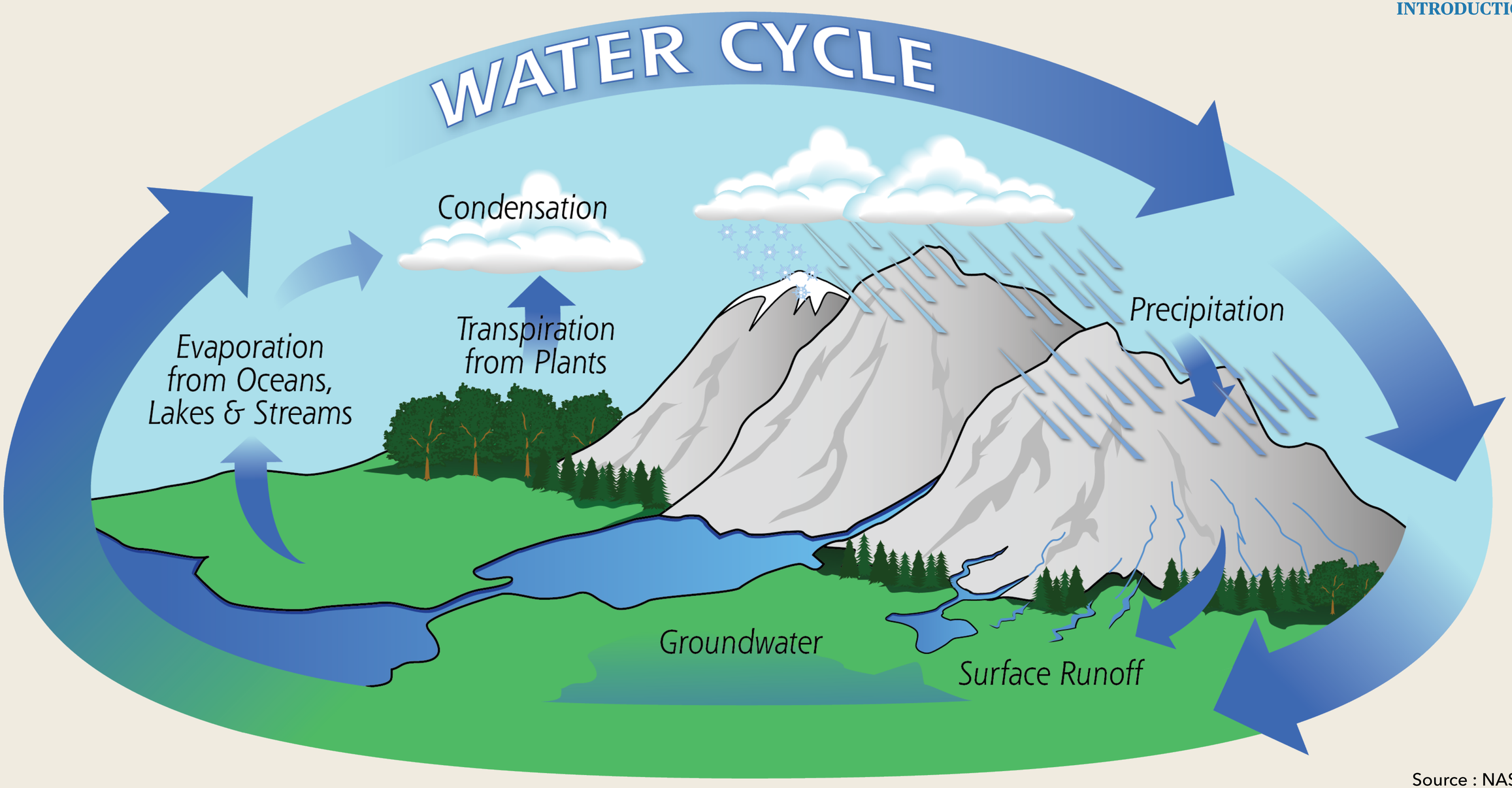
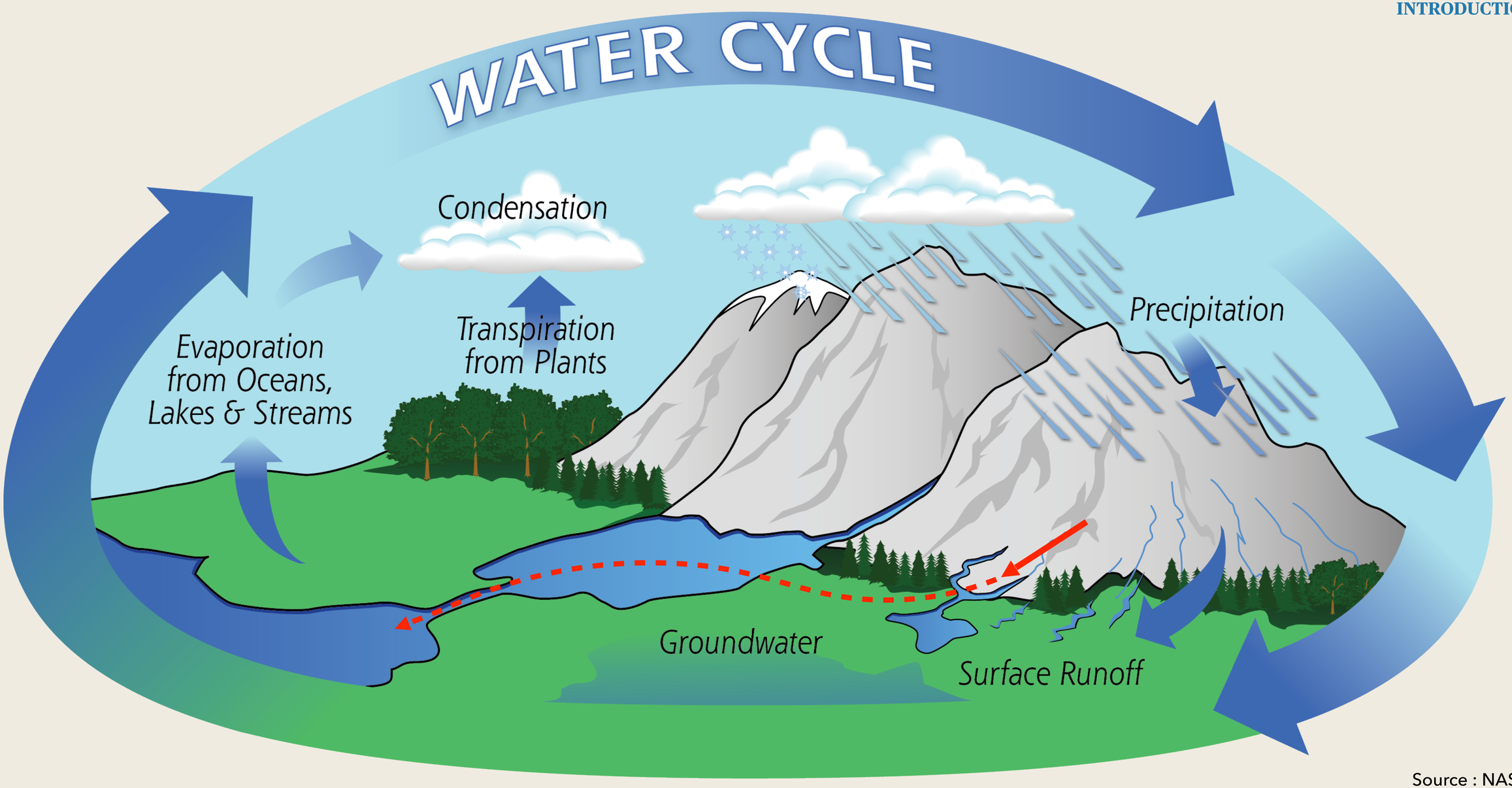
How groundwater creates river networks

And how rivers are markers of where aquifers lie beneath the ground


WATER CYCLE
Condensation
Transpiration
from Plants
Evaporation
from Oceans,
Lakes & Streams
Precipitation
Groundwater
Surface Runoff

Source : NASA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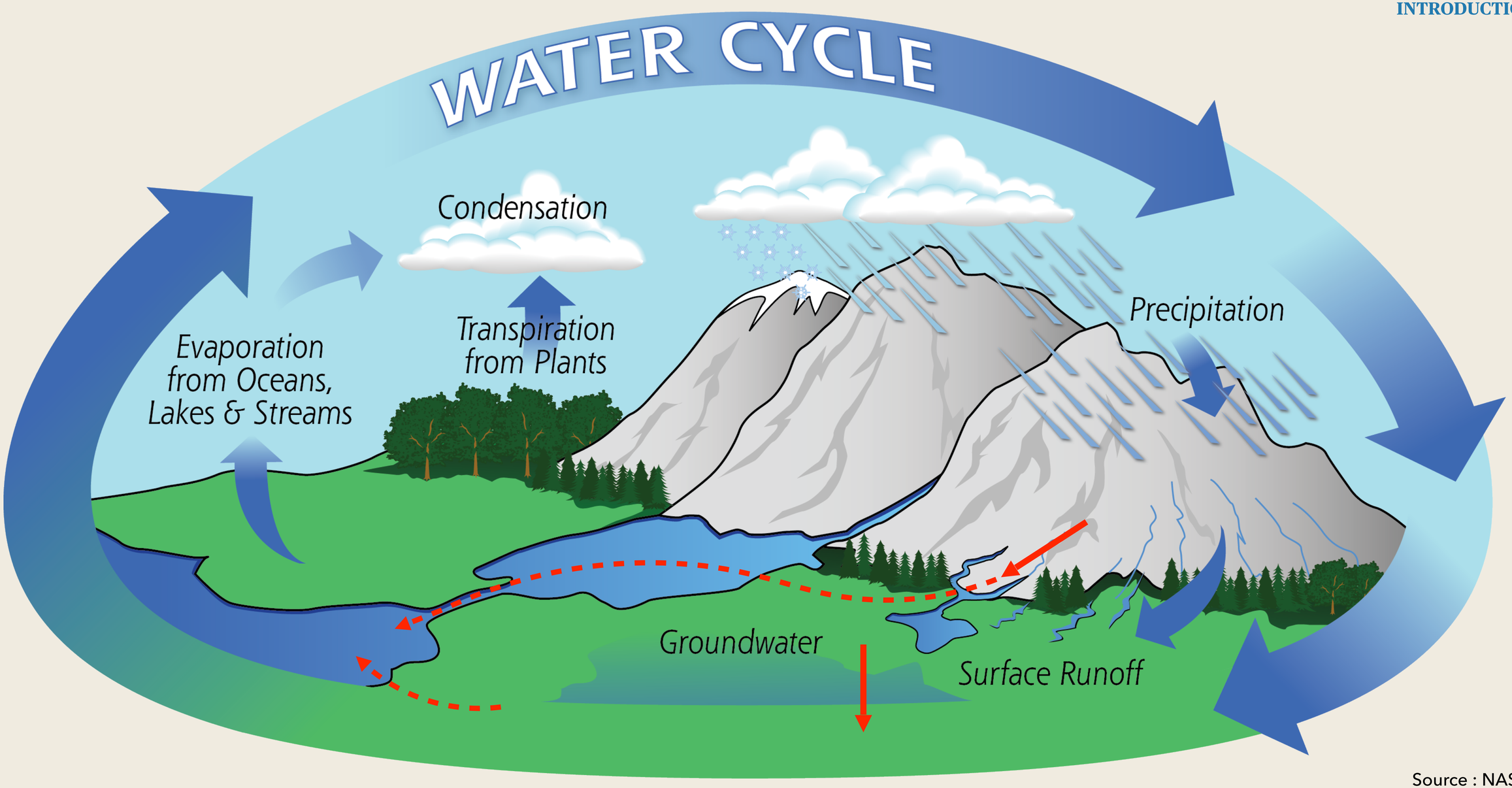
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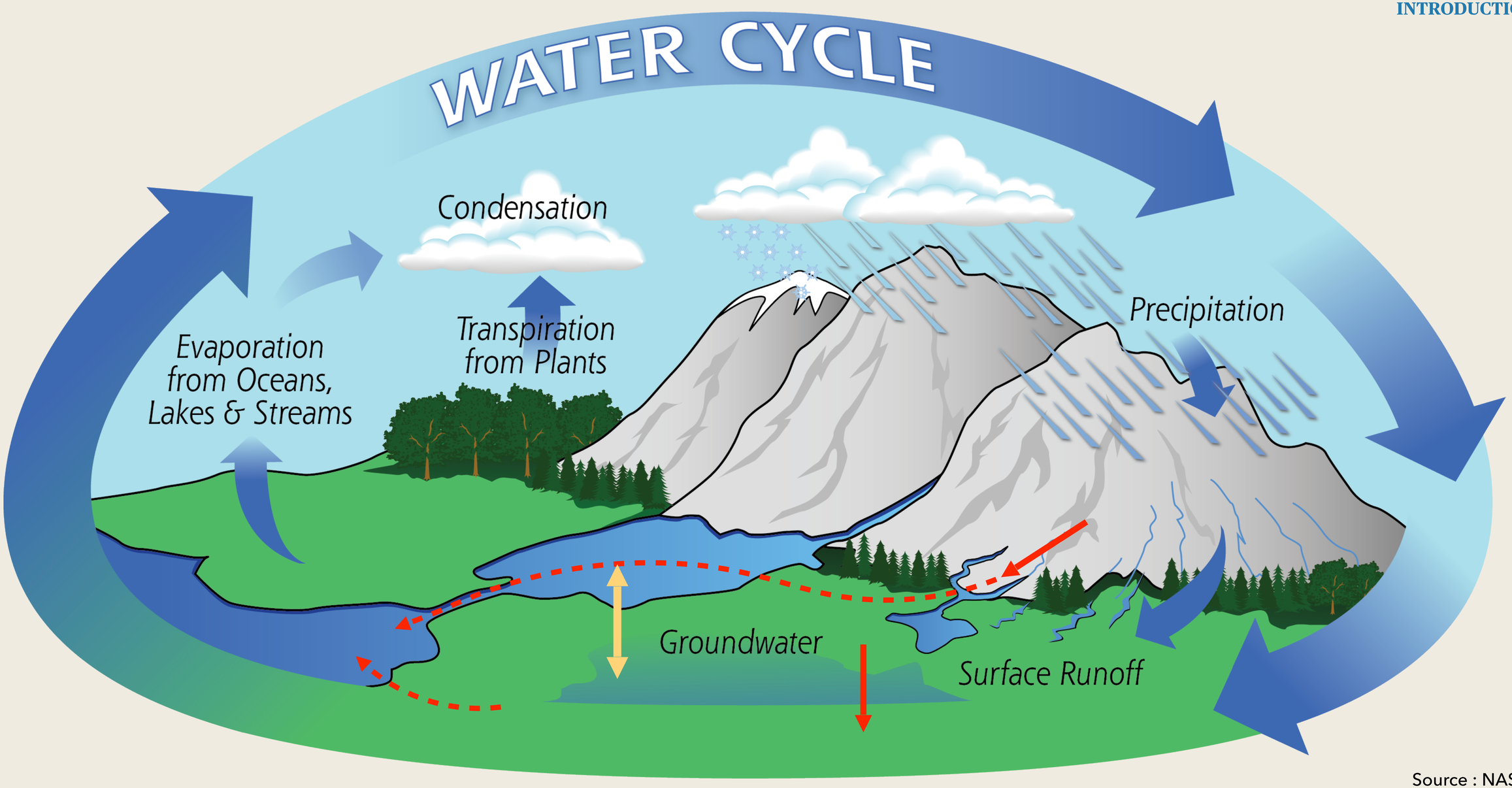
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Groundwater feed channels

