Hydrogeological properties

- **HYDRAULIC CONDUCTIVITY**

- The values of saturated hydraulic conductivity in soils vary within a wide range of several orders of magnitude, depending on the soil material.

Texture	Saturated Hydraulic Conductivity, K (m/yr)
Sand	5.55×10^{3}
Loamy sand	4.93×10^{3}
Sandy loam	1.09×10^{3}
Silty loam	2.27×10^{2}
Loam	2.19×10^{2}
Sandy clay loam	1.99×10^{2}
Silty clay loam	5.36×10^{1}
Clay loam	7.73×10^{1}
Sandy clay	6.84×10^{1}
Silty clay	3.21×10^{1}
Clay	4.05×10^{1}

Source: Clapp and Hornberger (1978).

The hydraulic head

- Groundwater move according to the pression field, going from areas with higher pressions to areas with lower ones.
- The hydraulic head (or piezometric head) is a specific measurement of the groundwater pressure with reference to a geodetic origin.

Total energy for a water particle

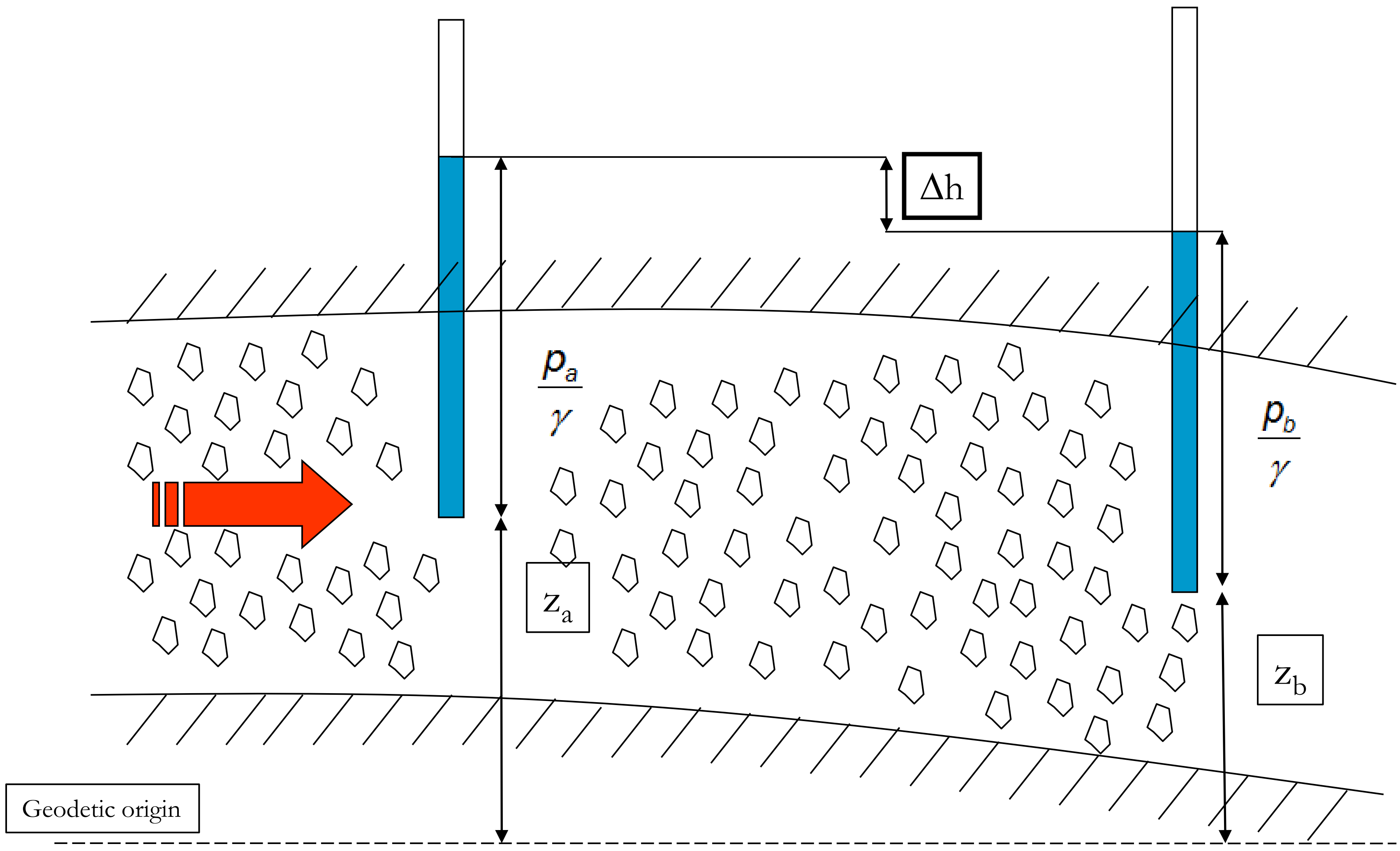
$$H = z_a + \frac{p_a}{\gamma} + \cancel{\frac{v_a^2}{2g}}$$

Potential energy

Kinetic energy

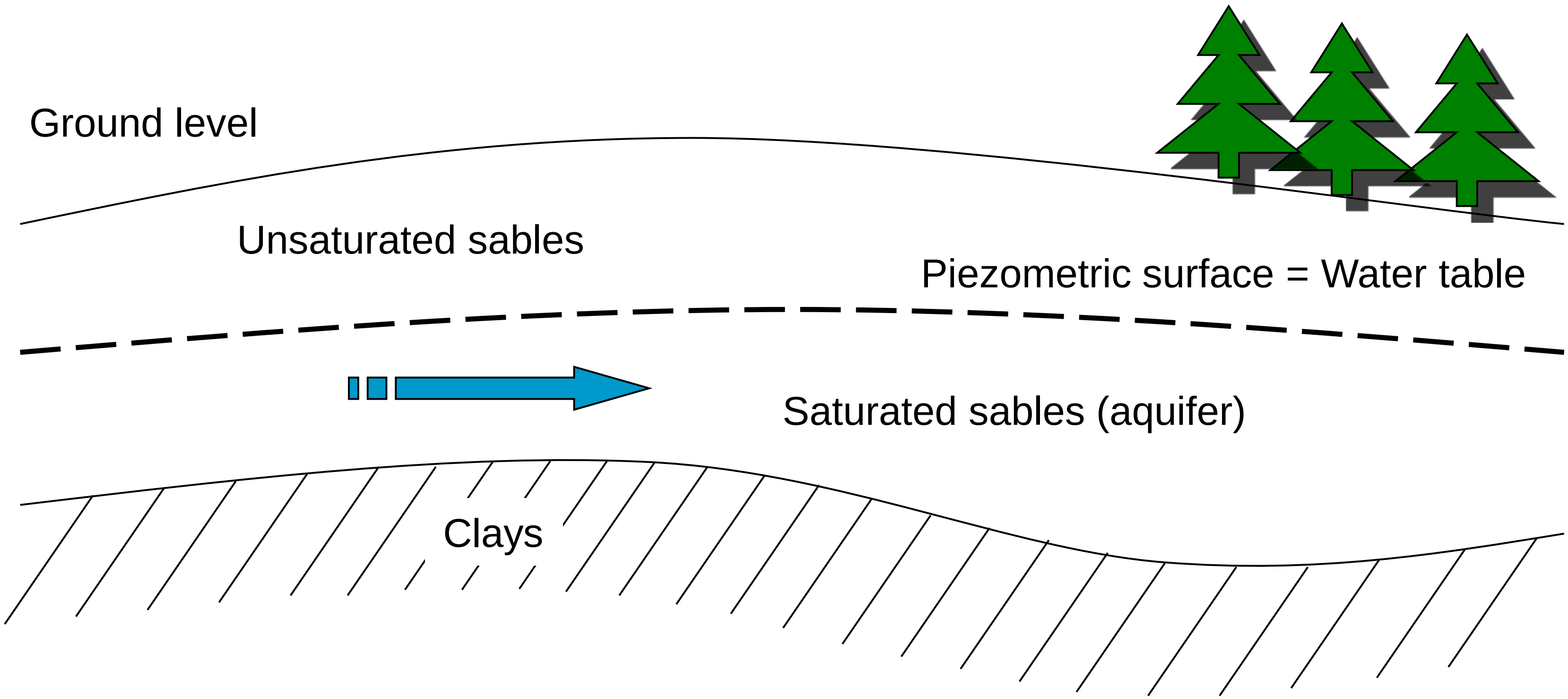
$$h = z + \frac{p}{\gamma}$$

The hydraulic head



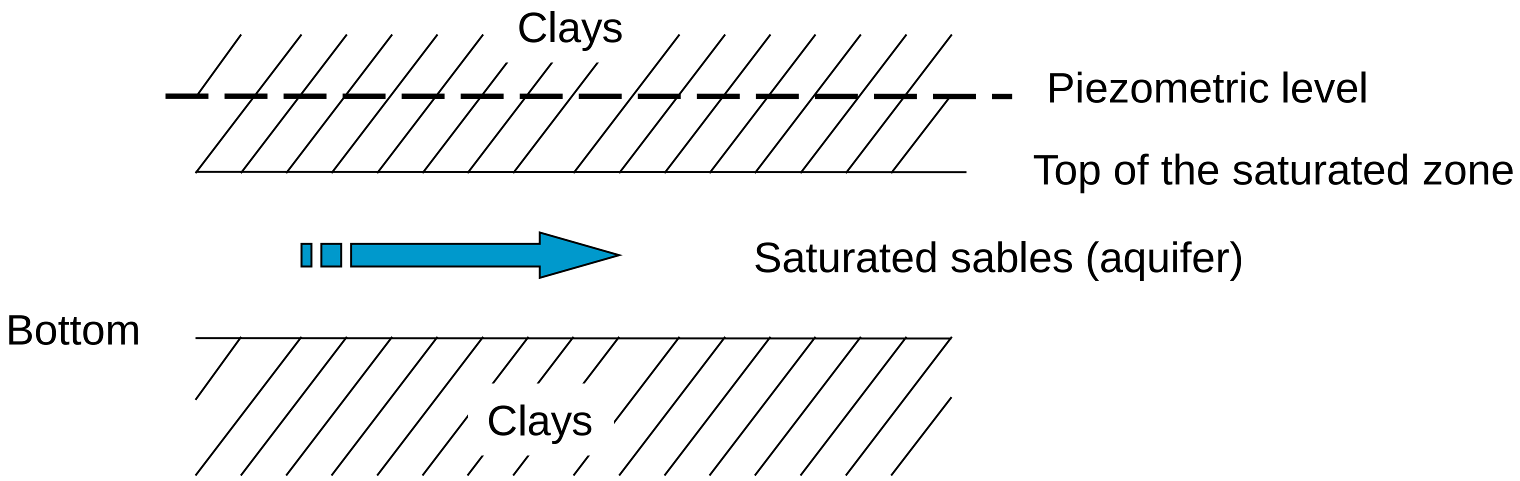
Unconfined aquifer

Unconfined aquifers are sometimes also called *water table* or *phreatic* aquifers, because their upper boundary is the water table or phreatic surface.



