Introduction to Hydrogeology

Guest Lectures at TTK University of Applied Sciences, Tallinn, Estonia

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Who's Teaching Today?

Andy Louwyck

- Master in Science: Geology

- Doctor in Science: Hydrogeology

- Associate Degree in Programming

- Micro Degree in AI & Data Science

- Lecturer in IT at Vives University of Applied Sciences

- AI Coordinator at Flanders Environment Agency

FLANDERS
ENVIRONMENT AGENCY

Flanders
State of the Art

vives | University of Applied Sciences

Where I Live and Where I Studied

Where I Teach

Informatics Program for Exchange Students

_INFORMATICS (KORTRIJK)

1st semester (Autumn) or 2nd semester (Spring) programme at VIVES Kortrijk

https://www.vives.be/en/commercial-sciences-business-management-and-informatics/informatics-kortrijk

The Informatics-programme is a programme consisting of lectures, group work, visits and projects in the field of Business and Informatics. Evaluation follows the rules of the European Credit Transfer System (ECTS). Incoming students can select a programme of up to 30 ECTS credits per semester.

New full-year program!

Title	ECTS	hours/week S1	hours/week S2	Semester
Introduction to Artificial Intellingence	5	3	0	1
Programming in Python	3	2	0	1
Digital Workplace	3	2	0	1
Android App Development	5	3	0	1
E-business en E-marketing	3	2	0	1
Introduction to linux	3	2	0	1
Cybersecurity	5	3	0	1
Professional and International Communication 3 (English)	3	2	0	1
	30	**19**	**0**	
Machine Learning - Fundamentals	6	0	4	2
IT-Project	5	0	3	2
Power Tools	3	0	3	2
Full-Stack Development in .NET	6	0	4	2
Mobile App Development iOS	5	0	4	2
Data Engineering	5	0	3	2
Node.js Development	3	0	2	2
	33	**0**	**23**	

Let's Dive In!

- What is hydrogeology?

- What is groundwater?

- What is an aquifer?

- How do we measure groundwater levels?

- What is Darcy's law?

- What is the continuity equation?

- What is a pumping well?

- What is groundwater modeling?

- What is an axisymmetric model?

- Demo + exercises

What is Hydrogeology?

= hydor (water) + ge (earth) + logia (study) = the science of **groundwater**

- **Definition:** Hydrogeology is the branch of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust.
- **Focus areas:**
  - Aquifers and groundwater reservoirs
  - Flow dynamics and water quality
  - Interaction with surface water and ecosystems
- **Why is it important?**
  - Drinking water supply
  - Agriculture and industry
  - Environmental protection and sustainability

Groundwater accounts for **97%** of global freshwater resources

Essential to human and economic development

1/3 of the world's drinking water

40% of the world's irrigation water

25% of the world's industrial water

Groundwater-Dependent Ecosystems (GDE)
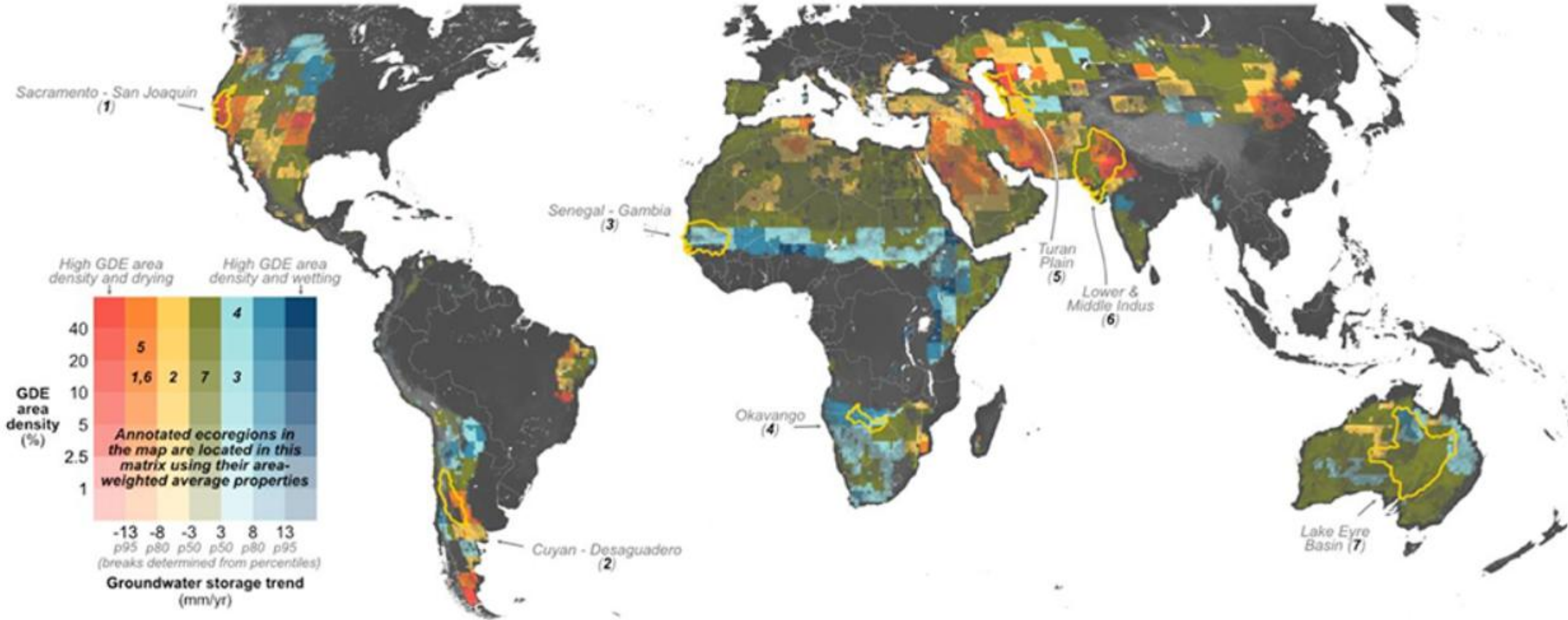
What is Groundwater?

- **Groundwater as part of the hydrosphere:**
  - Water stored beneath the Earth's surface in soil and rock pores
  - Represents a major component of the hydrological cycle

- **Role in the hydrological cycle:**
  - Infiltration from precipitation
  - Storage in aquifers
  - Discharge to rivers, lakes, and oceans

- **Importance:**
 - Largest source of freshwater on Earth (excluding ice)
  - Critical for ecosystems and human use
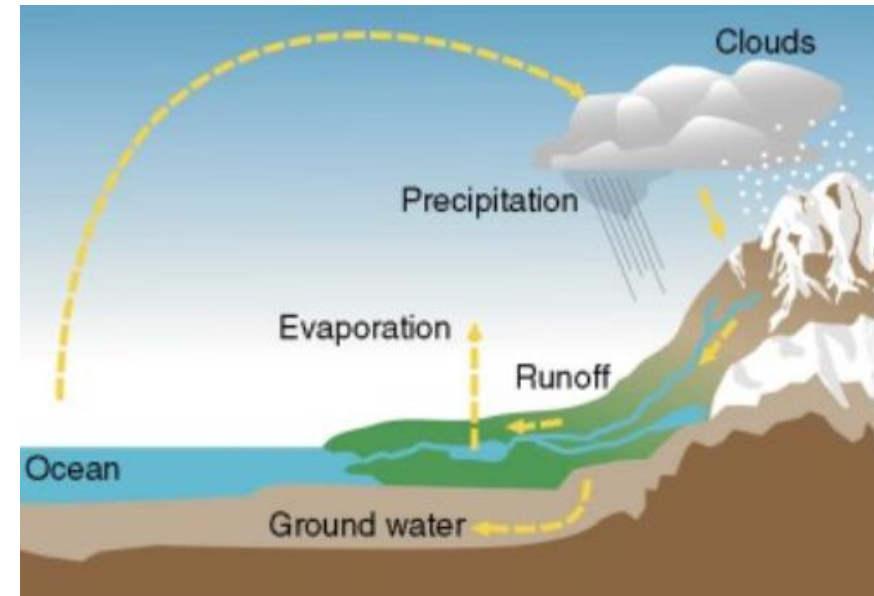
# The Hydrological Cycle (a.k.a. the Water Cycle)
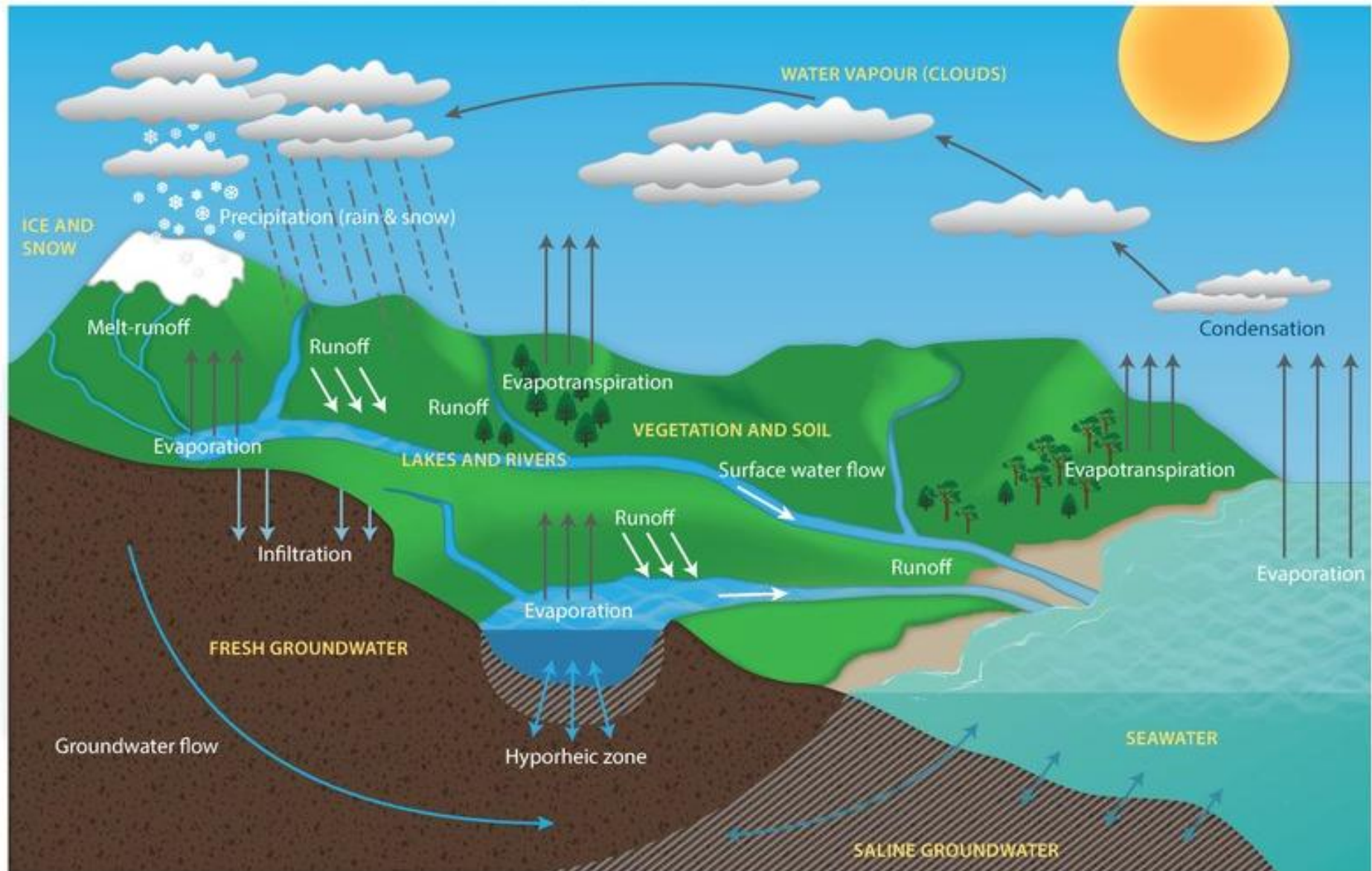
What is an Aquifer?

