Previous Lecture

- **structure of the subsurface**
- **grain size distribution of unconsolidated porous media**
- **subterranean water**
- **questions?**

Today

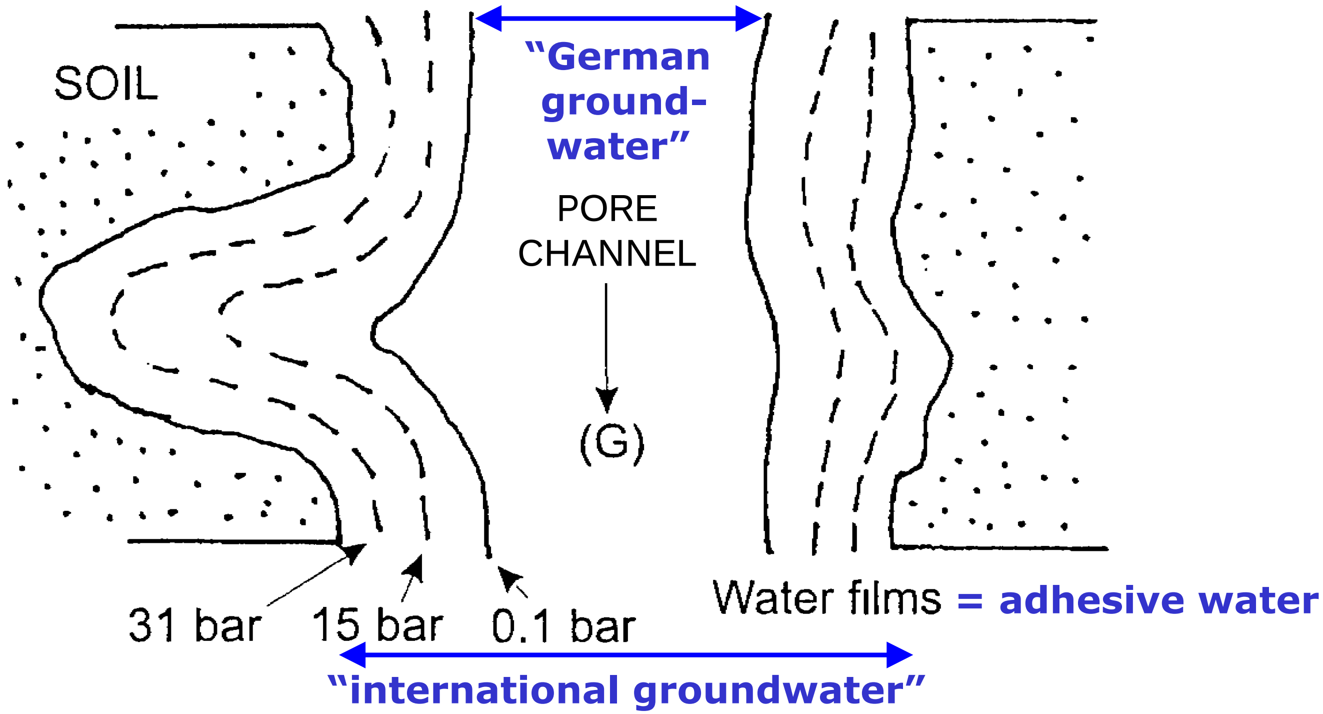
- **groundwater and aquifers**
- **pressure**
- **storage properties**

Groundwater and Aquifers

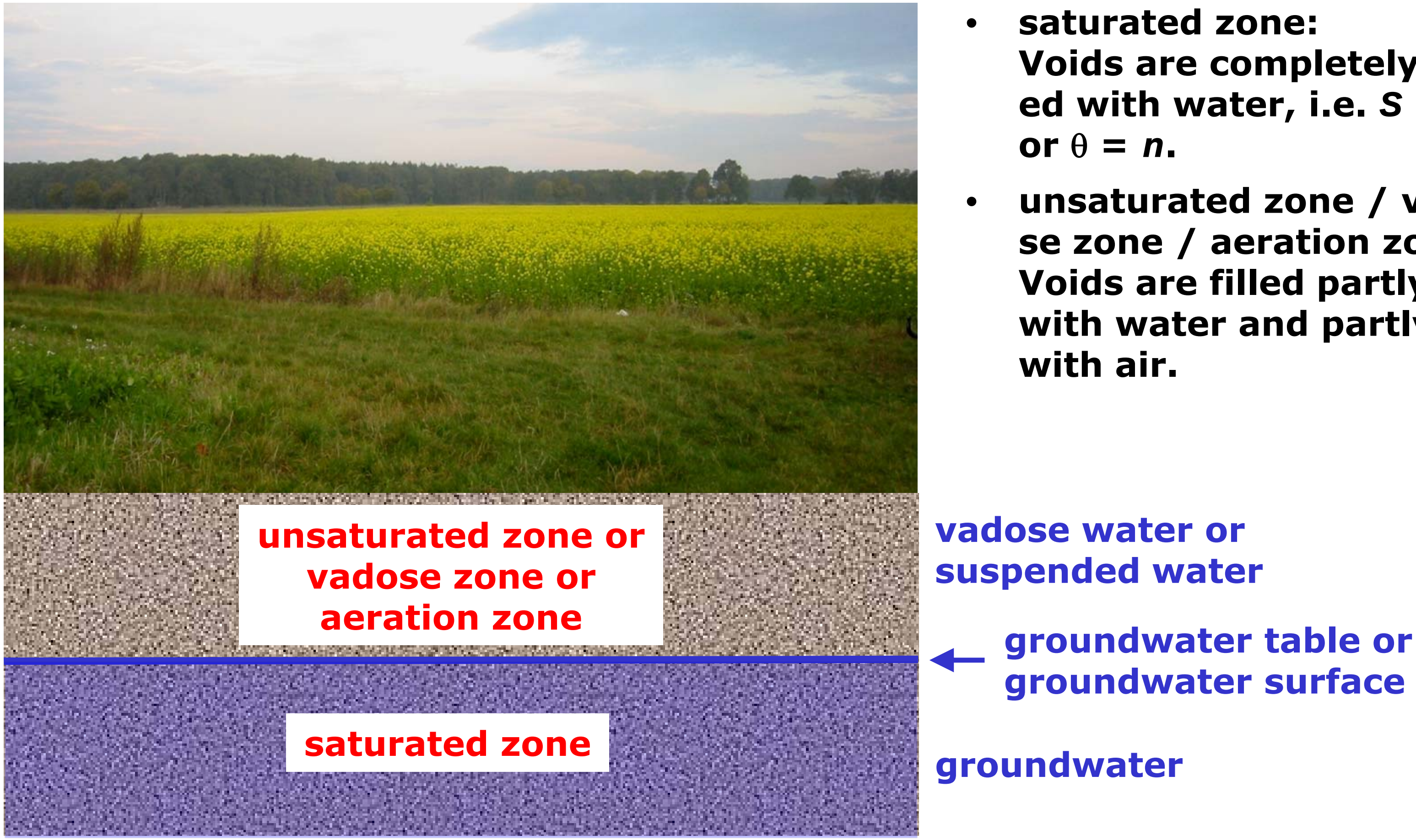
What is Groundwater?