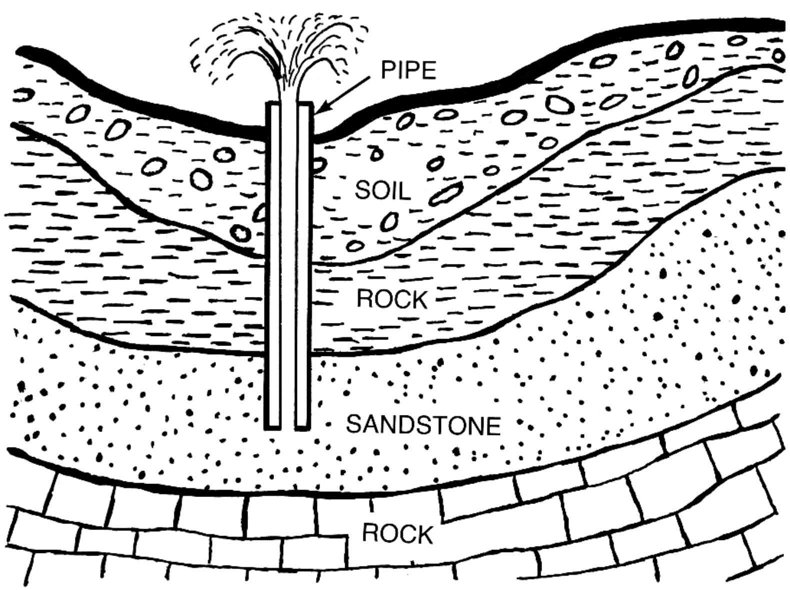
Confined aquifer

A **confined** aquifer is an aquifer bounded both at the bottom and at the top by an impermeable stratum and fully filled with water which is usually pressure

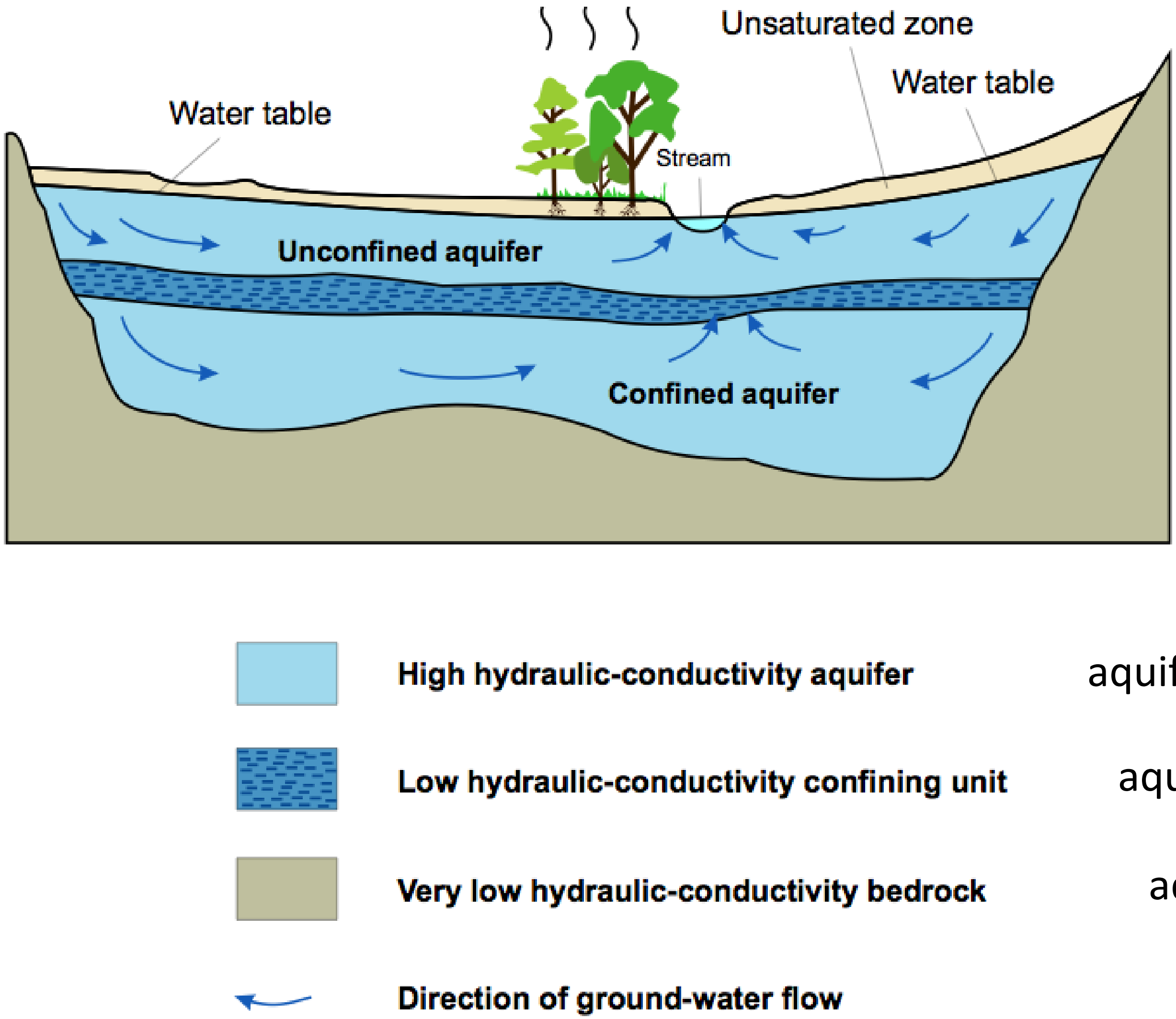


Confined (artesian) aquifer

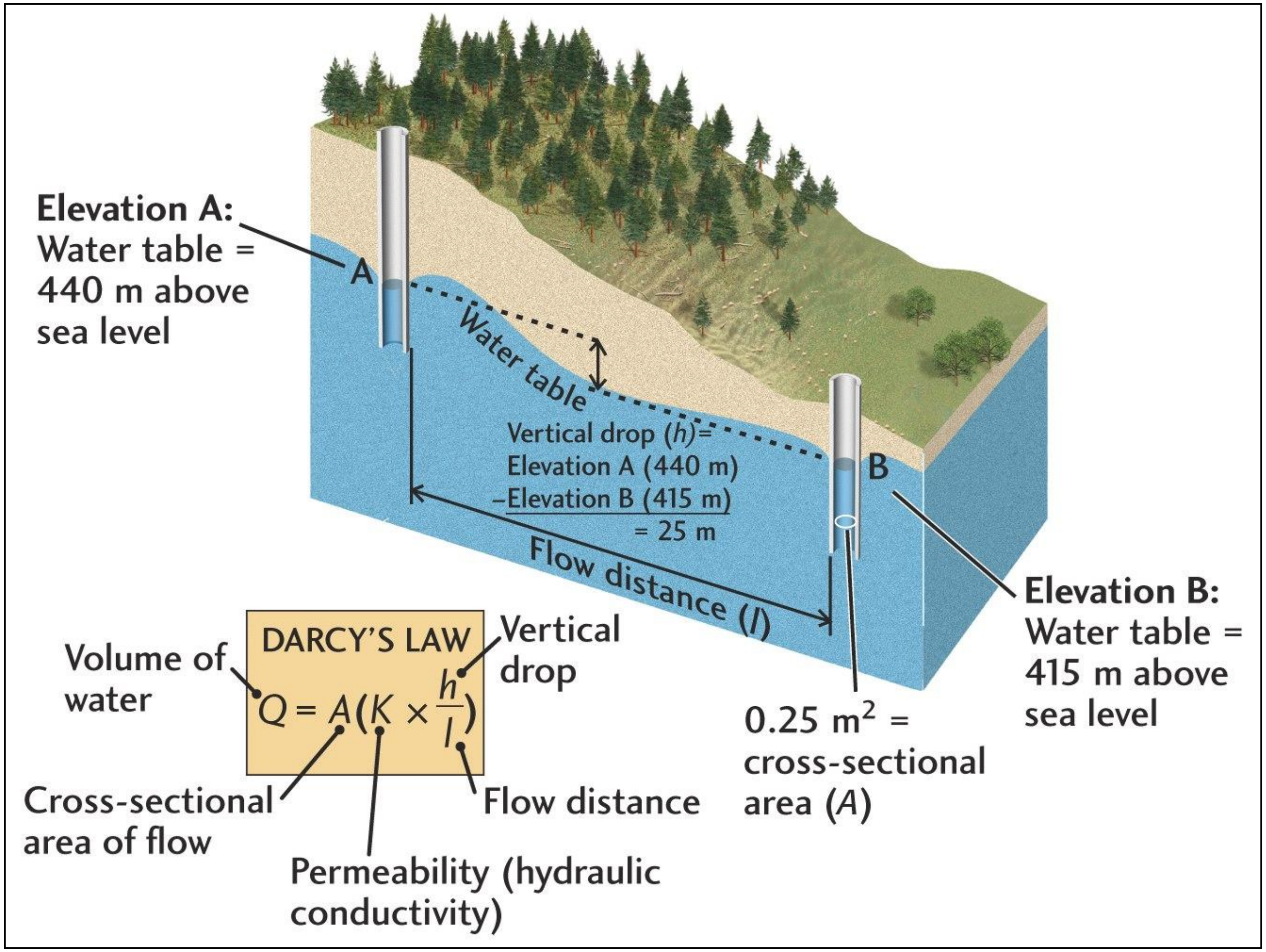
If the aquifer pressure is such as to make the piezometric surface reach the ground level, the aquifer is called **artesian** and the groundwater will rise above the ground level without need to pumping it out.