- **Definition:** An aquifer is a geological formation that can store and transmit groundwater
- **Types of aquifers:**
  - **Unconfined or phreatic**: is not overlain by a less permeable layer, so its upper surface is the water table exposed to atmospheric pressure
  - **Confined**: bounded above and below by less permeable layers, so the groundwater is under pressure and does not directly connect to the atmosphere
- **Other formations:**
  - **Aquitard**: A layer with low permeability that slows down groundwater flow
  - **Aquiclude**: A layer that is essentially impermeable
- **Examples**:
  - **Sand and gravel**: typical aquifer materials
  - **Silt and clay**: often acts as an aquitard
  - **Fractured rock**: can act as an aquifer
 - **Solid rock**: can act as an aquiclude
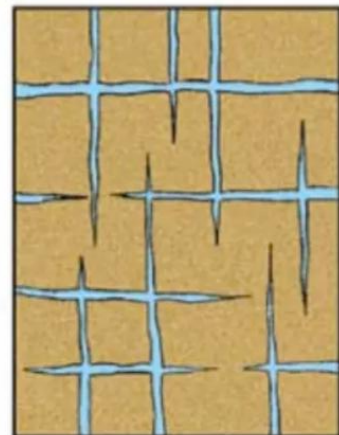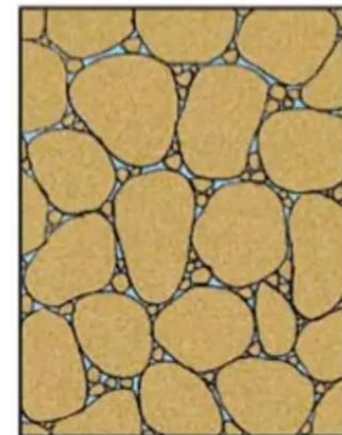
The Groundwater Reservoir
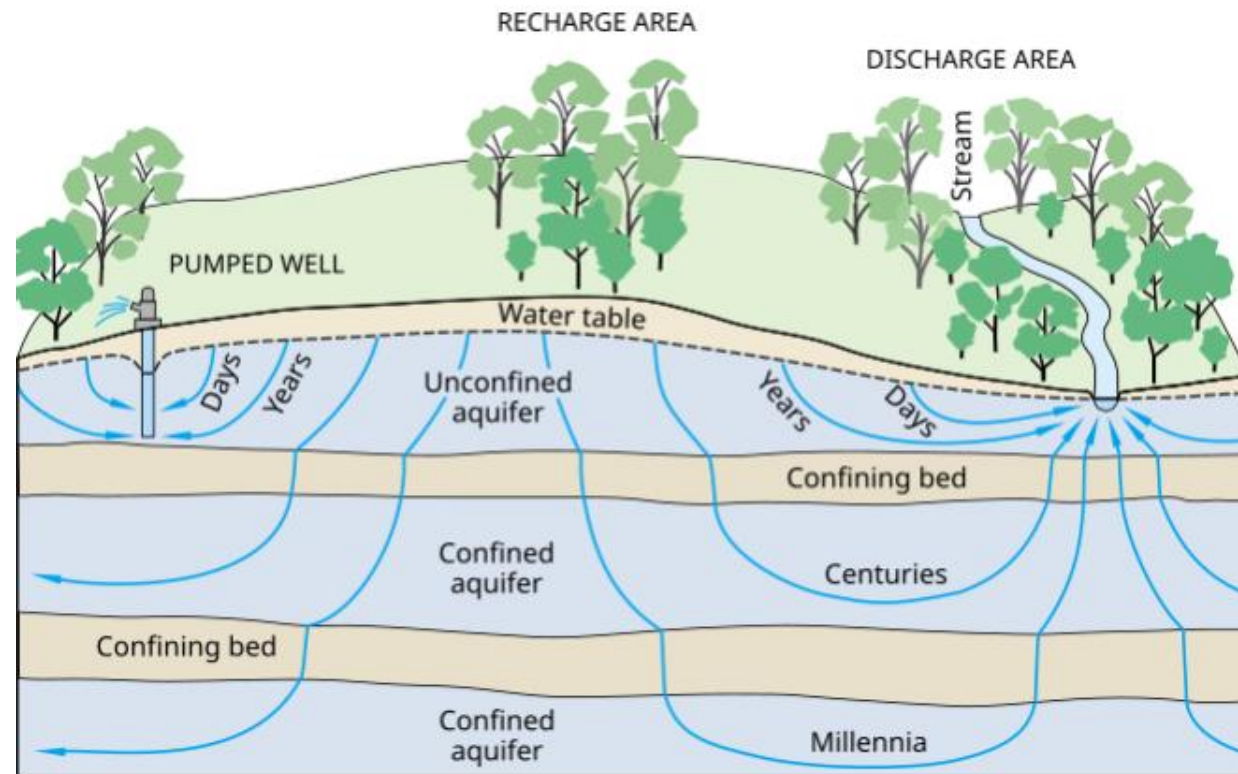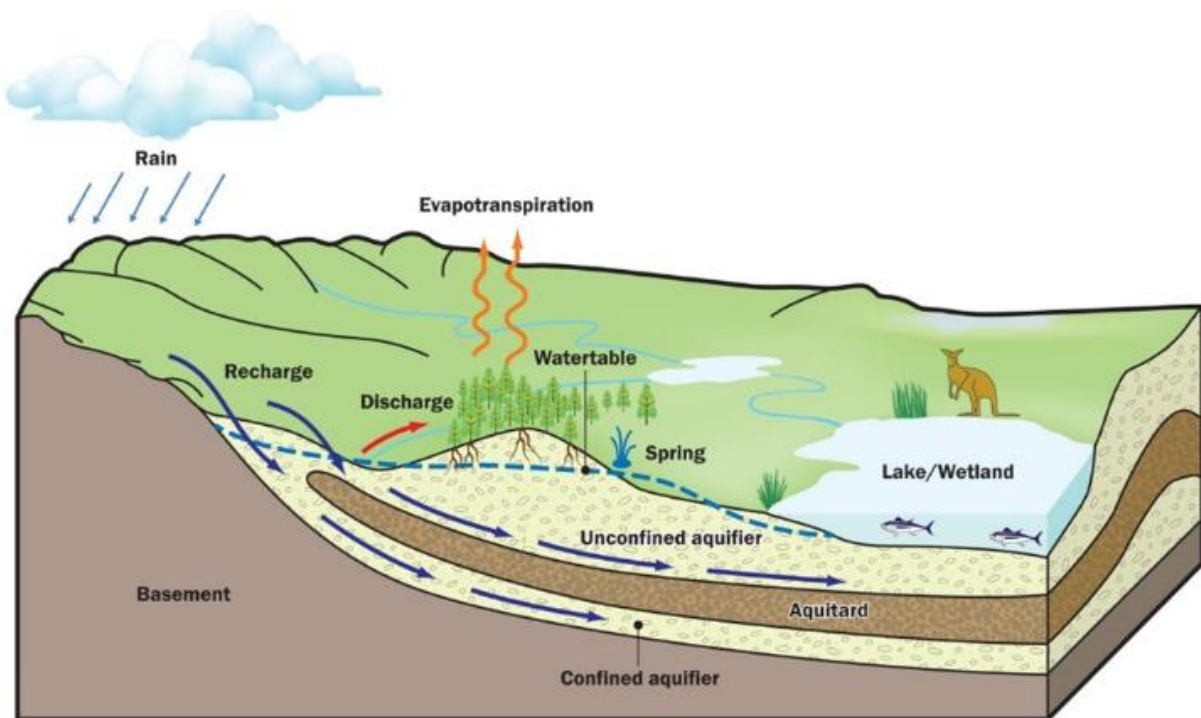
Systems Thinking in Hydrogeology

- **Groundwater Reservoir as an Open System:**
  - Interacts with surface waters, climate, land use, human activities, …
- **Events:**
  - Examples: droughts, contamination incidents, …
  - Measurements: water level monitoring, groundwater sampling, …
- **Patterns:**
  - Long-term trends in groundwater levels, recharge, quality, …
  - AI can help detect patterns (e.g., machine learning, timeseries analysis)
    = black-box models: can predict patterns but do not explain
- **Structures:**
  - Conceptual and mathematical models simulate processes
    = white-box models: explain system behavior, not just predict
- **Mental Models:**
  - Mathematical models support evidence-based groundwater policy
  - Example: Flanders Environment Agency uses computer models for sustainable groundwater management and policy
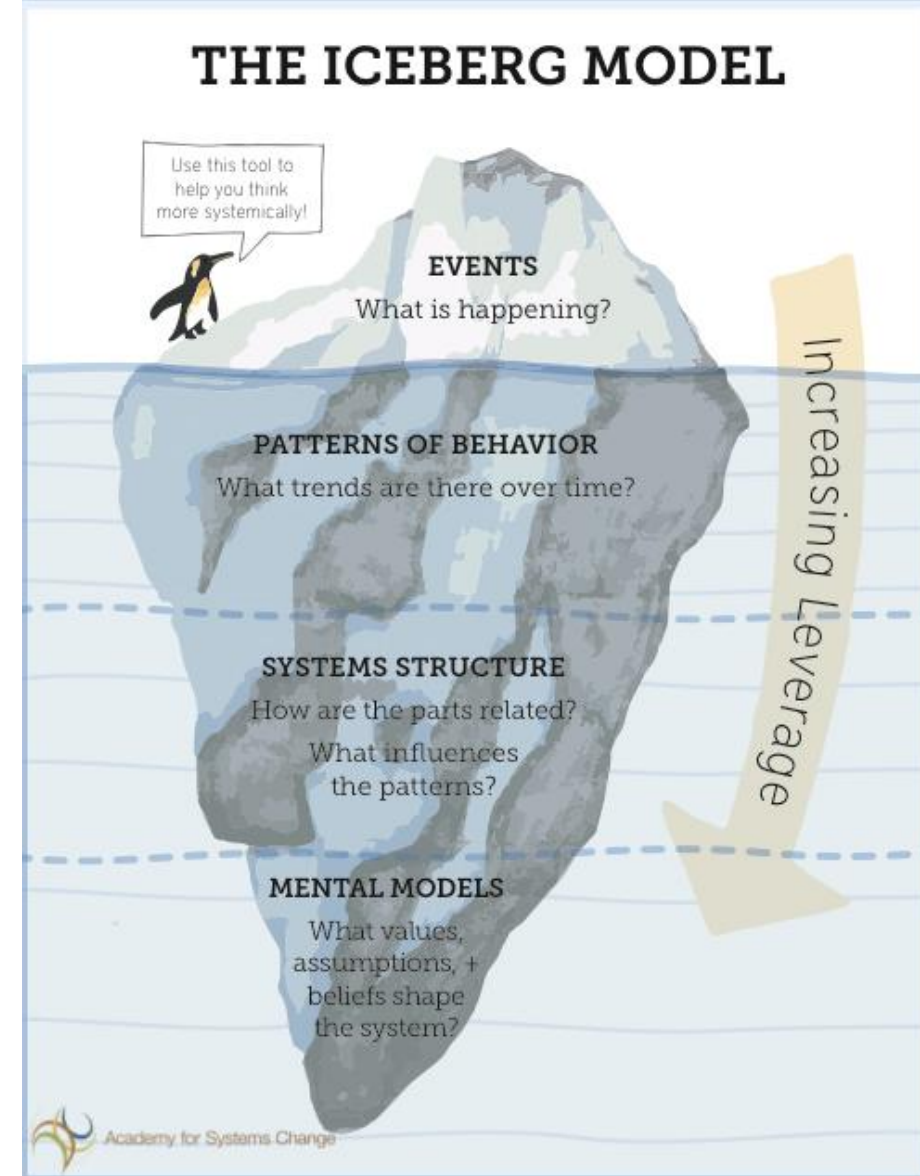
How Do We Measure Groundwater Levels?