<u>Groundwater</u> = subterranean water which

- **completely fills the pore space**
- **and – in Germany! – is not subject to other forces than gravity.**



Schematic Overview



- **saturated zone:**
  Voids are completely fill-ed with water, i.e. *S* = 1 or $\theta = n$.
- **unsaturated zone / vado-se zone / aeration zone:**
  Voids are filled partly with water and partly with air.

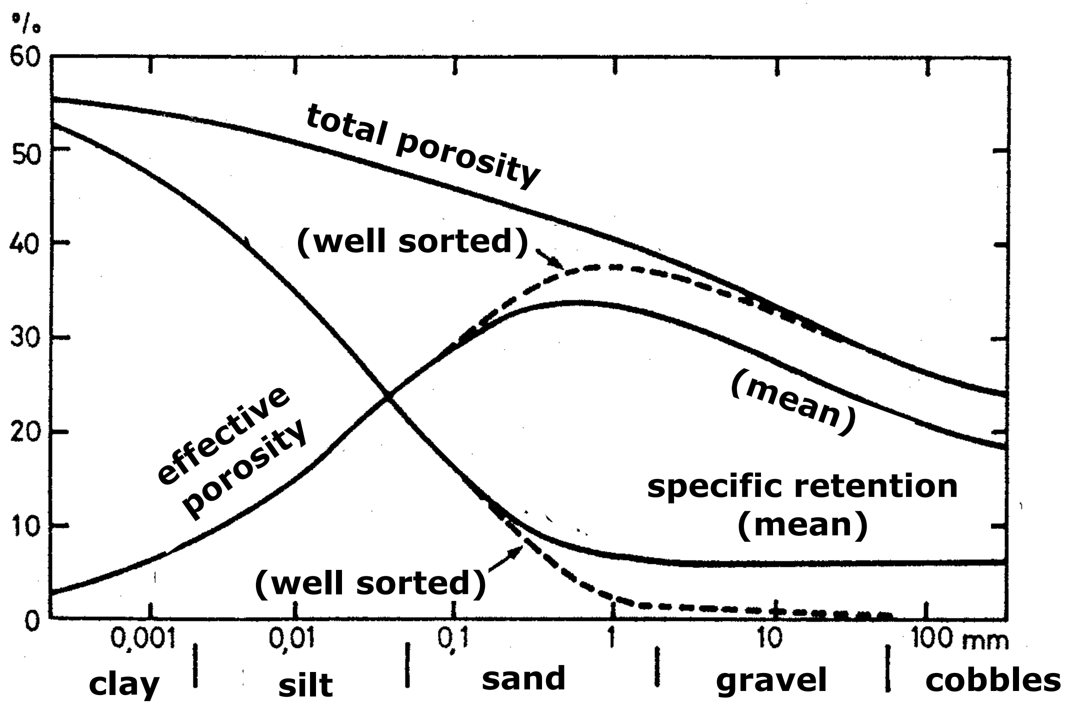
Effective Porosity

- **Adhesive water does not participate in water movement. The same is true for water in isolated pores or in dead-end pores.**
- **<u>immobile water</u> = subterranean water not participating in water movement**
- **<u>mobile water</u> = subterranean water participating in water movement**
- **The volumetric share of voids which can be occupied by mobile water is termed <u>effective porosity</u> or <u>flow-through porosity</u>:**

$$n_e = \frac{V_{v,m}}{V_T}$$

Effective vs. Total Porosity

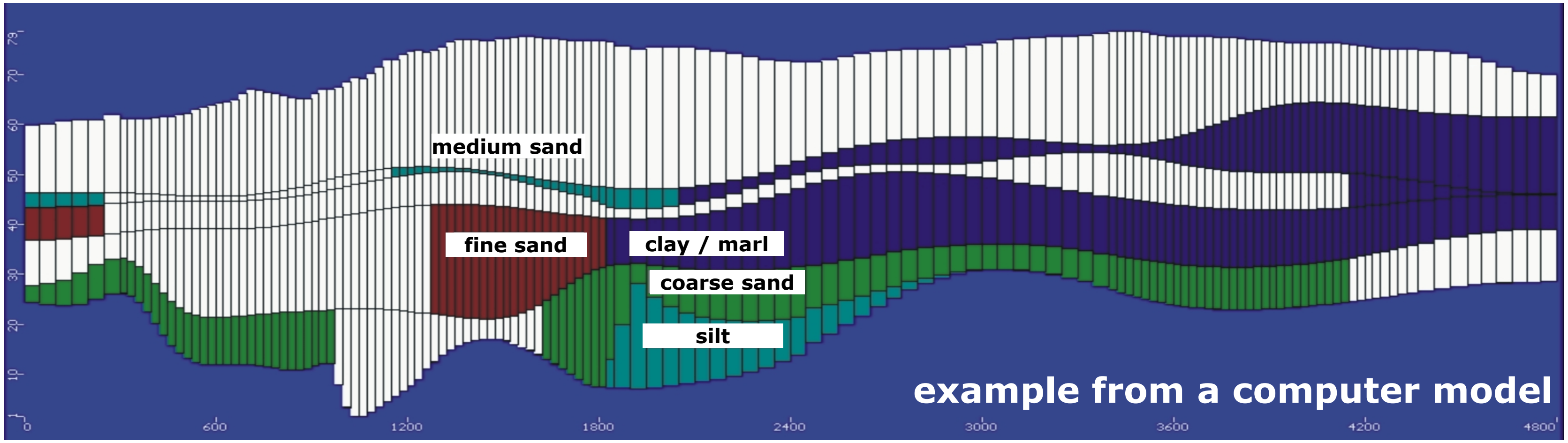
- **Effective porosity cannot exceed total porosity, i.e. $n_e \leq n$.**
- **The difference $n - n_e$ is termed <u>specific retention</u> or <u>field capacity</u>.**
- **Specific retention is the volumetric share of water which is retained in the porous medium after drainage due to gravitation.**