Hydrogeological formations



Darcy's law



Elevation A:
Water table = 440 m above sea level
A
Water table
Vertical drop (h) = Elevation A (440 m) –Elevation B (415 m) = 25 m
B
Flow distance (l)
Elevation B:
Water table = 415 m above sea level
DARCY'S LAW
$Q = A(K \times \frac{h}{l})$
Volume of water
Vertical drop
Cross-sectional area of flow
Permeability (hydraulic conductivity)
Flow distance
0.25 m² = cross-sectional area (A)

Darcy’s law

Darcy's law is a simple mathematical statement which neatly summarizes several familiar properties that groundwater flowing in aquifers exhibits, including:

- if there is no pressure gradient over a distance, no flow occurs (these are hydrostatic conditions),
- if there is a pressure gradient, flow will occur from high pressure towards low pressure (opposite the direction of increasing gradient - hence the negative sign in Darcy's law),
- the greater the pressure gradient (through the same formation material), the greater the discharge rate, and
- the discharge rate of fluid will often be different — through different formation materials (or even through the same material, in a different direction) — even if the same pressure gradient exists in both cases.

Seawater intrusion in coastal aquifers

- Hydrodynamic approach
- Geophysical approach
- Geochemical approach

Coastal aquifers

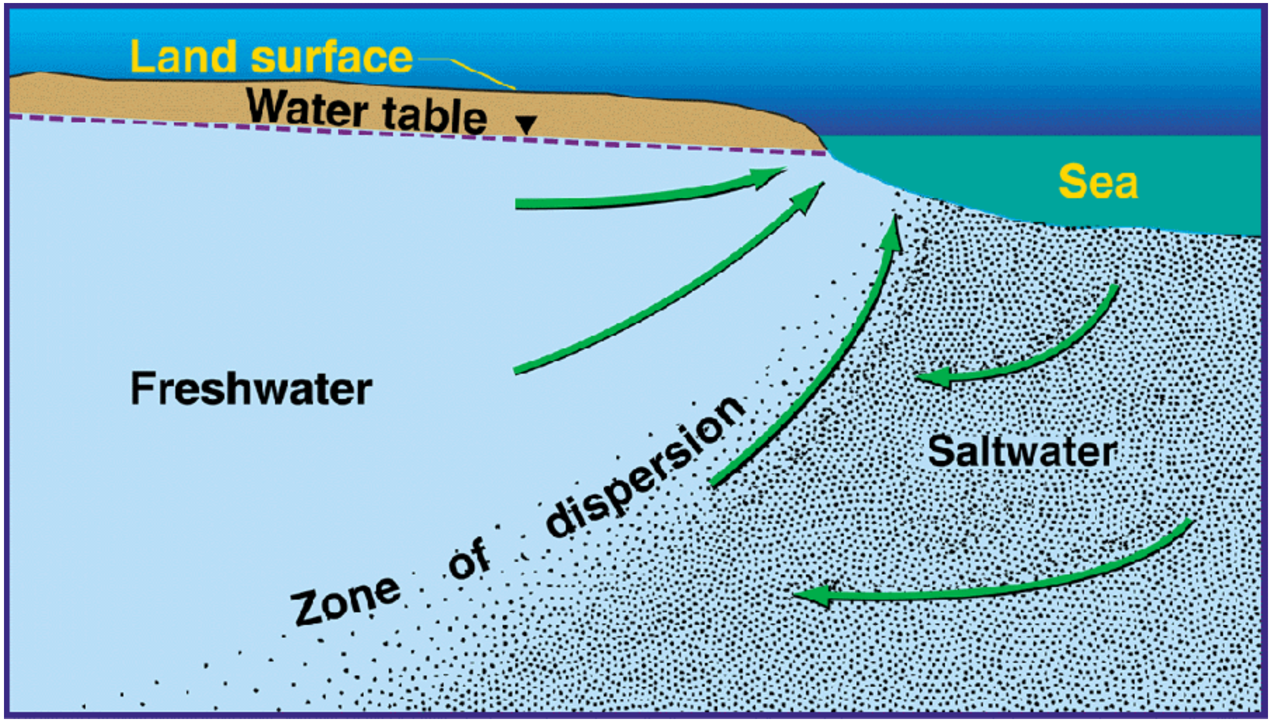
A coastal aquifer is defined when it is partially or totally surrounded by the sea and there is a hydraulic continuity between fresh and seawater

Coastal aquifers

The main features of a coastal aquifer are:

- good characteristics of permeability of the rock outcrops along the coastline and / or on the seabed;
- the basic level of groundwater circulation coincides with the average sea level;
- the groundwater discharge occurs through coastal springs (subaerial or underwater), normally draining brackish waters;
- At least in the areas closest to the coast, the freshwater are supported at the base by the saltwater of marine origin penetrated inland.

Coastal aquifers

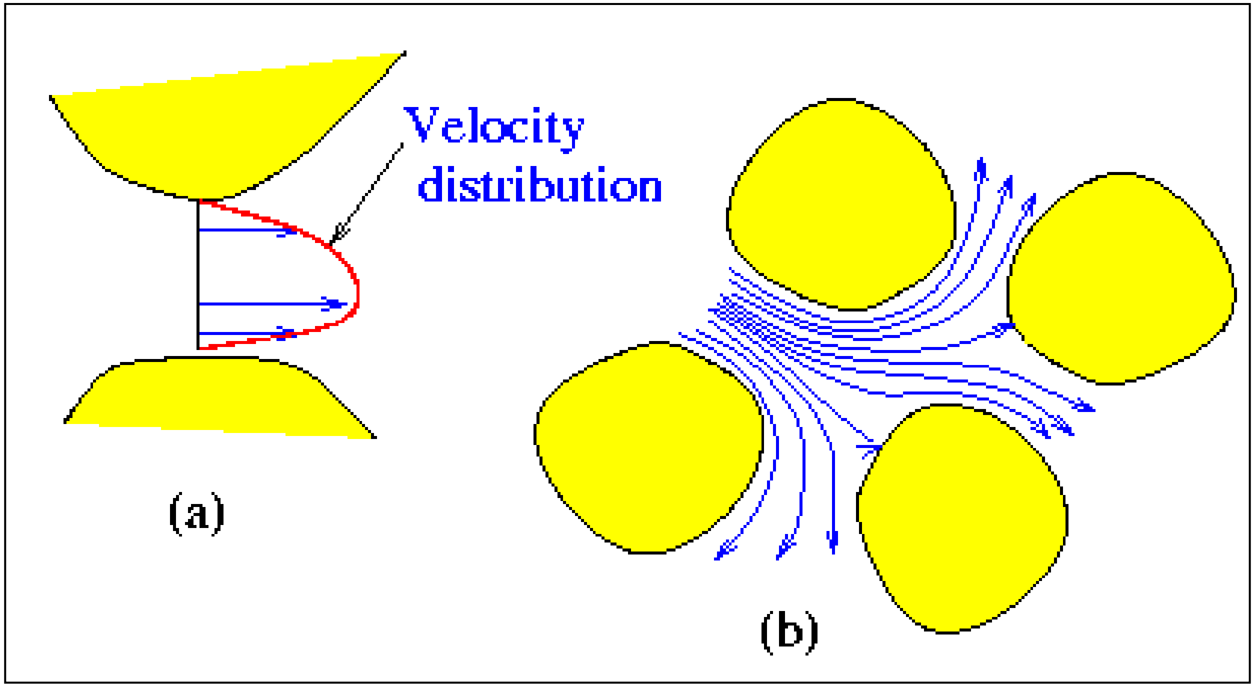


Between the two phases is assumed that there is a limit of separation (interface), although the miscibility between fresh and salt water will not allow that this interface is definite.

Into real world, instead of the interface net, there is a mixing zone where both phenomena of diffusion and dispersion act (transition zone).

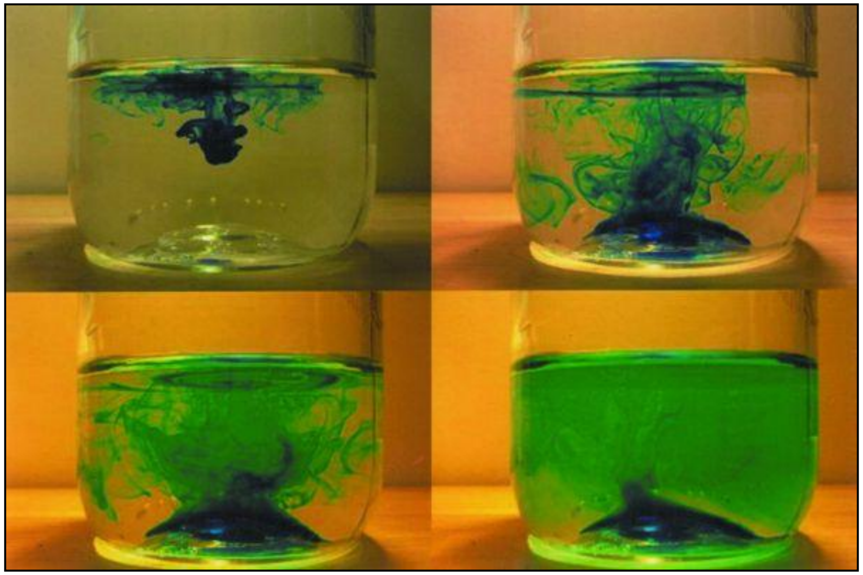
Coastal aquifers

The **dispersion** is a process related to the movement of water through a porous medium along lines of the current variable speed: the dispersion is related to the permeability of the medium.



Coastal aquifers

The **diffusion** is manifested at the molecular level or ionic, with respect to the thermal agitation of the particles and as a result of the presence of concentration gradients.