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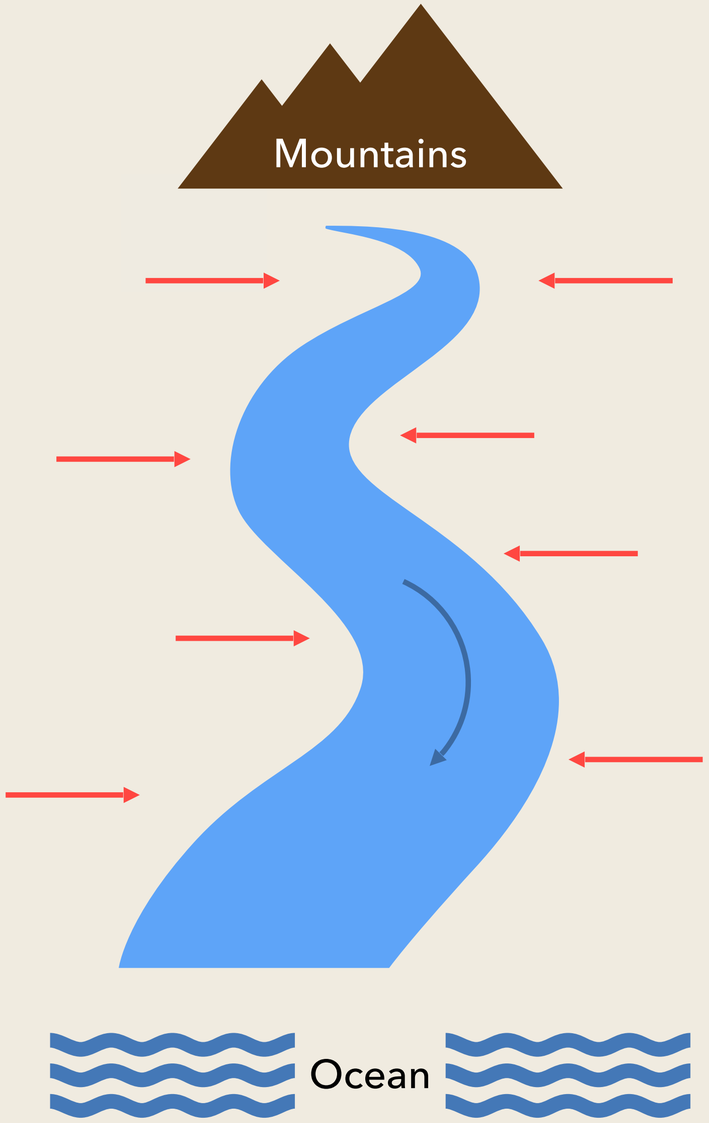
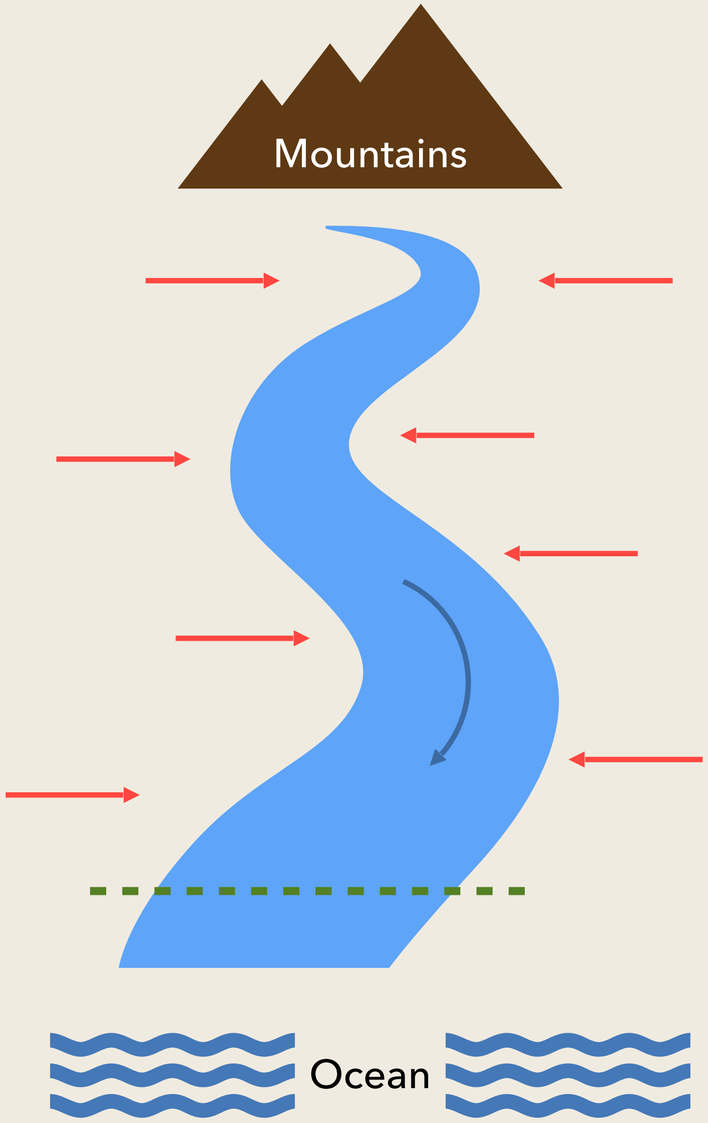
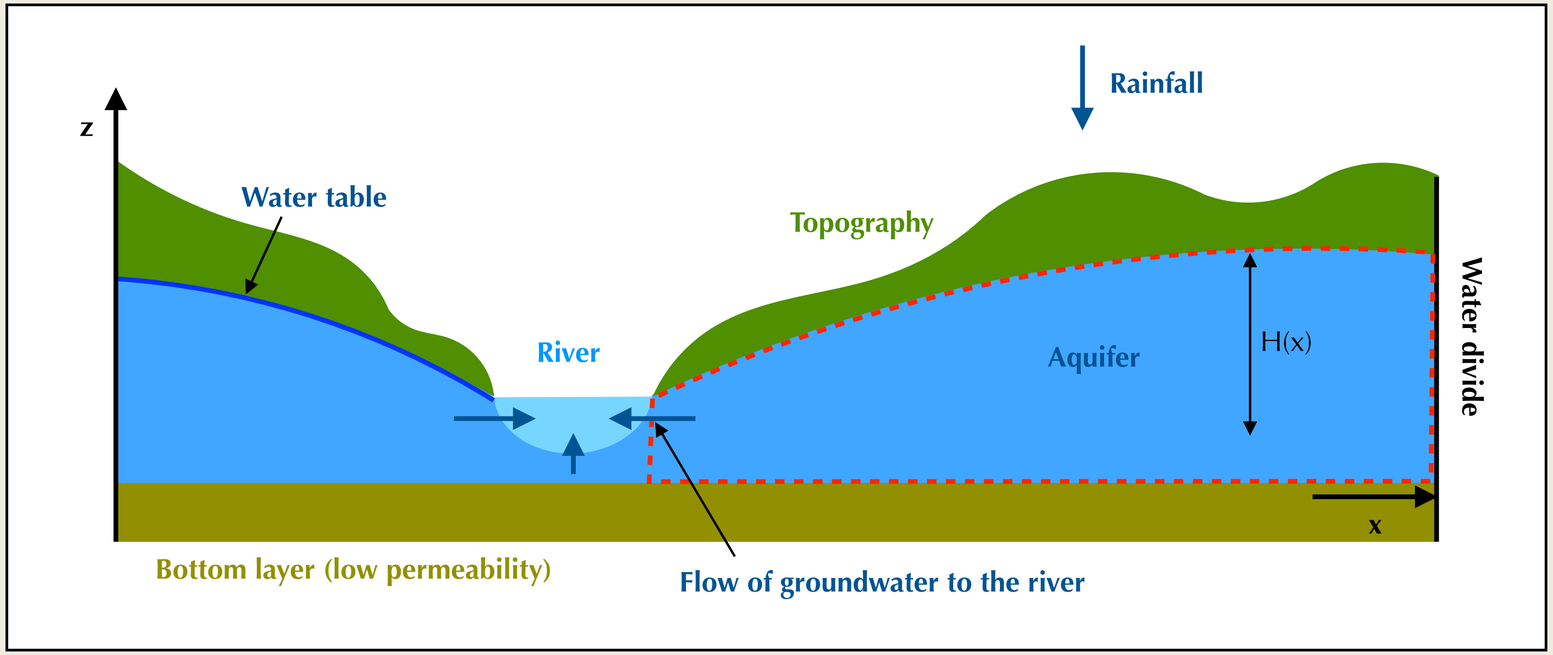


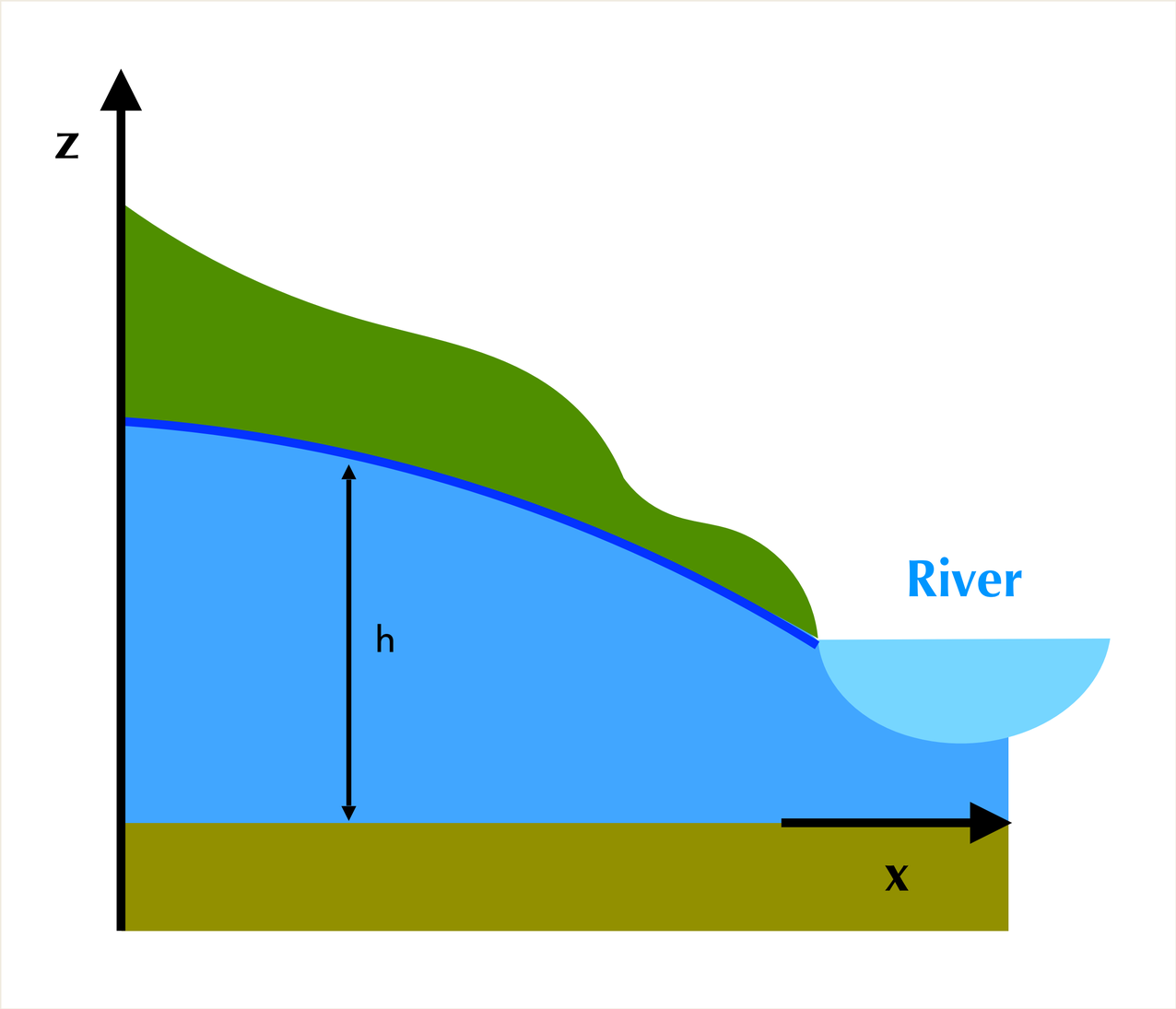
Groundwater feed channels

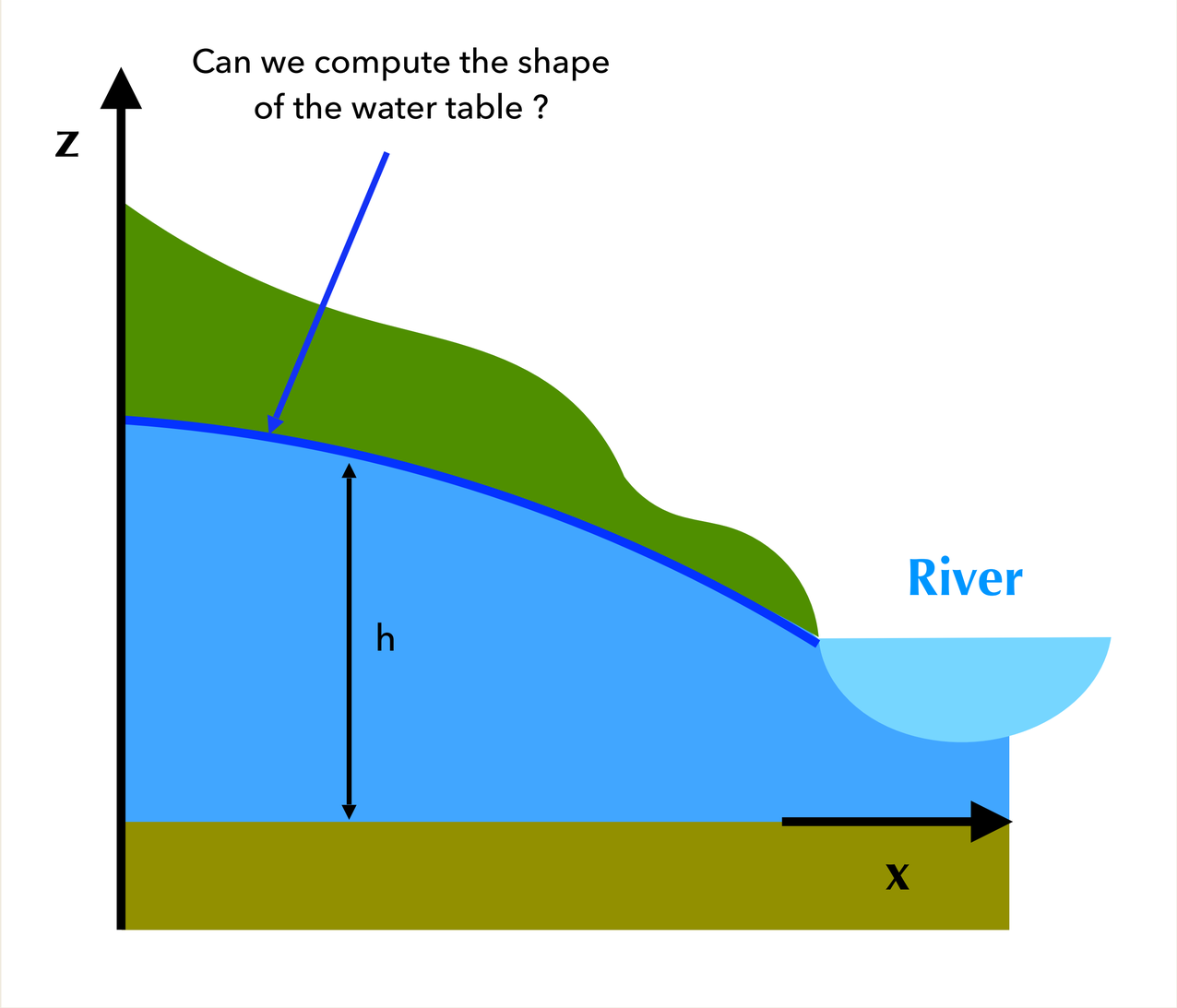


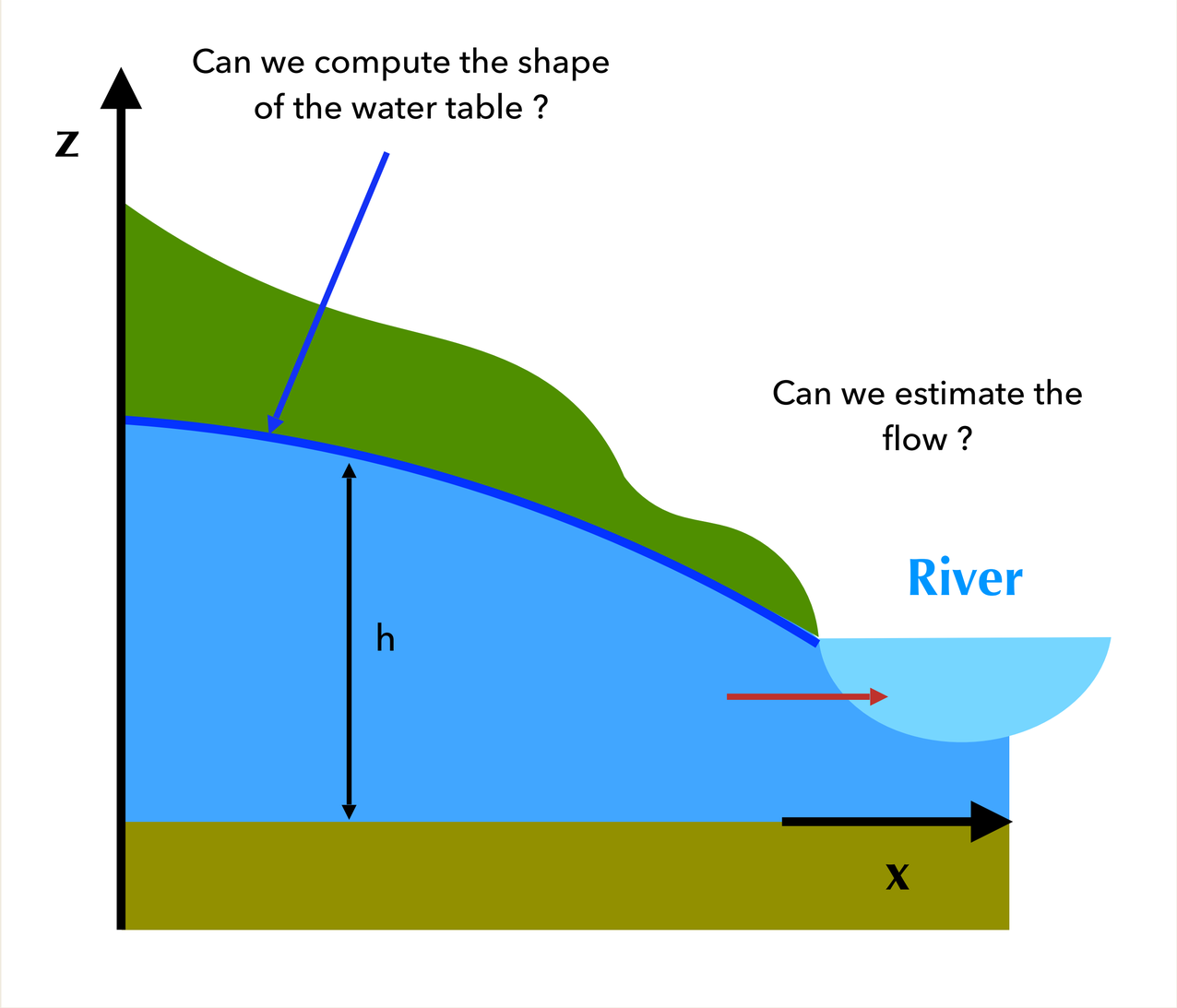


What is the relationship between river networks and groundwater flow ?

