Introduction to Hydrogeology

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

8 – 12 December 2025

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Vives University of Applied Sciences, Kortrijk, Belgium

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

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Flanders State of the Art

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Where Do I Live?

Where Do I Teach?

Informatics Program for Exchange Students

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.

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	

New full-year program!

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

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

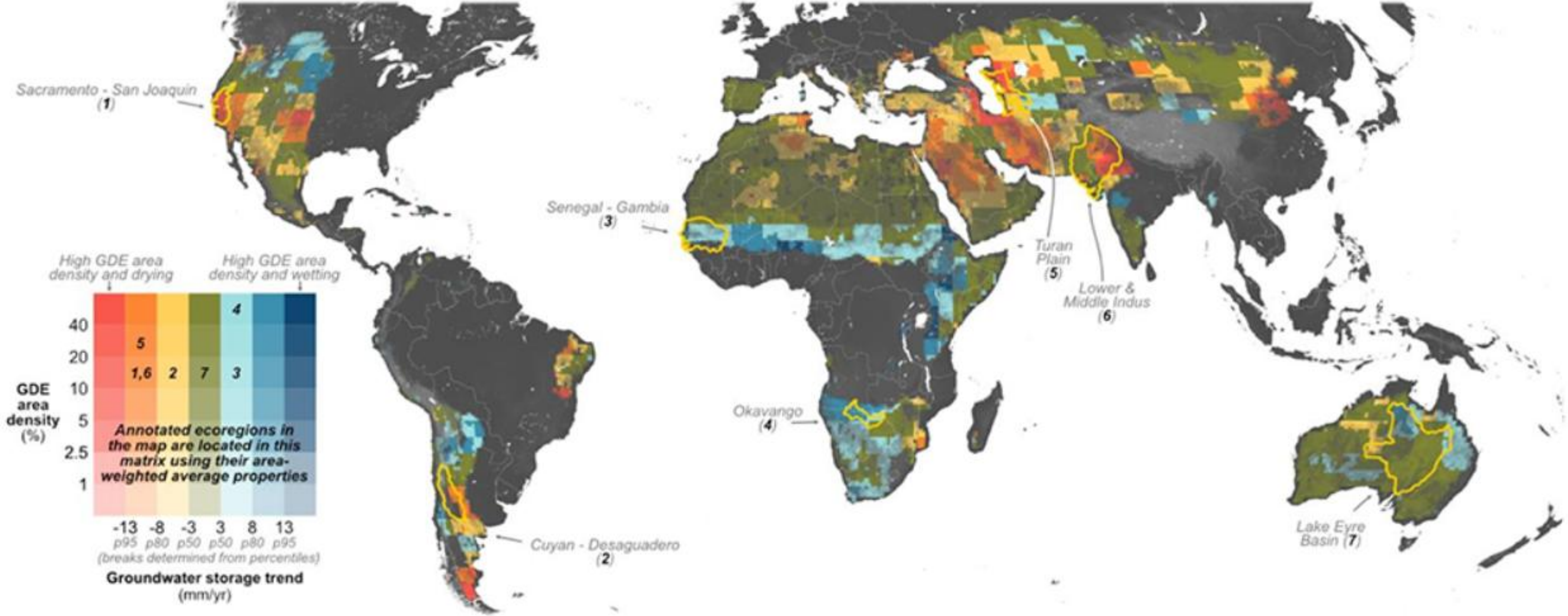
Essential to human and economic development

1/3 of the world's **drinking water**

40% of the world's **irrigation water**

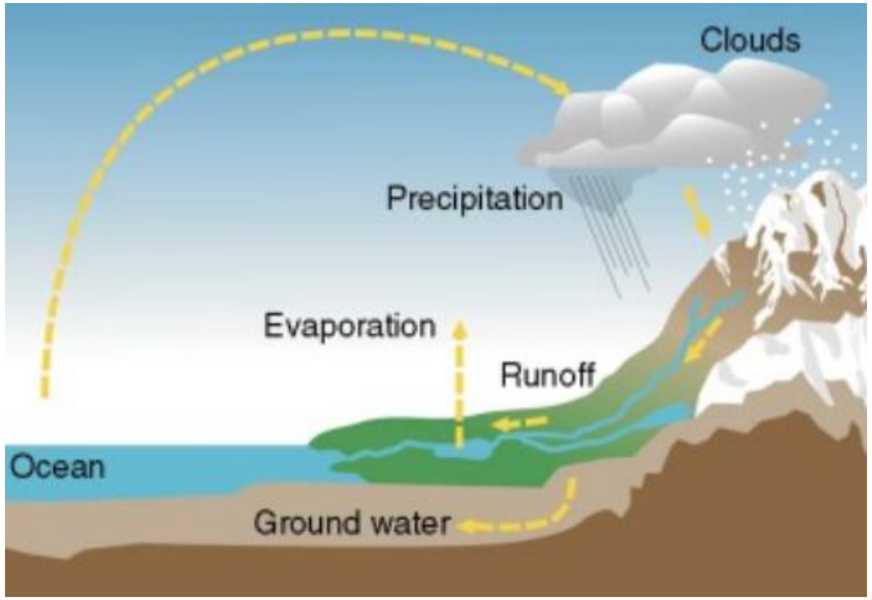
25% of the world's **industrial water**

Groundwater-Dependent Ecosystems (GDE)

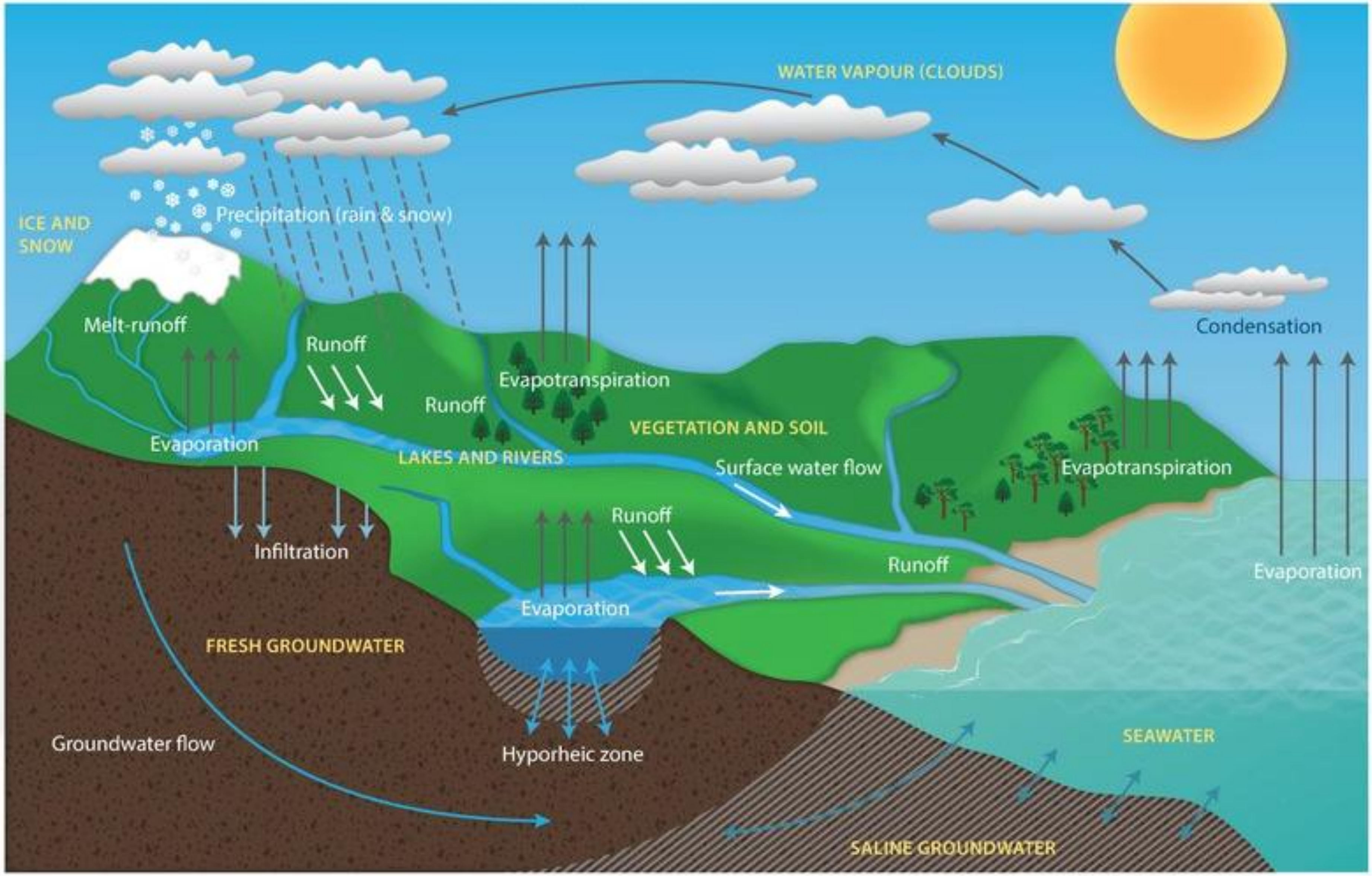


What is Groundwater?