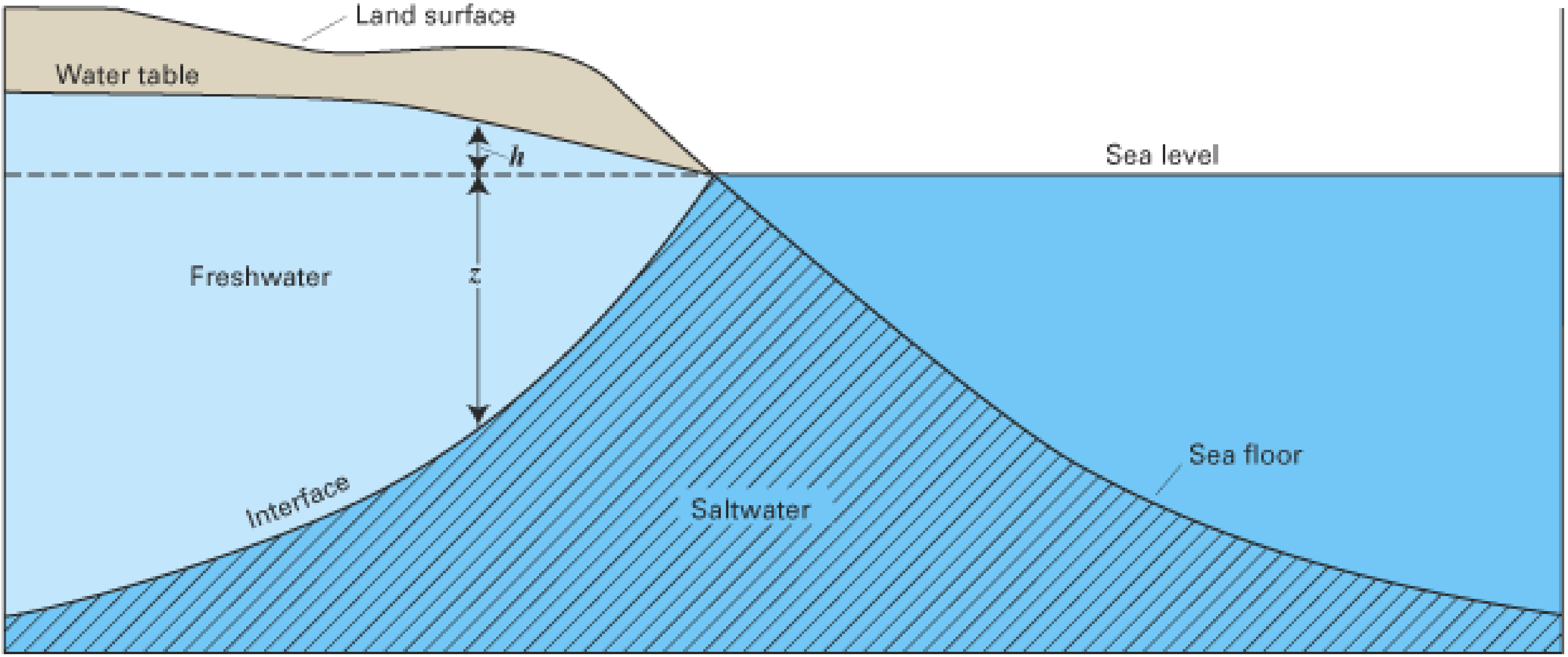
The combined result of the processes of mechanical dispersion and molecular diffusion is known as **hydrodynamic dispersion.**

Coastal aquifers

The first formulations for the physical location of the interface fresh water - salt water were established by W. Badon-Ghijben (1888, 1889) and A. Herzberg (1901), thus called the Ghyben-Herzberg relation.
They derived analytical solutions to approximate the intrusion behavior, which are based on a number of assumptions that do not hold in all field cases:

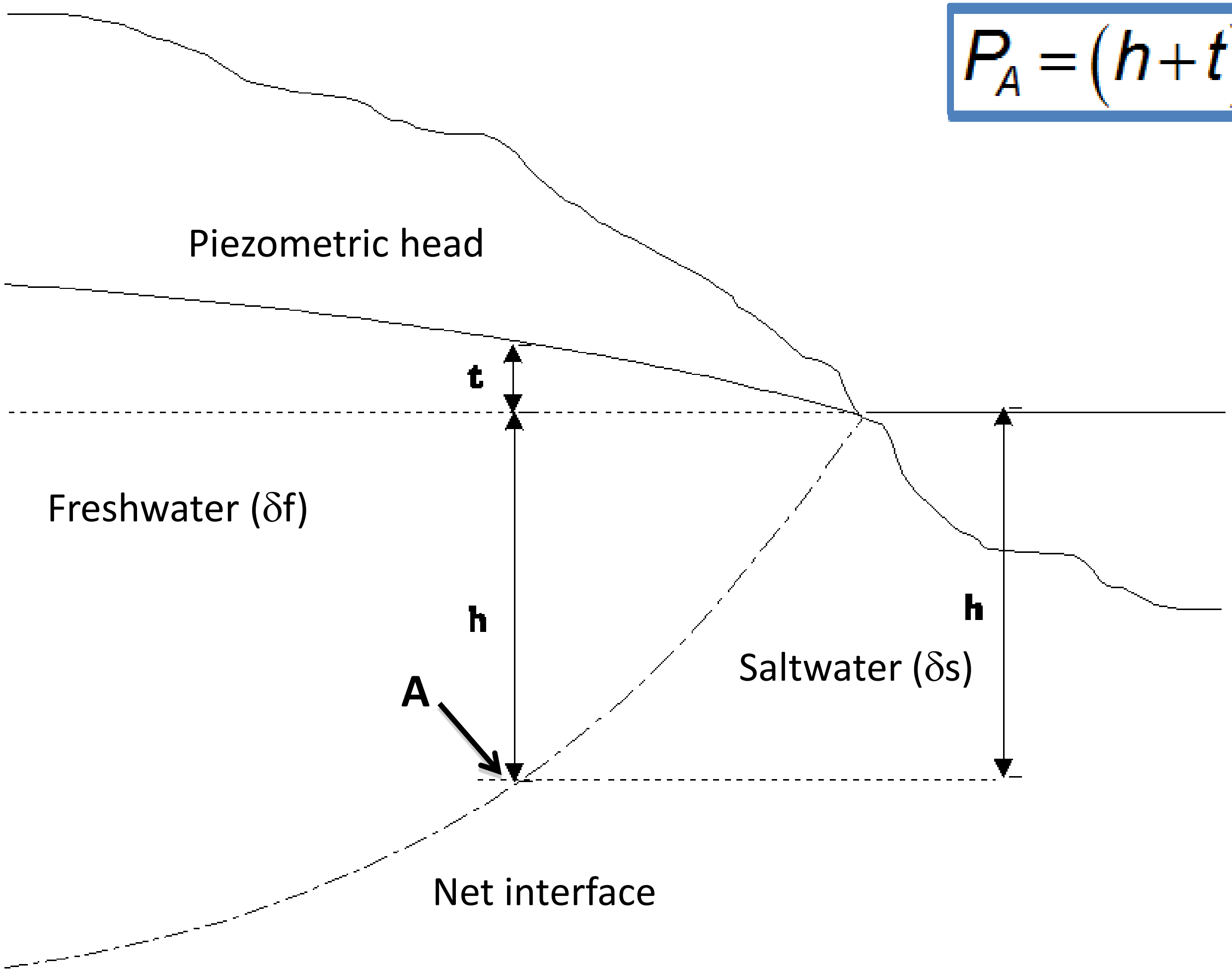
Freshwater flows above the still saltwater (saltwater piezometric head = 0);
Lower values for the freshwater piezometric gradient;
2D flows (Dupuit-Forcheimer hypotesis);
Freshwater and saltwater not mixable (no transition zone, but net interface);
Low aquifer sensibility to seasonal variations in direct recharge.

Coastal aquifers



The calculation of the depth of the interface is based on a balance of two static columns of different density.