- **Hydraulic head:**
  - A measure of the total mechanical energy in groundwater
  - Expressed as height (meters)
  - Combines elevation head and pressure head
- **Why is it important?**
  - Indicates groundwater flow direction (from high head to low head)
  - Used to map water tables and design wells
- **How do we measure it?**
  - We use observation wells or piezometers
  - We measure water level relative to a reference point
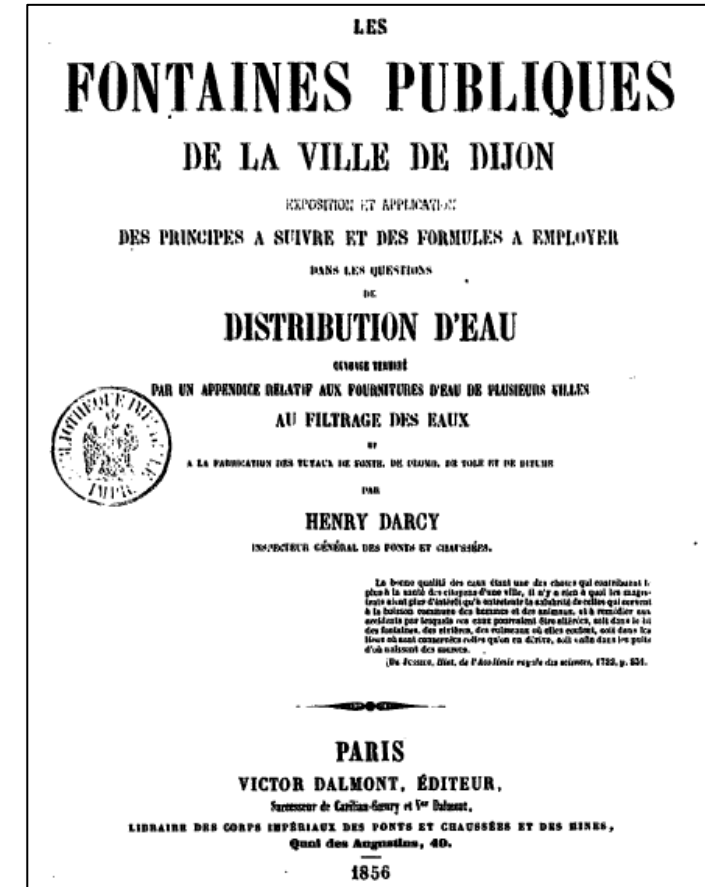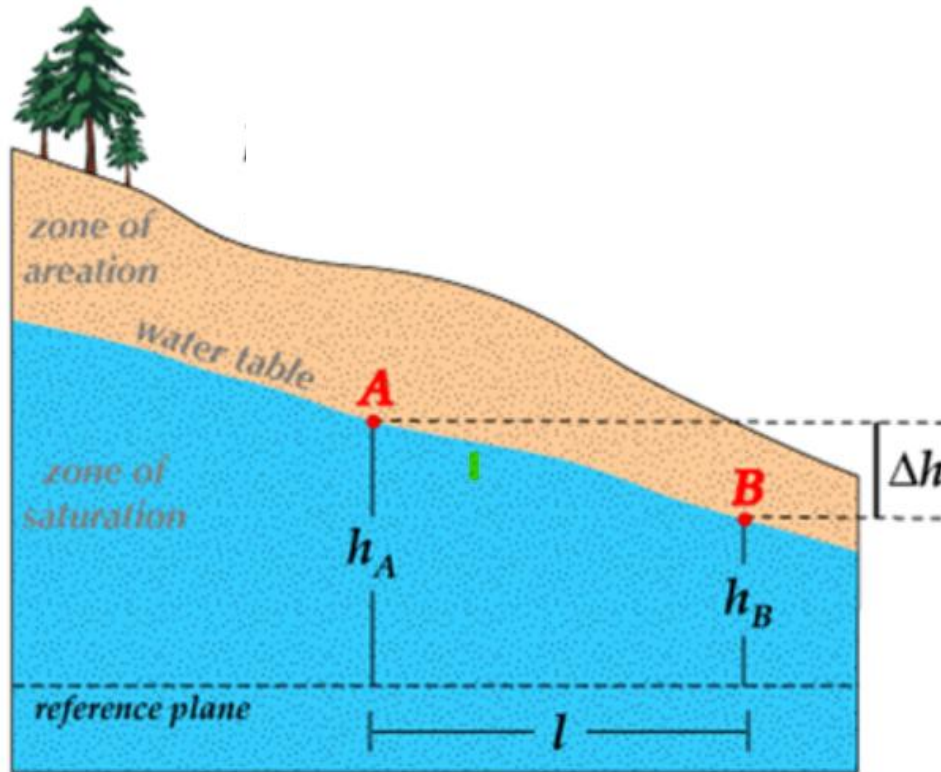
    (usually ground surface or sea level)

TALLINNA
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TTK UNIVERSITY OF APPLIED SCIENCES

Hydraulic Head *h*
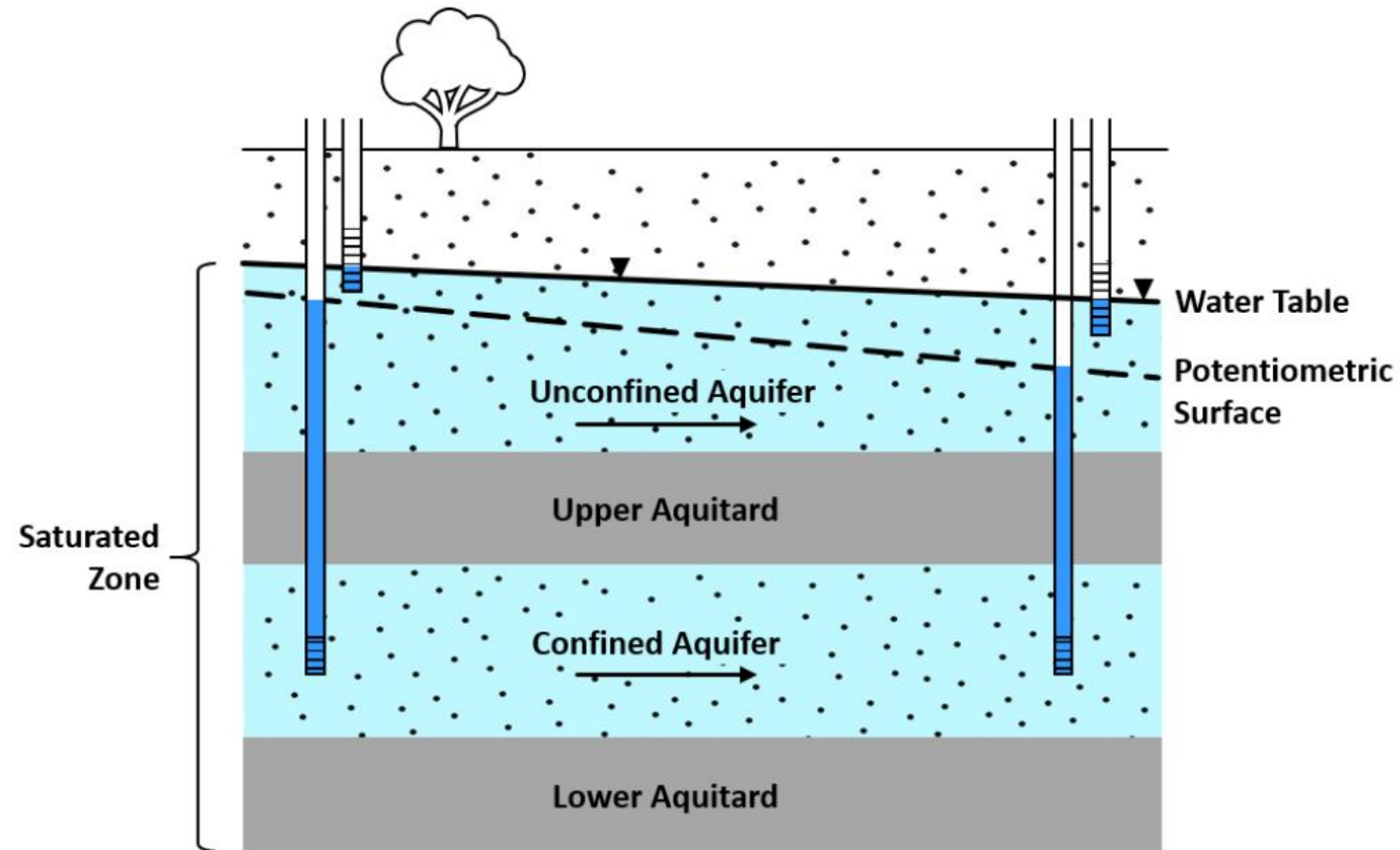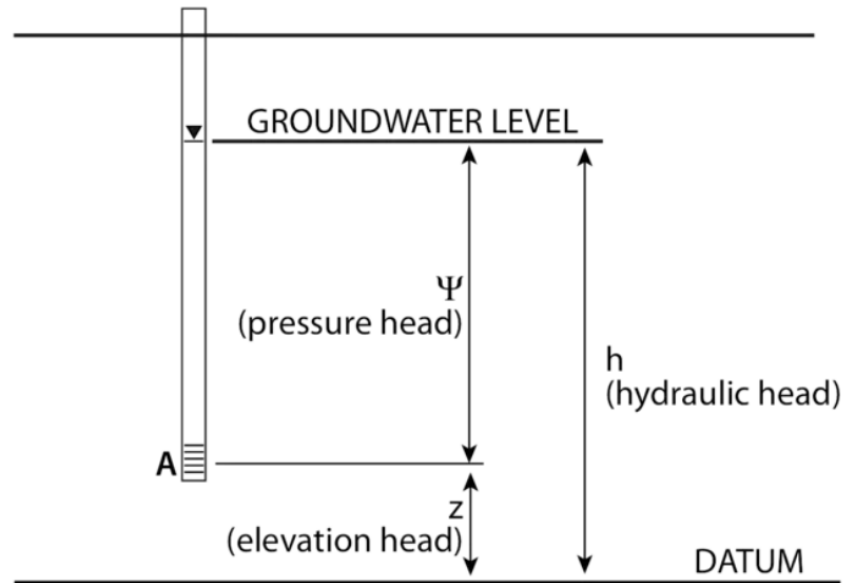
Groundwater Flow and Darcy's Law

Laminar flow in porous media (Darcy, 1856)

$$q \cong -K\frac{\Delta h}{\Delta x} = -K\frac{h_B - h_A}{l}$$

Henry Darcy

The Fundamental Law of Hydrogeology

- **Darcy's law** expresses the fundamental principle in hydrogeoloy
- **Flow rate q** [L/T] of groundwater through a porous medium is directly proportional to the hydraulic gradient **dh/dx** [-] and the hydraulic conductivity **K** [L/T] of the material:

$$q = -K\frac{dh}{dx}$$

- **Hydraulic conductivity K** is a measure of how easily water can move through a porous material, such as soil or rock, under a hydraulic gradient
- **Hydraulic gradient dh/dx** is the slope of the water table or potentiometric surface, representing the change in hydraulic head per unit distance in the direction of flow

Darcy's Law: Example

- $h_A = 50\text{m}$
- $h_B = 40\text{m}$
- $L = 100\text{m}$
- $K = 10\text{m/d}$

- $q = -K\dfrac{h_B - h_A}{L} = -10.\dfrac{40-50}{100} = 1\text{m/d}$

$$\text{hydraulic gradient} = \frac{dh}{dx} = \frac{h_B - h_A}{dx}$$
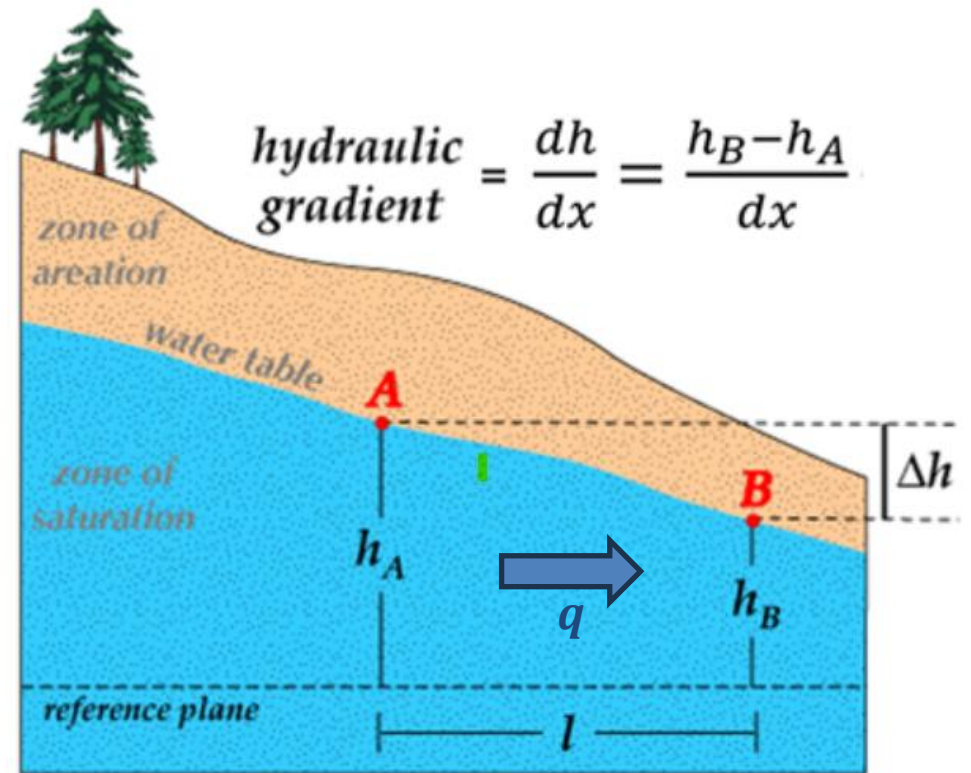
The Continuity Equation