- **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

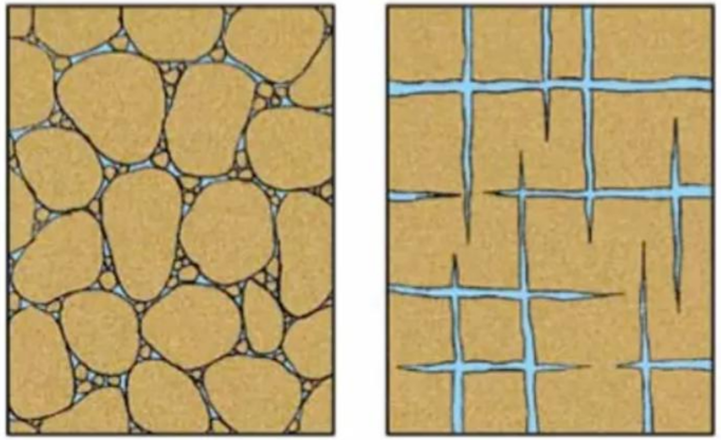


The Hydrological Cycle (a.k.a. the Water Cycle)

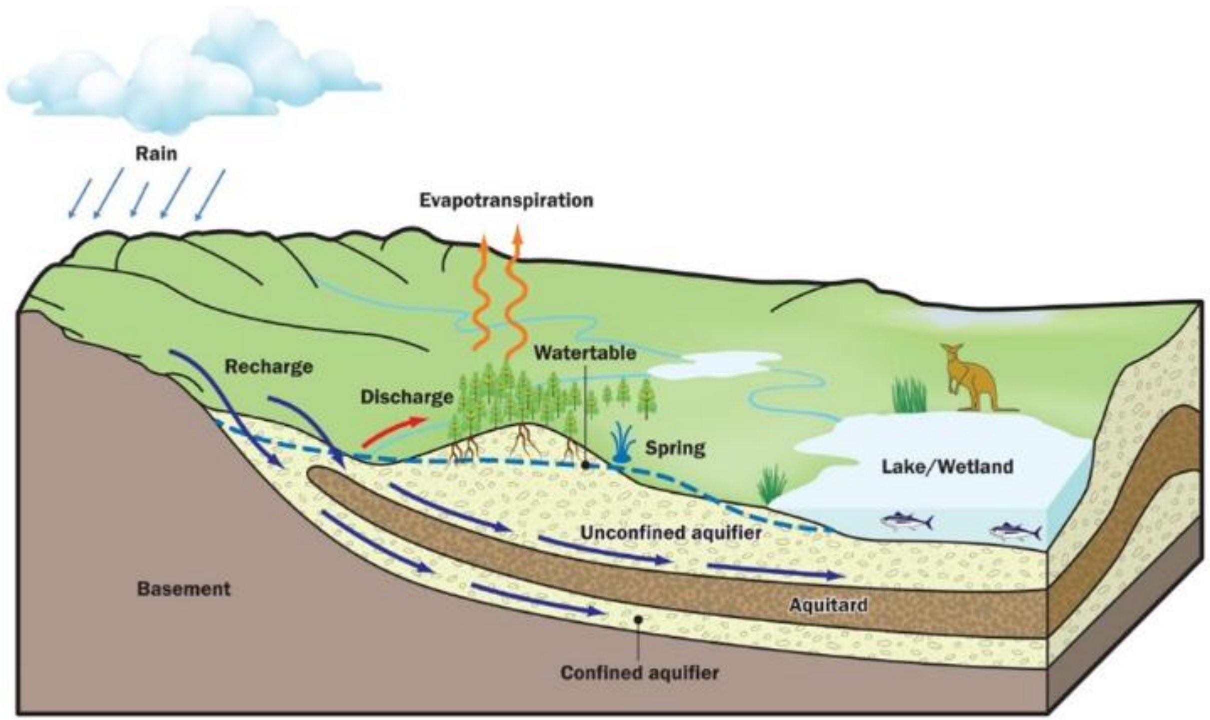


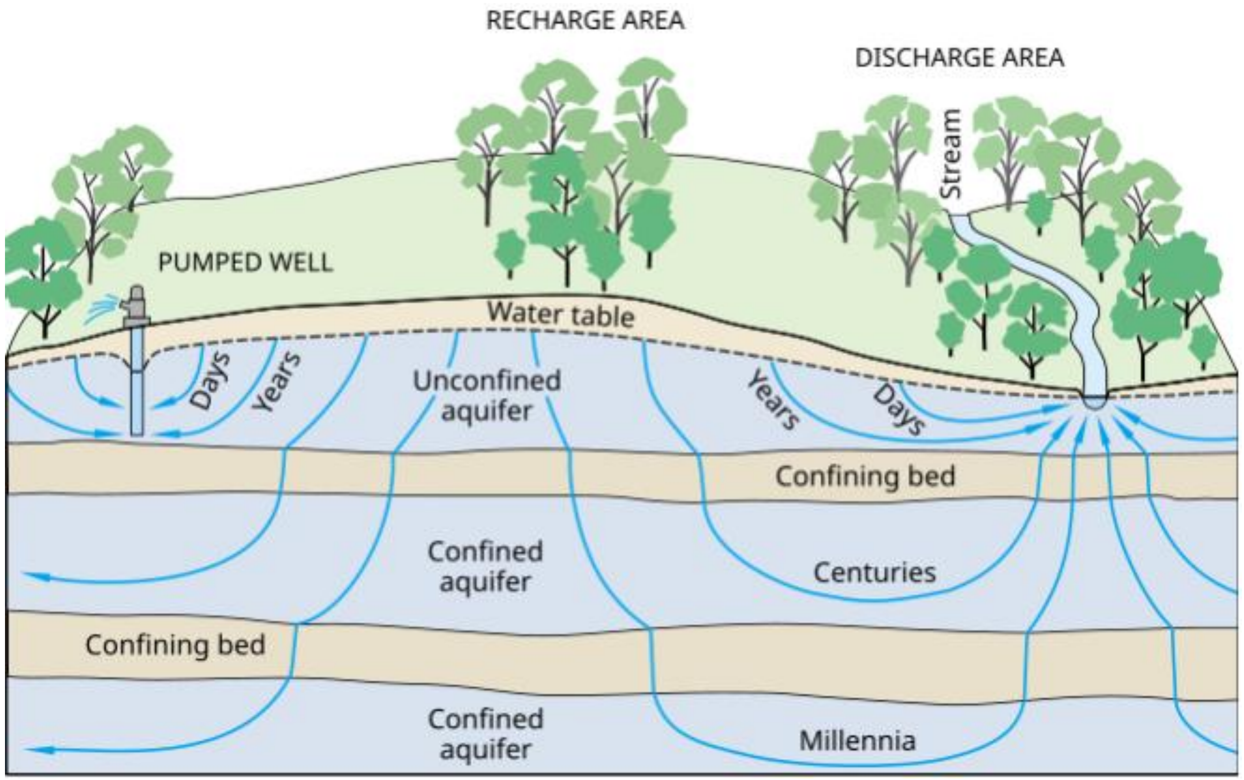
What is an Aquifer?

- **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





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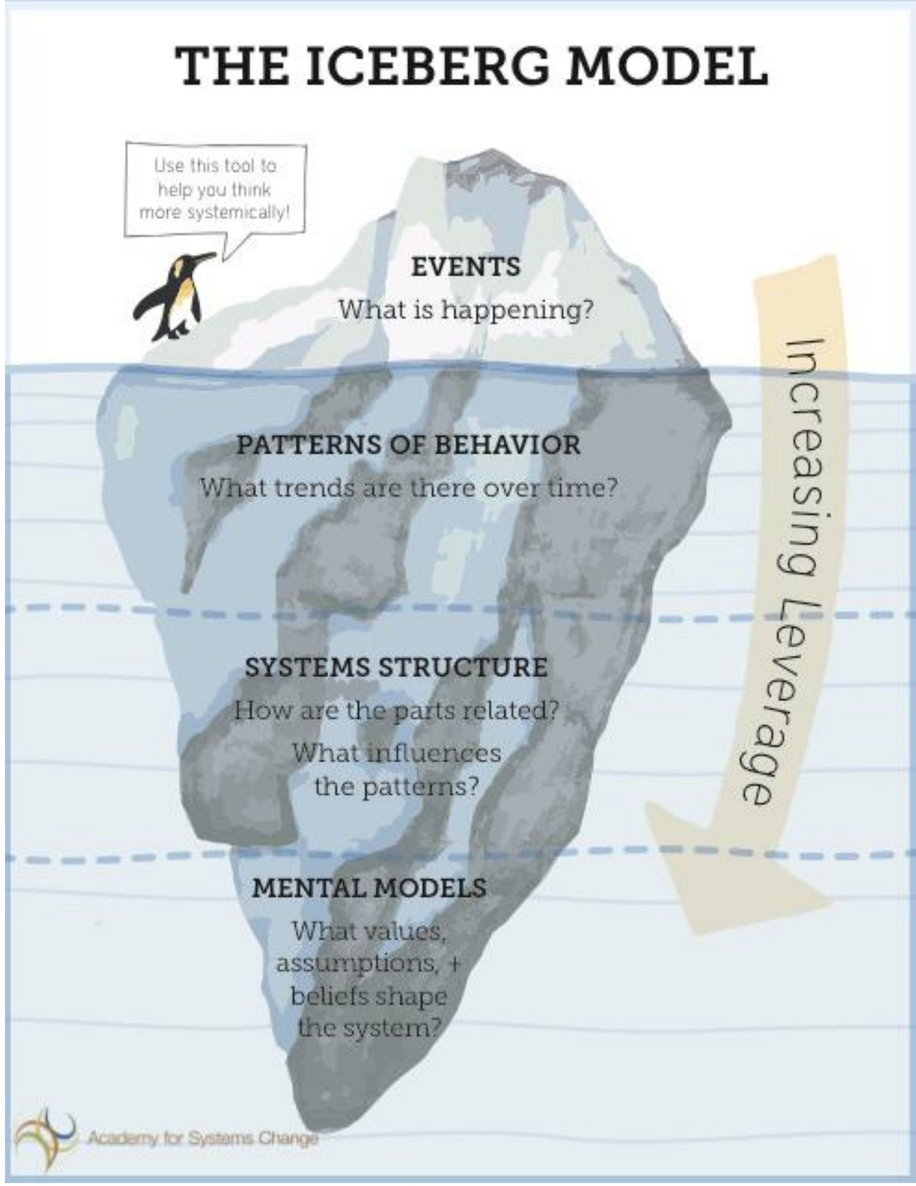
Systems Thinking in Hydrogeology

- **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



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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)