Coastal aquifers



$$P_A = (h+t)\cdot g\cdot \delta_f = h\cdot g\cdot \delta_s$$

$$h = \frac{\delta_d}{\delta_s - \delta_d}\cdot t$$

Coastal aquifers

$$h = \frac{\delta_d}{\delta_s - \delta_d} \cdot t$$

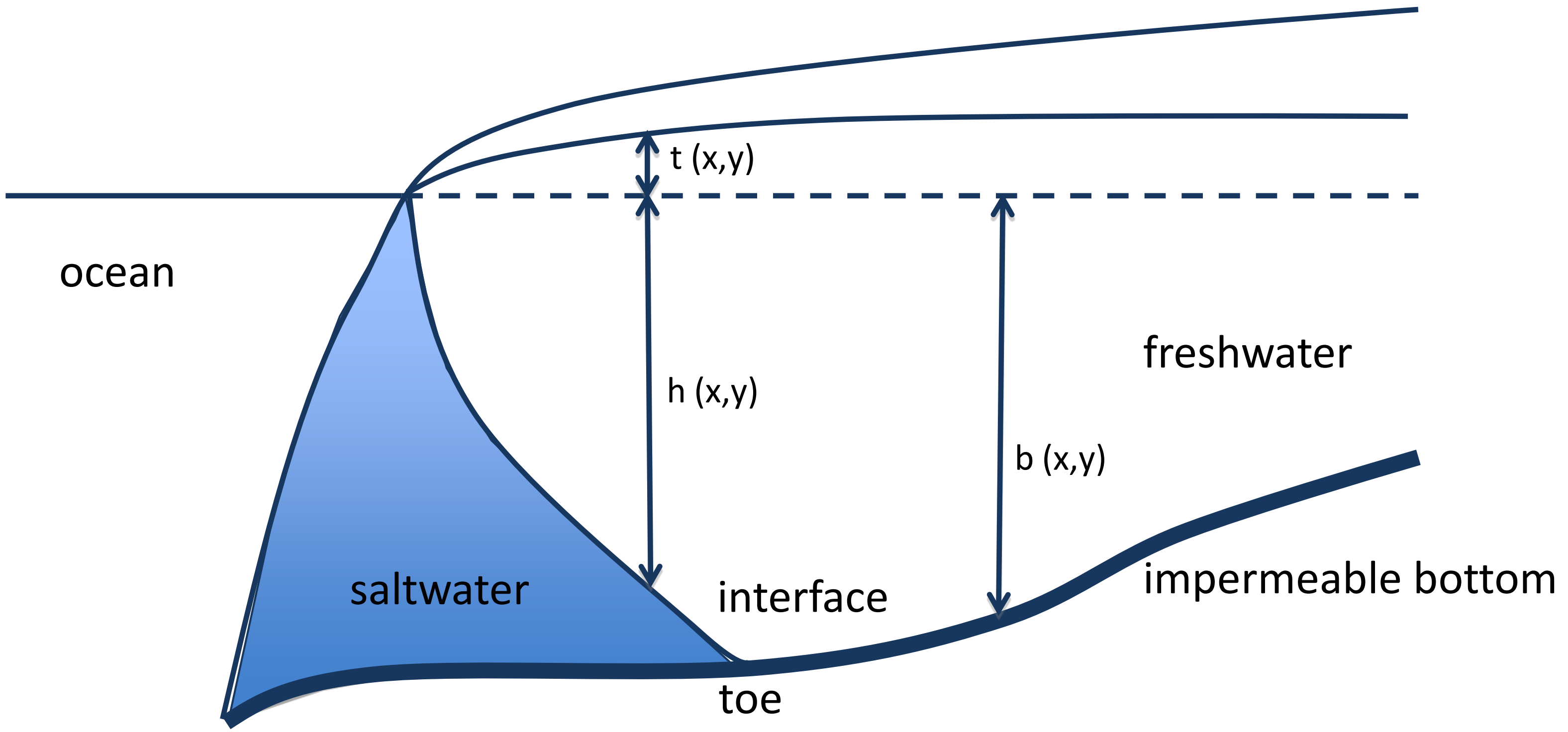
The depth of the interface (h) depends on the piezometric head of the water (t) and the density of the two liquids.

Freshwater has a density of about 1.000 grams per cubic centimeter (g/cm^3) at 20 ° C, whereas that of seawater is about 1.025 g/cm^3 for a salinity of about 42 g/l.

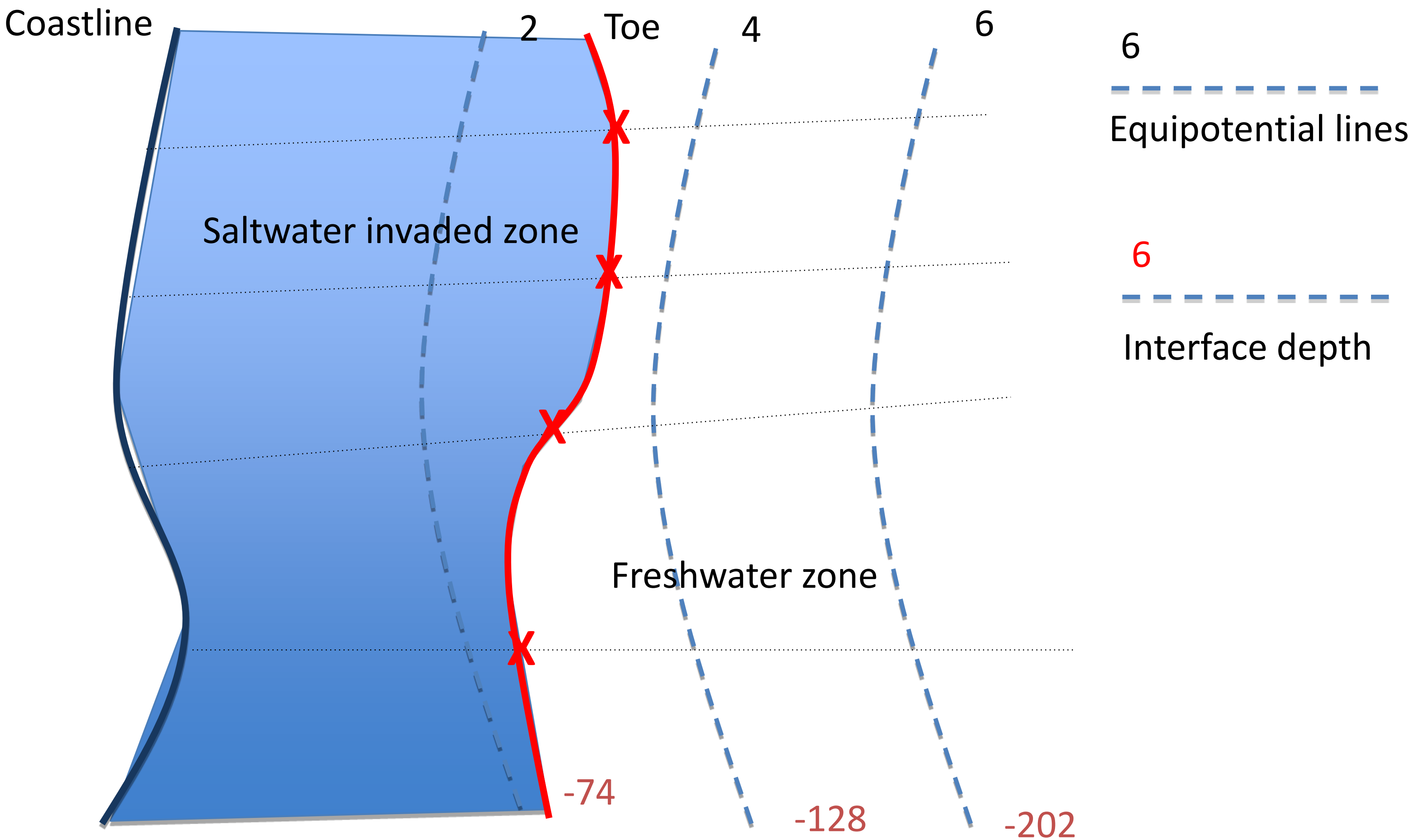
Depending on the values of actual densities of fresh and salt water, this ratio can vary between 33 and 50, assuming 37 as the average value.

The Ghyben-Herzberg ratio states, for every foot of fresh water in an unconfined aquifer above sea level, there will be 37 feet of fresh water in the aquifer below sea level.

Coastal aquifers



Coastal aquifers



Coastal aquifers

Main limits of Ghyben-Herzberg hypotesis

Freshwater and saltwater are perfectly mixable; that is why the net interface is only a theory but into real conditions there is a zone of variable density (transition zone);

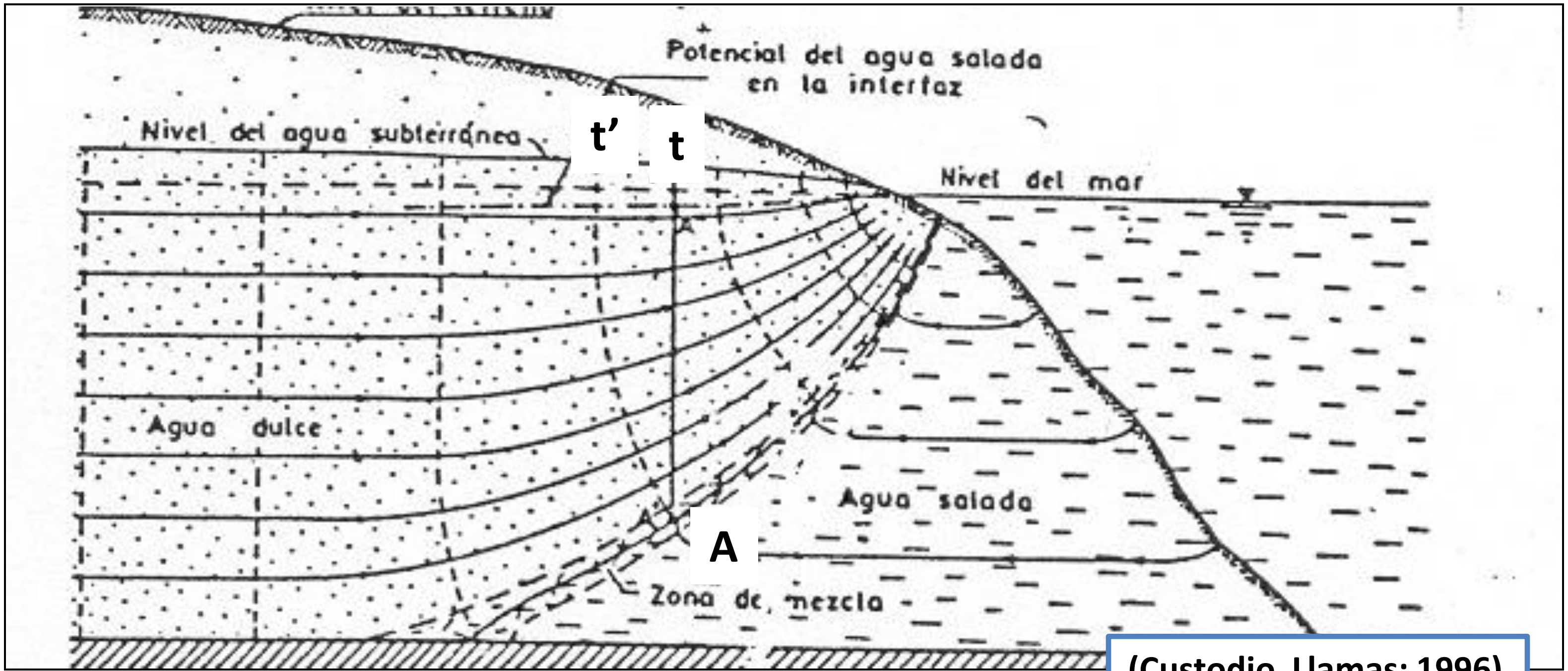
Close to the coastline, the increasing gradient make a vertical flow components rise, so the 2D flow conditions are not valid in this area;

Almost near the coastline, the seawater is not still but it has its own movement due to a small gradient direct towards the inland.

Coastal aquifers

Hubbert correction

The point “A” of the interface has an hydraulic head (t ') greater than can be measured on its vertical (t).