Aquifer, Aquitard, Aquiclude, Aquifuge

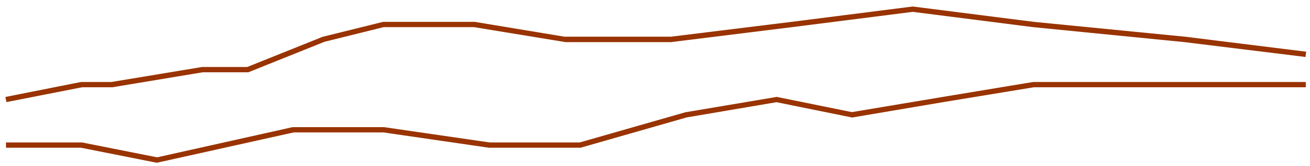
Subterranean formations can be classified by the capability to store and / or transmit groundwater under natural conditions:

- **An aquifer or a groundwater reservoir can store and transmit significant (= exploitable) amounts of groundwater.**
- **An aquitard can store and transmit groundwater but to a much lesser extent than an (adjacent) aquifer.**
- **An aquiclude can store groundwater but cannot transmit groundwater.**
- **An aquifuge can neither store nor transmit groundwater.**

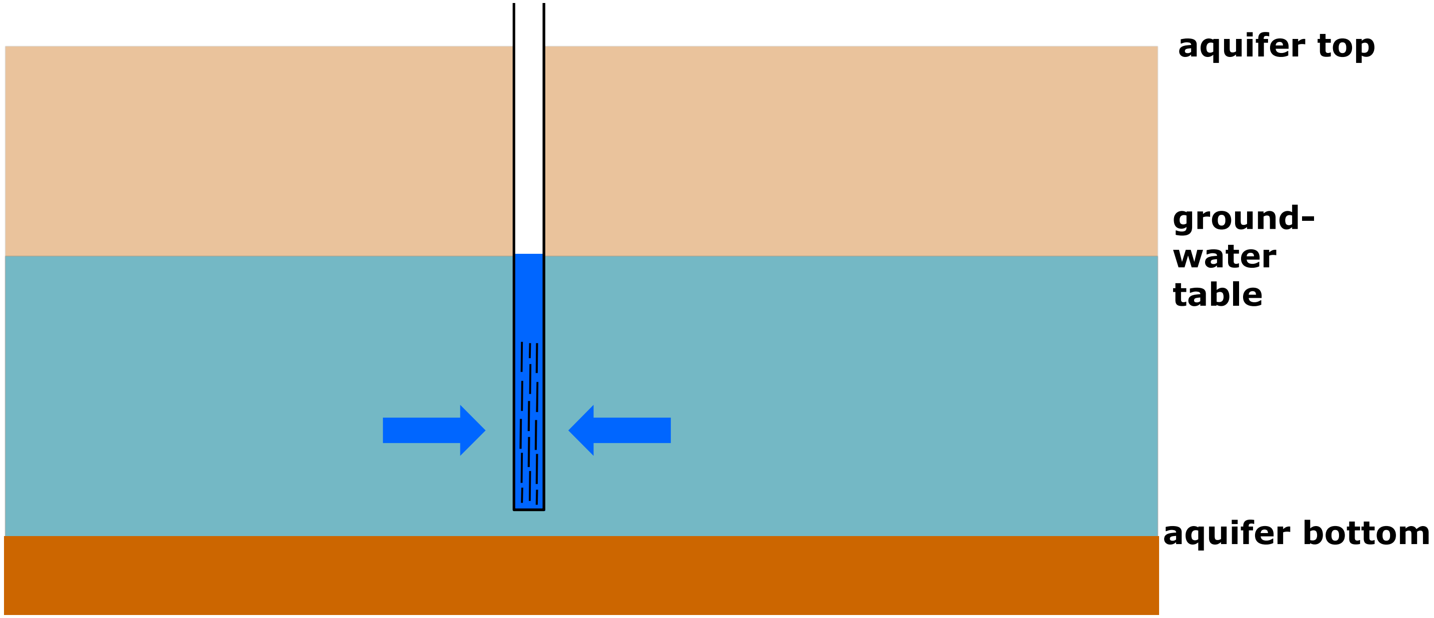


Top, Bottom, and Thickness

- **Aquifers usually appear as "layers", i.e. their lateral extent is rather large as compared to their vertical extent (maybe 10 – 100 km vs. 10 – 100 m).**
- **The upper aquifer boundary is called <u>aquifer top</u>; the lower boundary is called <u>aquifer bottom</u>.**
- **The vertical distance between aquifer top and aquifer bottom is called <u>aquifer thickness</u>.**
- **Upper and lower aquifer boundaries do not have to be horizontal and the thickness may be spatially variable.**
- **Schematic example (vertical cross section):**