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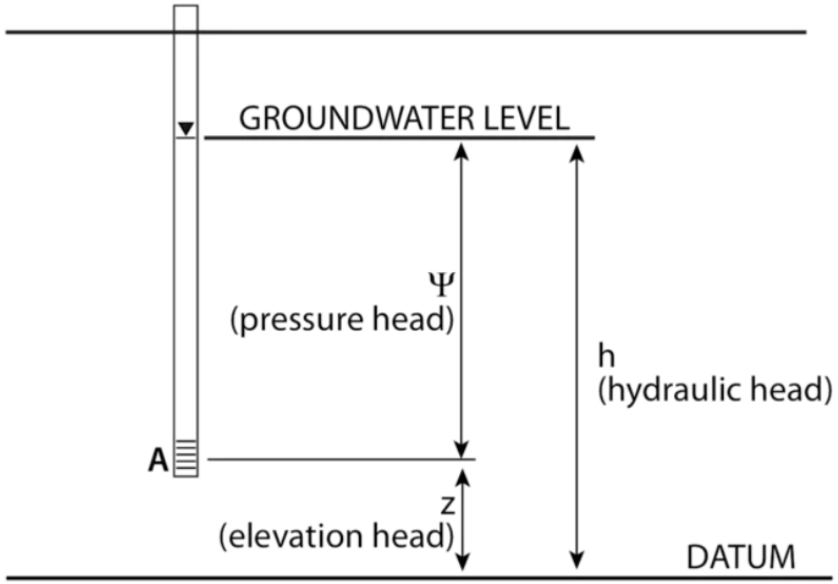
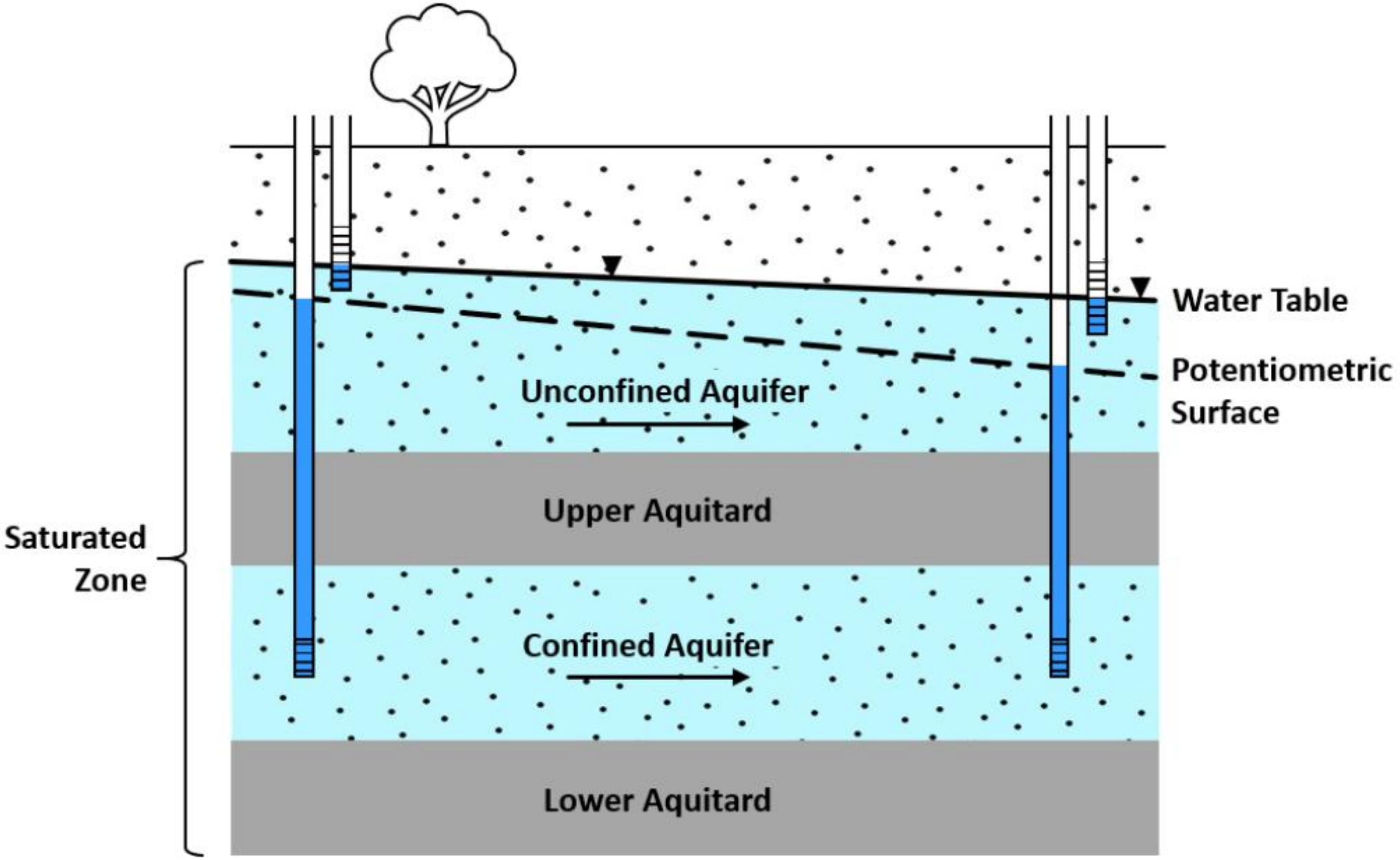
Hydraulic Head *h*

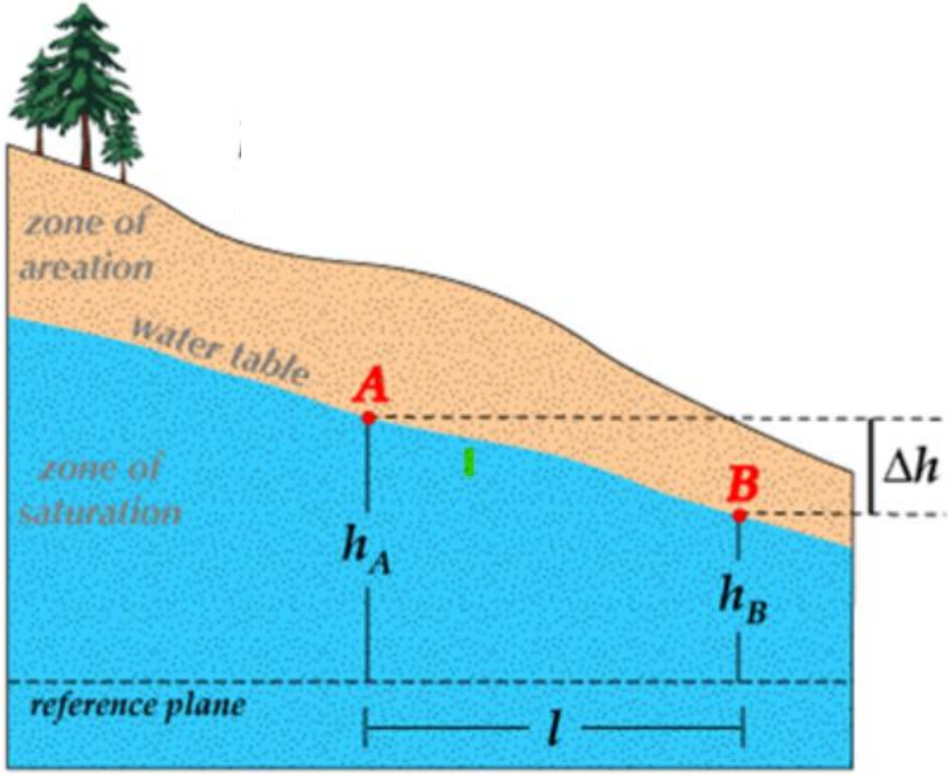


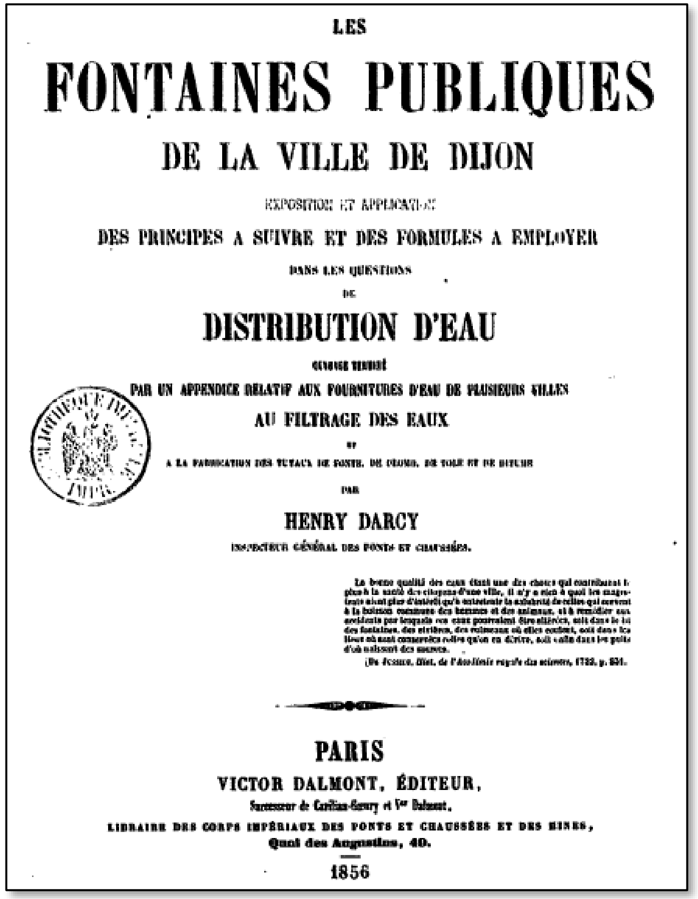


Groundwater Flow and Darcy’s Law

Laminar flow in porous media (Darcy, 1856)

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





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AU FILTRAGE DES EAUX

ET

A LA FABRICATION DES TUYAUX DE FONTE, DE PLOMB, DE TOLE ET DE BITUME

PAR

HENRY DARCY

INSPECTEUR GÉNÉRAL DES PONTS ET CHAUSSÉES.

PARIS

VICTOR DALMONT, ÉDITEUR,

Successeur de Carilian-Gœury et V^{ve} Dalmont,

LIBRAIRE DES CORPS IMPÉRIAUX DES PONTS ET CHAUSSÉES ET DES MINES,

Quai des Augustins, 49.