GROUNDWATER FLOWS INTO RIVERS : A CROSS SECTION




Can we compute the shape
of the water table ?
z
h
River
x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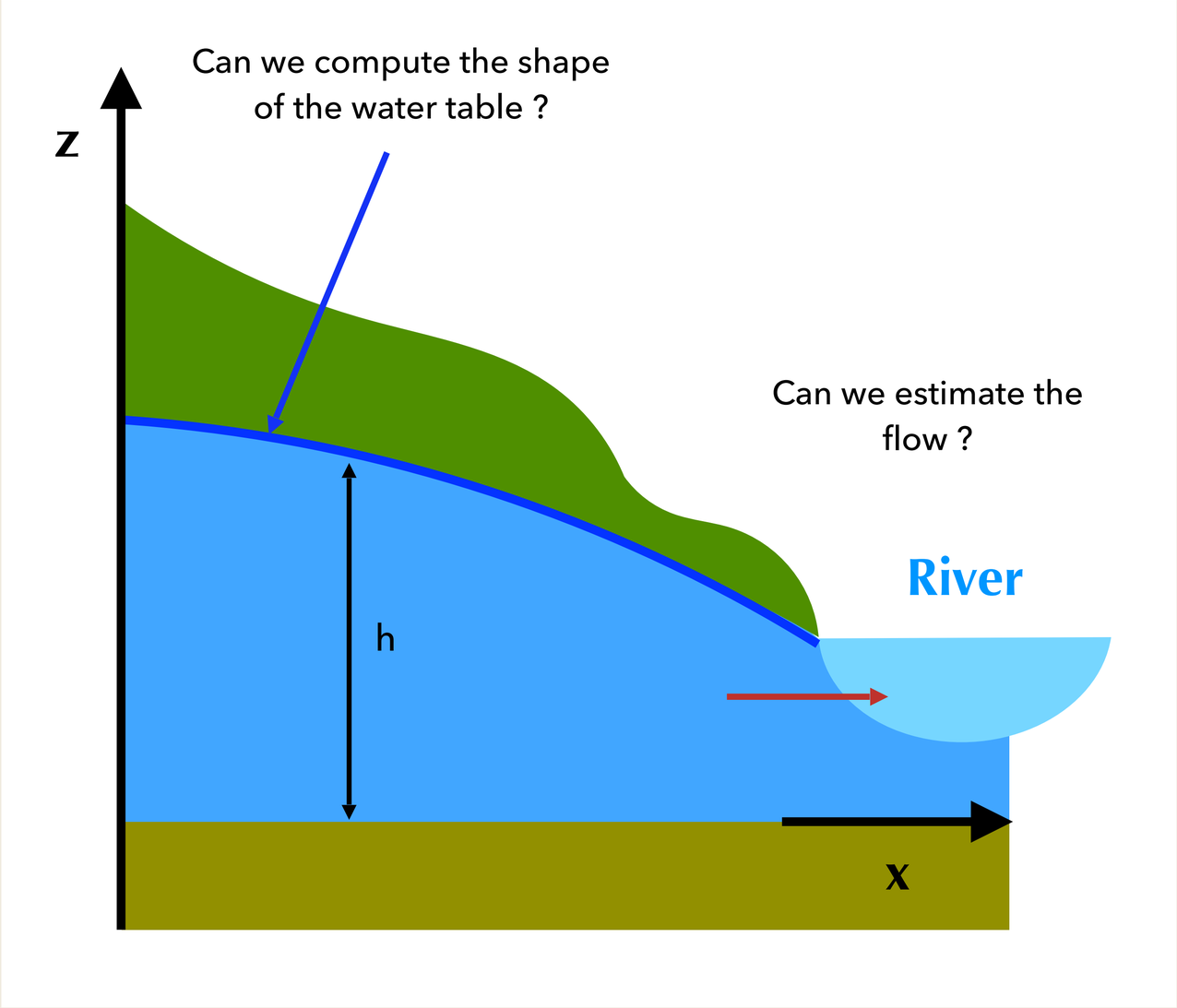

Groundwater balance equation

$$\omega \frac{\partial h}{\partial t} = \frac{K}{2} \triangle h^2 + R$$

- h : water table elevation (m)
- R : recharge (m/s)
- ω porosity
- K : hydraulic conductivity (m/s)

Averaged in time

$$\frac{K}{2} \triangle h^2 + R \simeq 0$$

Averaged in time

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Based on

Shallow-water approximation

- Aquifer depth << Aquifer length
- Flow is mostly **horizontal**
- $v_{xy} >> v_z$
- $v_{xy} \propto \partial_{xy} h$

Averaged in time

$$\frac{K}{2} \triangle h^2 + R \simeq 0$$

Based on

Shallow-water approximation

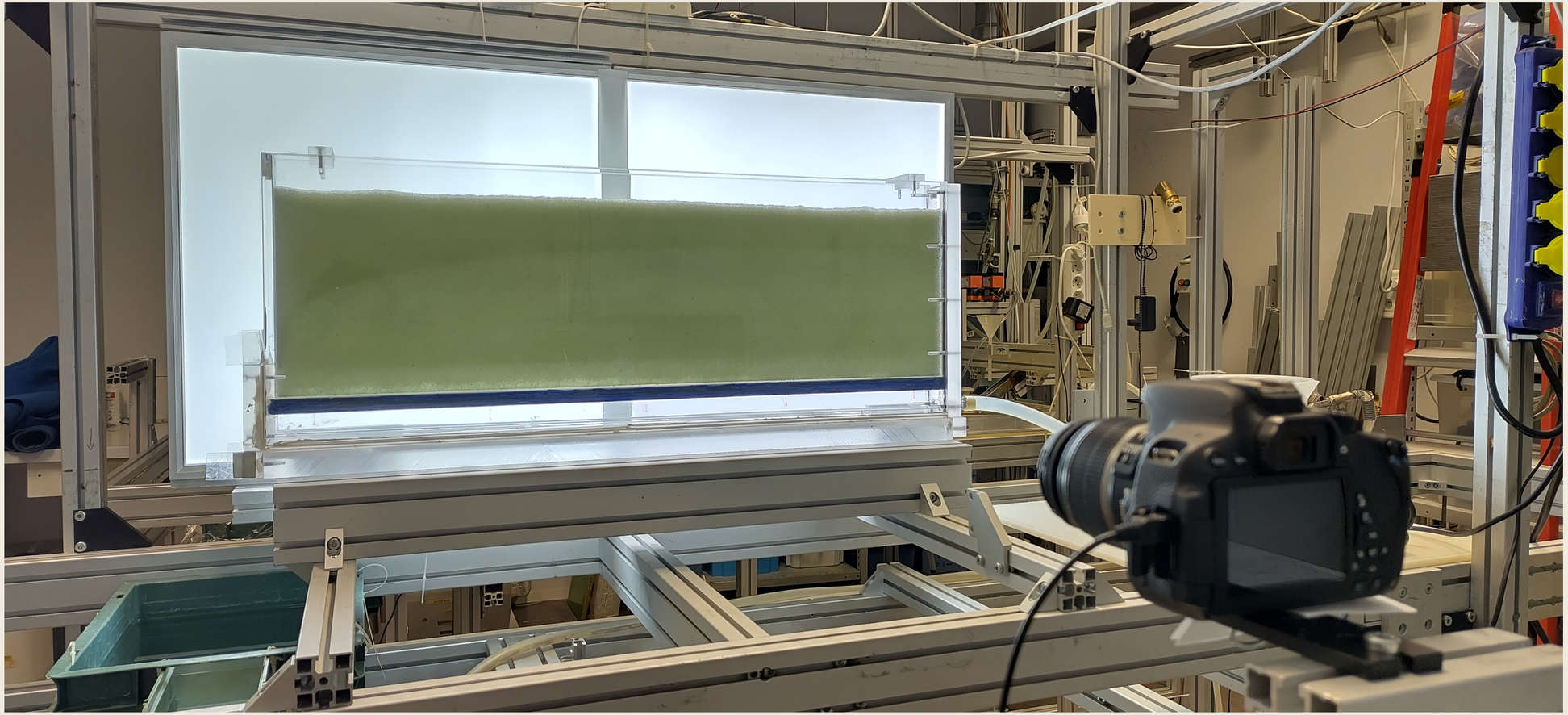
- Aquifer depth << Aquifer length
- Flow is mostly **horizontal**
- $v_{xy} >> v_z$
- $v_{xy} \propto \partial_{xy} h$