- A mathematical expression of the **law of conservation of mass**
- It states that **mass entering** a system **equals mass leaving**

- In hydrogeology, **water** is nearly **incompressible**
- Therefore, we work with **volumes**
- If **transient**, it also considers **change in storage**

a) **Steady State Conditions**

b) **Transient Conditions**
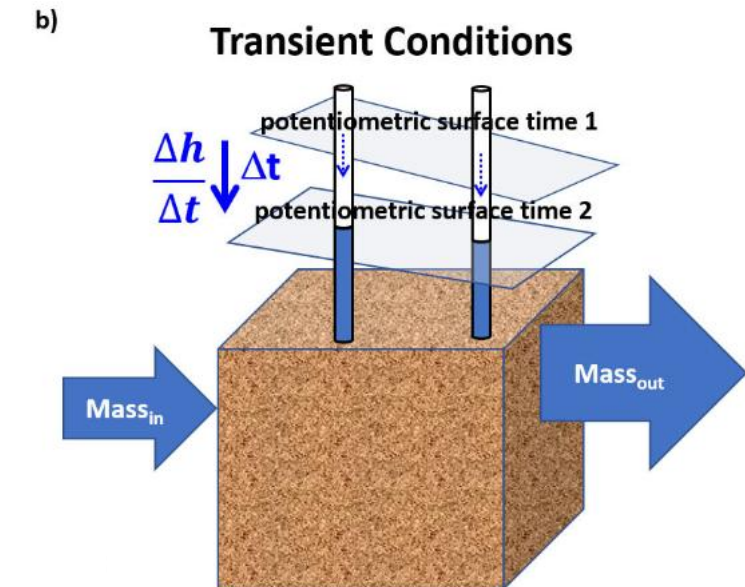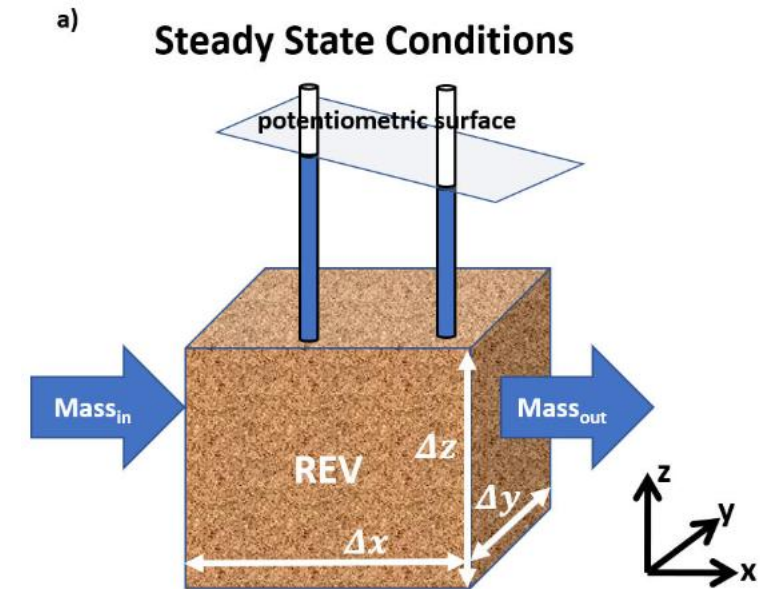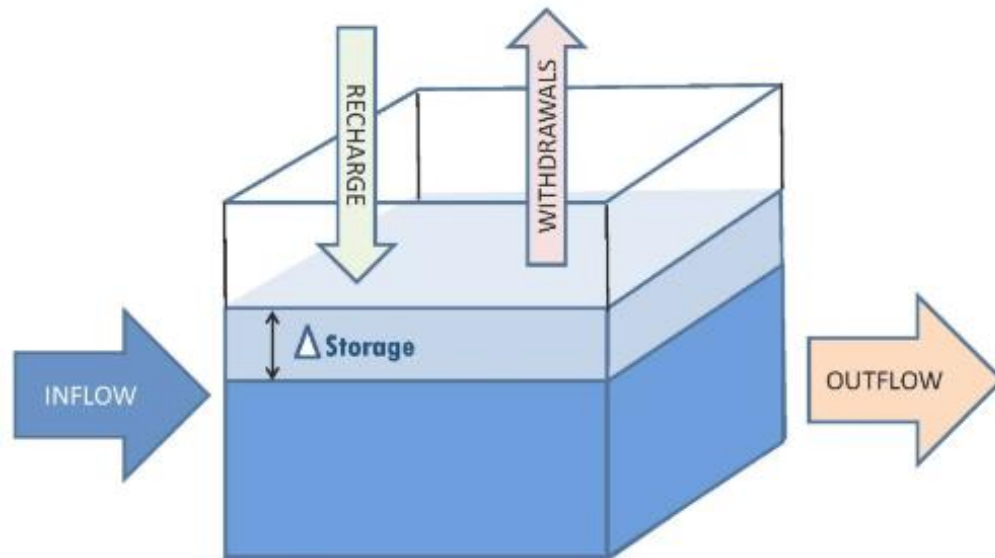
Sources & Sinks
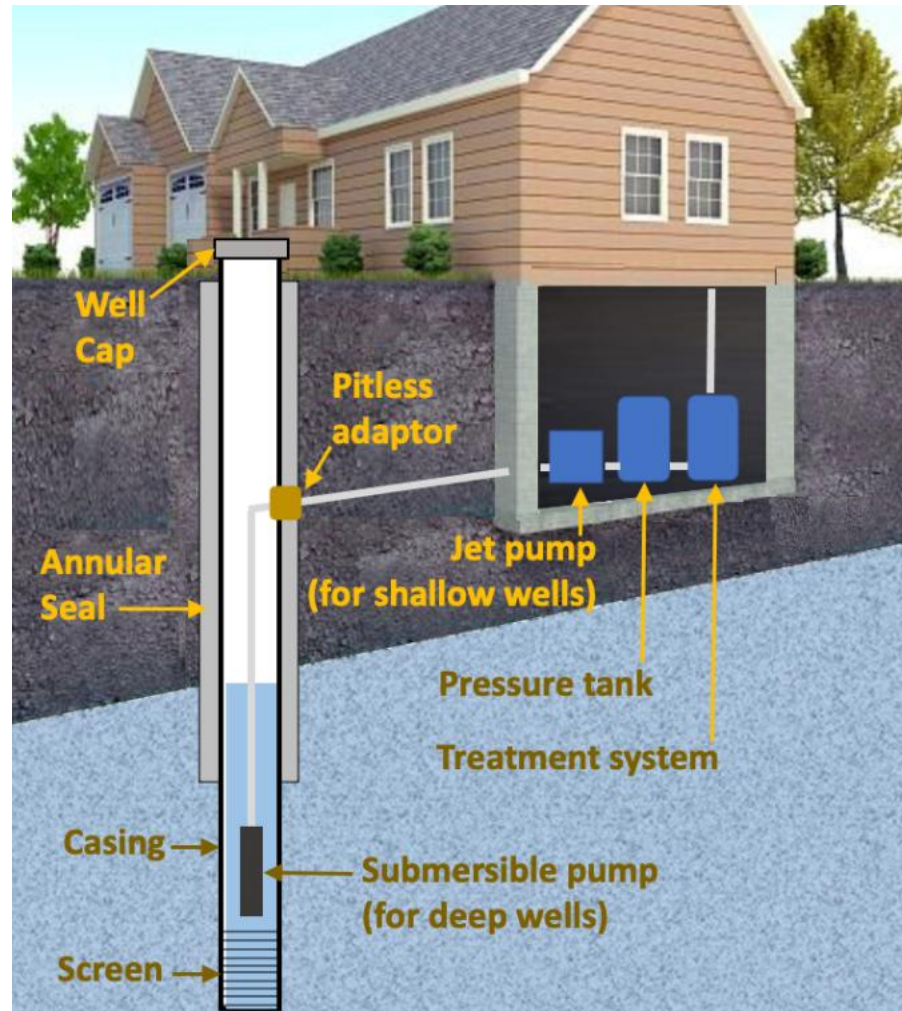(inflow & outflow)
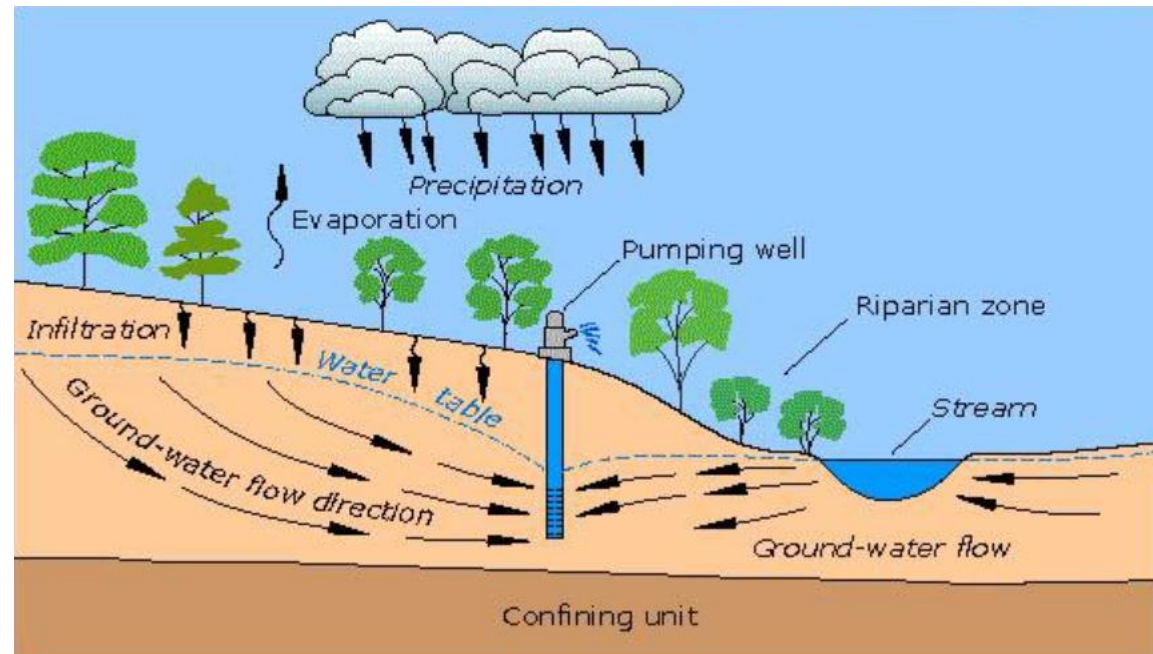
Sources = groundwater recharge