1856

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:

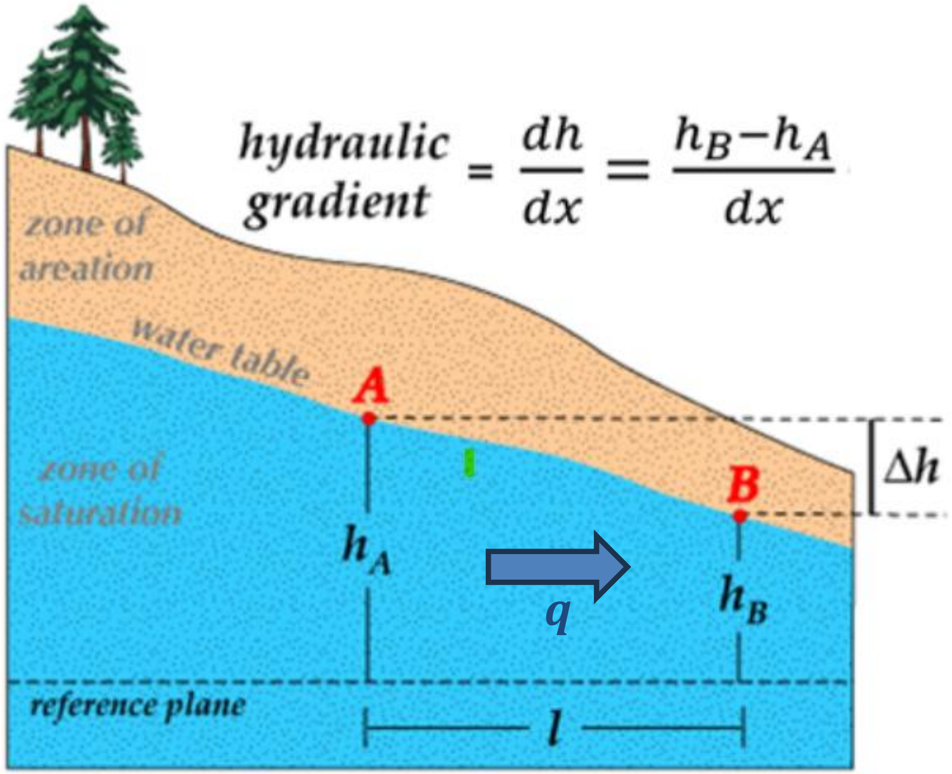
$$q = -K\frac{dh}{dx}$$

- **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

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

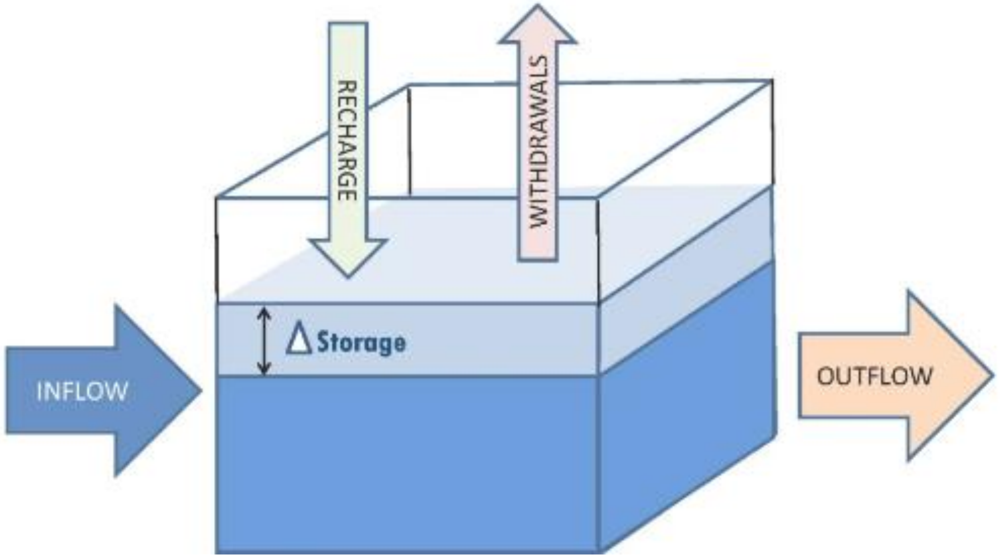
- $q = -K\frac{h_B - h_A}{L} = -10.\frac{40-50}{100} = 1\text{m/d}$

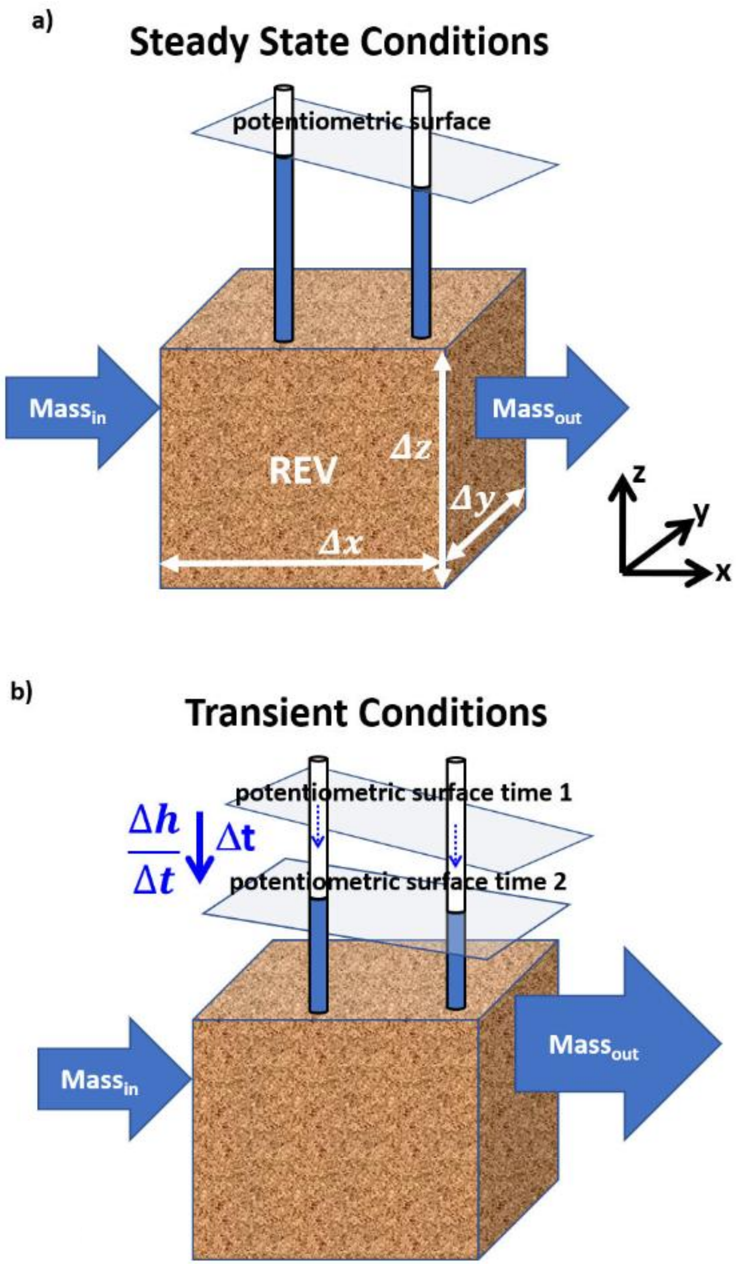


The Continuity Equation

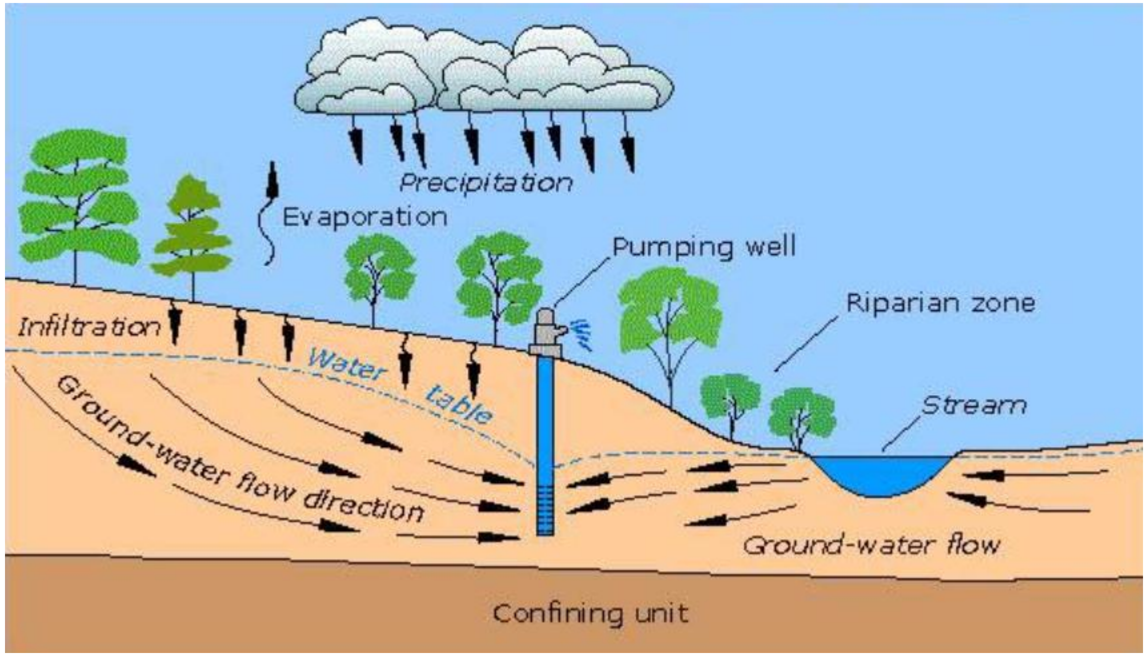
- A mathematical expression of the **law of conservation of mass**
- It states that **mass entering** a system **equals mass leaving**

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





Sources & Sinks
(inflow & outflow)