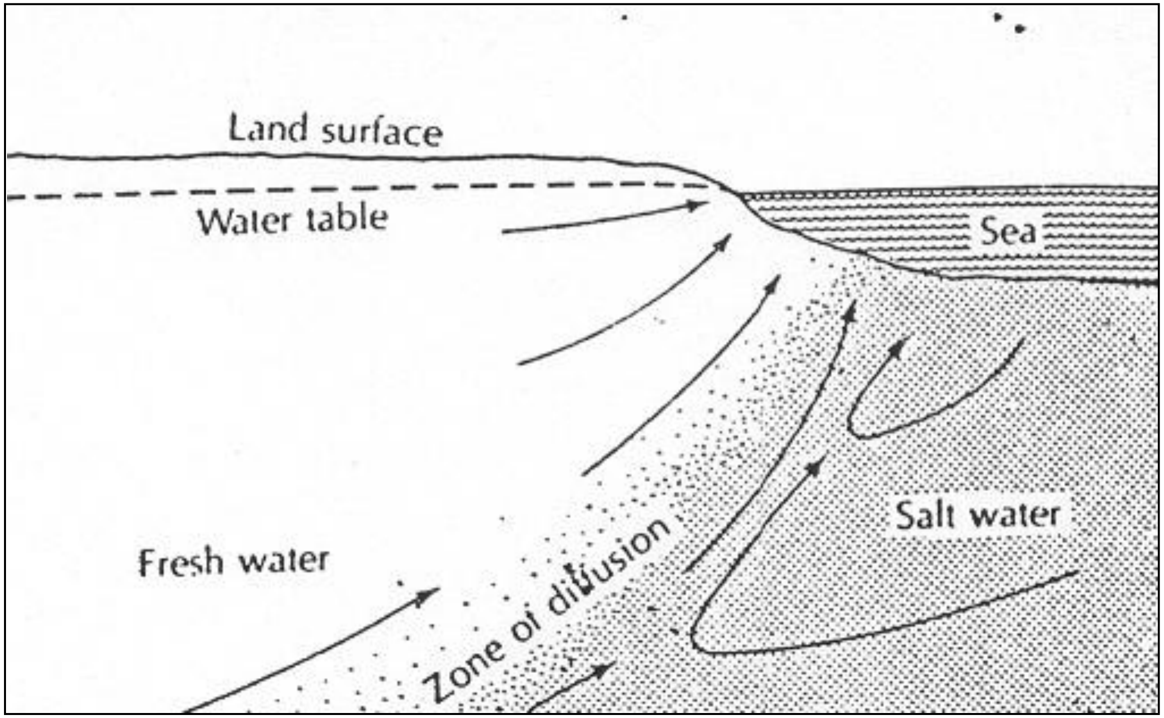


(Custodio, Llamas; 1996)

Coastal aquifers

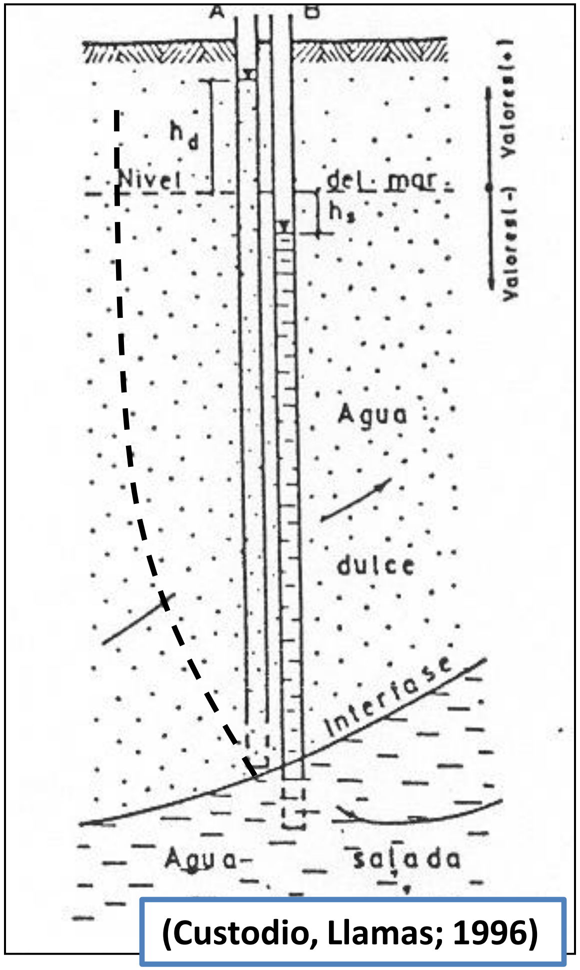
Hubbert correction

In the areas close to the coast, the movement of seawater towards the inland creates a so-called "cyclic flow" of saltwater that enters the continent and is brought back to the sea from coastal springs discharge.



Coastal aquifers

Hubbert correction



(Custodio, Llamas; 1996)

Hubbert introduces in its evaluation of the depth of the interface different values for the piezometric head of freshwater and saltwater.

First piezometer only screened above the interface, draining only freshwater; hydraulic head h = h_d=t'

Second piezometer open below the interface, draining only saltwater; hydraulic head h = h_s = t_s

The saltwater hydraulc head is lower than the sea level according to the seawater movement towards the inland.

Coastal aquifers

Hubbert correction

The equation for the new equlibrium is

$$P_A = \left(h + t'\right) \cdot g \cdot \delta_f = \left(h + t_s\right) \cdot g \cdot \delta_s$$

$$h = \frac{\delta_d}{\delta_s - \delta_d} t'_d - \frac{\delta_s}{\delta_s - \delta_d} t_s$$

Hubbert formula

The first term of the equation is equal to the Ghyben-Herzberg formula with the “corrected” hydraulic head for the vertical flow;
The second one is the correction due to the seawater movement;
Since t_s is generally negative, the net interface depth obtained with the Hubbert formula is greater than the one obtained with the G-H law.

Seawater intrusion

	TDS [mg / l]
Freshwater	0 - 1000
Brackish waters	1000 - 5000
Saltwater	5000 - 30000
Seawater	> 30000

Seawater intrusion

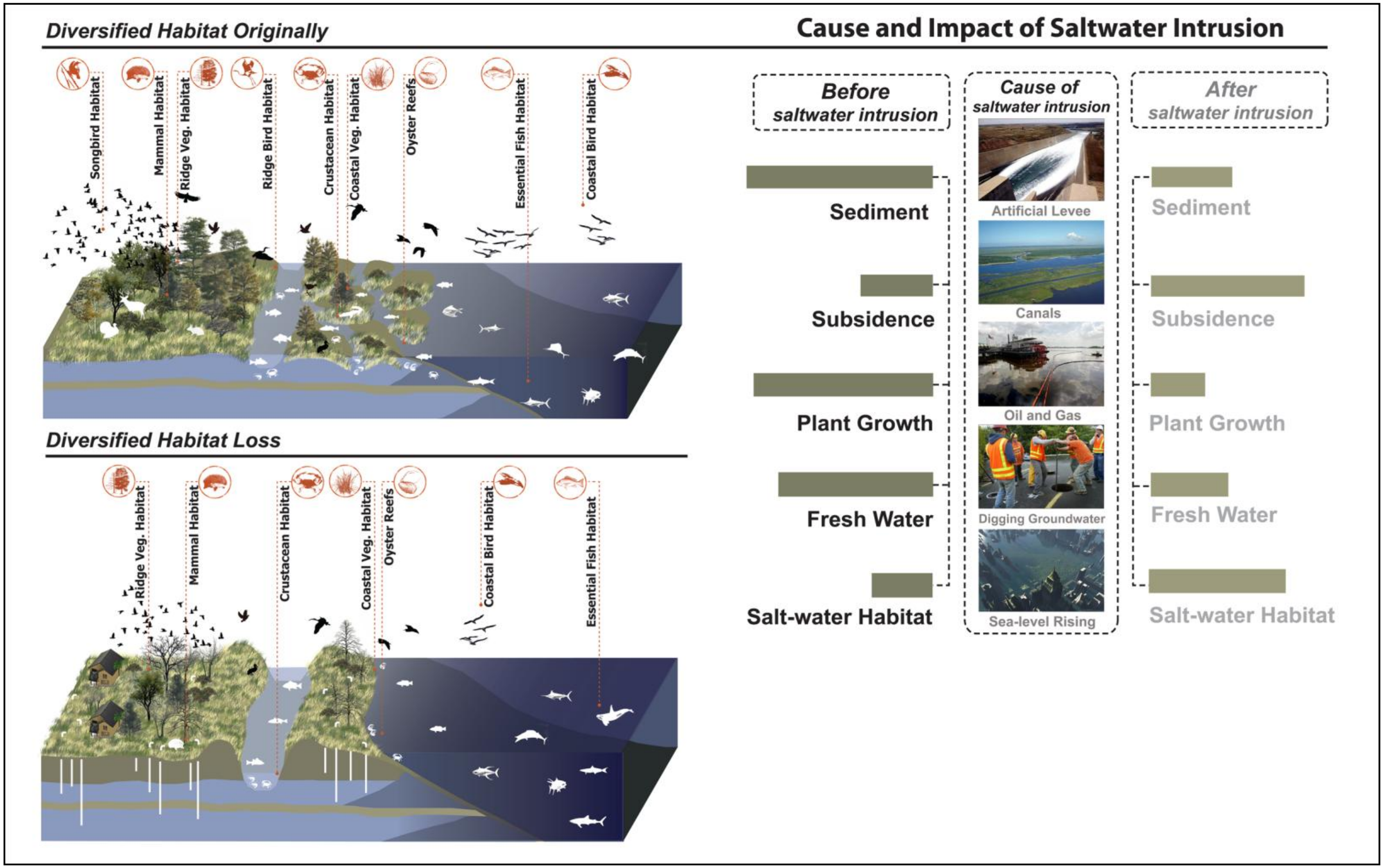
Permanent or transient movement of seawater into a coastal aquifer

Natural phenomena that could be amplified by different factors such as:

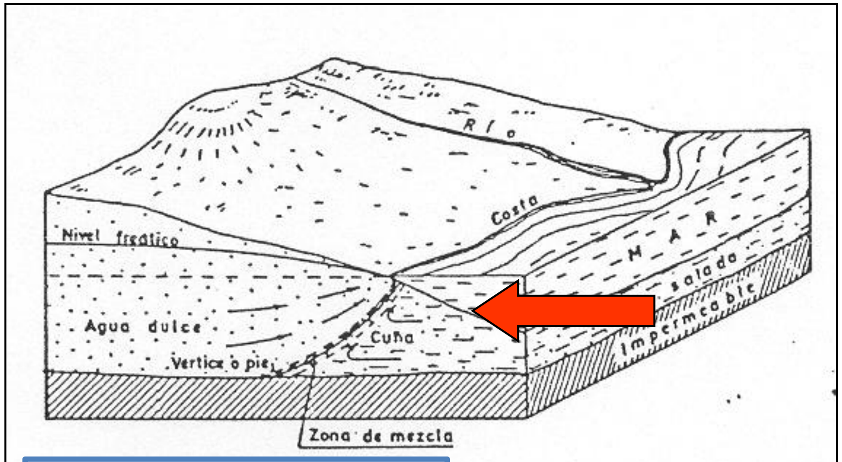
Human activities (aquifer overexploiting, land impermeabilization, coastal erosion, etc.);

Change in climatic conditions (sealevel rising, loss in aquifer recharge, coastal erosion, etc.)