- Injection wells
- Irrigation
- Infiltrating rivers
- Infiltration from precipitation
- Recharge from lakes
- Seepage from wetlands
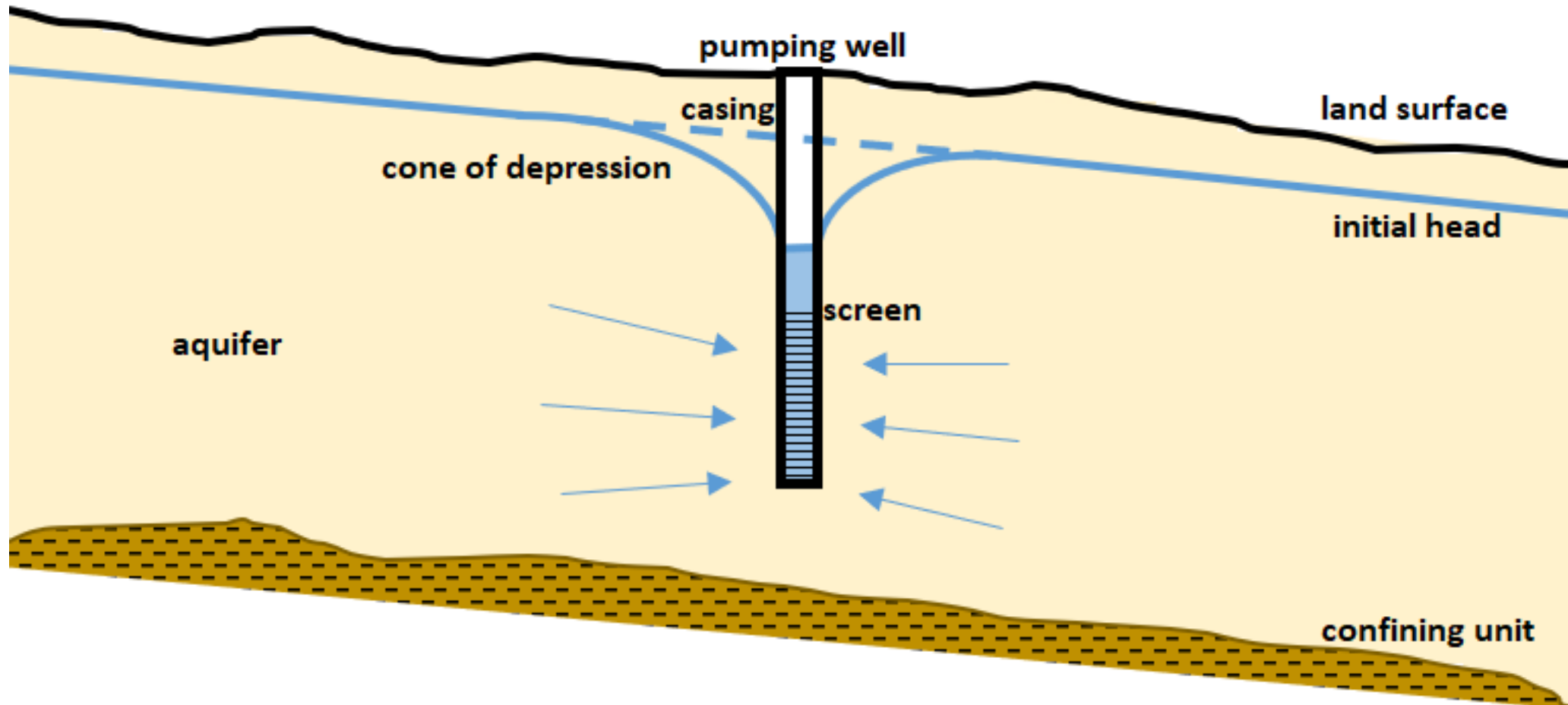- …

Sinks = groundwater discharge

- Pumping wells
- Subsurface drainage
- Draining rivers
- Evapotranspiration
- Springs
- Draining swamps
- …

What is a Pumping Well?

- Drilled hole to extract groundwater
- Uses a pump to draw water from the aquifer

- Lowers the groundwater level
- Creates a cone of depression

- Commonly used for water supply and irrigation

Well Cap
Pitless adaptor
Annular Seal
Jet pump (for shallow wells)
Pressure tank
Treatment system
Casing
Submersible pump (for deep wells)
Screen

Flow to a Pumping Well

What is Groundwater Modeling?

- Groundwater modeling is the **simulation** of groundwater flow, water quality, and related conditions using **computer models**.

- Models help **understand and predict** how aquifers respond to changes, such as pumping or climate.

- They are used for **water management**, **contamination studies**, and **environmental impact assessments**.

- Models can be **simple or complex**, 1D, 2D, or 3D, depending on the question.

- They are based on **real-world data** and **assumptions** about the subsurface.
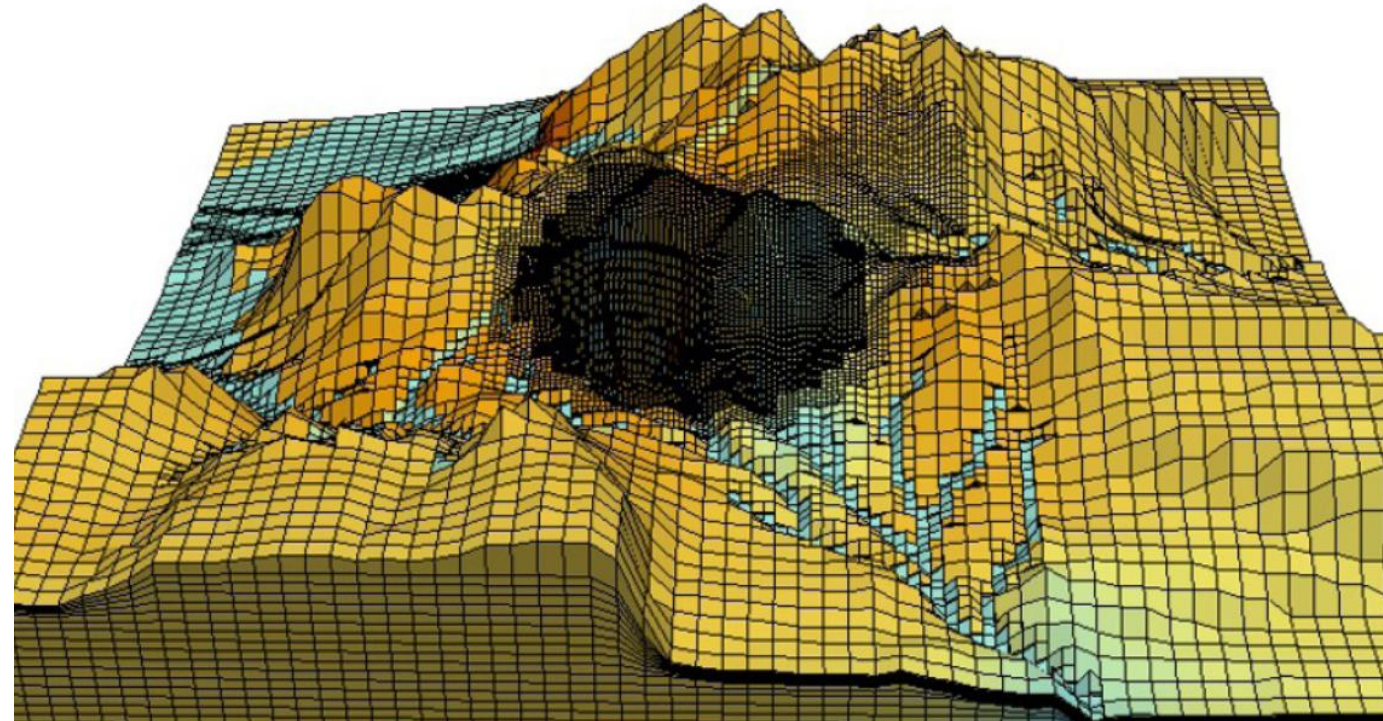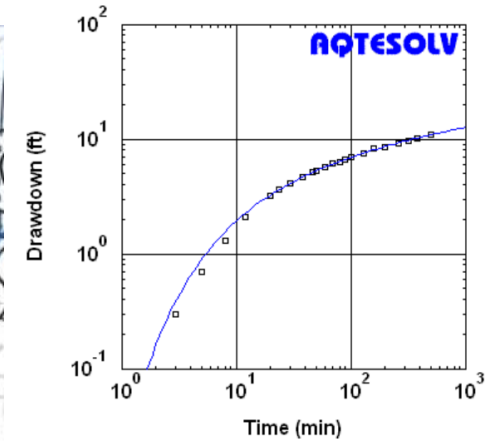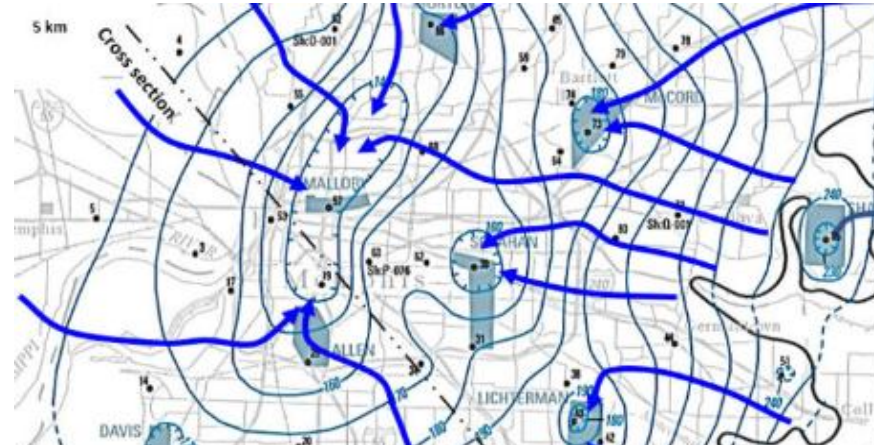
How Do We Model Groundwater Flow?

- **Approach:**
  - Represent the physical system as a **mathematical model** (= process-based!)
  - Use governing equations based on **Darcy's Law** and the **continuity equation**

- **Key equation**:
 - **Groundwater flow equation** (simplified):

inflow – outflow

applying Darcy's law

$$T\nabla^2 h = S\frac{\partial h}{\partial t}$$

storage change

where: h is hydraulic head [L], T is transmissivity [L/T], S is storativity [-]

  - **Boundary conditions** = sources and sinks expressed as additional equations

How Do We Solve Groundwater Flow Equations?

- **Analytical solutions**
  - exact
  - closed-form equations
  - methods from calculus
  - e.g. integral transforms

- **Software tools:**
  - MODFLOW (industry standard)
  - FloPy (Python interface for MODFLOW)
  - TimML (Python library for analytical models)

- **Numerical solutions**
  - approximate
  - discretization of the model domain
  - iterative methods
  - e.g. finite differences, finite elements, ...
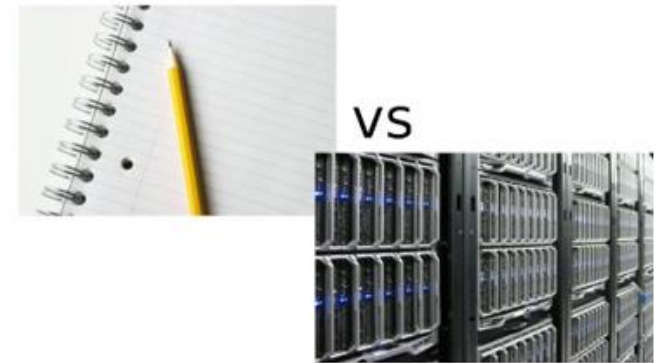
Axisymmetric Models