Sources = groundwater recharge

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

Sinks = groundwater discharge

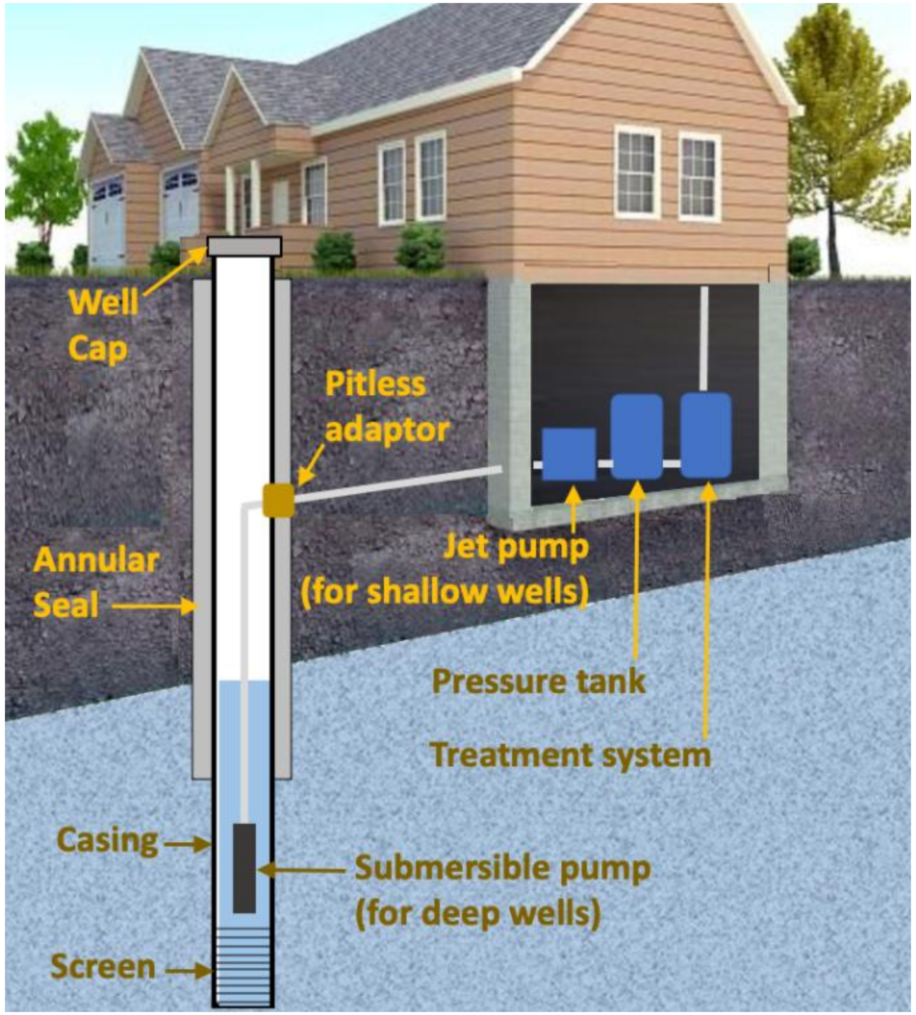
- Pumping wells
- Subsurface drainage
- Draining rivers
- Evapotranspiration
- Springs
- Draining swamps
- …

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



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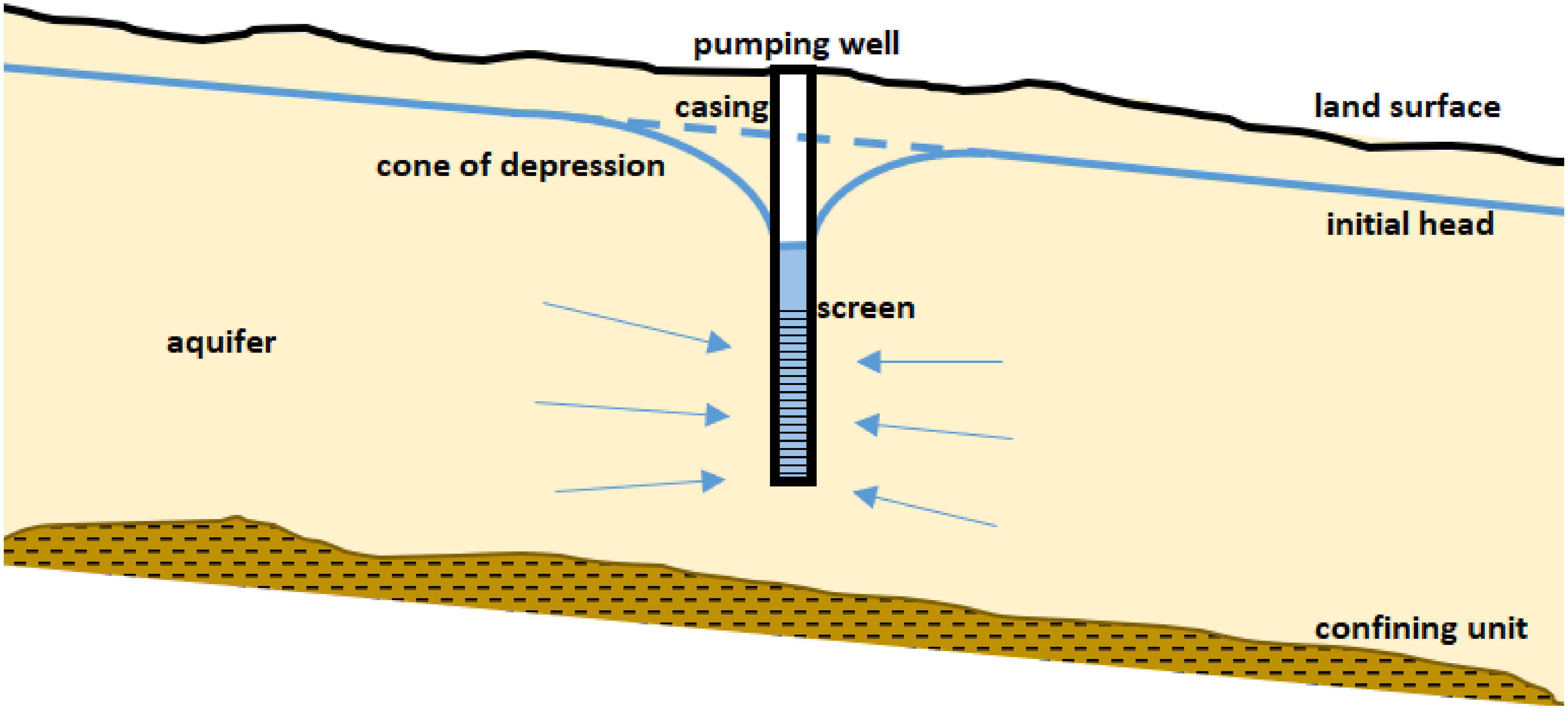
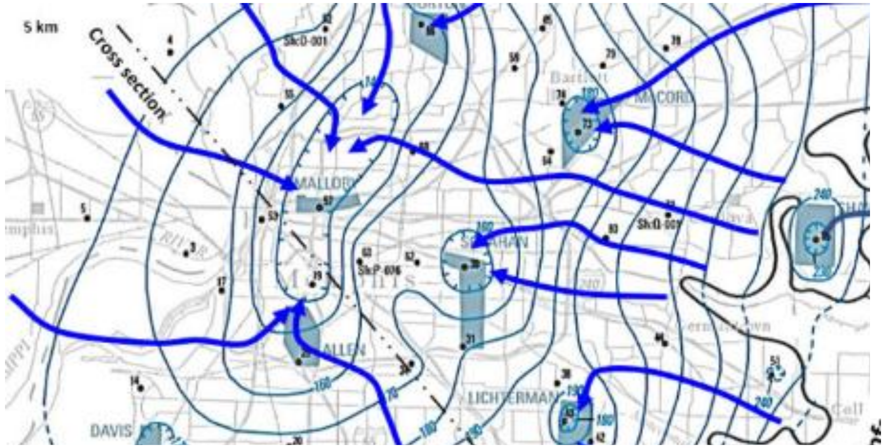
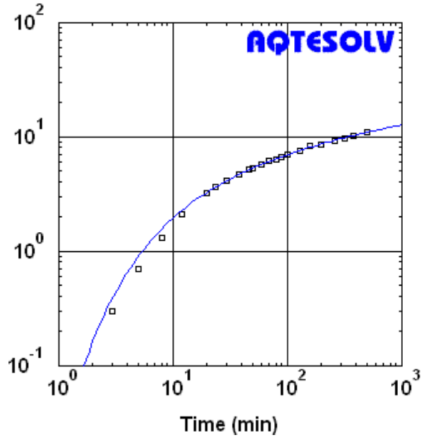
Flow to a Pumping Well

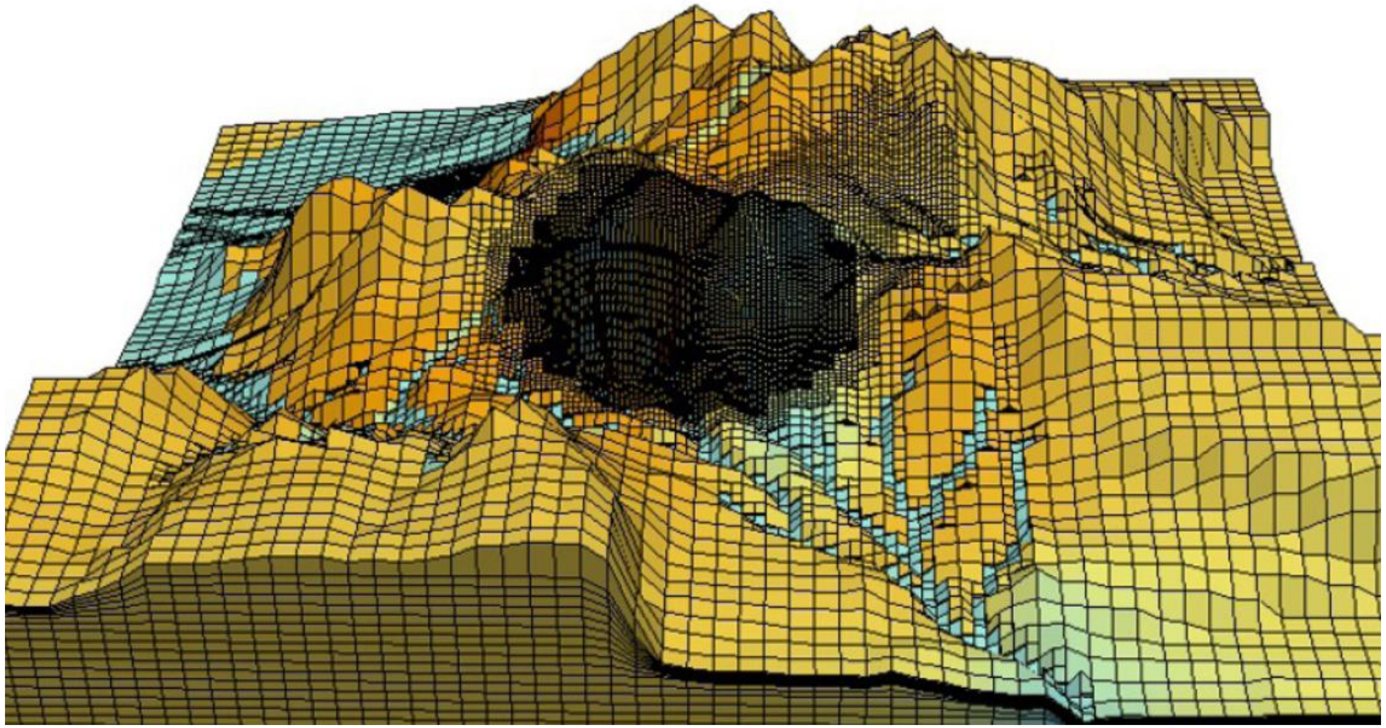


What is Groundwater Modeling?