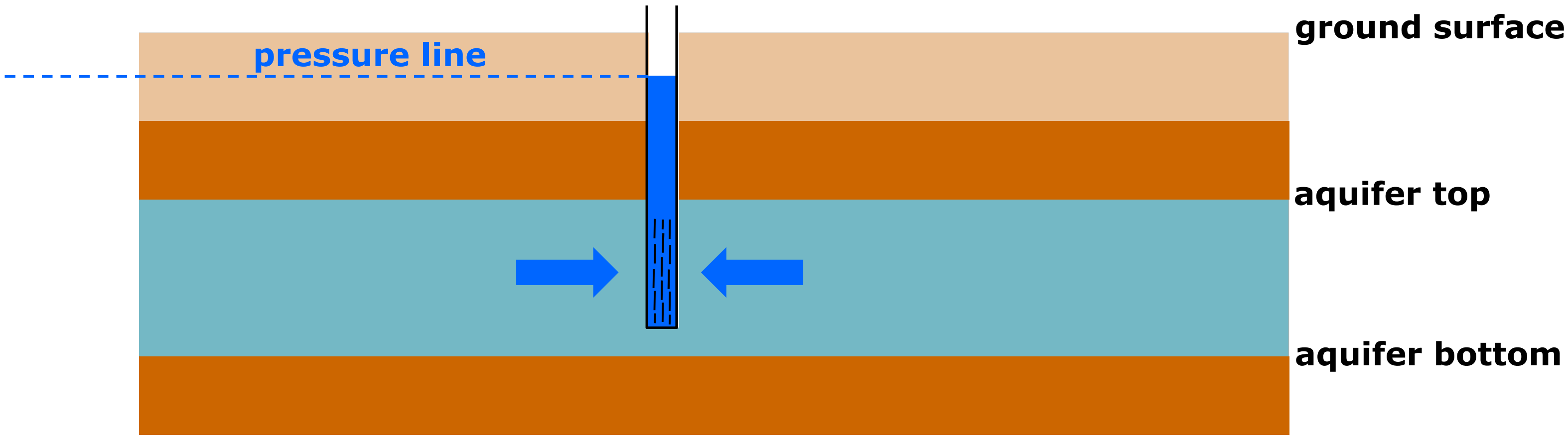


Unconfined Aquifer / Groundwater



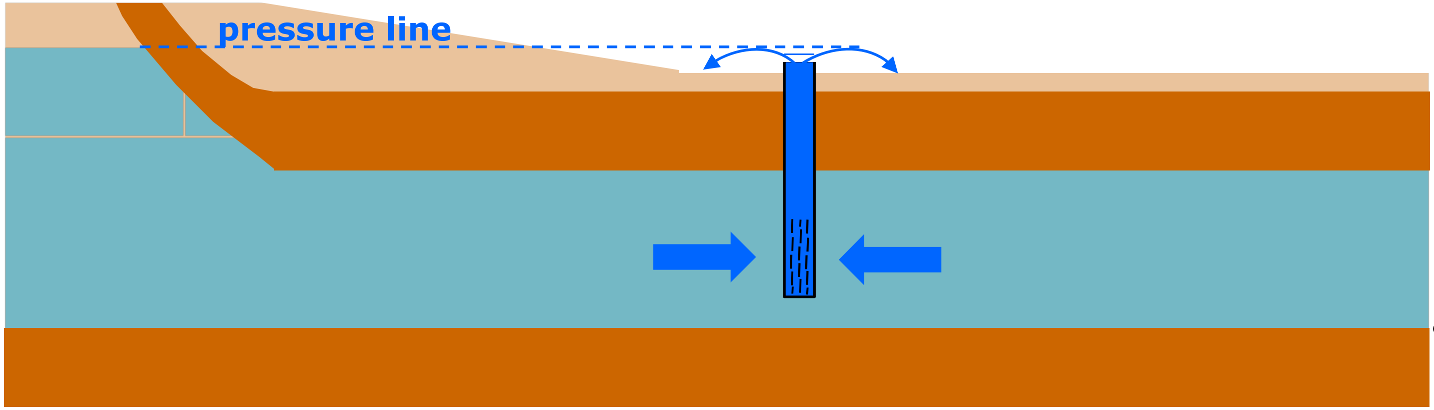
- **Groundwater or an aquifer is termed unconfined (phreatic), if the groundwater does not extend up to the aquifer top.**
- **The position of the groundwater table is therefore changed during water injection or extraction ("free" groundwater table).**
- **Water in a borehole rises up to the groundwater table.**

Confined Aquifers / Groundwater



- **Groundwater or an aquifer is termed <u>confined</u>, if the aquifer contains groundwater throughout its entire thickness.**
- **The pore space remains completely water filled during water injection or (moderate) extraction.**
- **This requires a low permeable cover layer. In addition, the groundwater recharge area must be located at higher altitude than the aquifer top.**
- **The elevation of the groundwater table in the recharge area defines the position of the confined aquifer's <u>pressure line</u>.**
- **Water in a borehole rises up to the pressure line, i.e. higher than the elevation of the aquifer top.**

Artesian Groundwater



- **<u>Artesian groundwater</u> is confined groundwater with the pressure line above ground surface.**
- **Water in a borehole rises up to the ground surface and then forms a fountain.**
- **Artesian springs and Artesian wells are based on this principle.**