used to simulate flow to a pumping well
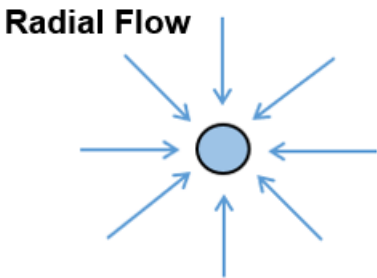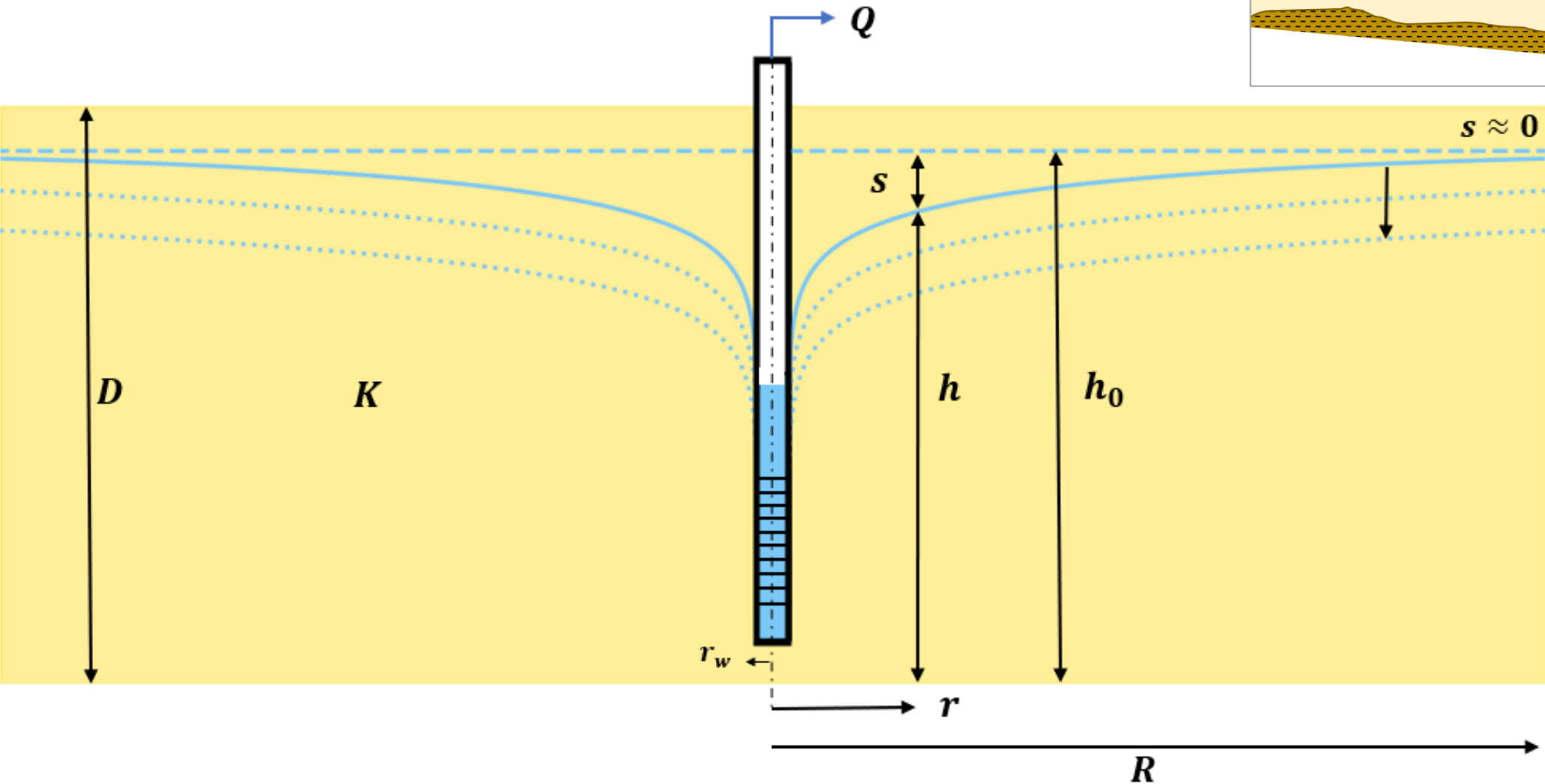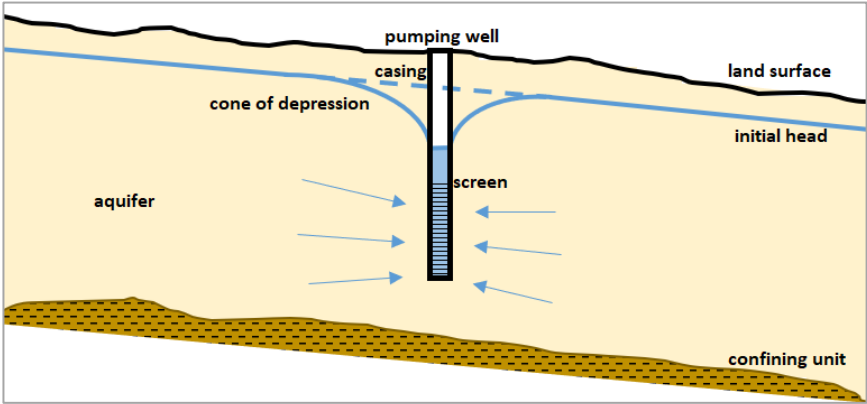
pumping rate	Q
aquifer thickness	D
aquifer conductivity	K
aquifer transmissivity	$T = KD$
hydraulic head	h
initial head	h_0
drawdown	s
radial distance	r
well radius	r_w
radius of influence	R

We Use Cylindrical Coordinates!

- **Cartesian** coordinates: (x, y, z)

- **Cylindrical** coordinates: (r, ϑ, z)
  - Polar coordinates: (r, ϑ)

- **Axial symmetry**: (r, z)
  - No ϑ dimension!
  - 1D flow: only r
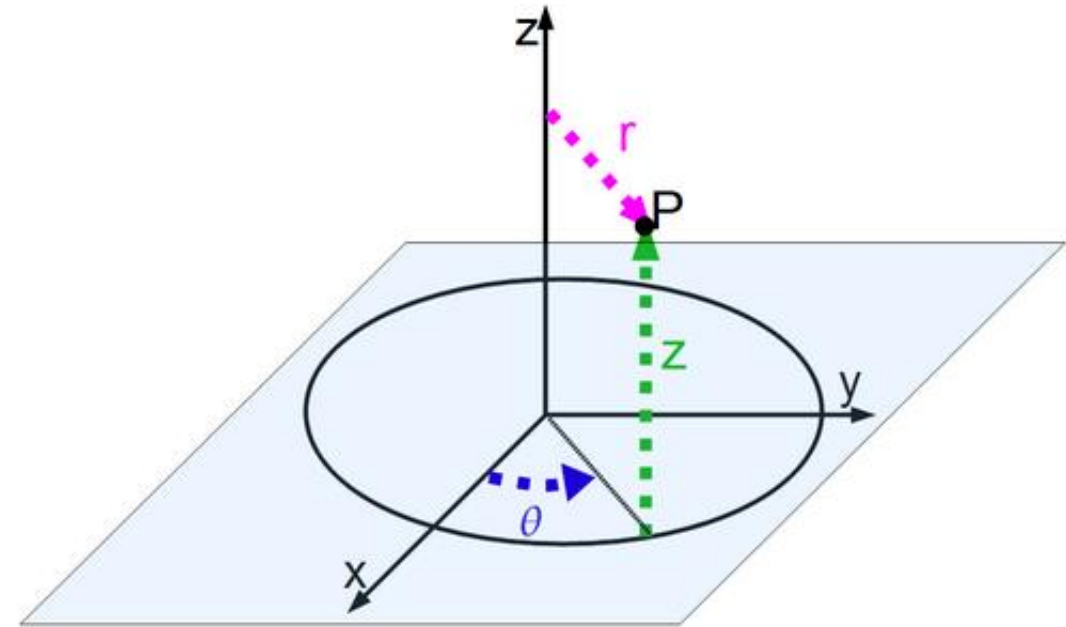
$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \end{cases}$$

$$r = \sqrt{x^2 + y^2}$$

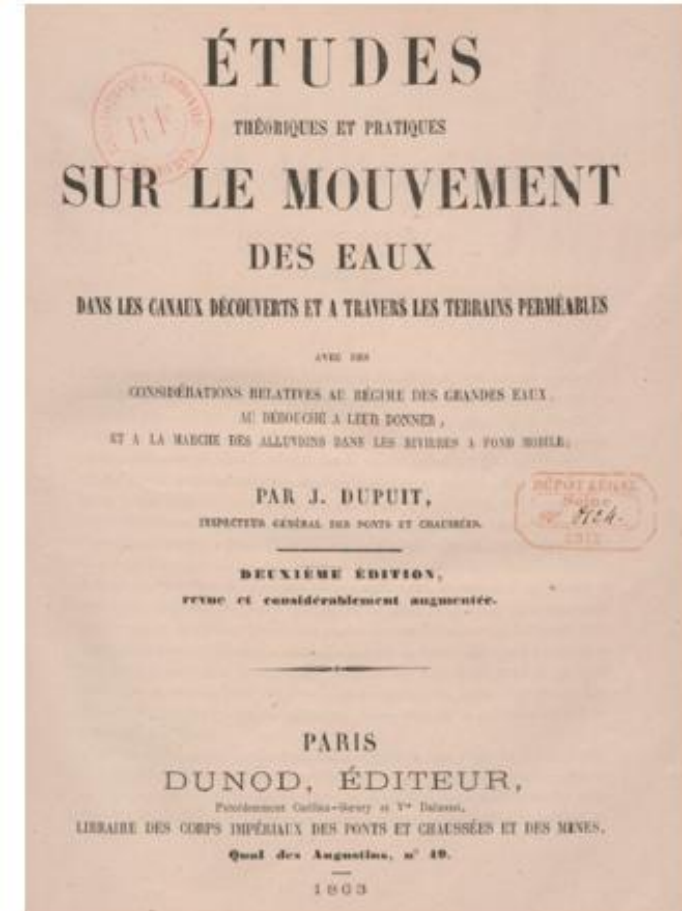# The Thiem-Dupuit Formulas

- Steady confined flow (Thiem, 1870, 1906)

$$s(r) = \frac{Q}{2\pi KD} \ln\left(\frac{R}{r}\right)$$

Initial head h_0 is not required

- Steady unconfined flow (Dupuit, 1857, 1863)

$$s(r) = h_0 - \underbrace{\sqrt{h_0^2 - \frac{Q}{\pi K} \ln\left(\frac{R}{r}\right)}}_{h}$$

Initial head h_0 is required!

ÉTUDES

THÉORIQUES ET PRATIQUES

SUR LE MOUVEMENT

DES EAUX

DANS LES CANAUX DÉCOUVERTS ET A TRAVERS LES TERRAINS PERMÉABLES

PAR J. DUPUIT,

DEUXIÈME ÉDITION,
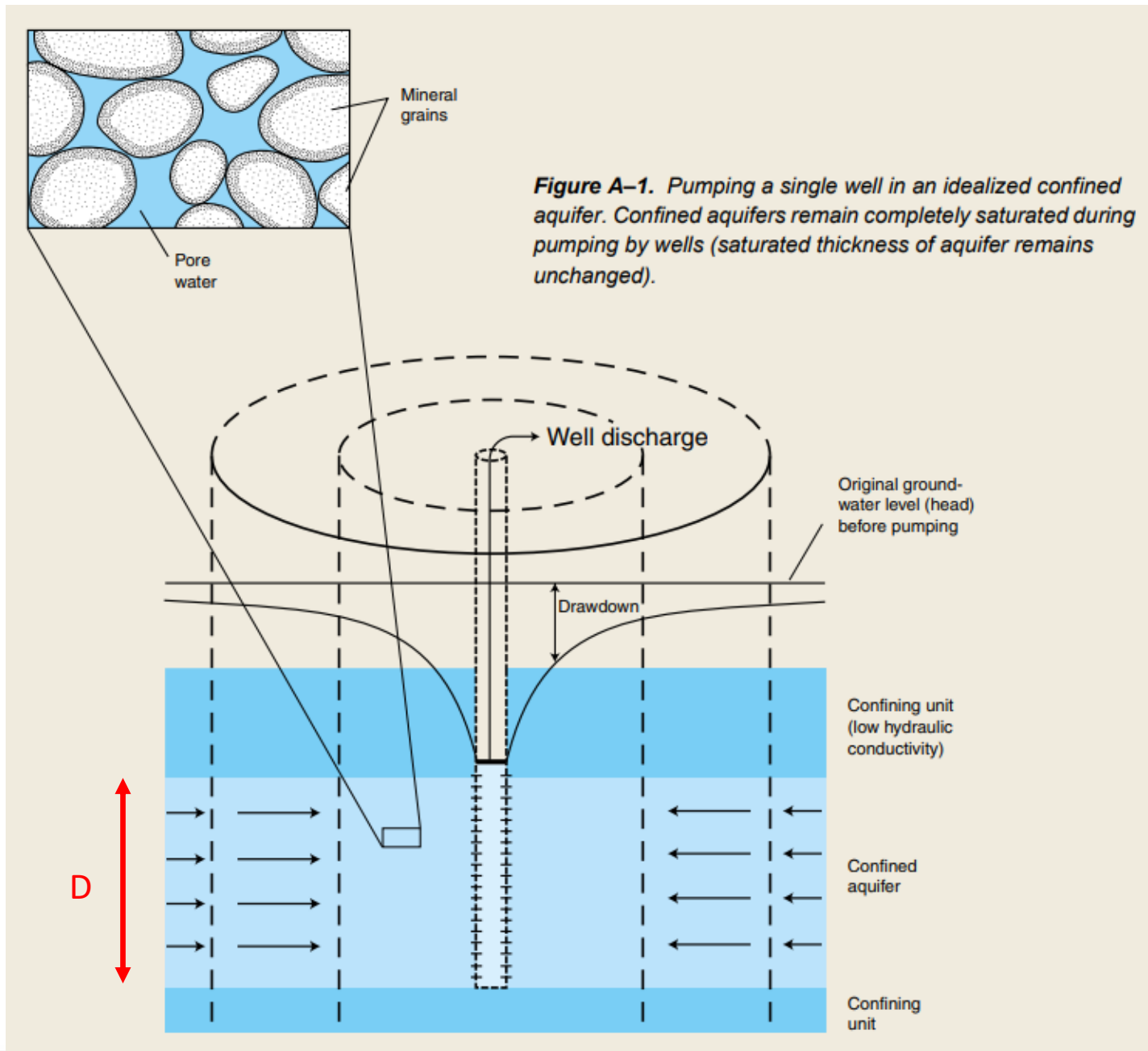
PARIS

DUNOD, ÉDITEUR,

1863

Jules Dupuit

Adolf Thiem

Günther Thiem

Confined Flow

– Confined aquifer

– Constant saturated thickness **D**

– If aquifer is homogeneous:
  – *K* is constant
  – *T* is constant
  – **T = KD**

– **Linear** problem

Figure A–1. Pumping a single well in an idealized confined aquifer. Confined aquifers remain completely saturated during pumping by wells (saturated thickness of aquifer remains unchanged).