- 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

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

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

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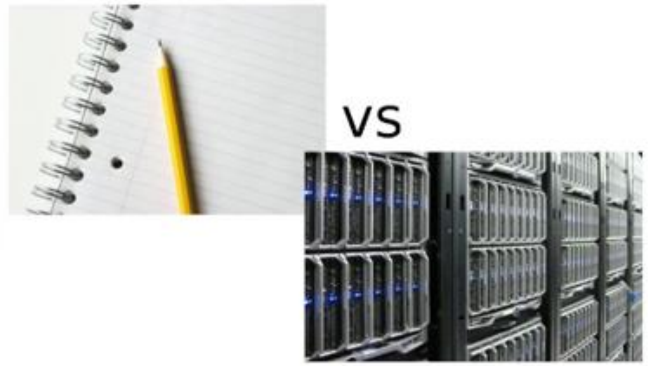
How Do We Solve Groundwater Flow Equations?

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

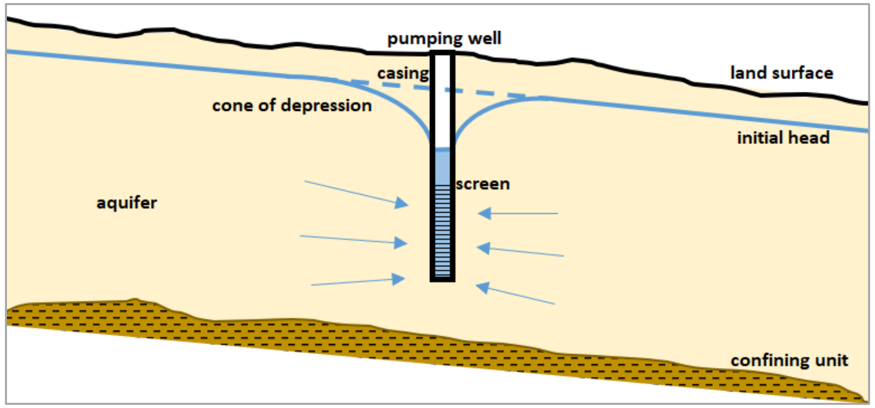
- **Numerical solutions**
  - approximate
  - discretization of the model domain
  - iterative methods
  - e.g. finite differences, finite elements, …

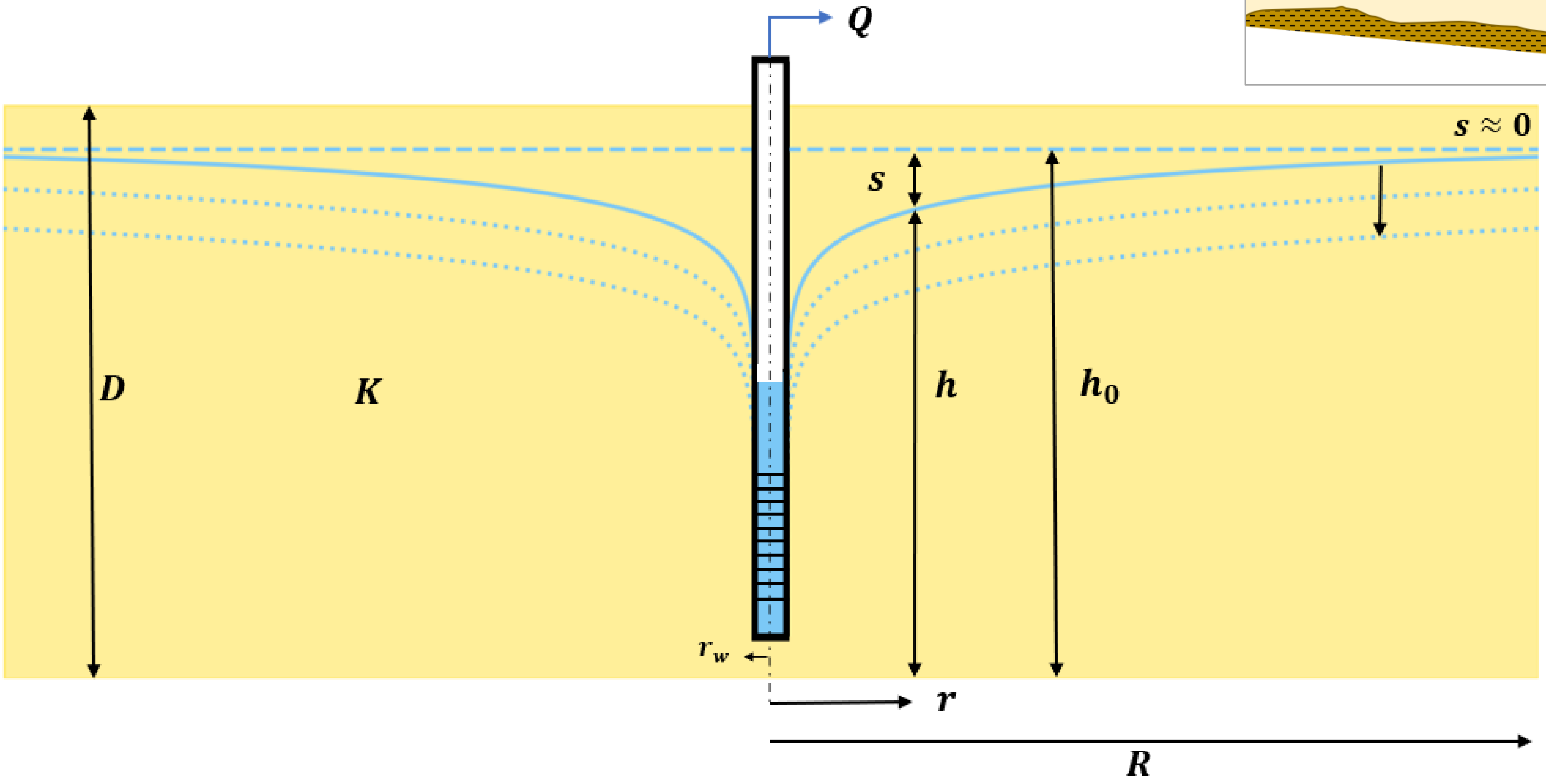
- **Software tools:**
  - MODFLOW (industry standard)
  - FloPy (Python interface for MODFLOW)
  - TimML (Python library for analytical models)

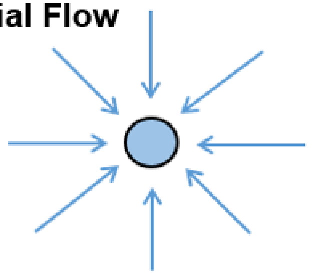


Axisymmetric Models

used to simulate flow to a pumping well



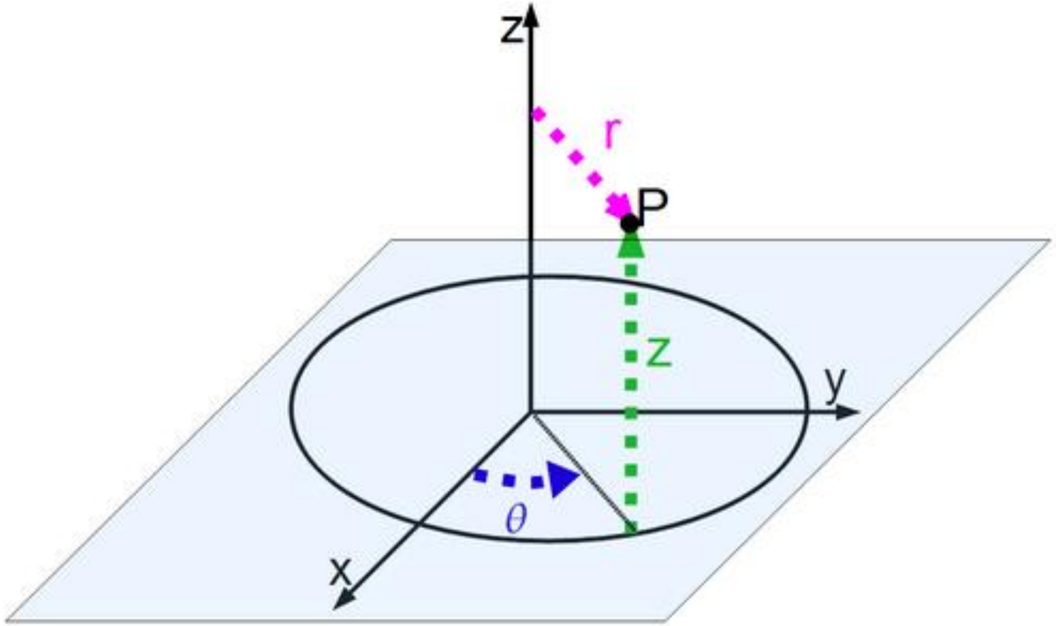




pumping rate	Q
aquifer thickness	D
aquifer conductivity	K
aquifer transmissivity	$T = KD$
hydraulic head	h
initial head	h_0
drawdown	s
radial distance	r
well radius	r_w
radius of influence	R

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*



$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \end{cases}$$

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

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The Thiem-Dupuit Formulas

- Steady confined flow (Thiem, 1870, 1906)