Spring chamber (up) for the Artesian well (right) at Albertplatz, Dresden

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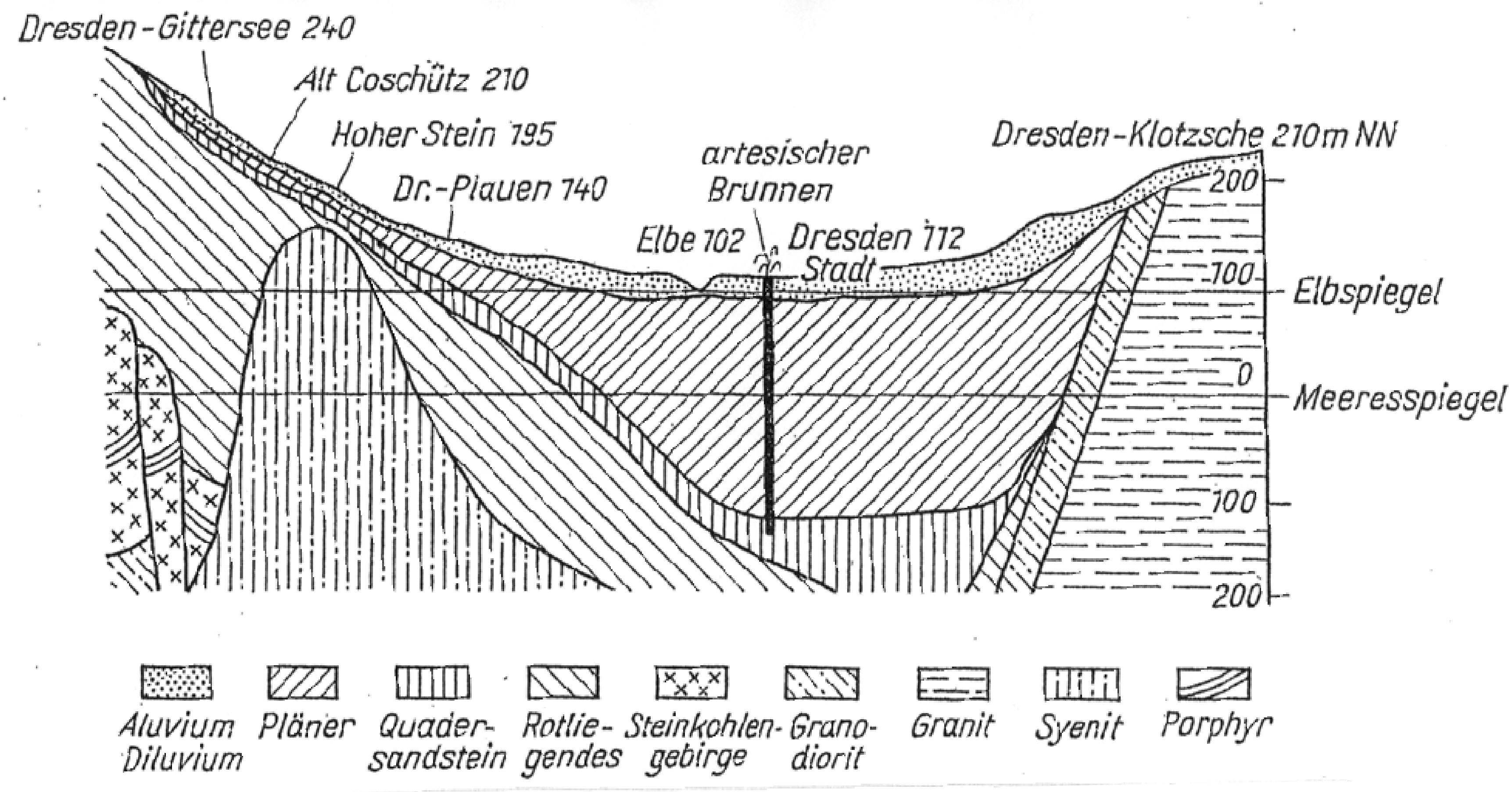
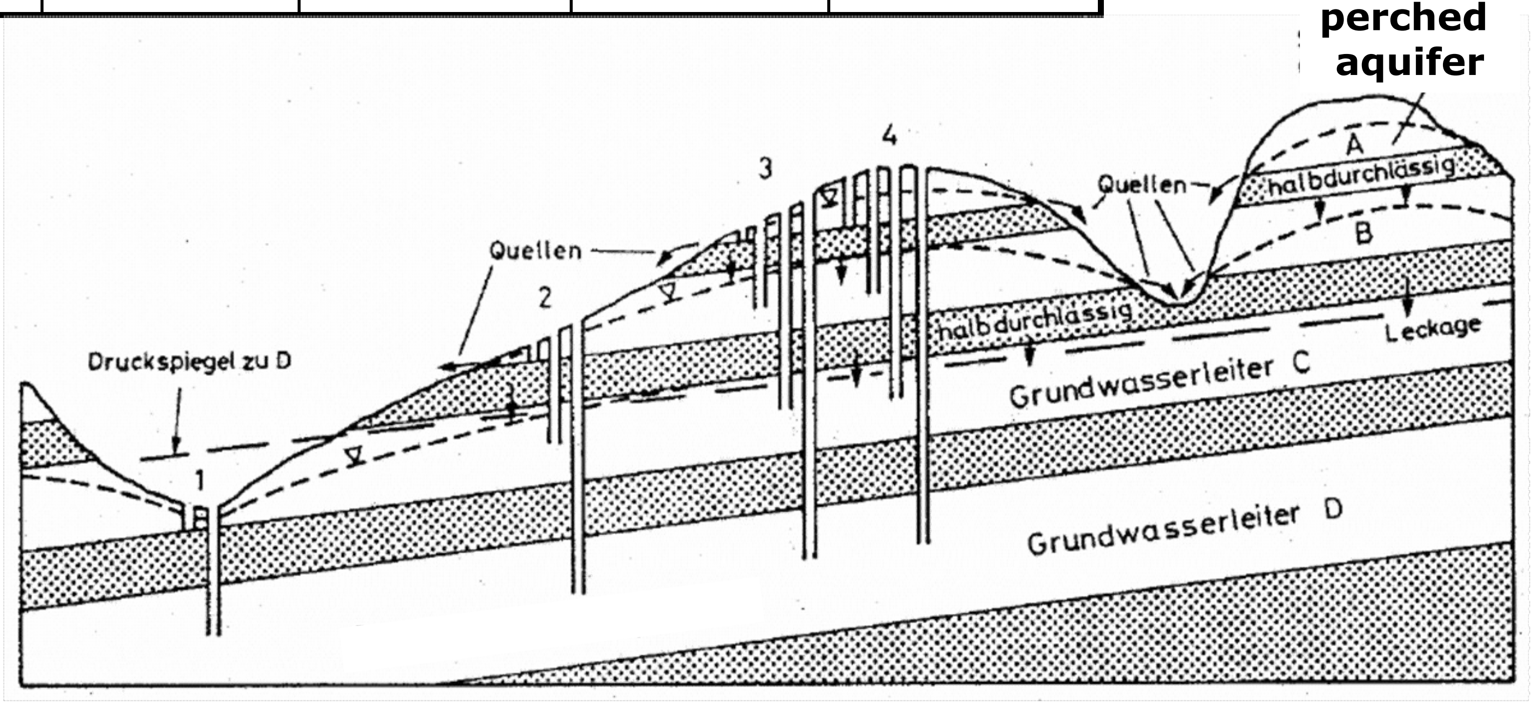
Subsurface Underneath Dresden