Seawater intrusion

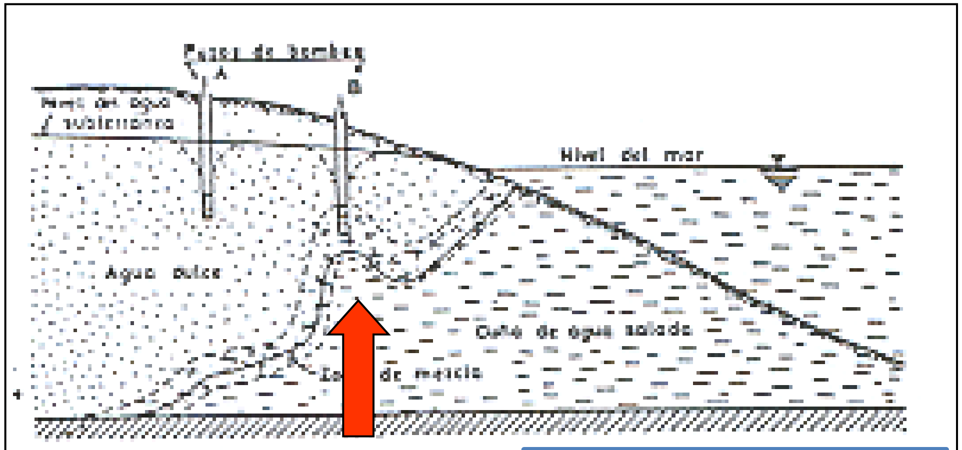


Seawater intrusion



(Custodio, Llamas; 1996)

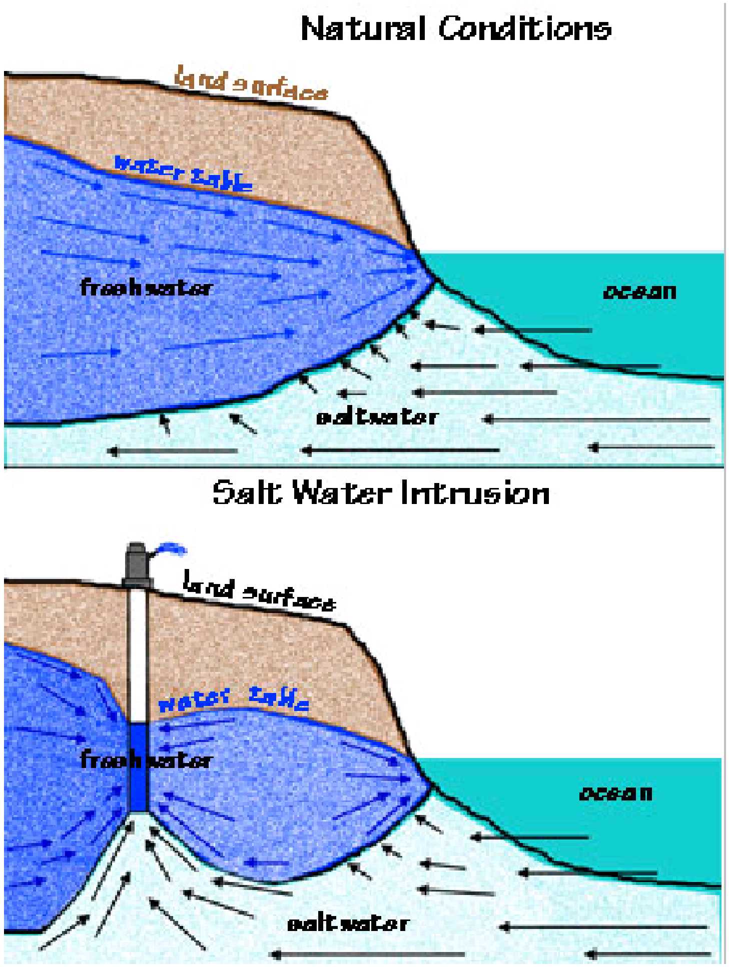
Lateral intrusion



(Custodio, Llamas; 1996)

Upconing

Seawater intrusion

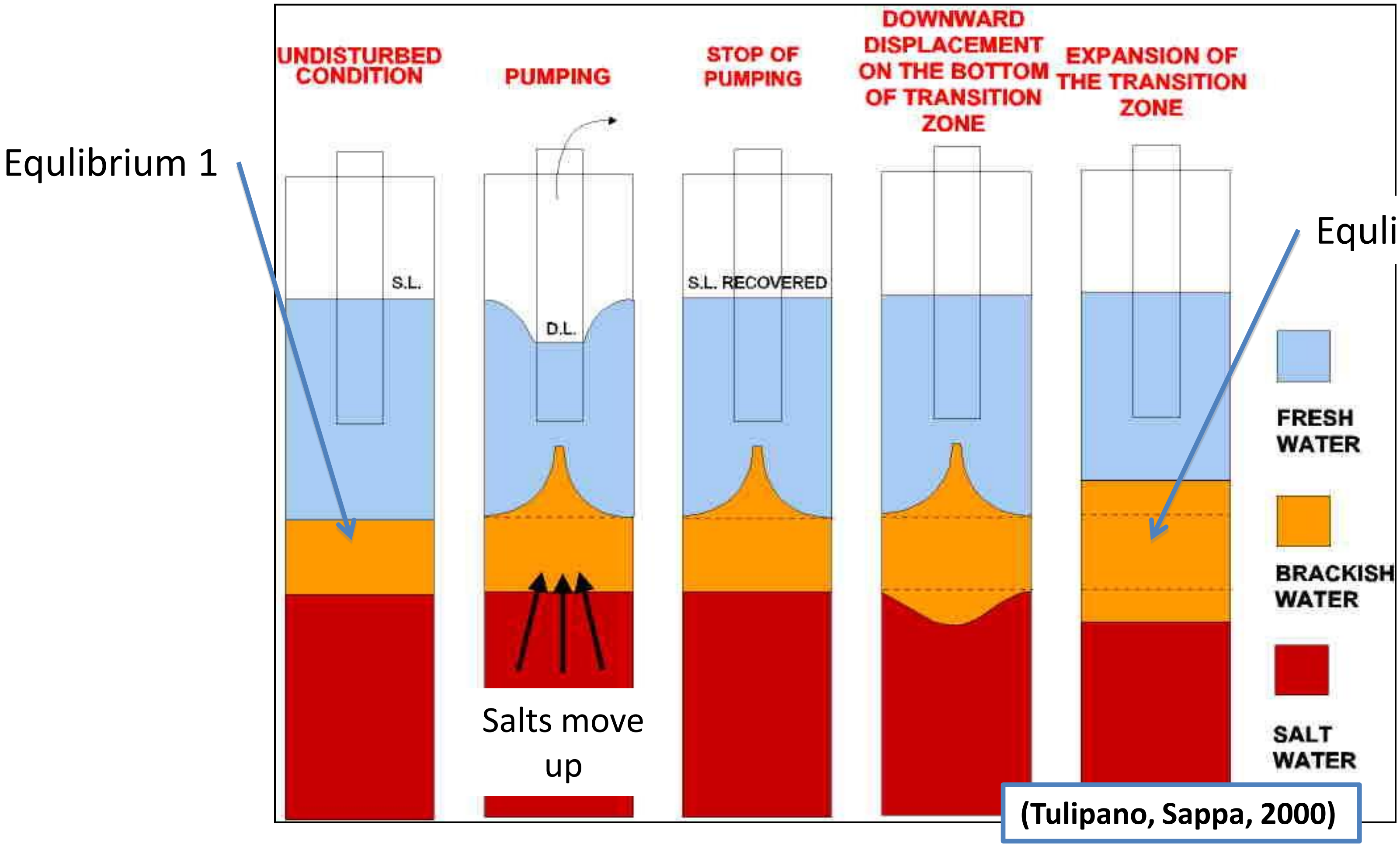


Schematic diagram of upconing phenomena due to aquifer overexploitation.

In the real conditions there is no net interface and there's no interface shifting but only the seawater salts spreading and moving up.