To verify

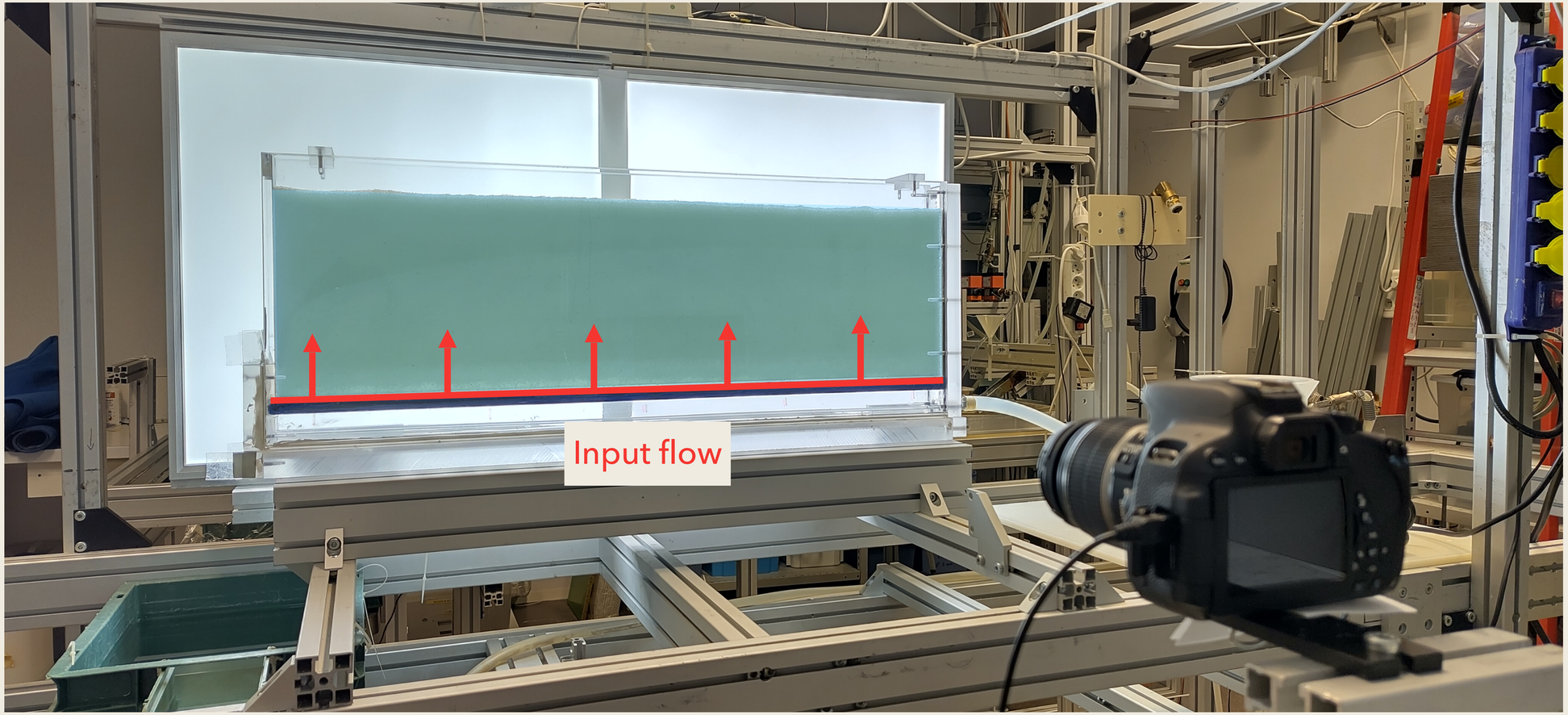
Looking at a river cross-section

- Solve numerically using FreeFEM
- Reproduce experimentally

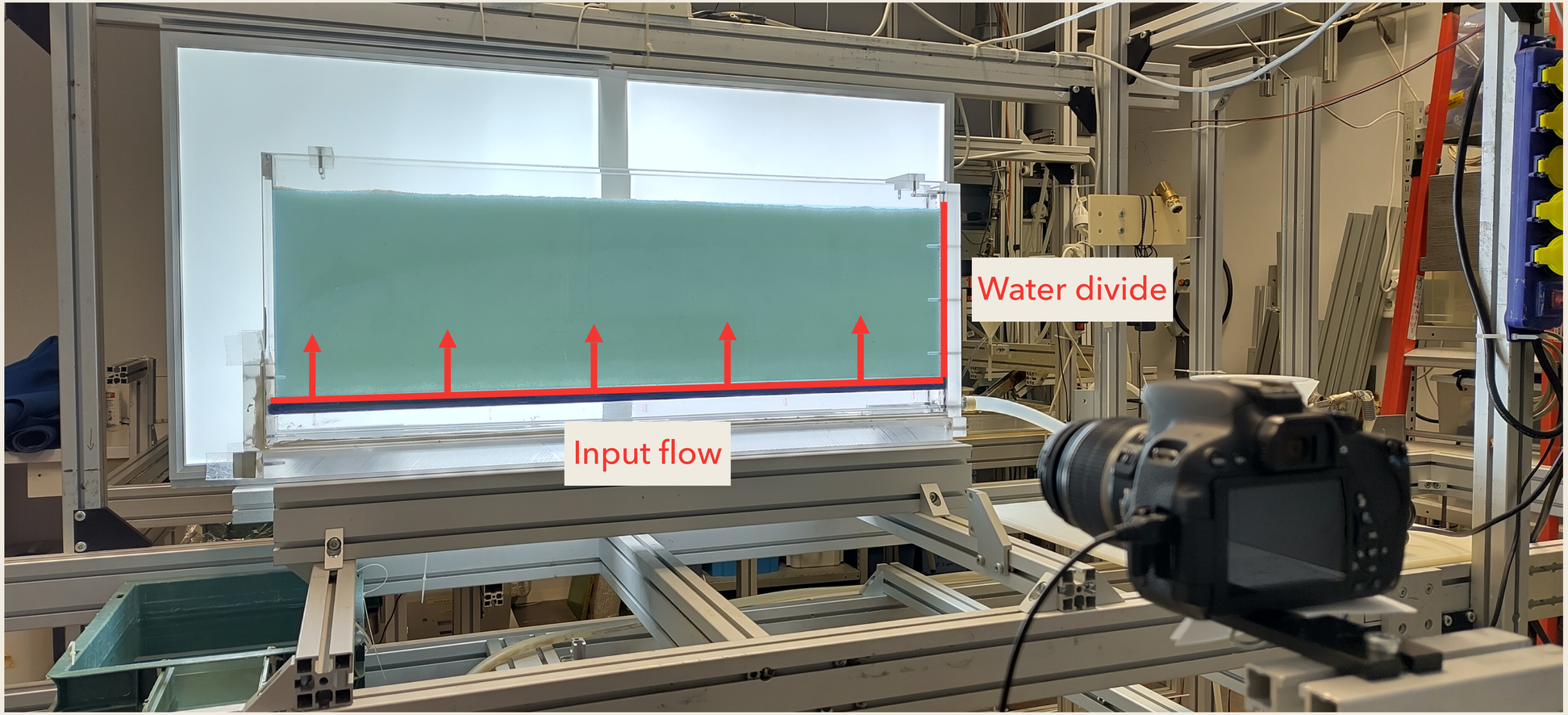
Experimentally



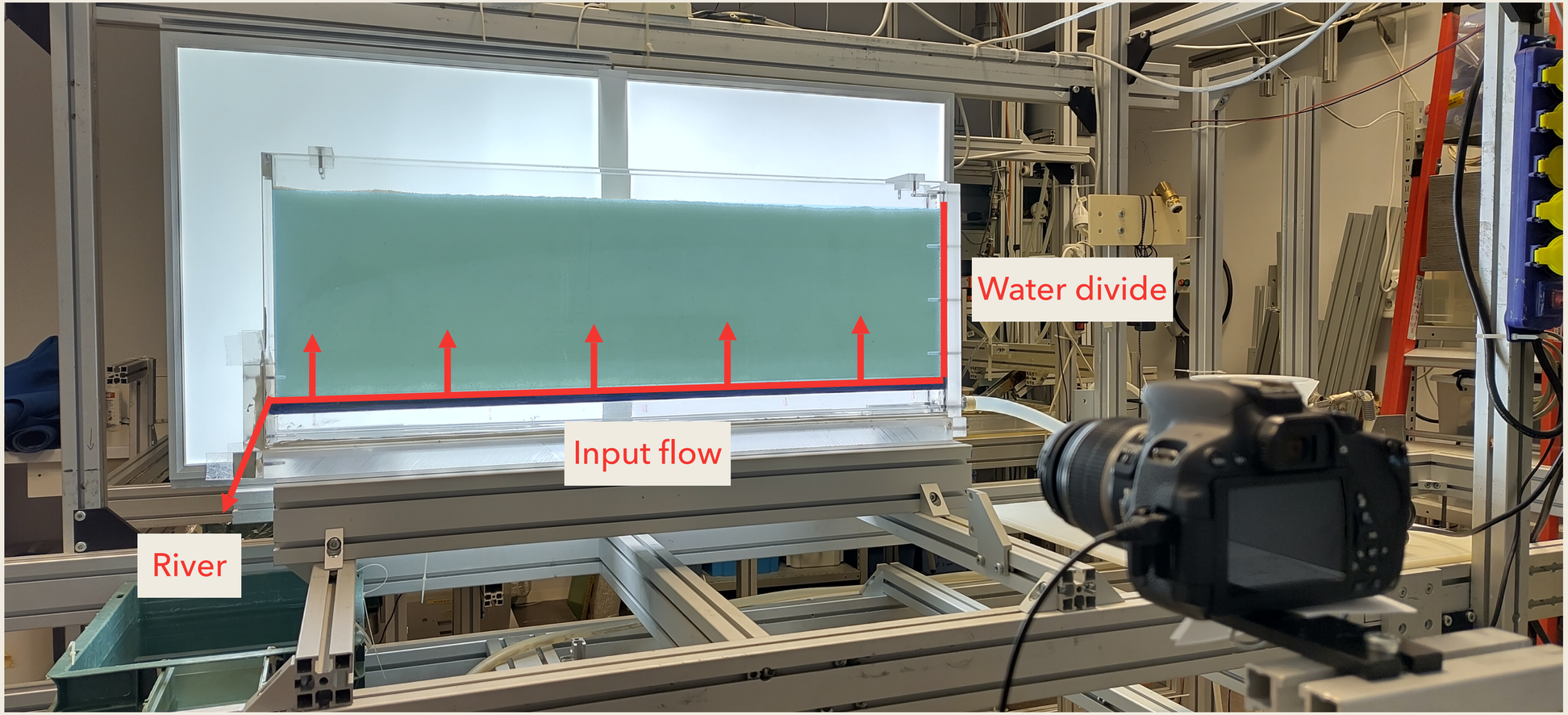
Experimentally



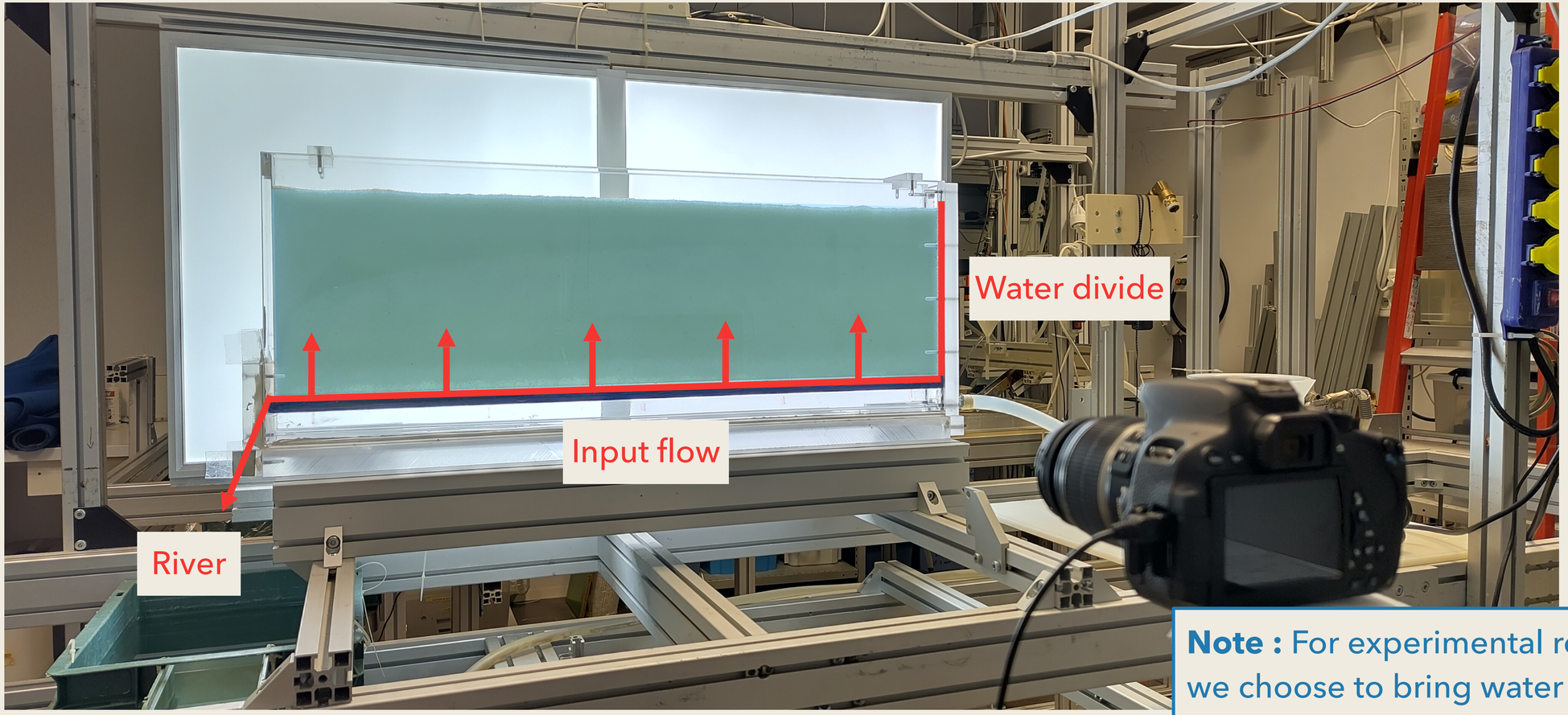
Experimentally



Experimentally

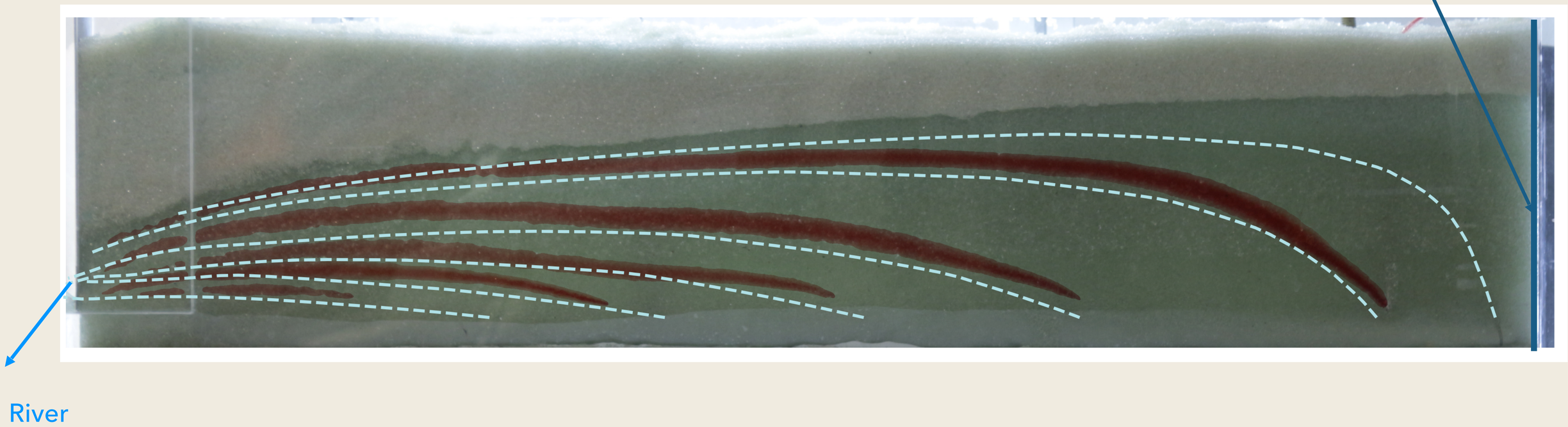


Experimentally

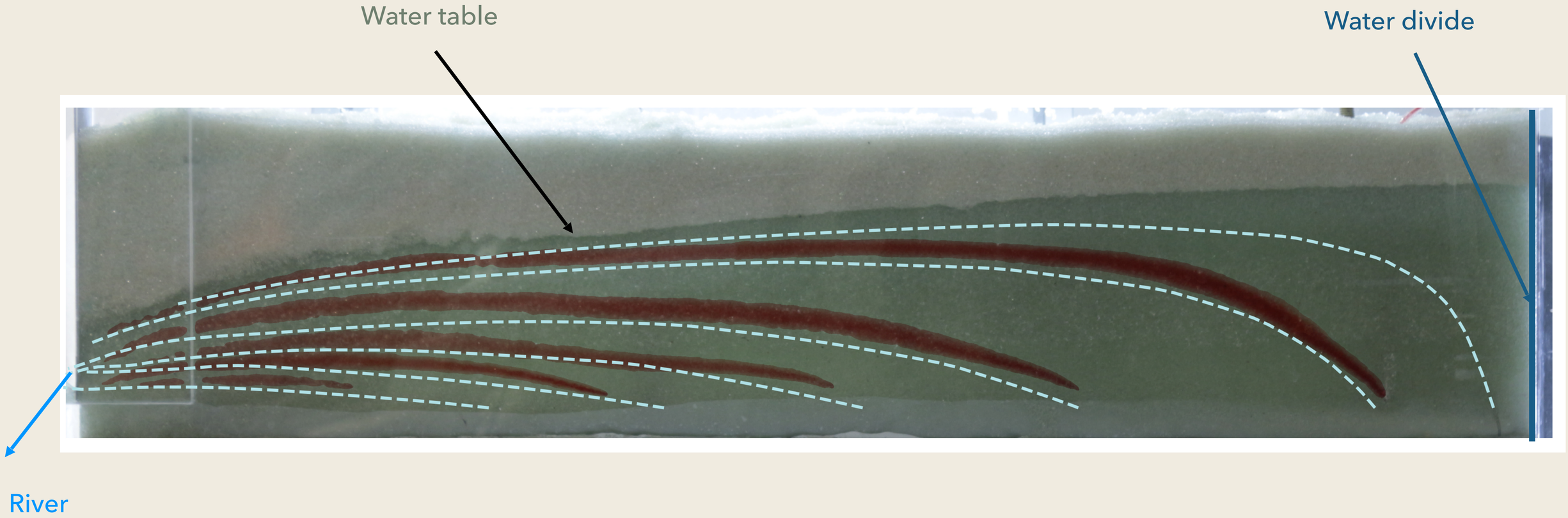


Note : For experimental reasons we choose to bring water from under the aquifer

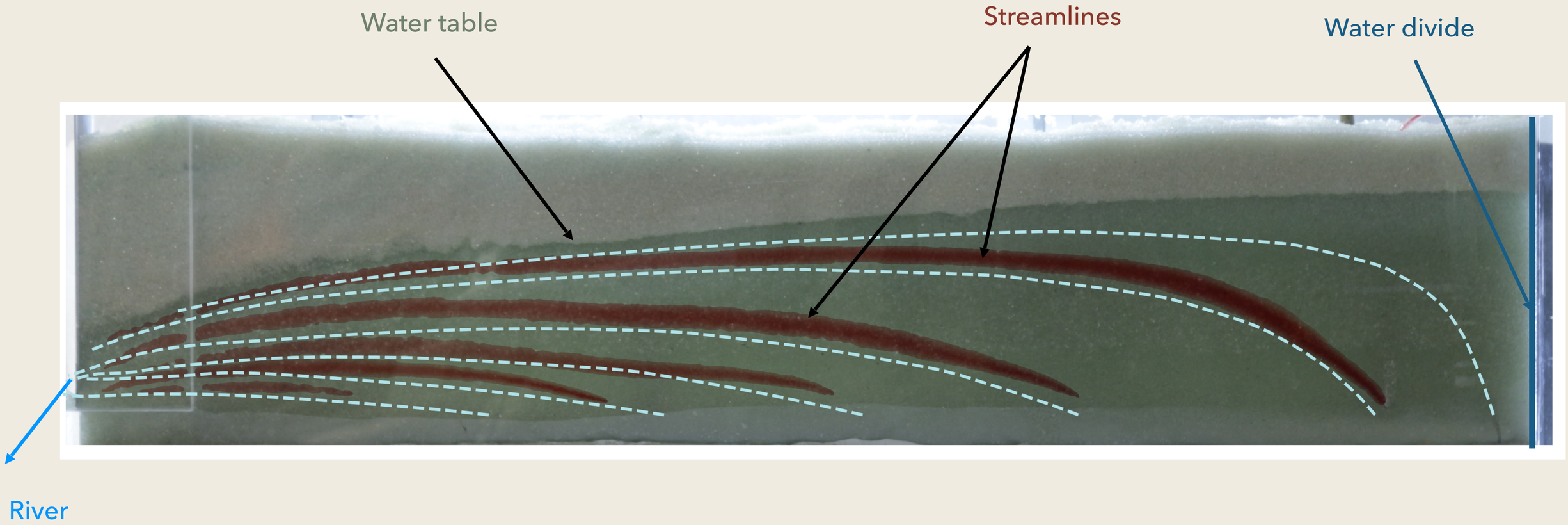
Experimentally



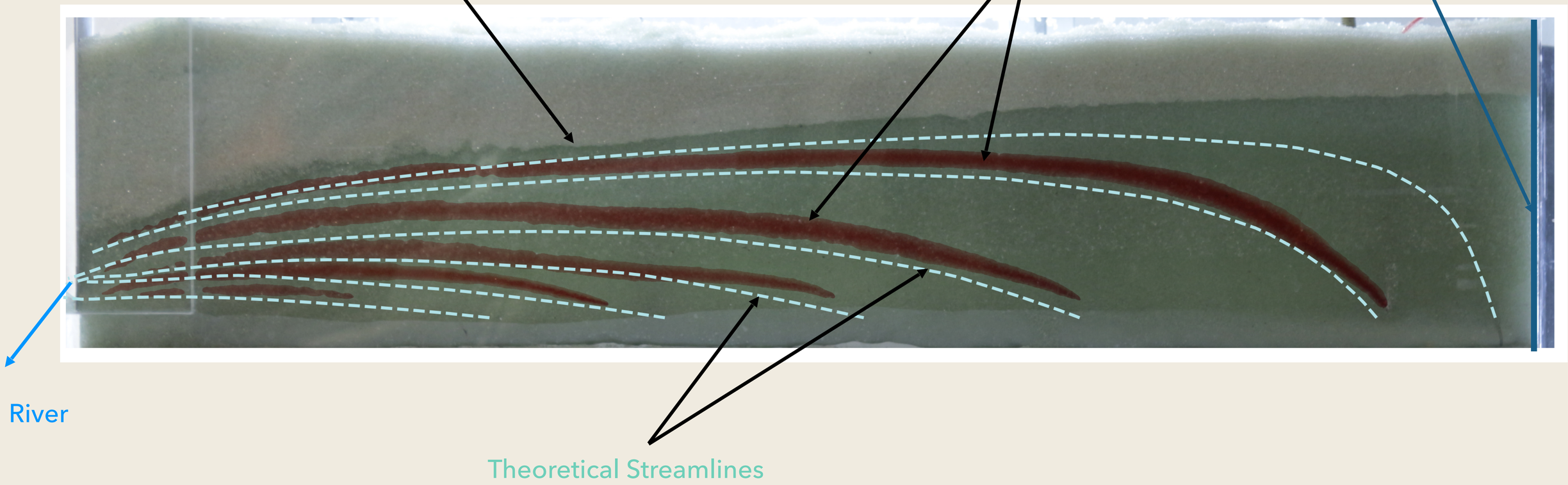
Experimentally



Experimentally



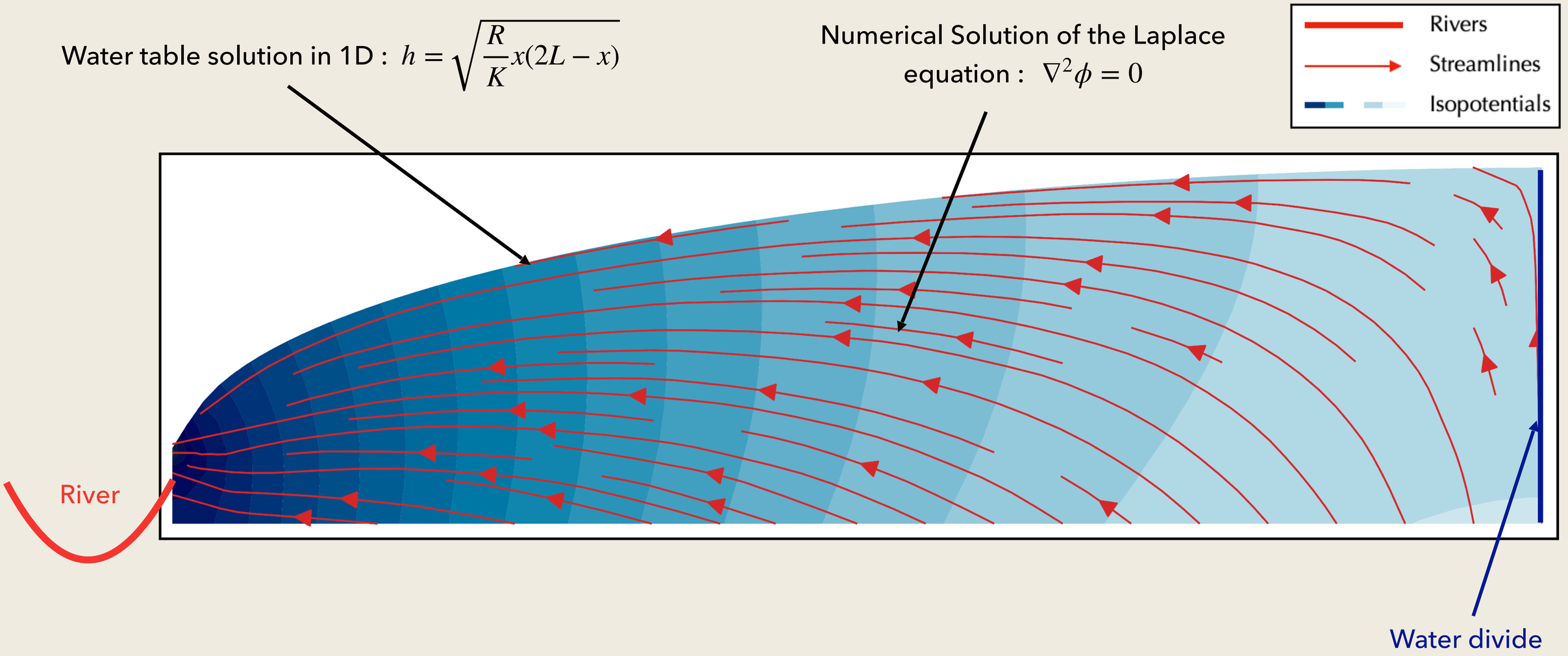
Experimentally



Numerically

Water table solution in 1D : $h = \sqrt{\frac{R}{K}x(2L - x)}$

Numerical Solution of the Laplace equation : $\nabla^2 \phi = 0$