Example

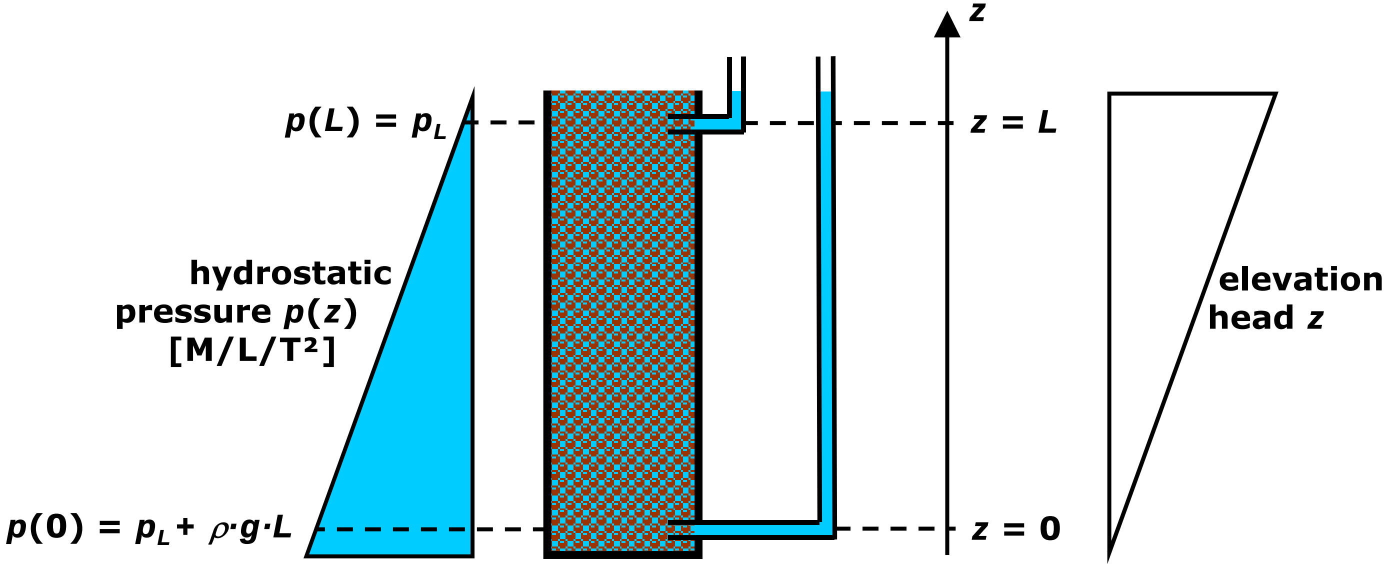
Aquifer	Obs. point 1	Obs. point 2	Obs. point 3	Obs. point 4
A	---	---		
B	---			
C				
D				



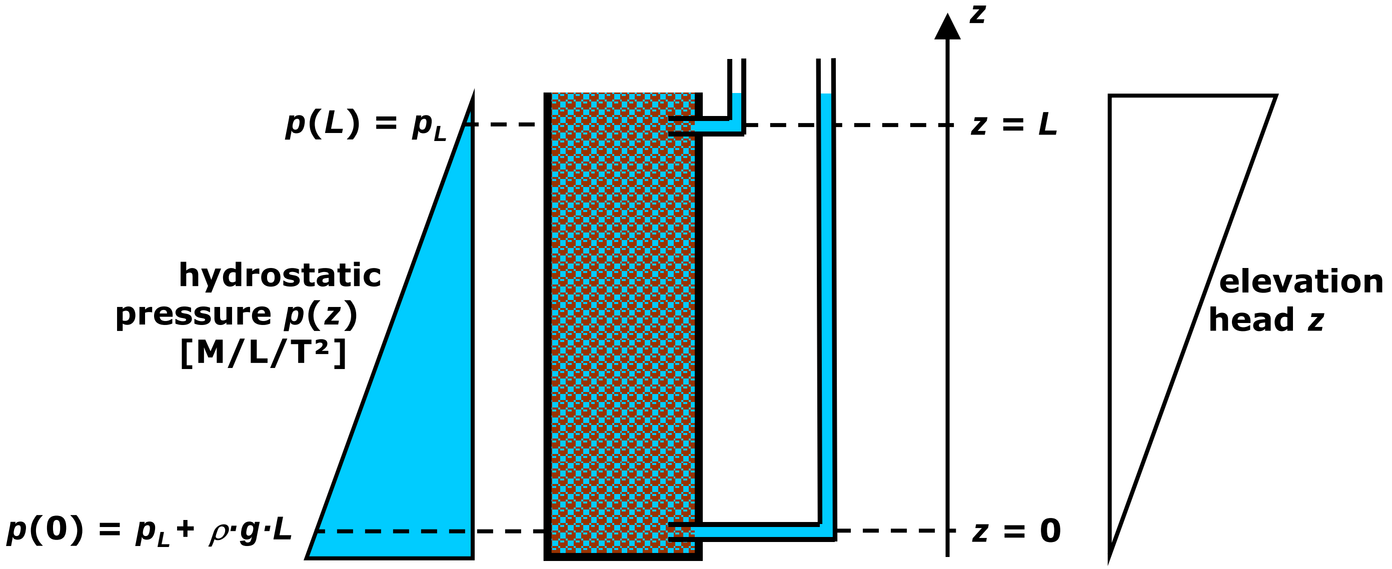
Pressure

Hydrostatic Pressure I

- **Lets consider a vertical column containing a porous medium and water filling the voids completely. The bottom of the column is closed and the water therefore does not move.**
- **There are two observation points for hydrostatic pressure *p* at elevation $z = 0$ and $z = L$, respectively.**