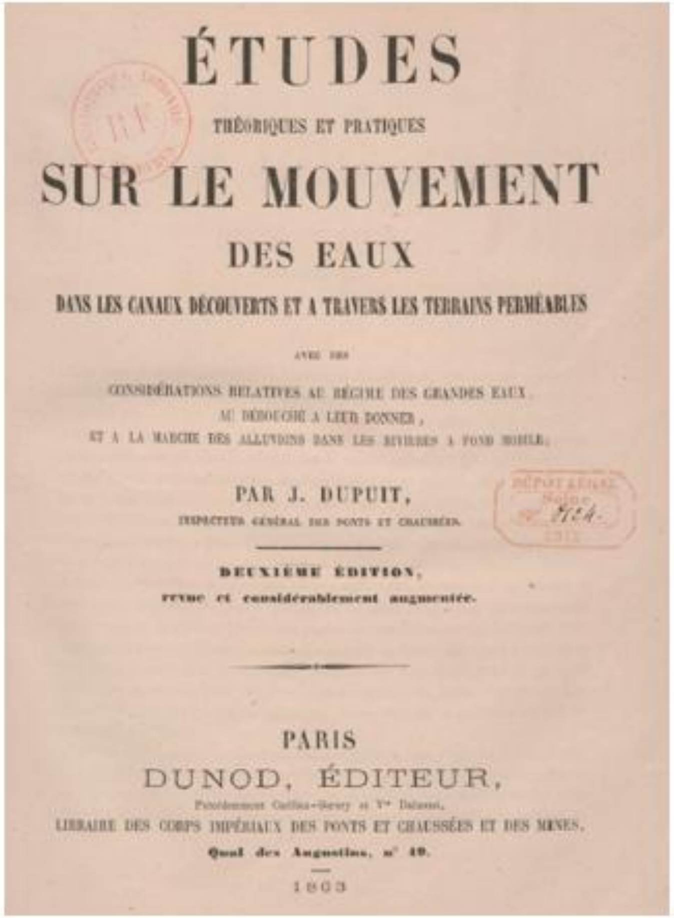
$$s(r) = \frac{Q}{2\pi KD} \ln\left(\frac{R}{r}\right)$$

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!



Jules Dupuit

Adolf Thiem

Günther Thiem

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Confined Flow

- Confined aquifer
- Constant saturated thickness ***D***
- If aquifer is homogeneous:
  - *K* is constant
  - *T* is constant
  - ***T = KD***
- **Linear** problem

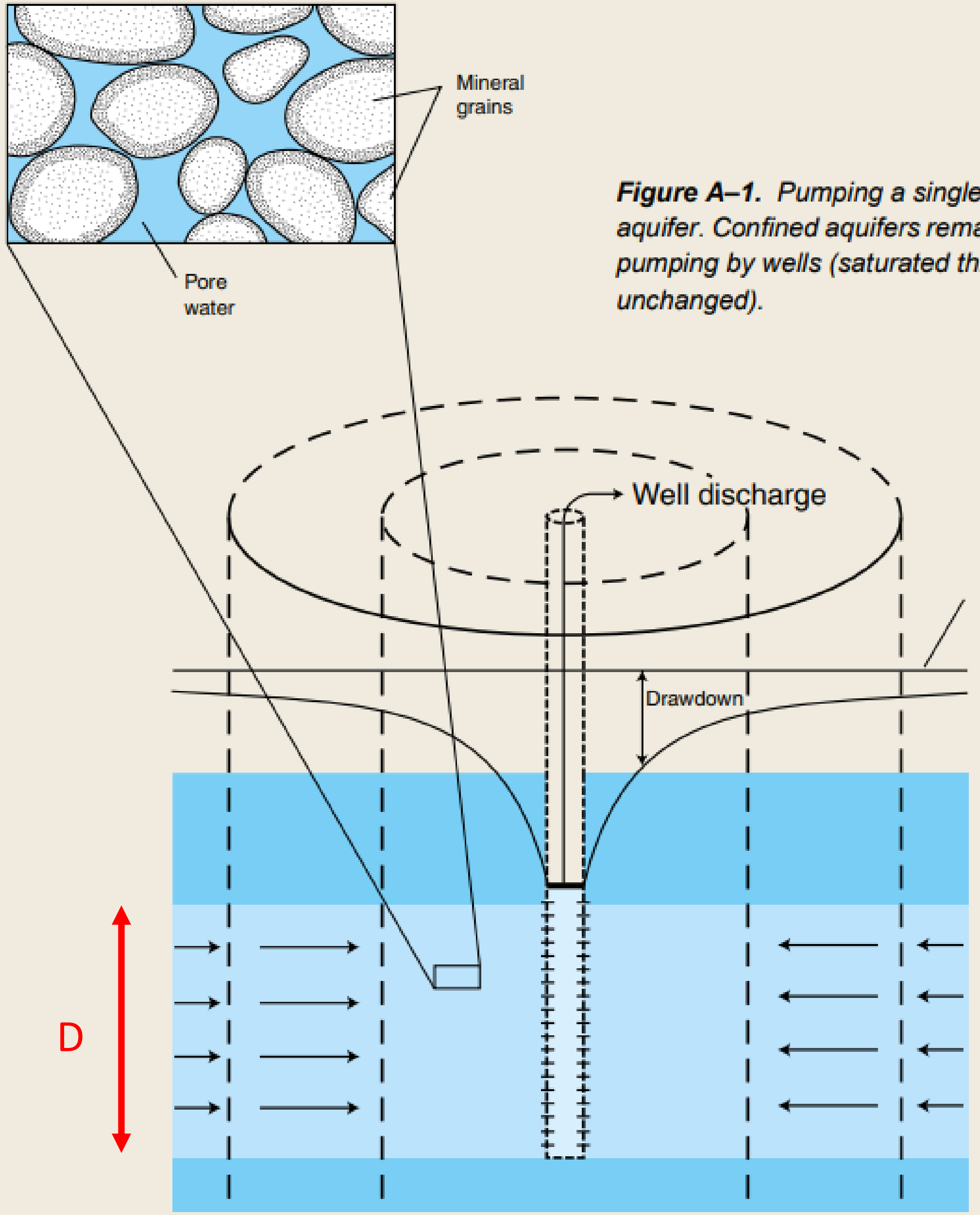

Figure A–1. *Pumping a single well in an idealized confined aquifer. Confined aquifers remain completely saturated during pumping by wells (saturated thickness of aquifer remains unchanged).*

Unconfined Flow

– Unconfined aquifer

– Saturated thickness = head ***h***

– If aquifer is homogeneous:
  – K is constant
  – T is head-dependent
  – $\boldsymbol{T = Kh}$

– **Nonlinear** problem

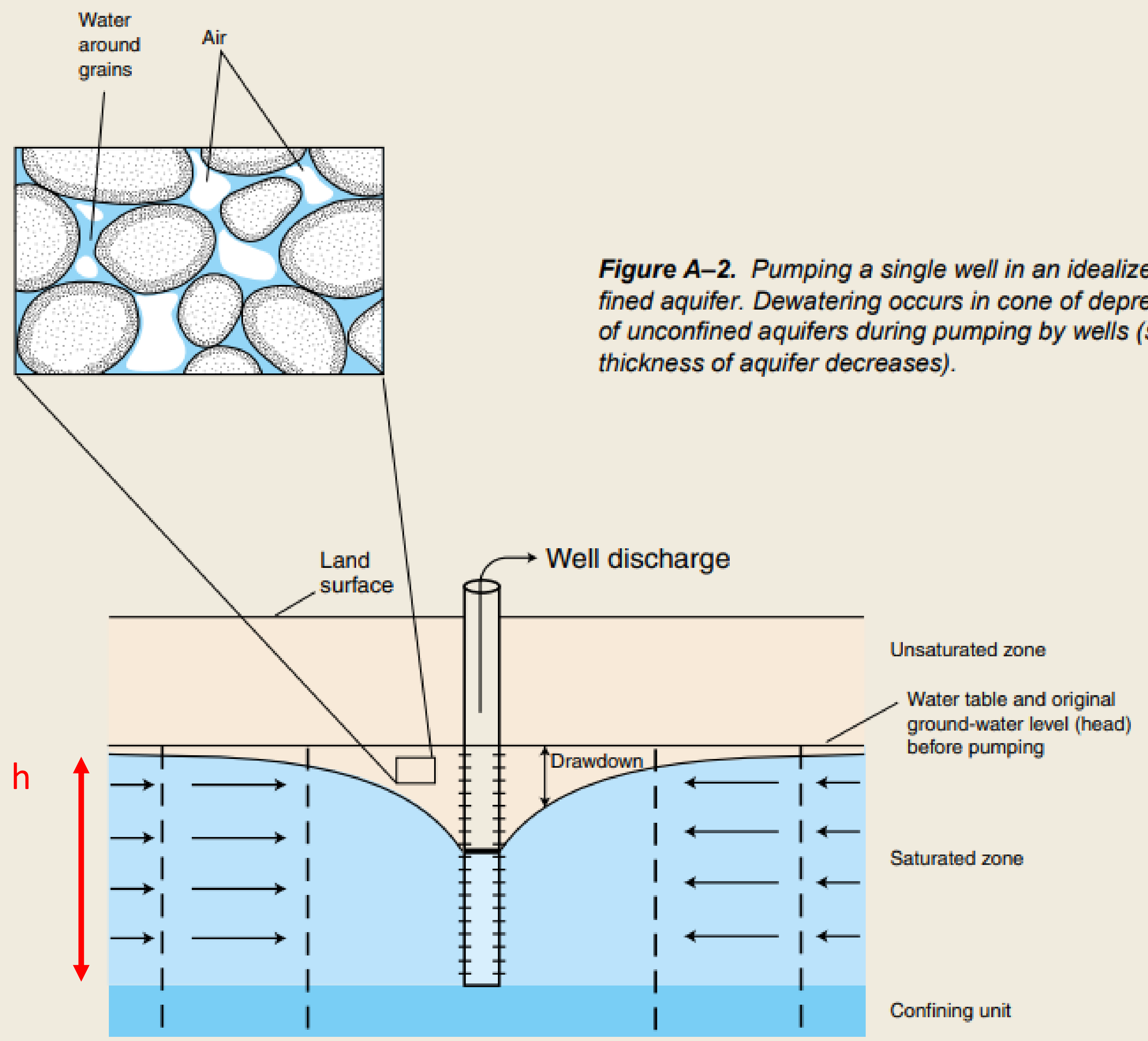

Figure A–2. *Pumping a single well in an idealized unconfined aquifer. Dewatering occurs in cone of depression of unconfined aquifers during pumping by wells (saturated thickness of aquifer decreases).*