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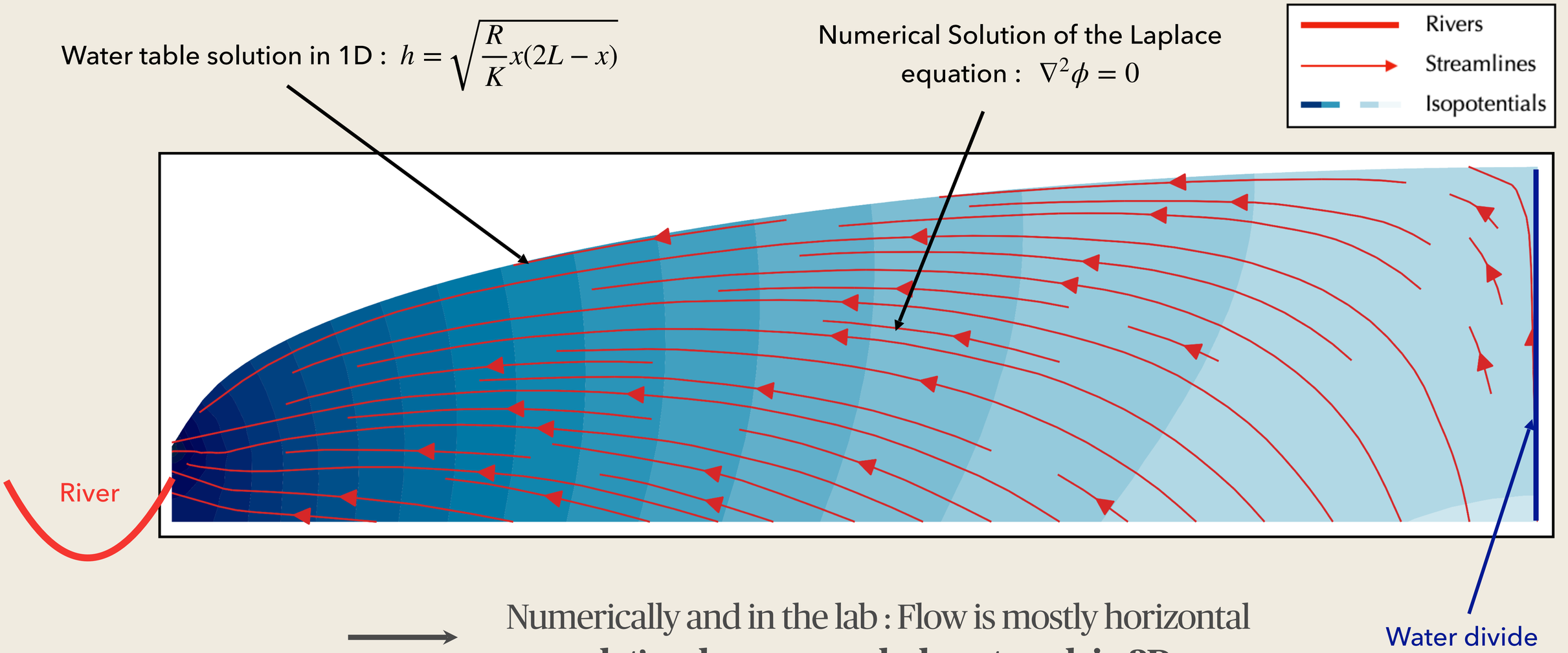

Numerically and in the lab : Flow is mostly horizontal

- let's solve over a whole network in 2D

In 2D : the Poisson equation

$$\frac{K}{2} \triangle h^2 + R \simeq 0 \longrightarrow \boxed{\triangle h^2 \simeq -\frac{2R}{K}}$$

In 2D : the Poisson equation

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Boundary conditions :

River topography

In 2D : the Poisson equation

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+

Average recharge and ground properties

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+

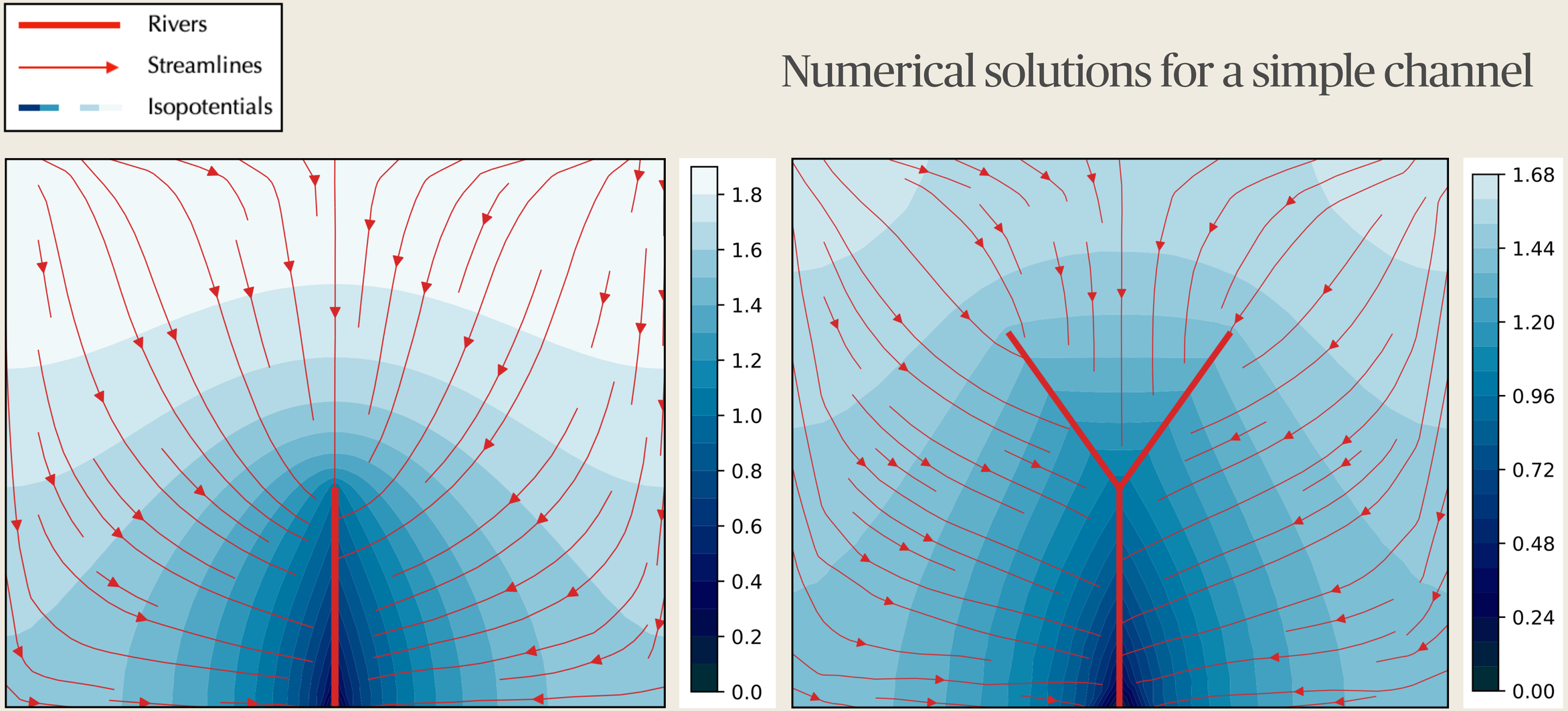
Average recharge and ground properties

= Numerical solution

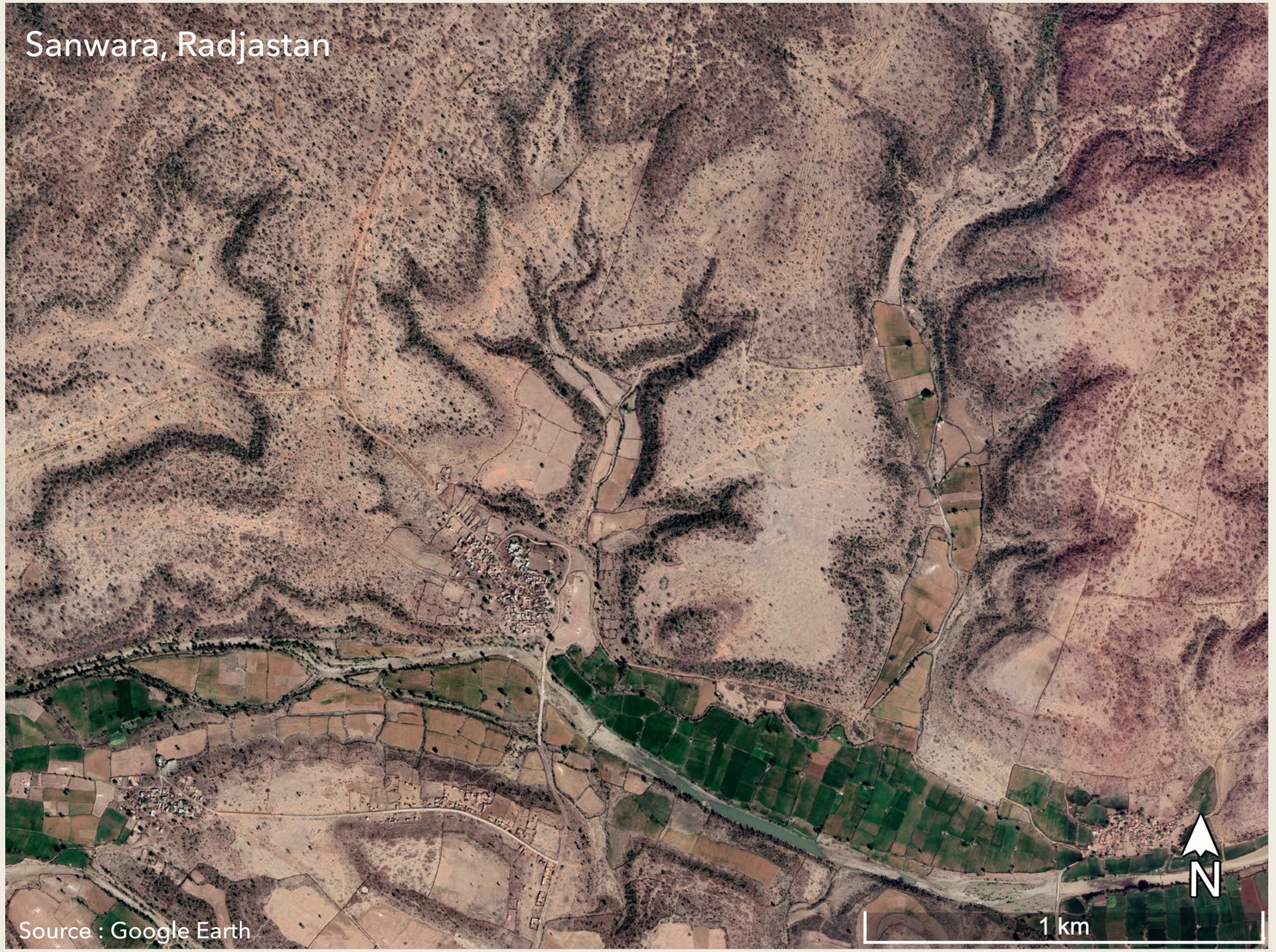
⟶ Finite element solving software FreeFEM