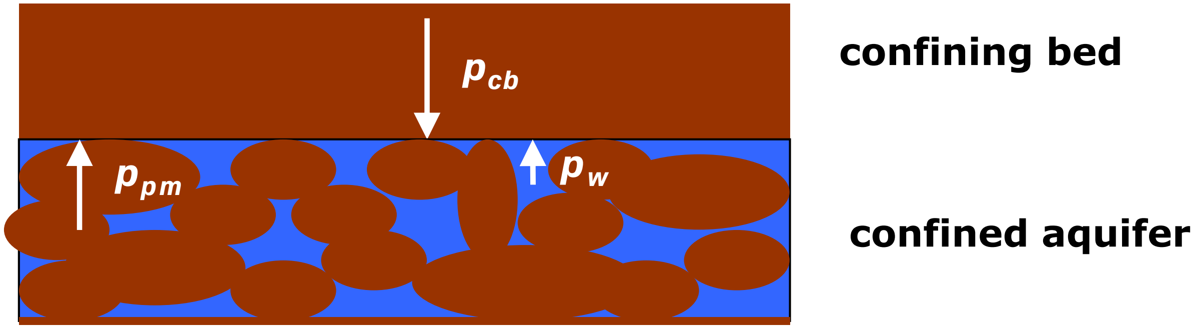


Hydrostatic Pressure II



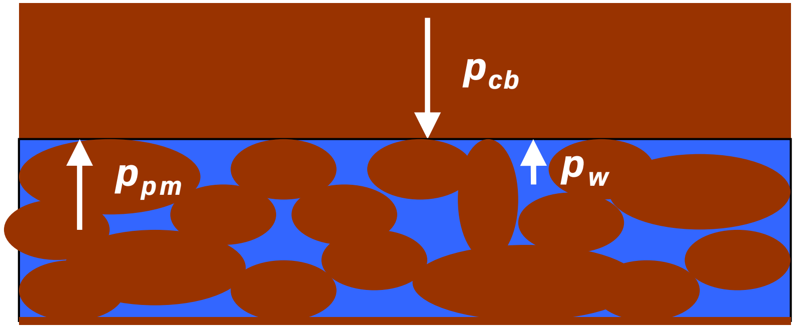
- **Hydrostatic pressure p linearly increases with depth.**
- **In the above setup we have: $p(z) = p_L + \rho \cdot g \cdot (L-z)$**
- **Pressure difference between the observation points:**
  $\Delta p = p(L) - p(0) = p_L - (p_L + \rho \cdot g \cdot L) = -\rho \cdot g \cdot L$
- **There is a pressure difference but no water flow!**

Pressure in a Confined Aquifer



- **The confining bed exerts a certain pressure p_{cb} on the aquifer.**
- **This pressure is compensated partly by the porous medium and partly by the groundwater (pressures p_{pm} and p_w, respectively).**
- **Thus: $p_{cb} + p_{pm} + p_w = 0$**
- **Storage properties of the aquifer and associated parameters can be understood by considering pressure changes.**

Change in Hydrostatic Pressure



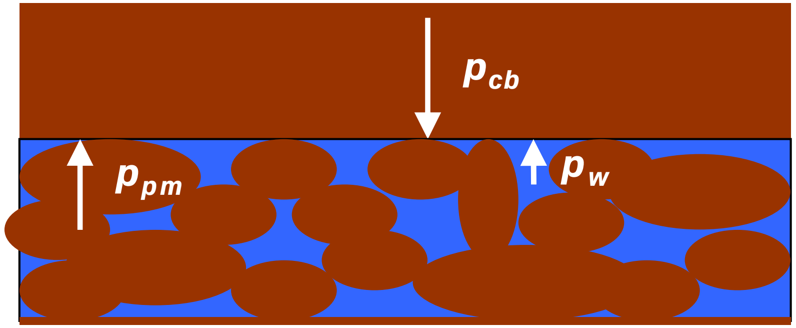
confining bed

$$p_{cb} + p_{pm} + p_w = 0$$

confined aquifer

- **Lets consider a change in hydrostatic pressure Δp_w due to injection or release of groundwater.**
- **From the above equation: $\Delta p_{cb} + \Delta p_{pm} + \Delta p_w = 0$**
- **Hydrostatic pressure changes do not affect the weight of the confining bed and the exerted downward pressure remains unchanged.**
- **Thus we have $\Delta p_{cb} = 0$ and consequently $\Delta p_{pm} = -\Delta p_w$.**
- **This implies that an increase / a decrease of hydrostatic pressure automatically results in a decrease / an increase in the pressure exerted by the porous medium.**

Hydrostatic Pressure and Water Volume



confining bed

$\Delta p_{pm} = -\Delta p_w$

confined aquifer

- **The change in hydraulic pressure will have two effects with regard to water volume.**
- **First, the hydraulic pressure change Δp_w directly leads to expansion / compression of water and the water volume is accordingly increased / decreased.**
- **Secondly, the opposite change $\Delta p_{pm} = -\Delta p_w$ leads to compression / expansion of the porous medium as a whole (not the individual grains!). This, in turn, results in a reduced / an enlarged pore space such that the stored water volume is decreased / increased.**
- **Both effects contribute to aquifer storage properties (see next section).**

Storage Properties

Change in Water Volume Invoked by Δp_w

- **The change in water volume due to a change in hydrostatic pressure is abbreviated by ΔV_w'.**
- **Relative changes in water volume, ΔV_w'/V_w, are proportional to Δp_w:**

$$\frac{\Delta V_w'}{V_w} = \alpha_w \cdot \Delta p_w$$

- **An increase / a decrease in hydrostatic pressure results in an inflow / outflow of water (compression / expansion of the water *already present*!).**
- **The compressibility of water is roughly $4.4 \cdot 10^{-10}$ m²/N.**
- **The above equation can be rearranged to yield**

$$\Delta V_w' = \alpha_w V_w \Delta p_w = n \alpha_w V_T \Delta p_w = n \alpha_w V_T \rho_w g \Delta \psi$$

Change in Total Volume Invoked by Δp_{pm}

- **A change Δp_{pm} in the pressure exerted by the porous medium on the confining layer results in a decrease / an increase ΔV_T in total aquifer volume (see previous section).**
- **Both quantities are proportional to each other via**

$$\frac{\Delta V_T}{V_T} = -\alpha_{pm} \cdot \Delta p_{pm}$$

- **The compressibility of the porous medium is roughly 10^{-10} – 10^{-8} m²/N for gravel, 10^{-9} – 10^{-7} m²/N for sand, and 10^{-8} – 10^{-6} m²/N for clay.**
- **The above equation can be rearranged to yield**

$$\Delta V_T = -\alpha_{pm} V_T \Delta p_{pm} = \alpha_{pm} V_T \Delta p_w = \alpha_{pm} V_T \rho_w g \Delta \psi$$