Seawater intrusion

Real effect of an exploiting water well on the transition zone

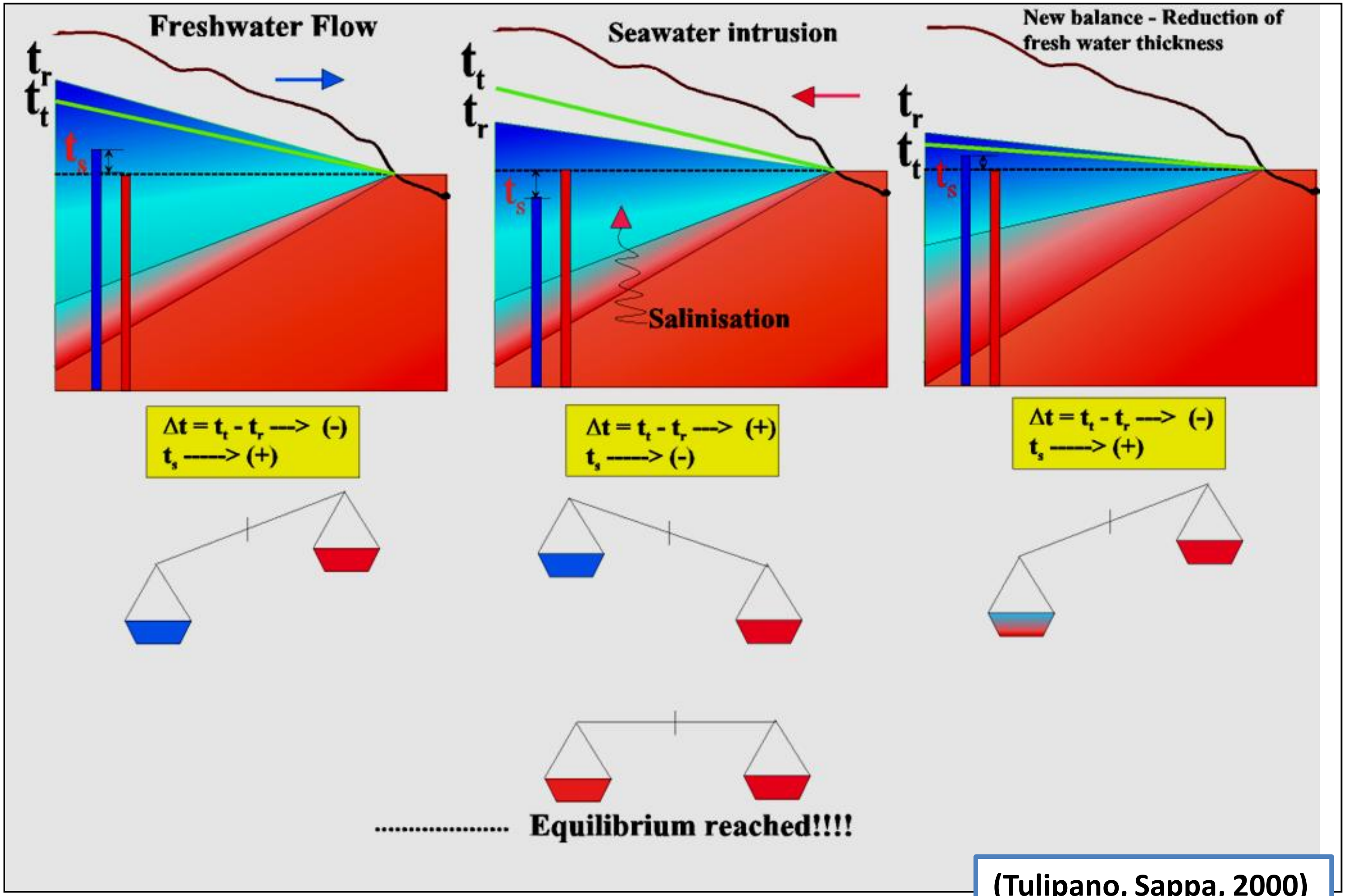


Seawater intrusion

The groundwater flow in coastal aquifer is ruled by the equilibrium between the freshwater flow towards the sea and the seawater flow towards the inland aquifer.
In natural conditions, this equilibrium follows the seasonal climatic variation or tidal excursion.

When natural conditions are modified (i.e. greater freshwater flow due to irrigation or lower freshwater flow due to overexploiting), the hydrogeological system reacts changing the two phases conditions to gain a new equilibrium state.

Seawater intrusion



(Tulipano, Sappa, 2000)

Seawater intrusion

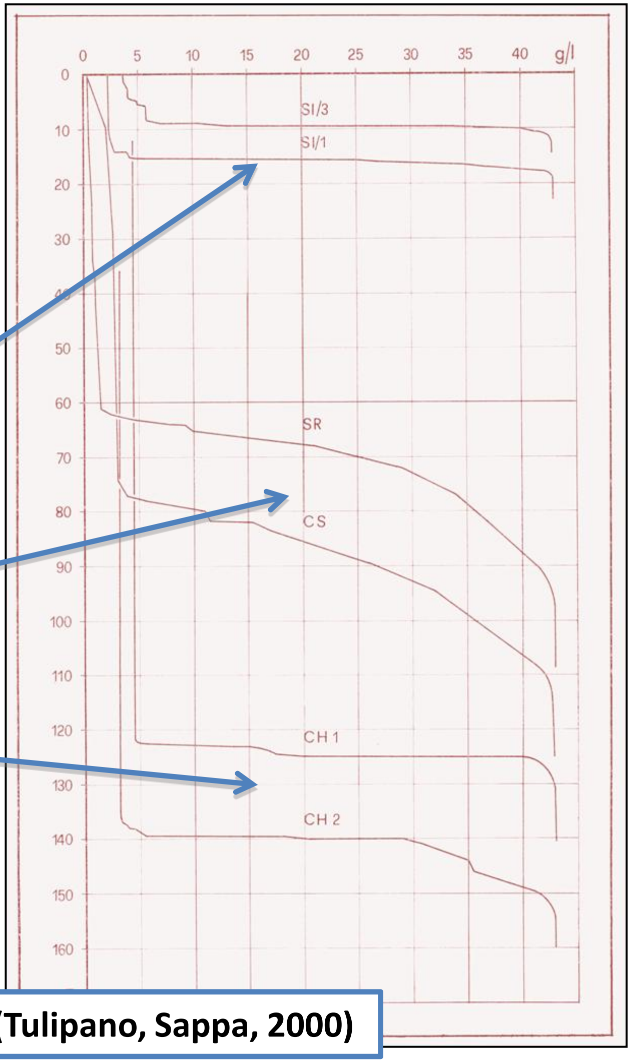
EXAMPLES

Transition zone thickness in different conditions and different distances form the coastline (Salinity profiles).

Near the coast, unconfined conditions

Far from the coast, unconfined conditions

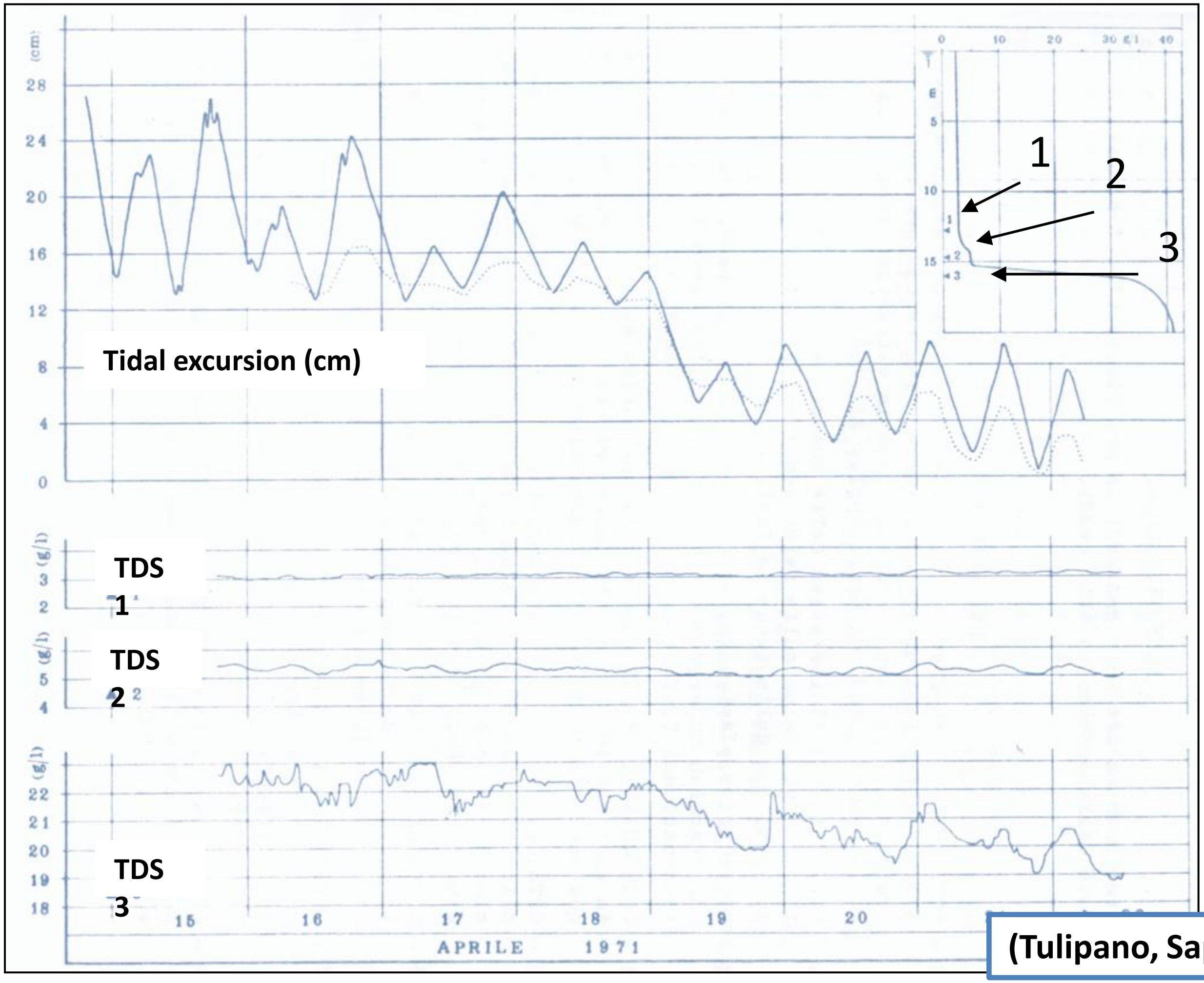
Near the coast, confined conditions



(Tulipano, Sappa, 2000)

Seawater intrusion

EXAMPLES



(Tulipano, Sappa, 2000)

Influence of tidal excursion on transition zone movement near the coastline.

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