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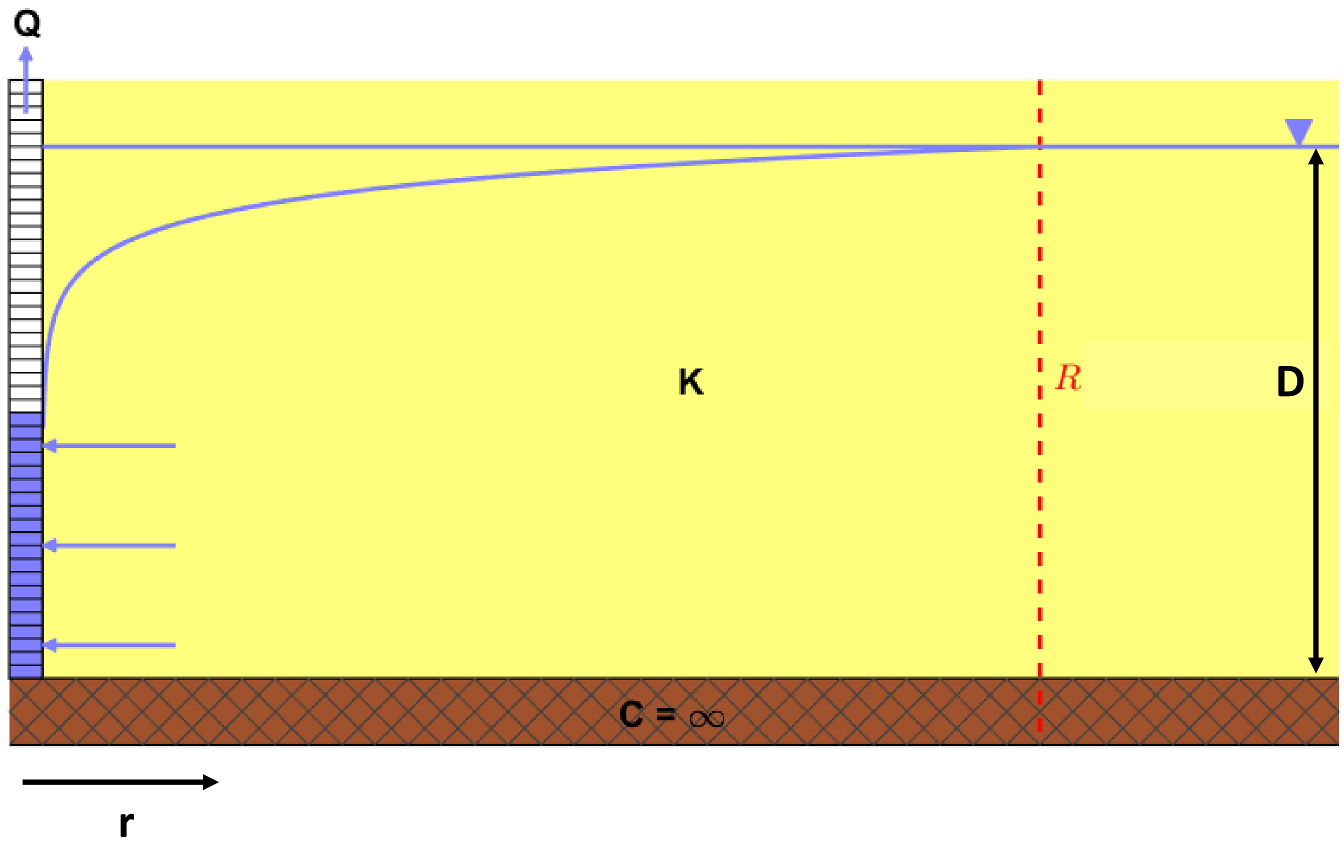
Thiem-Dupuit: Example

```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')
```

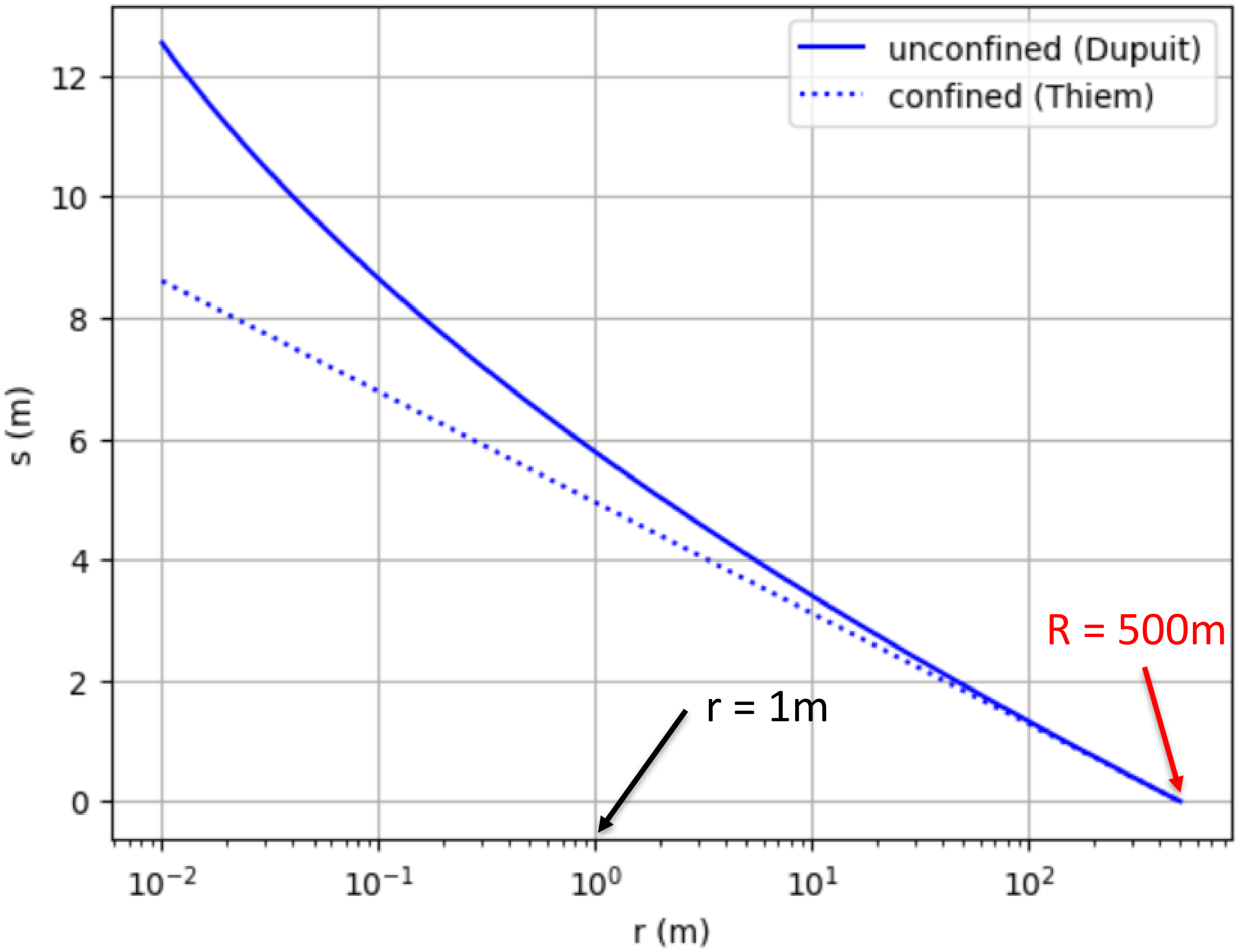
```
Drawdown according to Thiem:  s = 4.95 m
Drawdown according to Dupuit: s = 5.78 m
```



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
```

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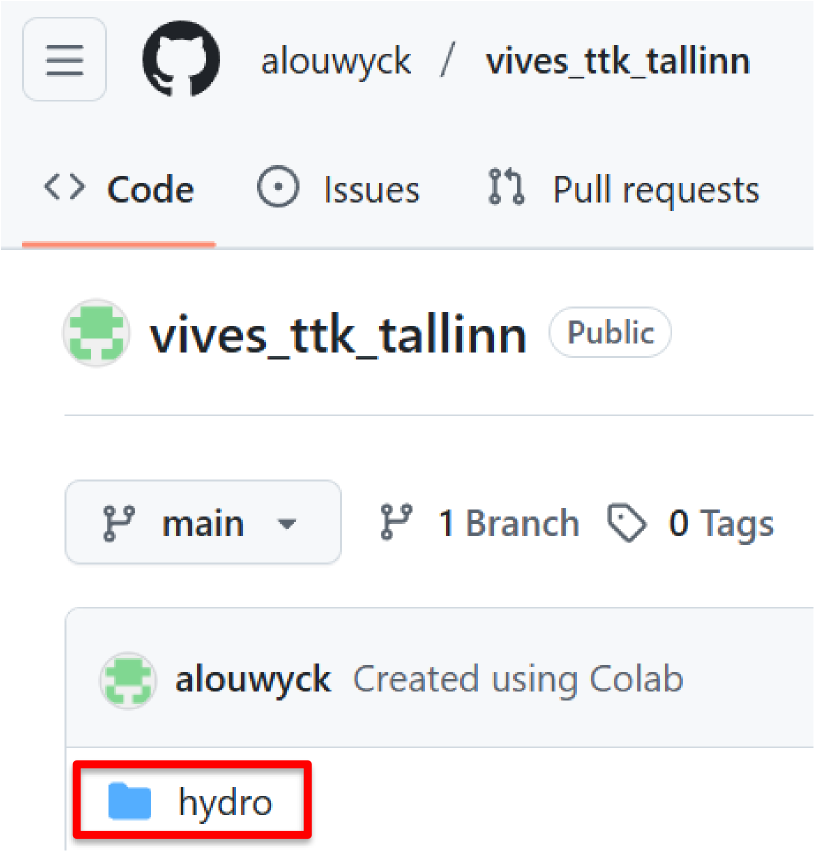
GitHub Repo

https://github.com/alouwyck/vives_ttk_tallinn



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Sources

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