- **ΔV_T represents a change in volume of the porous medium as a whole. It is composed of a change in volume ΔV_s of the solids (which is negligible!) and another change ΔV_w'' in water volume, i.e.**

$$\Delta V_T = \Delta V_s + \Delta V_w'' \approx \Delta V_w''$$

Change in Water Volume Invoked by Δp_{pm}

- **From**

$$\Delta V_T = \alpha_{pm} V_T \rho_w g \Delta \psi$$

and

$$\Delta V_T = \Delta V_w''$$

we can immediately derive

$$\Delta V_w'' = \alpha_{pm} V_T \rho_w g \Delta \psi$$

- **As mentioned above, ΔV_w'' denotes the change in water volume due to an increase / a decrease of pressure p_{pm} in the porous medium.**
- **A decrease of pressure in the porous medium leads to an expansion of the porous medium and an associated increase in water volume (enlarged pore space).**
- **An increase in pressure in the porous medium leads to a compression of the porous medium and an associated decrease in water volume (reduced pore space).**

Total Change in Water Volume

- **The total change ΔV_w in water volume consists of both effects caused by pressure changes Δp_w and Δp_{pm}.**
- **Therefore we have $\Delta V_w = \Delta V_w' + \Delta V_w''$.**
- **Using the results derived before, we can express how ΔV_w depends on changes $\Delta\psi$ in pressure head:**

$$\Delta V_w = \Delta V_w' + \Delta V_w'' = n\alpha_w V_T \rho_w g \Delta\psi + \alpha_{pm} V_T \rho_w g \Delta\psi$$

Specific Storage

- **Specific storage S_s is defined as the volume of water that is released from a unit aquifer volume if hydrostatic pressure head is reduced by one unit:**

$$S_s = \frac{\Delta V_w}{V_T \cdot \Delta \psi}$$

- **The dimension of specific storage is 1/L.**
- **Both impacts on water volume discussed before have to be considered in order to quantify ΔV_w in the above equation:**

$$\Delta V_w = n \alpha_w V_T \rho_w g \Delta \psi + \alpha_{pm} V_T \rho_w g \Delta \psi$$

- **Specific storage can therefore also be expressed as**

$$S_s = \left(n \alpha_w + \alpha_{pm} \right) \rho_w g$$

- **Typical values for specific storage range from 10^{-6} 1/m (e.g. gravel) to 10^{-2} 1/m (e.g. clay).**

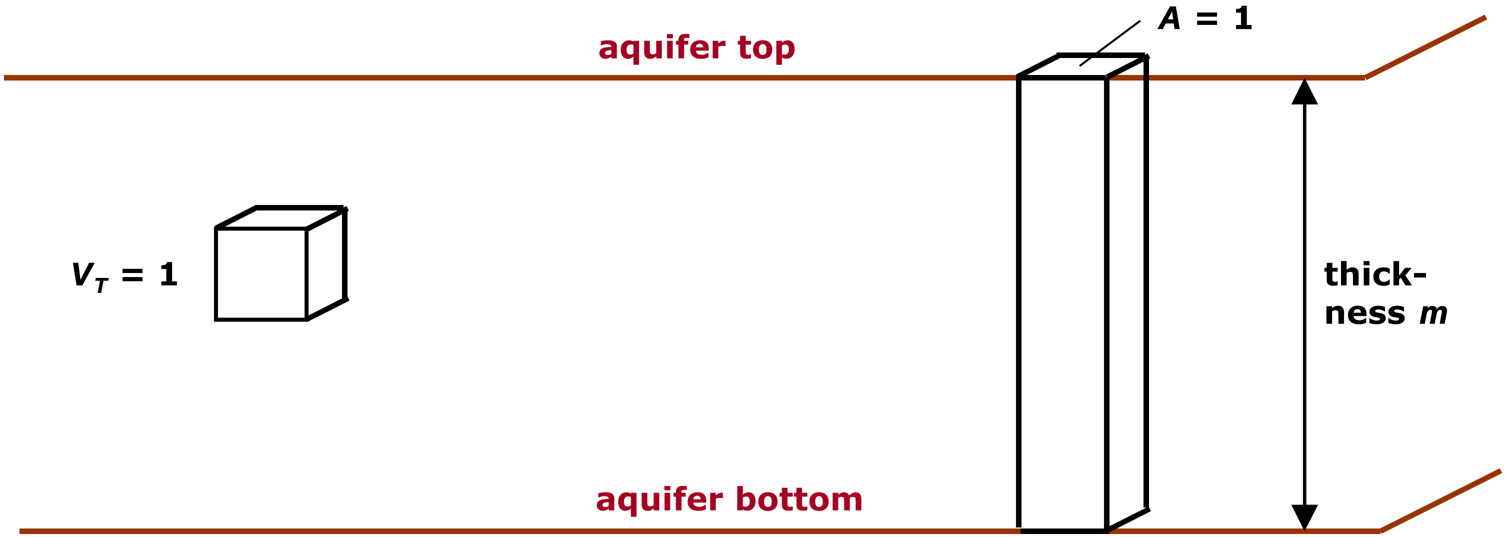
Storativity (Confined Aquifers)

- **Due to their relatively large lateral extent, aquifers are mostly considered as spatially two-dimensional (2D) systems.**
- **In this case, specific storage S_s is replaced by the storativity or storage coefficient S.**
- **For confined aquifers S is simply obtained by multiplying S_s by the aquifer thickness m:**

$$S = S_s \cdot m$$

- **Storativity can be interpreted as the volume of water released from an aquifer volume extending from the aquifer bottom up to the aquifer top over a unit area if the hydrostatic pressure is reduced by one unit.**
- **Storativity is dimensionless.**

Reference Volumes (Confined Aquifer)



The reference volume for defining specific storage S_s is a unit cube (e.g. V_T = 1 m³).

The reference volume for defining storativity S is a cuboid extending from the aquifer bottom to the aquifer top over a unit area (e.g. A = 1 m² and $V_T = A \cdot m$).

Storativity (Unconfined Aquifers)

- **Actually, unconfined aquifers are always treated as 2D systems.**
- **Thus, storativity is used to quantify water storage properties.**
- **The definition of storativity remains unchanged in principle but the considered aquifer volume now extends from the aquifer bottom up to the water table.**
- **For unconfined aquifers, storativity values correspond to effective porosities.**
- **This is explained by the free groundwater table:**
  Pressure changes simply lead to filling or emptying of voids.
- **This is fundamentally different from the storage properties of confined aquifers discussed before:**
  In confined aquifers all voids remain filled with groundwater during pressure changes and storage properties depend on the compressibilities of water and the porous medium.