Unconfined Flow

– Unconfined aquifer

– Saturated thickness = head *h*

– If aquifer is homogeneous:
  – *K* is constant
  – *T* is head-dependent
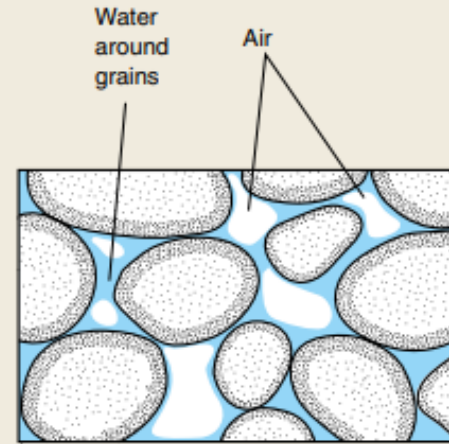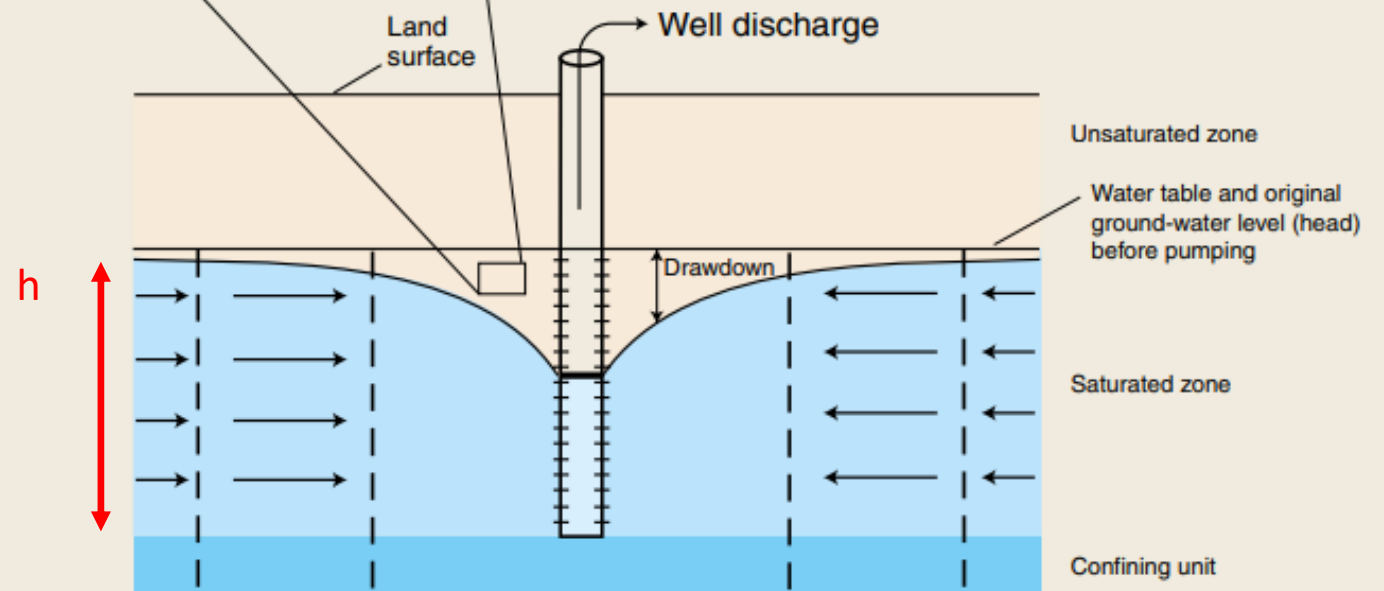 – ***T = Kh***

– **Nonlinear** problem

Figure A–2. Pumping a single well in an idealized unconfined aquifer. Dewatering occurs in cone of depression of unconfined aquifers during pumping by wells (saturated thickness of aquifer decreases).

Thiem-Dupuit: Example

```python
Q  = 1000    # pumping rate (m³/d): Q > 0 -> extraction
R  = 500     # radius of influence (m)
K  = 10      # conductivity (m/d)
h0 = D = 20  # initial head = initial aquifer thickness (m)
T  = K * D   # aquifer transmissivity (m²/d)

# calculate the drawdown at a distance of 1 m from the well
r = 1

# drawdown s according to the Thiem formula:
s1 = Q / 2 / np.pi / T * np.log(R / r)

# drawdown s according to the Dupuit formula:
s2 = h0 - np.sqrt(h0**2 - Q / np.pi / K * np.log(R / r))

# print the result
print(f'Drawdown according to Thiem:  s = {s1:.2f} m')
print(f'Drawdown according to Dupuit: s = {s2:.2f} m')
```
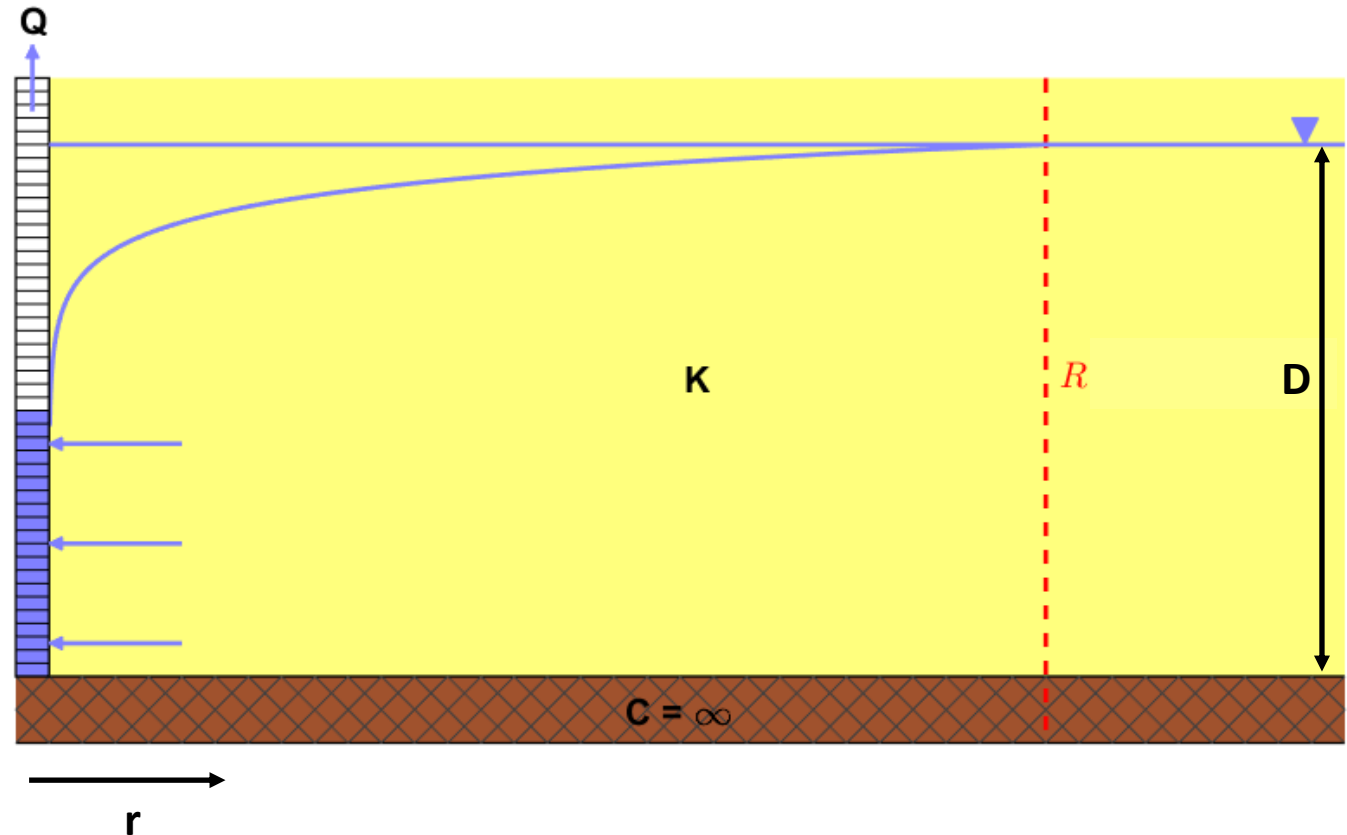
```
Drawdown according to Thiem:  s = 4.95 m
Drawdown according to Dupuit: s = 5.78 m
```

Thiem-Dupuit: Example

- Graph of drawdown *s* versus radial distance *r*
- Used to analyze pumping test data
- Semi-logarithmic plot!

- Dupuit formula results in higher calculated drawdown near the well

```
Q  = 1000      # pumping rate (m³/d): Q > 0 -> extraction
R  = 500       # radius of influence (m)
K  = 10        # conductivity (m/d)
h0 = D = 20    # initial head = initial aquifer thickness (m)
T  = K * D     # aquifer transmissivity (m²/d)
```

```
r = np.logspace(-2, np.log10(R), 100)      # radial distances (m)
s1 = dupuit(r=r, Q=Q, K=K, R=R, h0=h0)     # drawdown (m) according to the Dupuit formula
s2 = thiem(r=r, Q=Q, T=T, R=R)             # drawdown (m) according to the Thiem formula
```
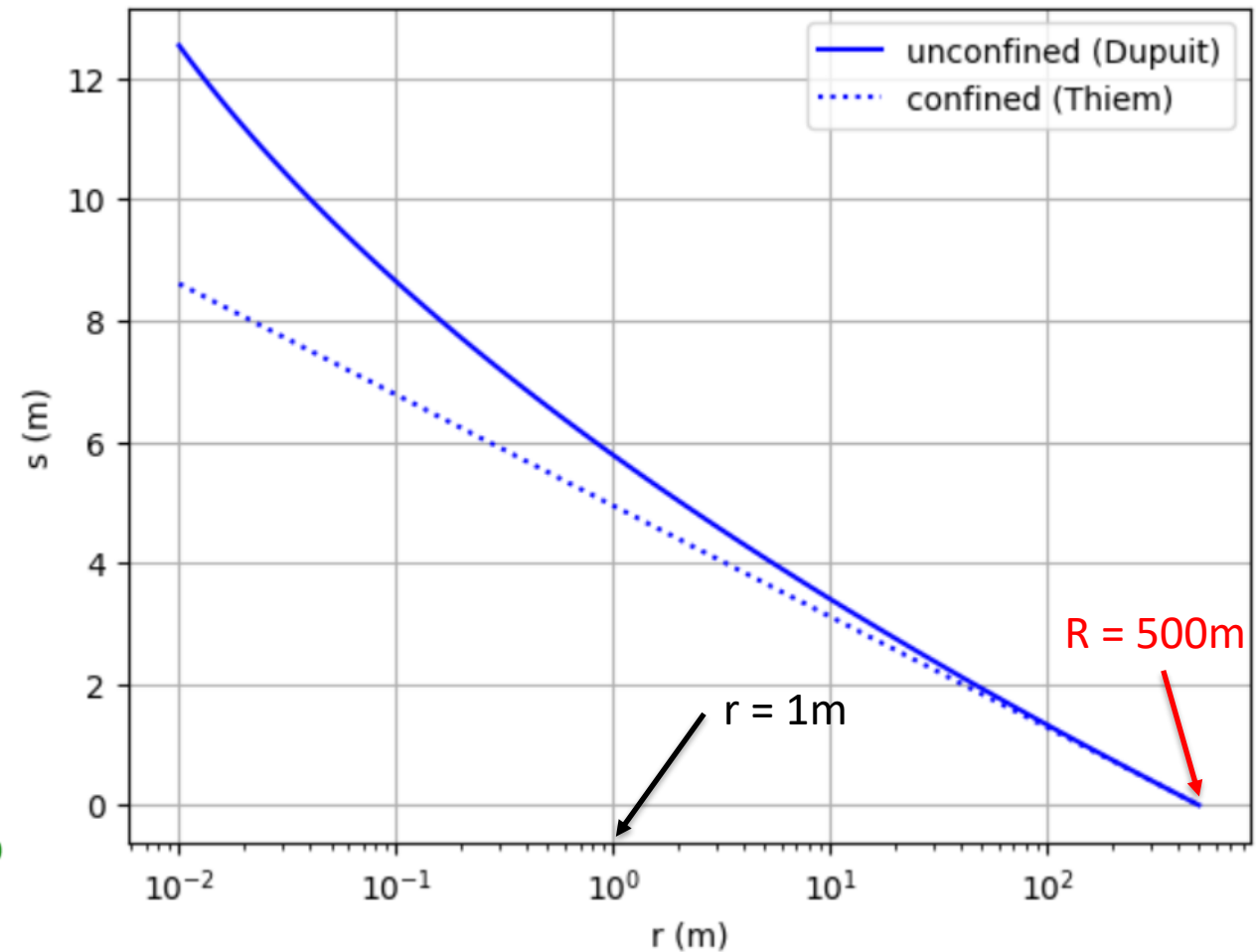
TimML: Advanced Analytical Groundwater Modeling