⟶ Python library pyFreeFEM

Numerical solutions for a simple channel



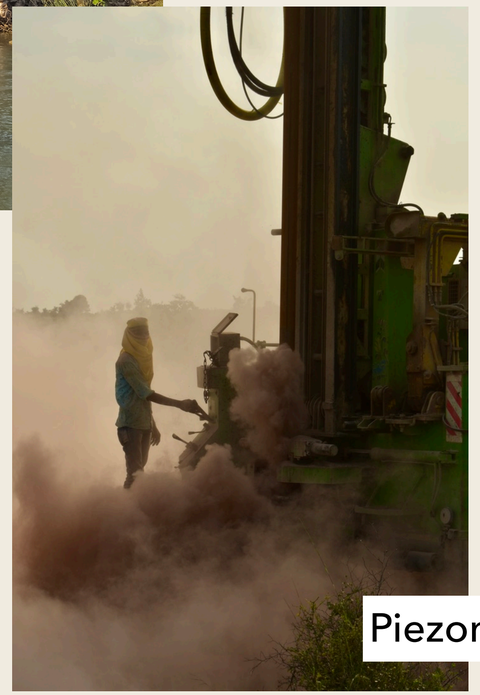
Modelling a larger, complex network


Sanwara, Radjastan
Source : Google Earth
N
1 km

Field measurements

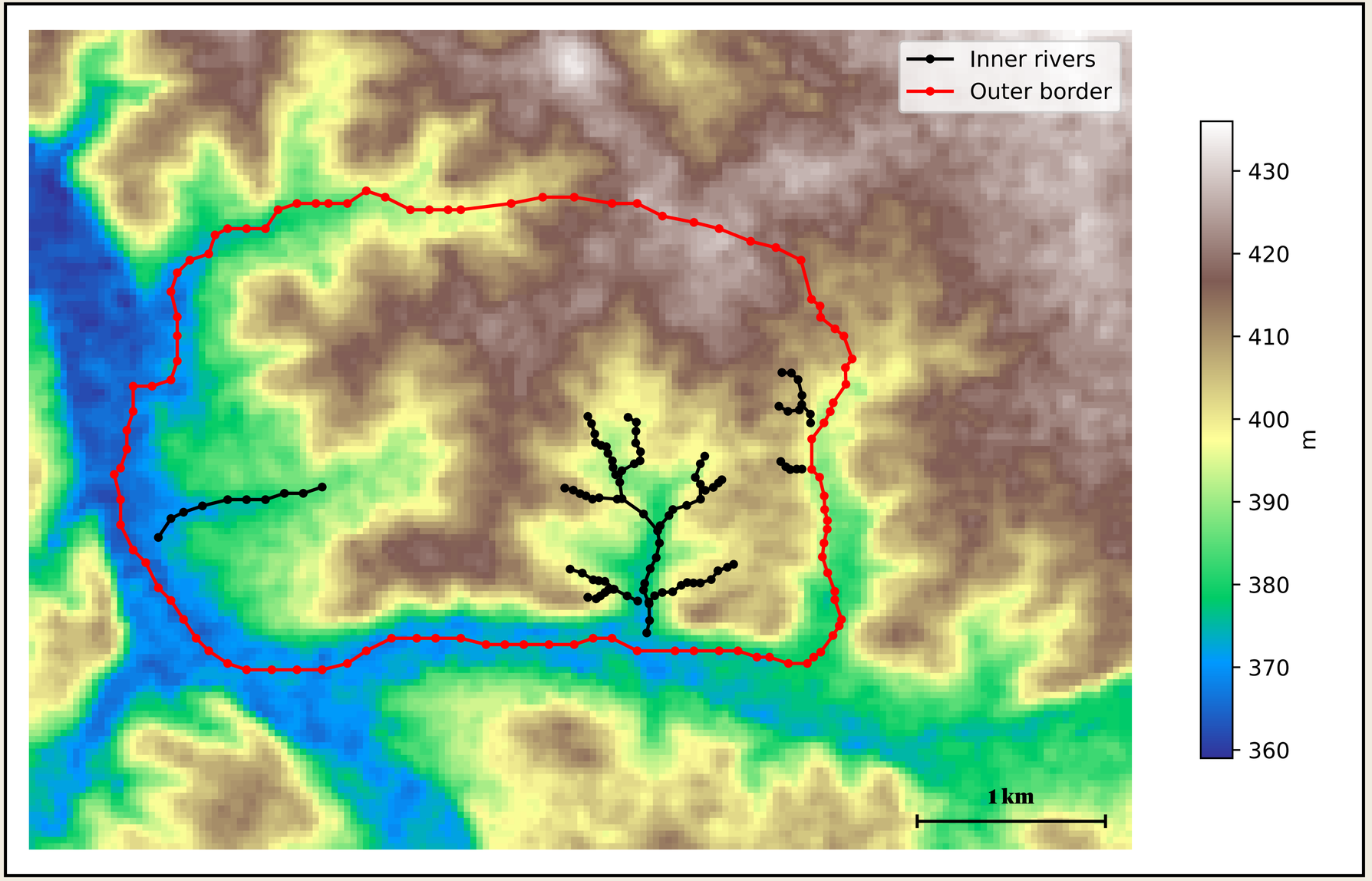

Grain size


Discharge

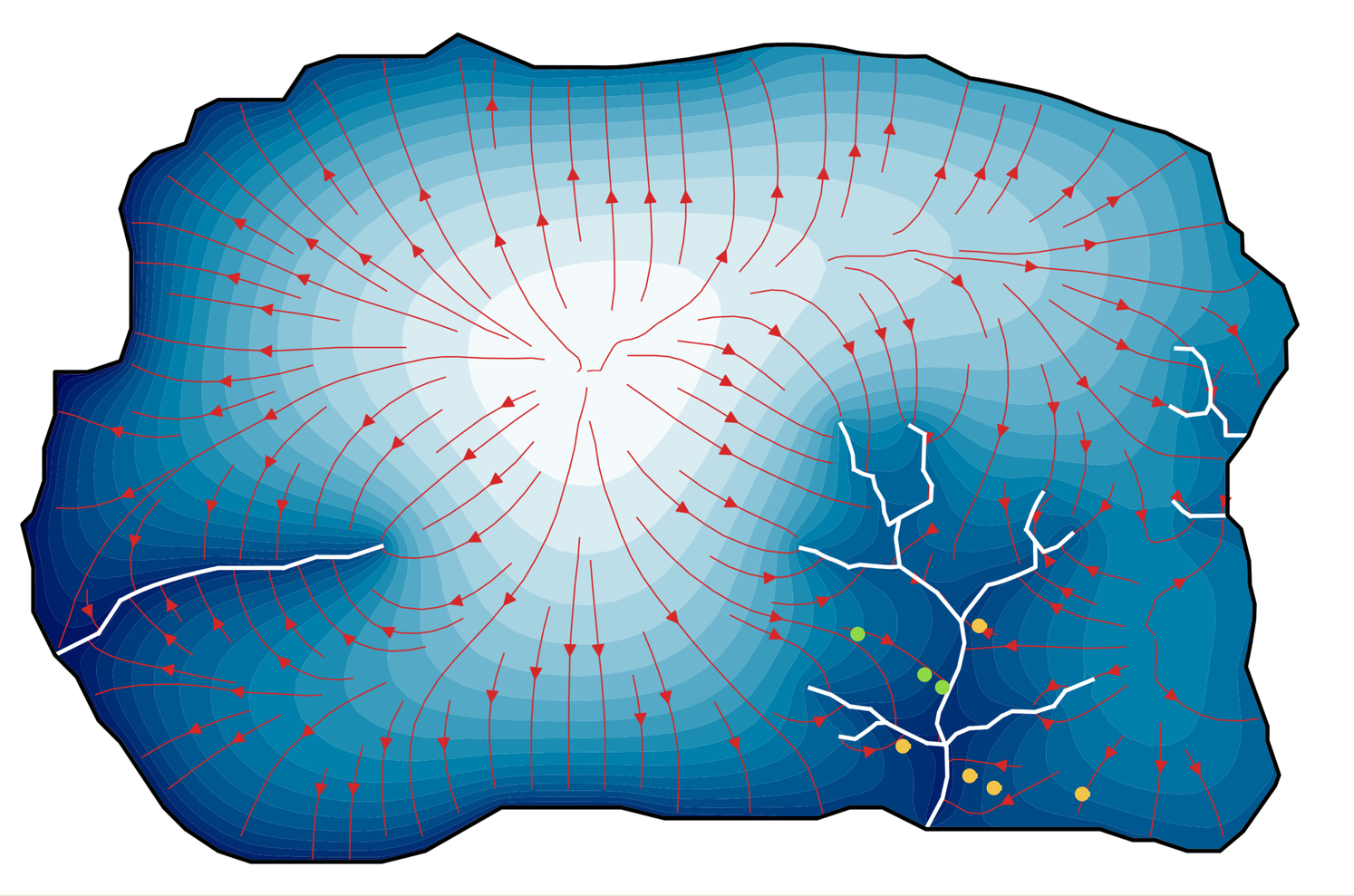

Piezometers

GPS and drone topography

Boundary conditions



Steady state solution



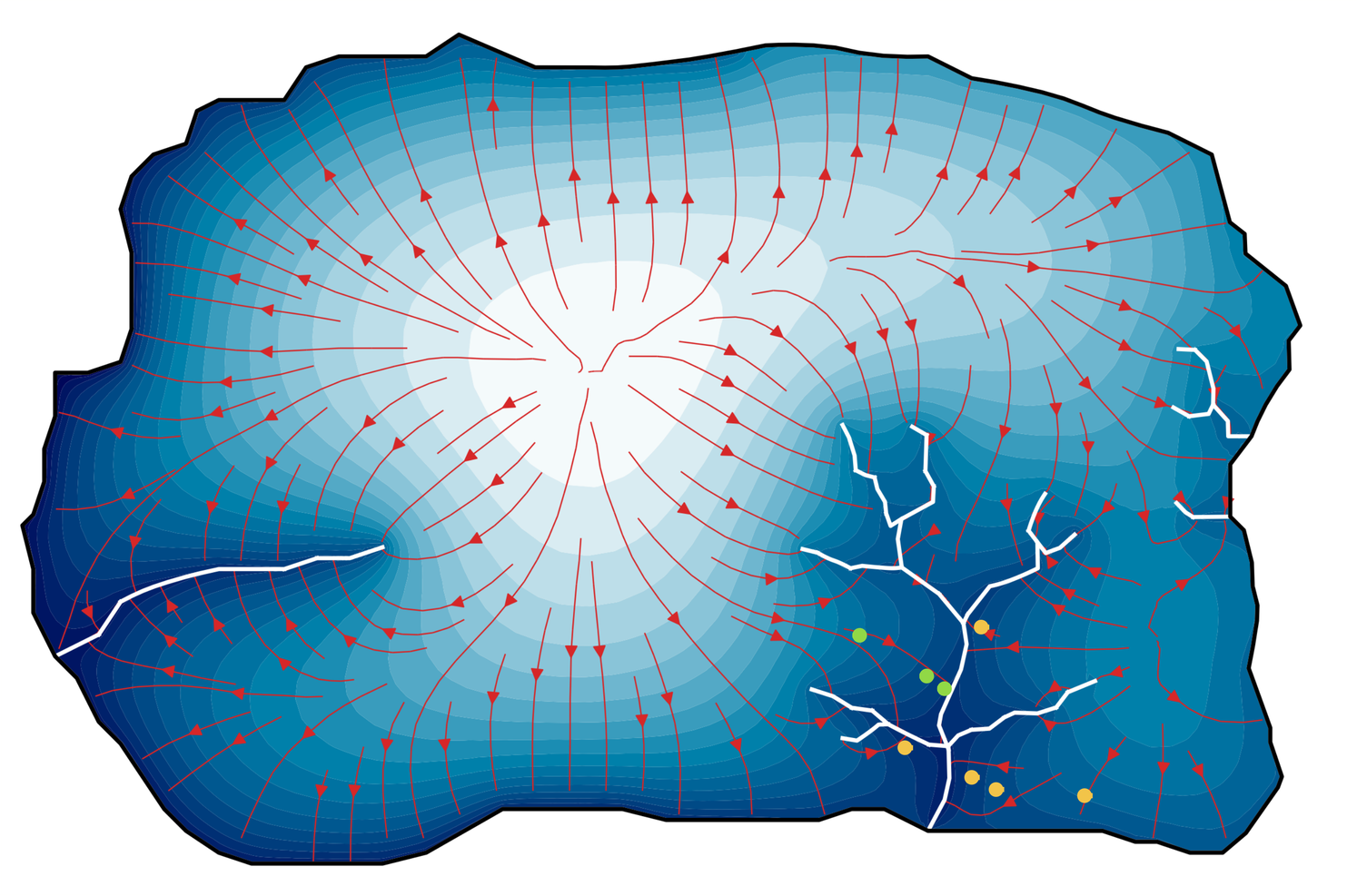
Steady state solution

Flow direction

Water table height

Wells

Piezometers



Steady state solution

Flow direction

Water table height

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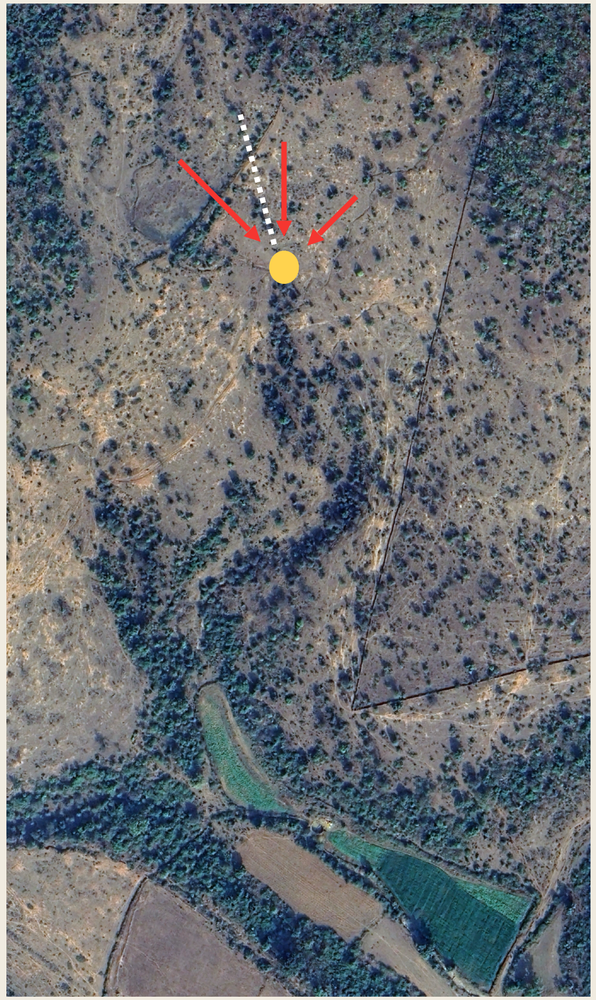
How do networks and groundwater flow change in time ?

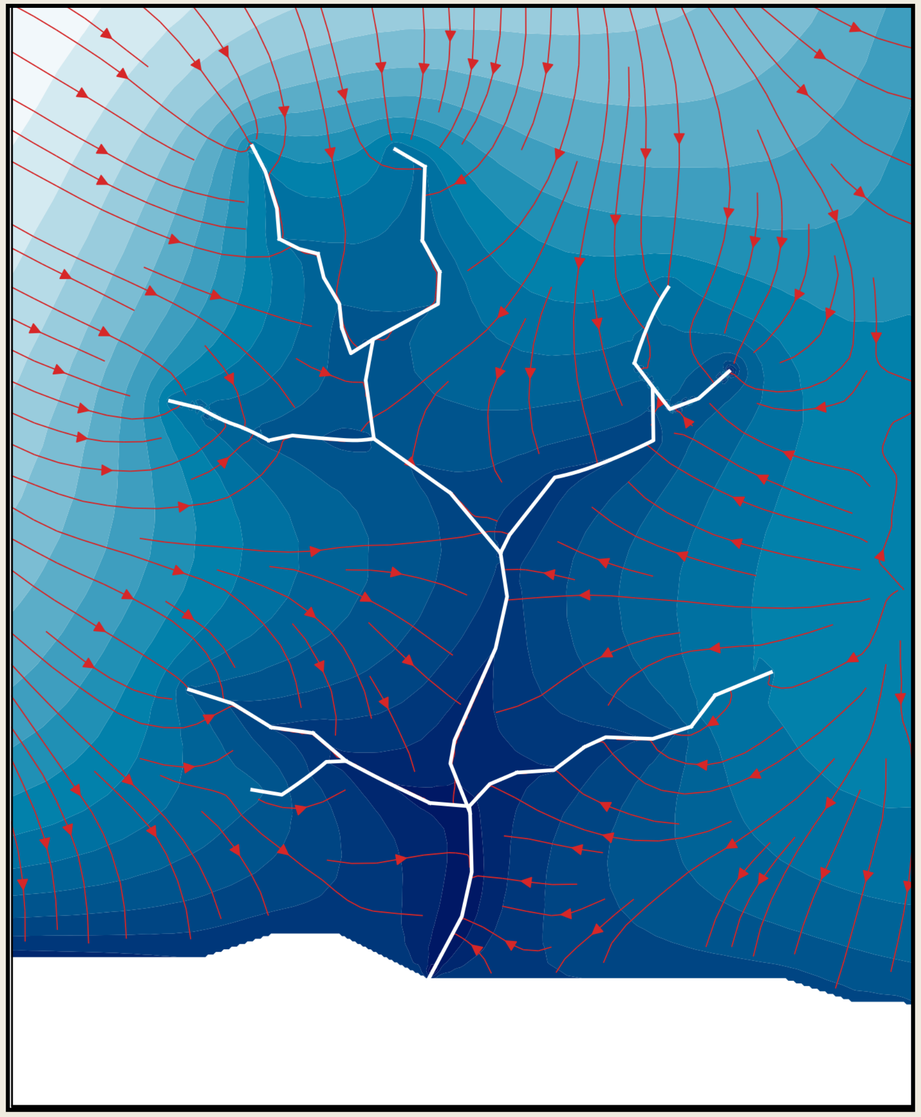
This flow erodes and grows channels



Sources

Flow direction

Future Channels ?



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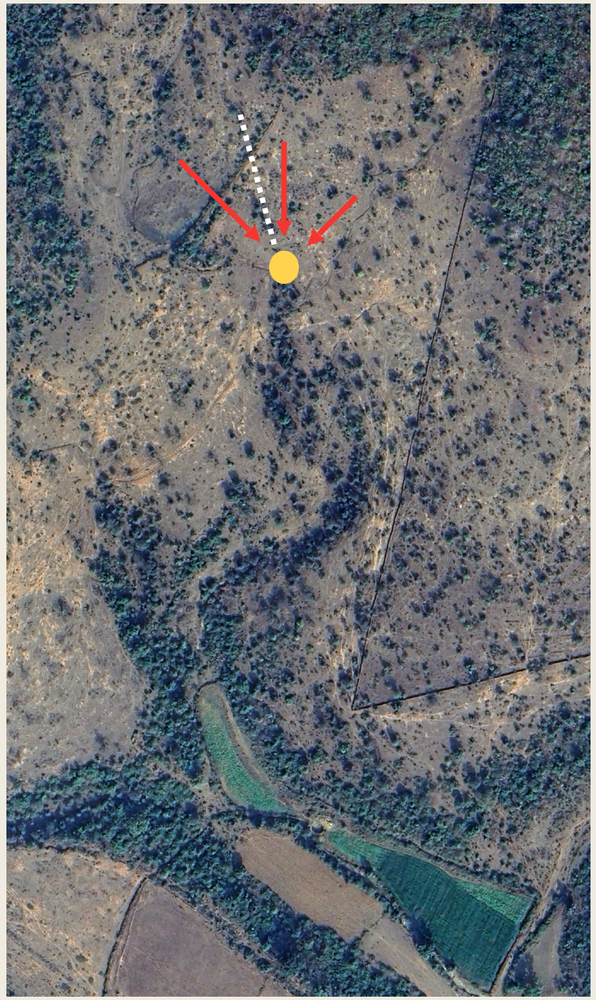
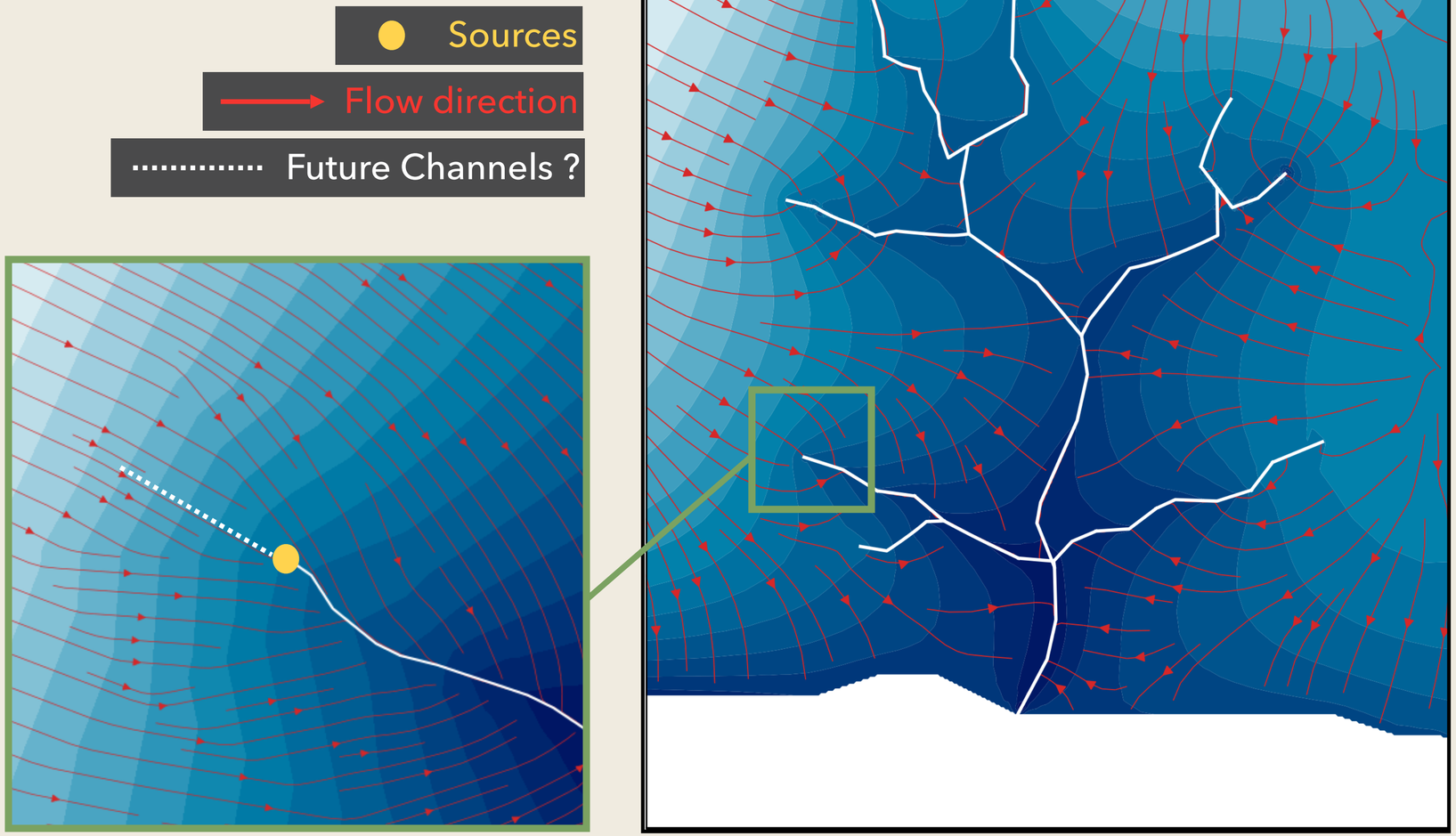
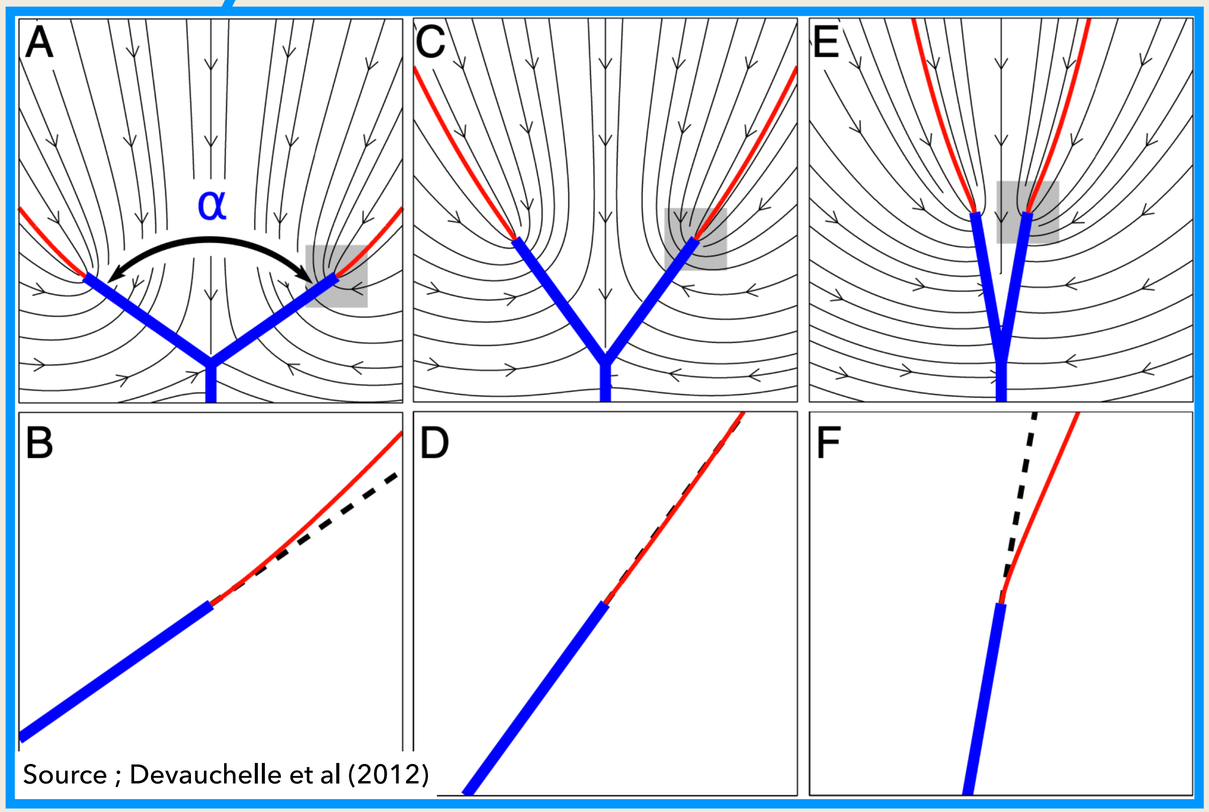


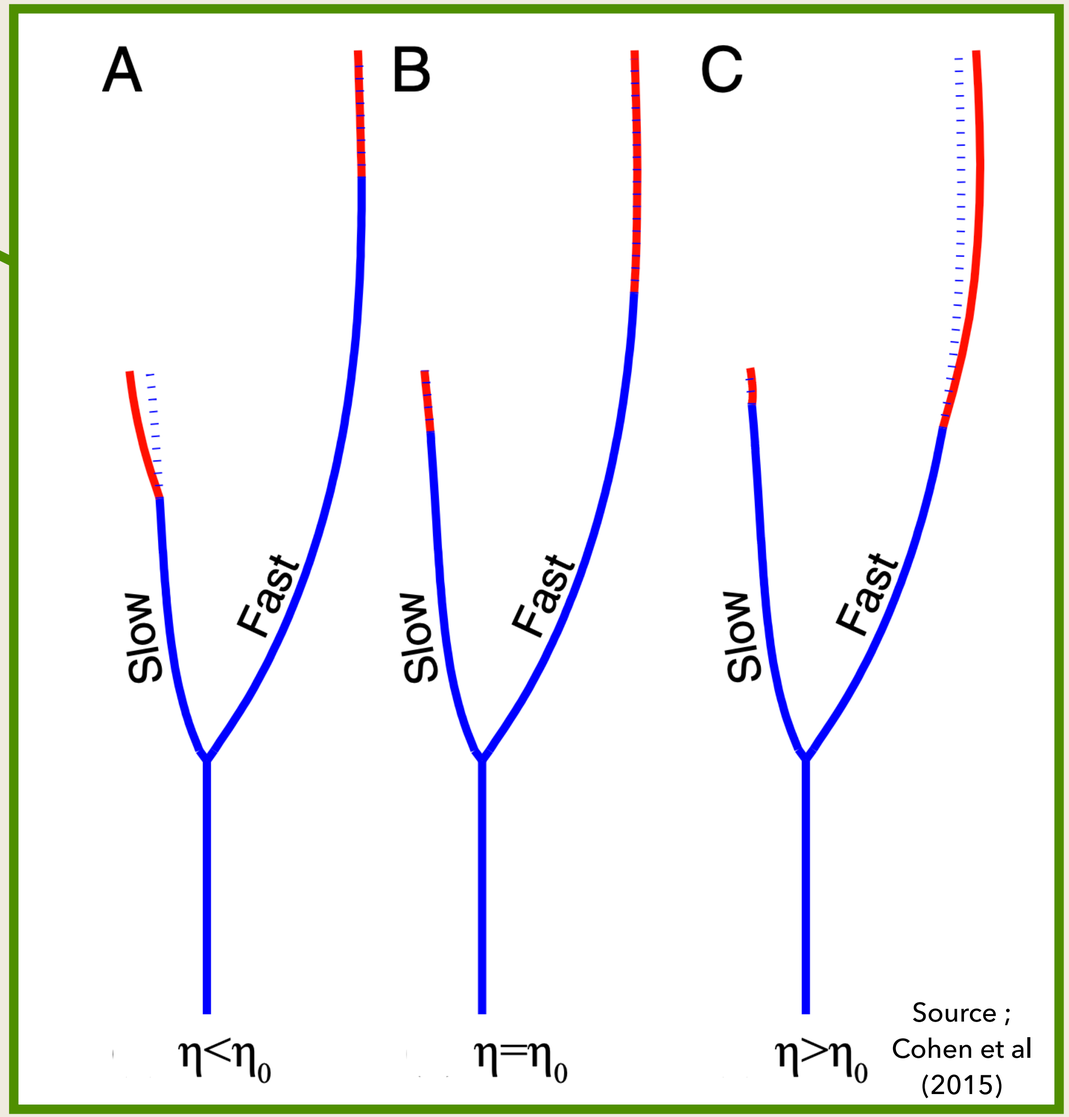


In what **direction** do channel grow ?



Source ; Devauchelle et al (2012)

At what **rate** do they grow ?

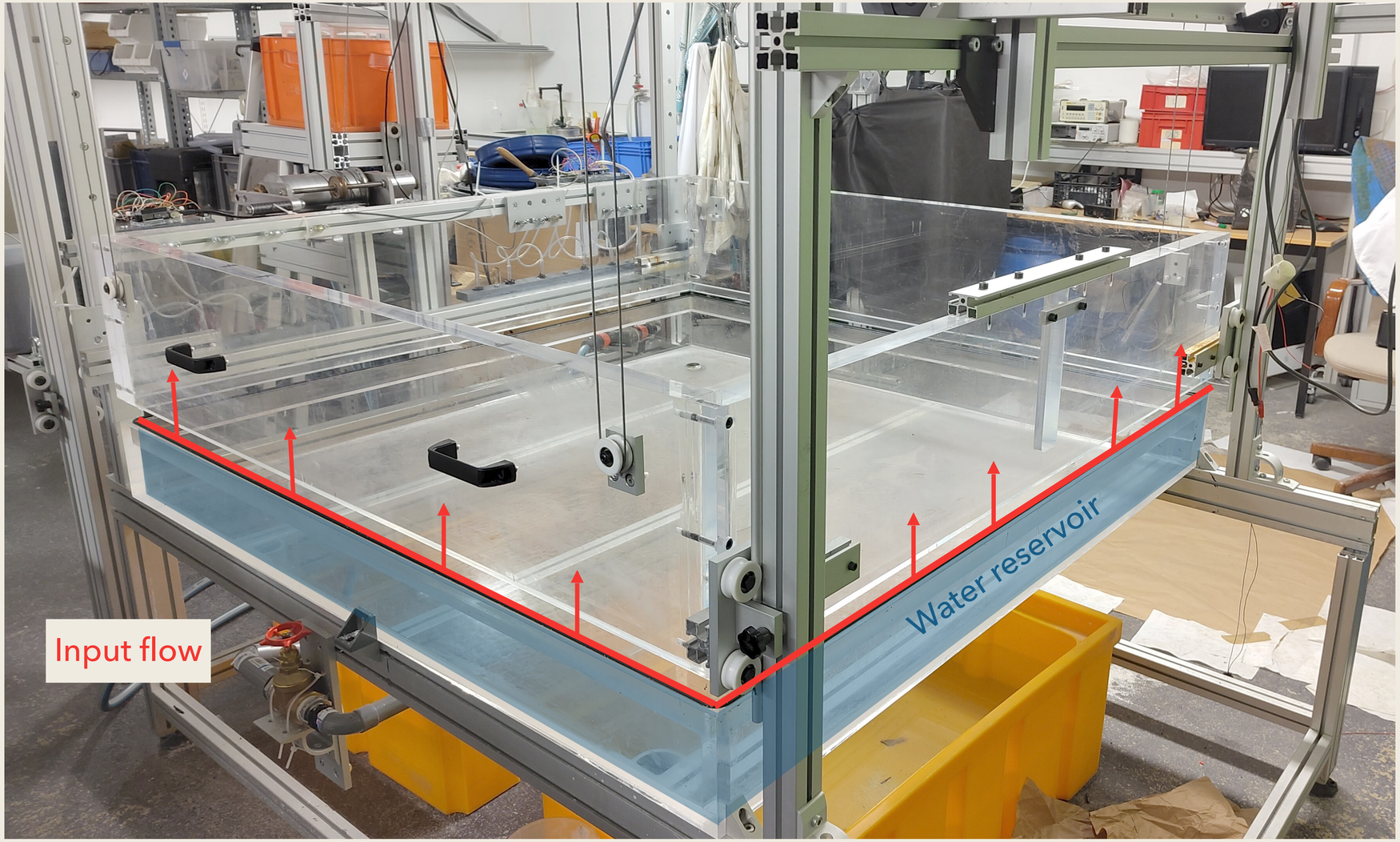


Source ; Cohen et al (2015)

Very slow processes → Hard to observe in nature

Networks in the lab

Networks in the lab



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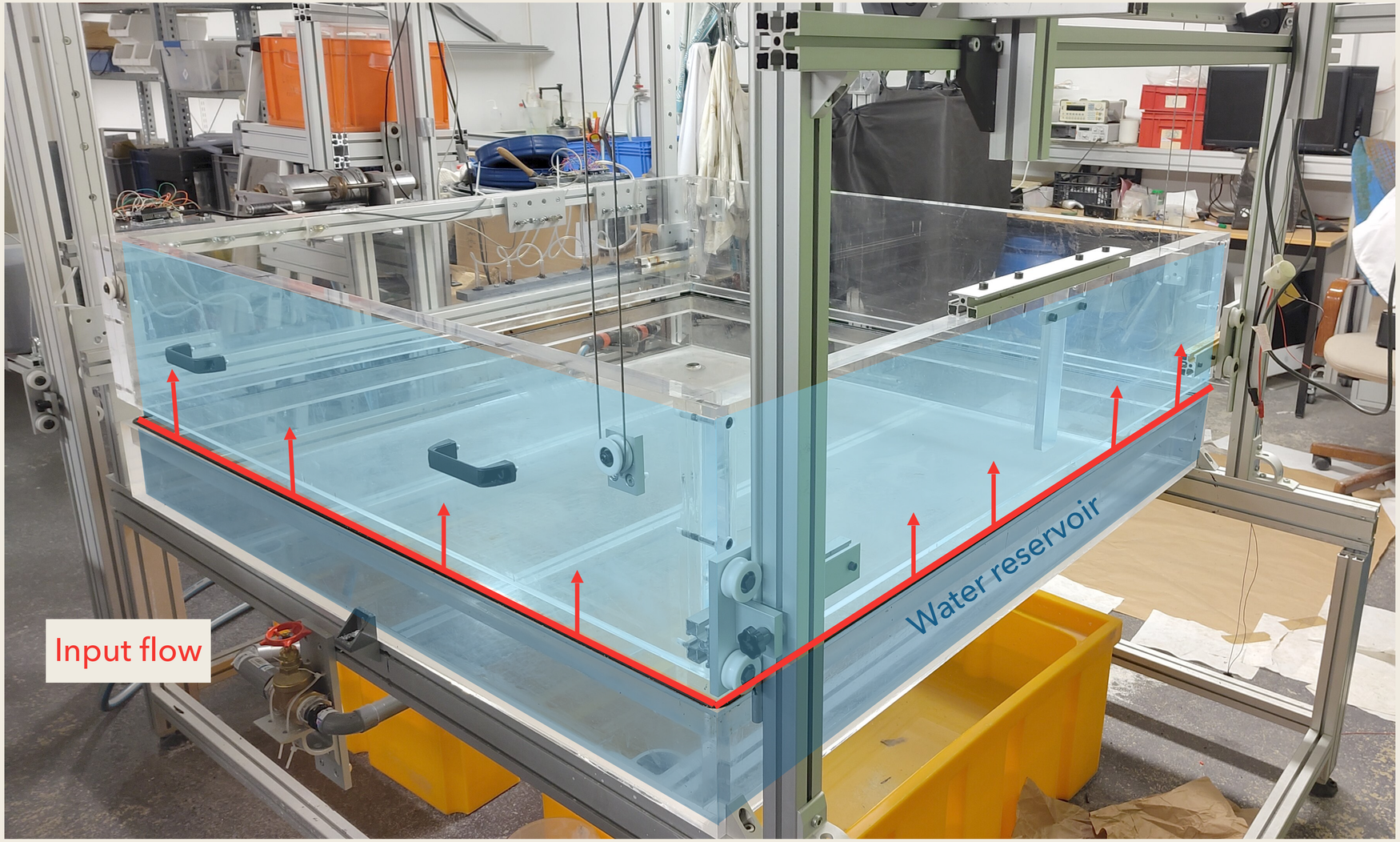