- **Python** package

- Simulating **steady-state groundwater flow**

- Groundwater systems with **multiple aquifers**

- Superposition of different **analytic elements**:

  » uniform flow

  » constant head

  » pumping wells

  » rivers and canals

 » infiltration areas

  » lakes

  » ...
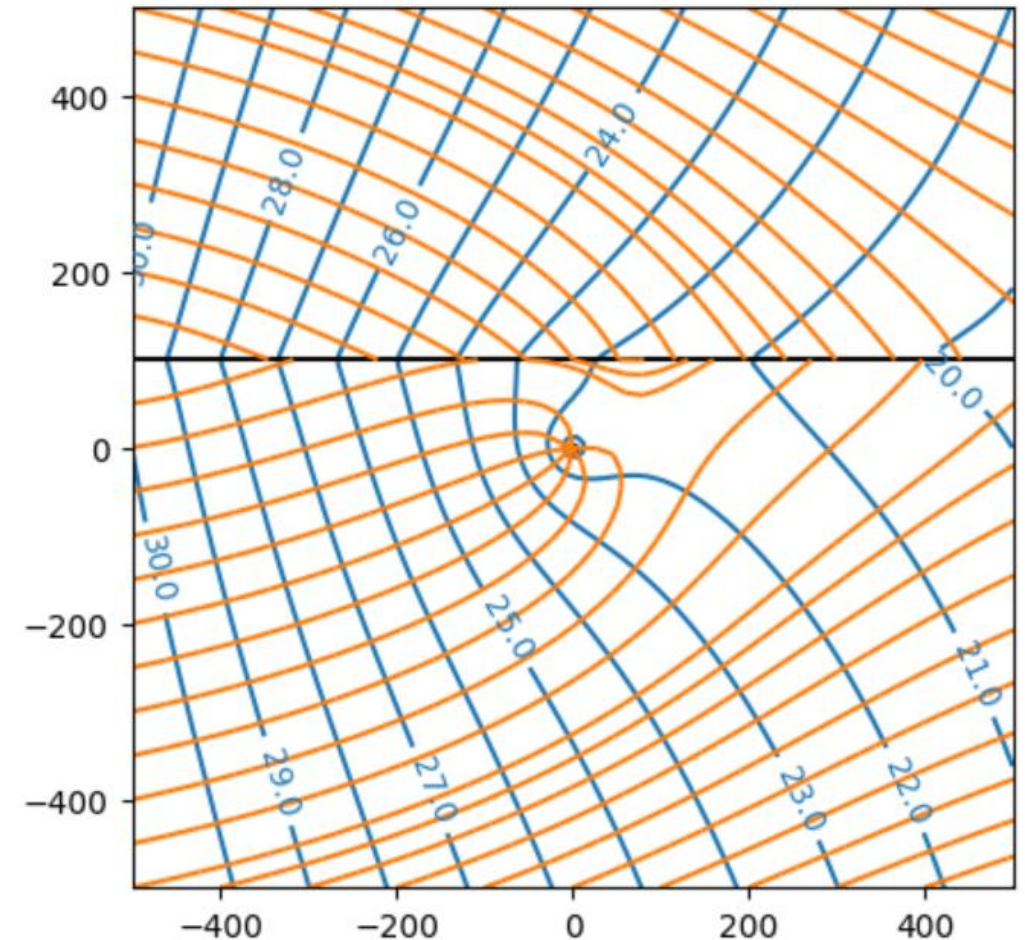
MODFLOW: Industry Standard in Groundwater Modeling

- State-of-the-art **numerical** model to simulate **3D groundwater flow**
- Developed and released for free by the [US Geological Survey](#)
- Python interface **FloPy**
- The groundwater reservoir is **discretized** into layers, rows and columns
  - Darcy's law and continuity equation is formulated for each cell
  - The resulting algebraic equations are solved numerically
- Sources and sinks are added via **packages**:
  - constant heads
  - pumping wells
  - rivers
  - infiltration
  - lakes
  - drains
  - ...
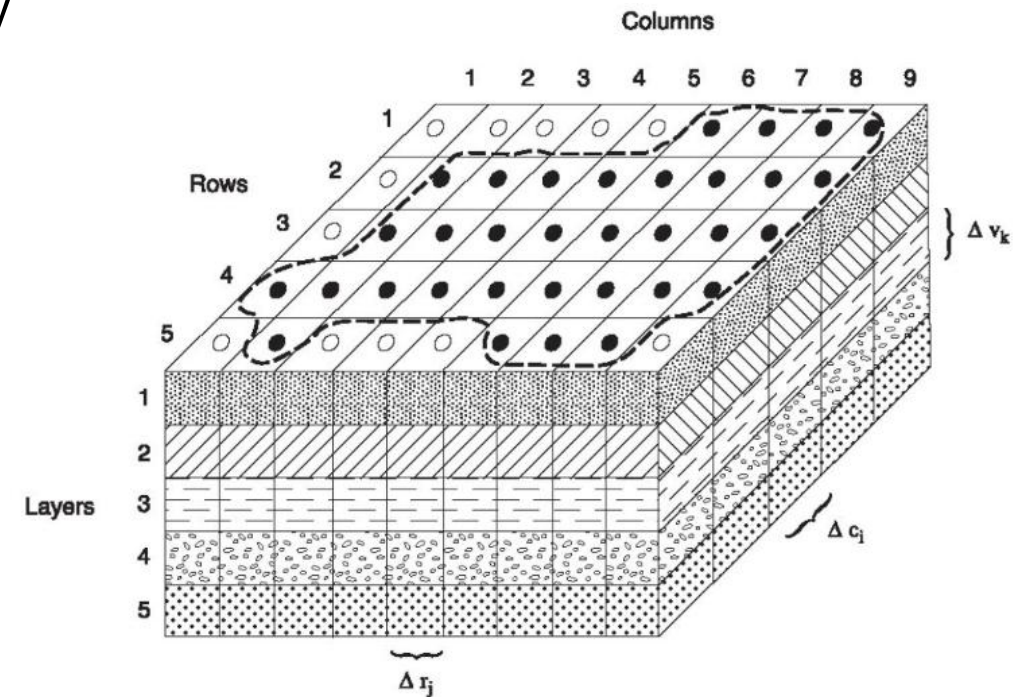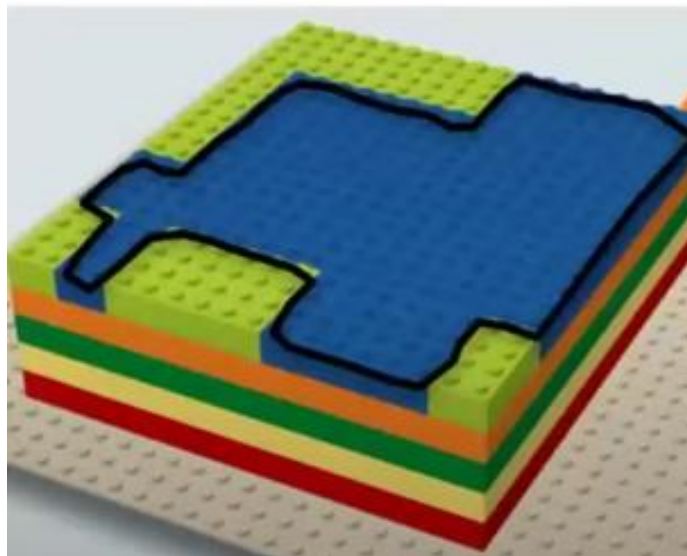
GitHub Repo

https://github.com/alouwyck/vives_ttk_tallinn
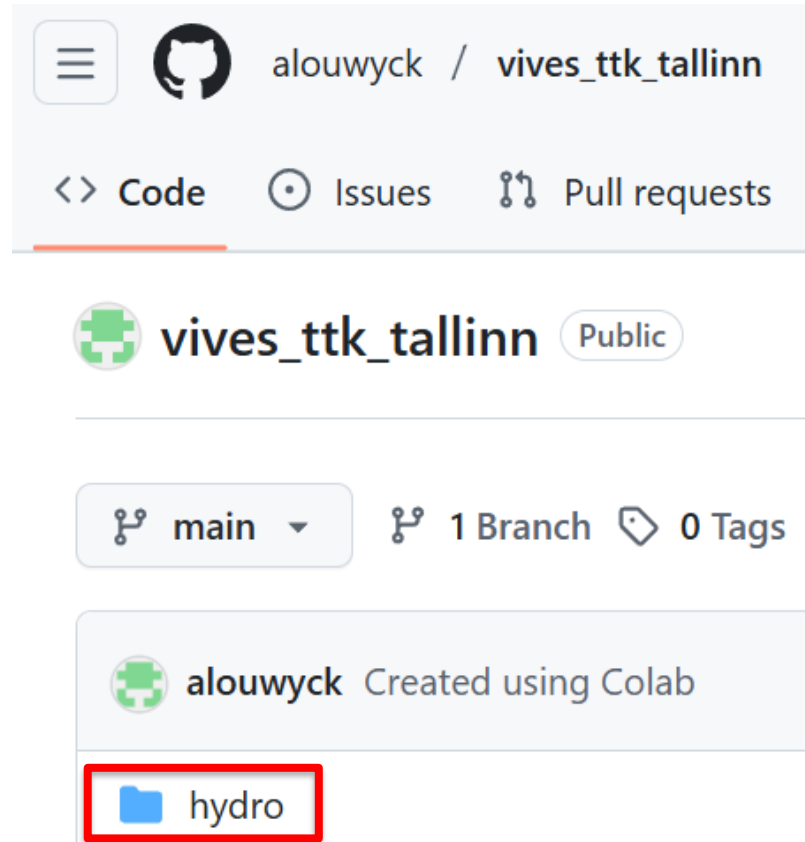
Sources

- Louwyck, A., 2023. Axisymmetric Flow in Multilayer Aquifer Systems: Solutions and Theoretical Considerations. PhD thesis, Laboratory for Applied Geology and Hydrogeology, Department of Geology, Ghent University, Belgium.
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- https://en.wikipedia.org/wiki/Groundwater
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- https://en.wikipedia.org/wiki/Aquifer
- https://en.wikipedia.org/wiki/Hydraulic_head
- https://en.wikipedia.org/wiki/Darcy%27s_law
- https://en.wikipedia.org/wiki/Groundwater_flow_equation
- https://en.wikipedia.org/wiki/Continuity_equation
- https://www.usgs.gov/water-science-school/science/groundwater-what-groundwater
- https://uon.sdsu.edu/groundwater_utilization_and_sustainability.html
- https://www.worldbank.org/en/news/feature/2022/03/23/groundwater-may-be-hidden-but-the-secret-to-its-sustainability-is-not
- https://www.dri.edu/groundwater-is-key-to-protecting-global-ecosystems/
- https://books.gw-project.org/hydrogeologic-properties-of-earth-materials-and-principles-of-groundwater-flow/chapter/basis-for-flow-equation-development/
- https://books.gw-project.org/domestic-wells-introduction-and-overview/chapter/components-of-a-domestic-well-and-water-system/
- https://www.royaleijkelkamp.com/nl/
- https://groundwater.com.au/groundwater-modelling/
- https://mavensnotebook.com/2021/01/27/feature-the-what-why-and-how-of-groundwater-modeling/
- https://pubs.usgs.gov/circ/circ1186/pdf/circ1186.pdf
- Microsoft Copilot was used to generate some of the content