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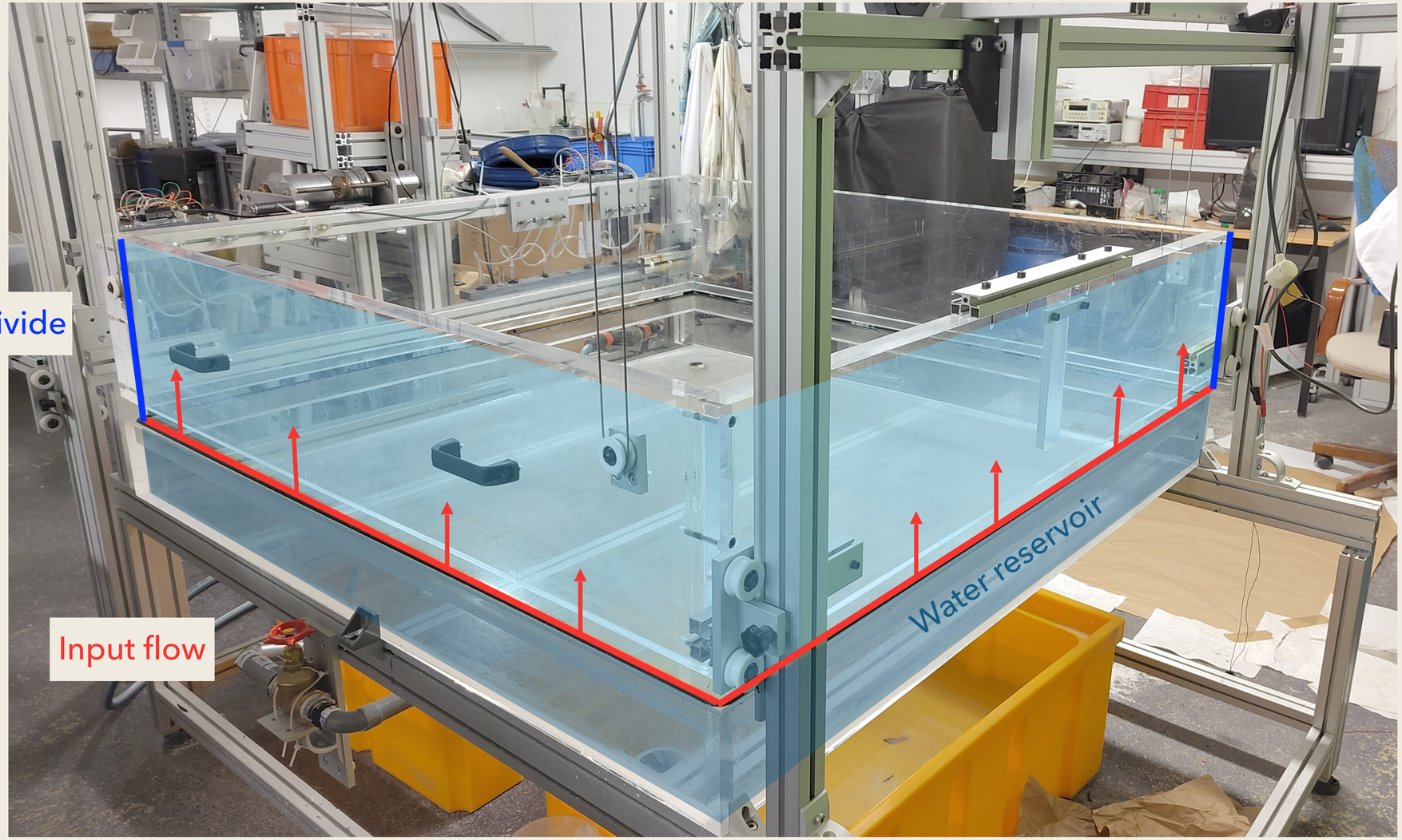

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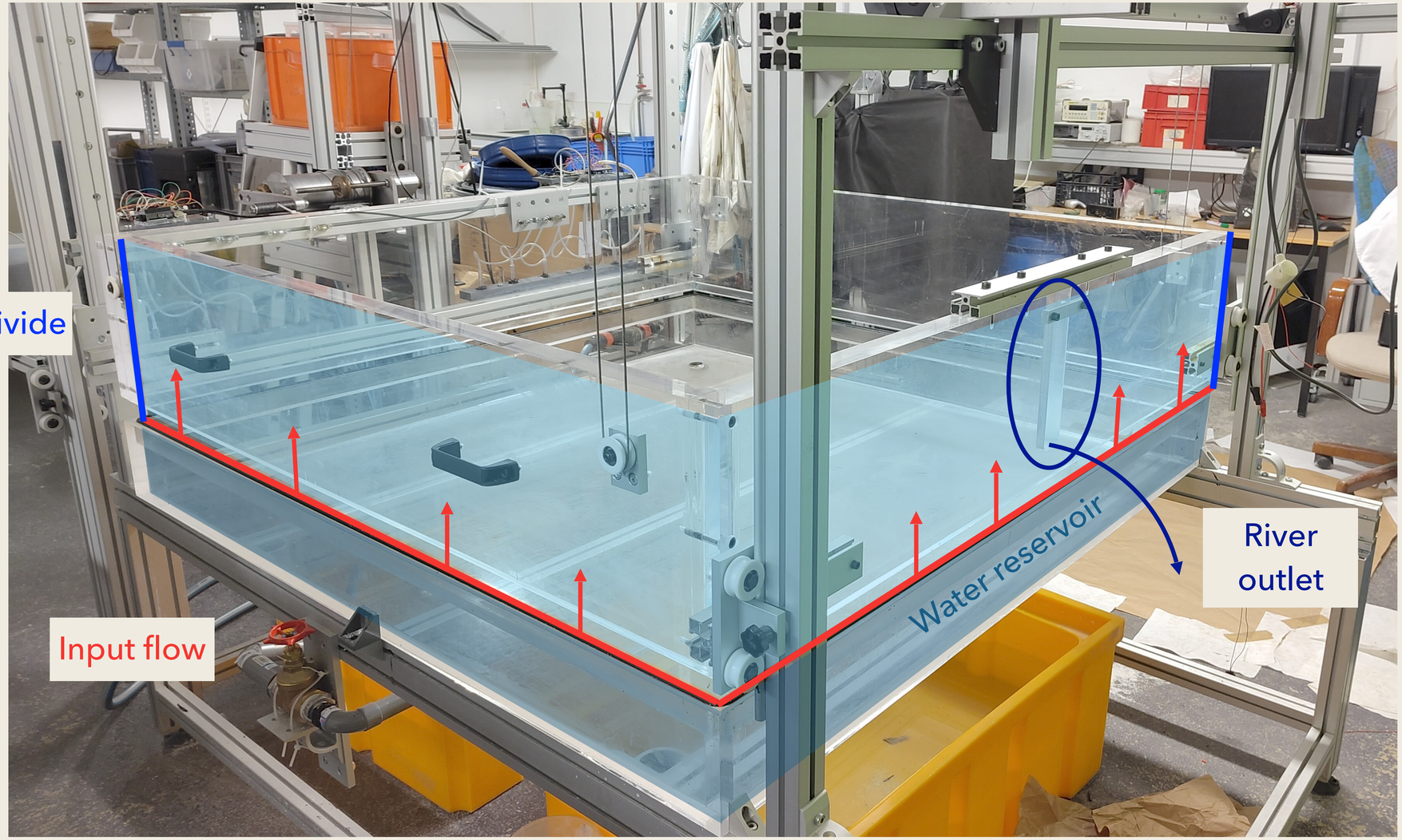
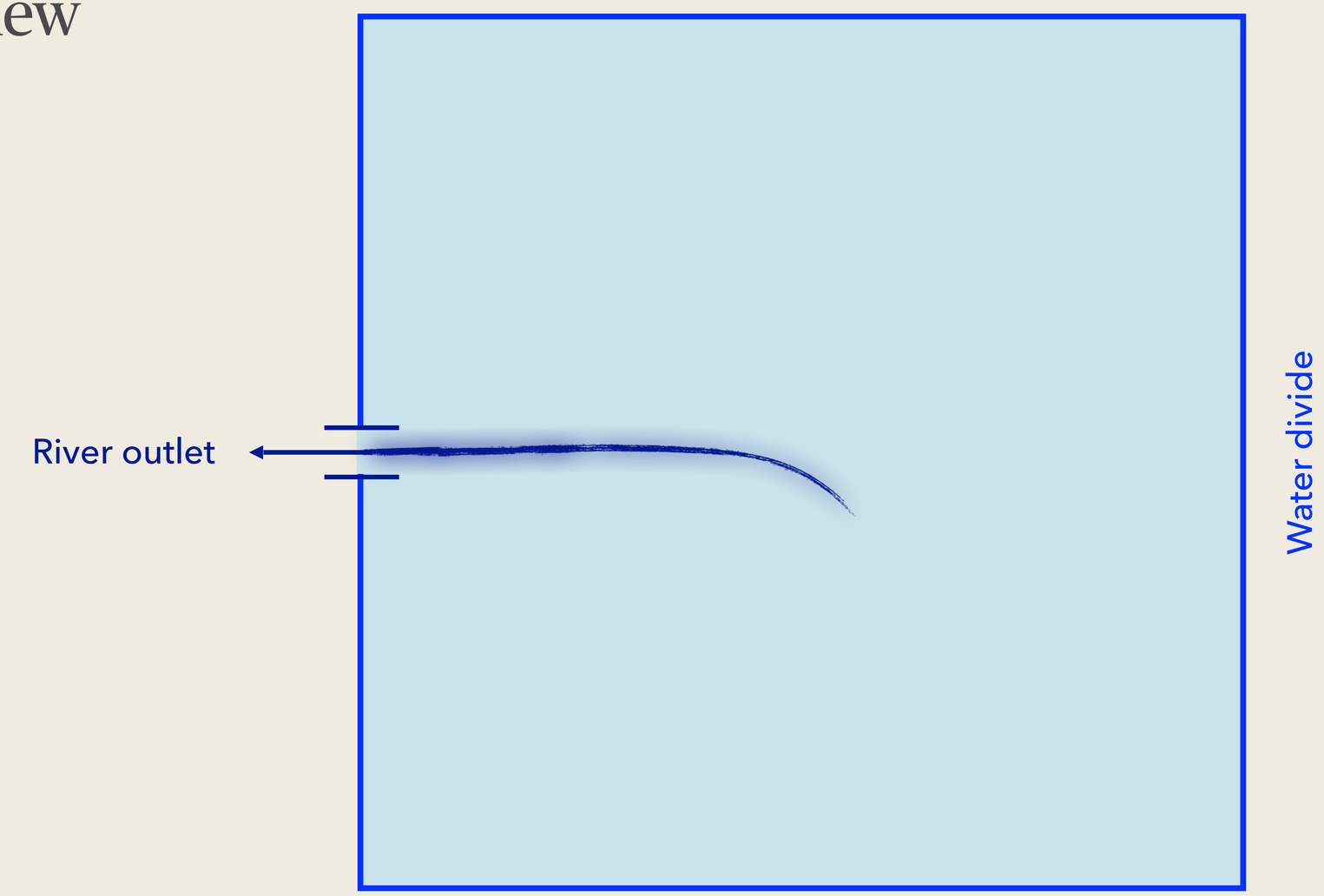


Networks in the lab : top view

Measurements :

- Topography
- Pressure field
- Grain and water discharge



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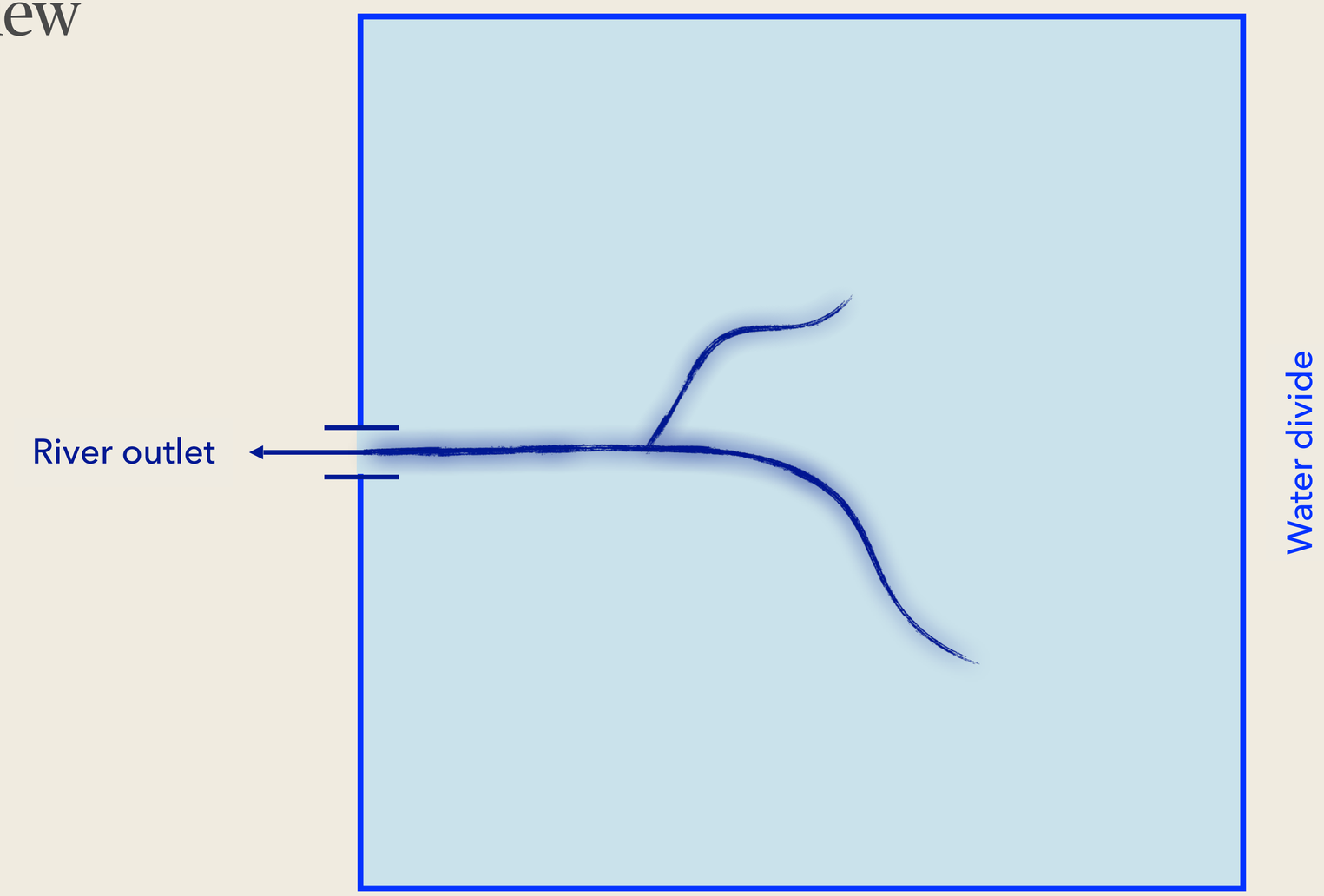

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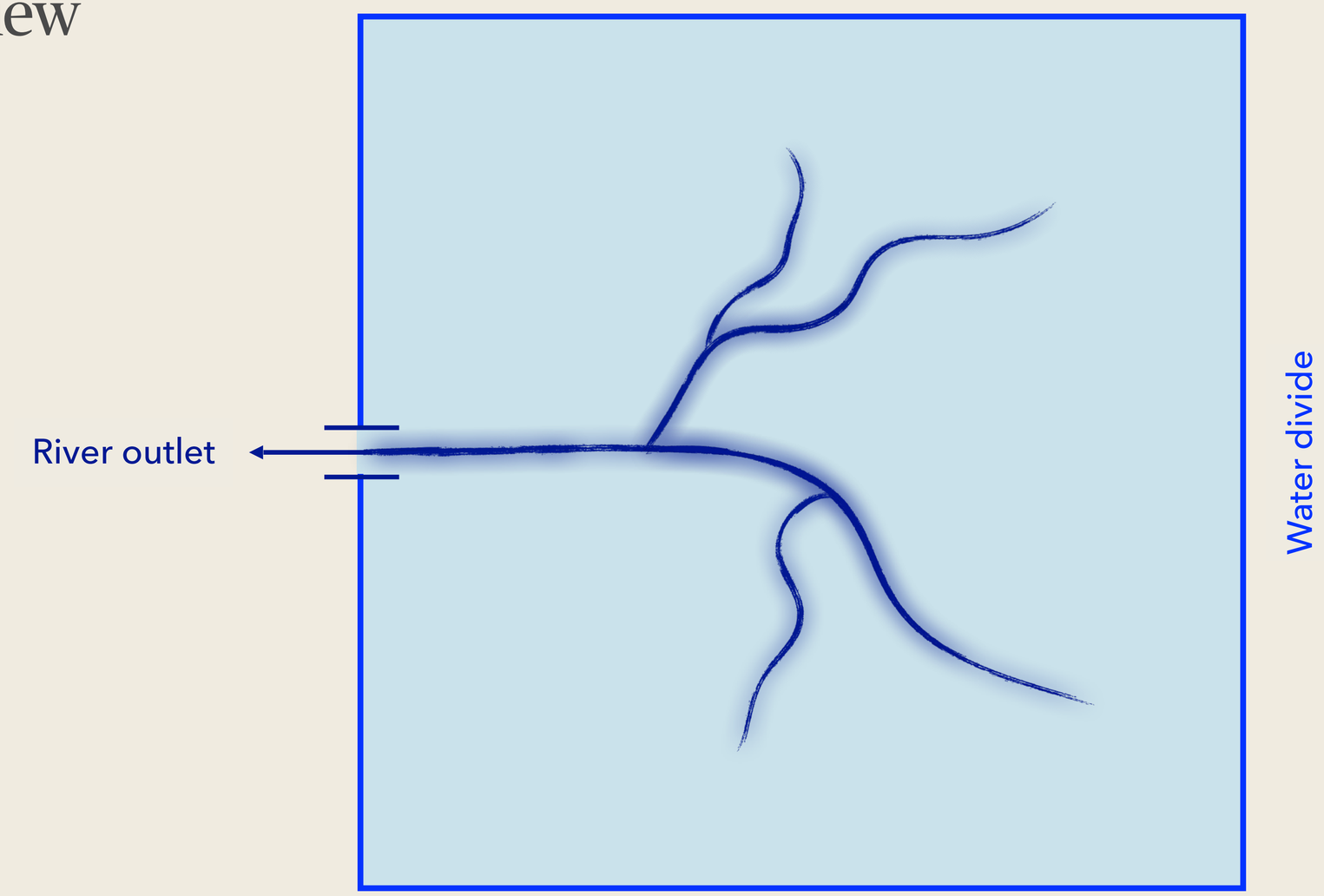

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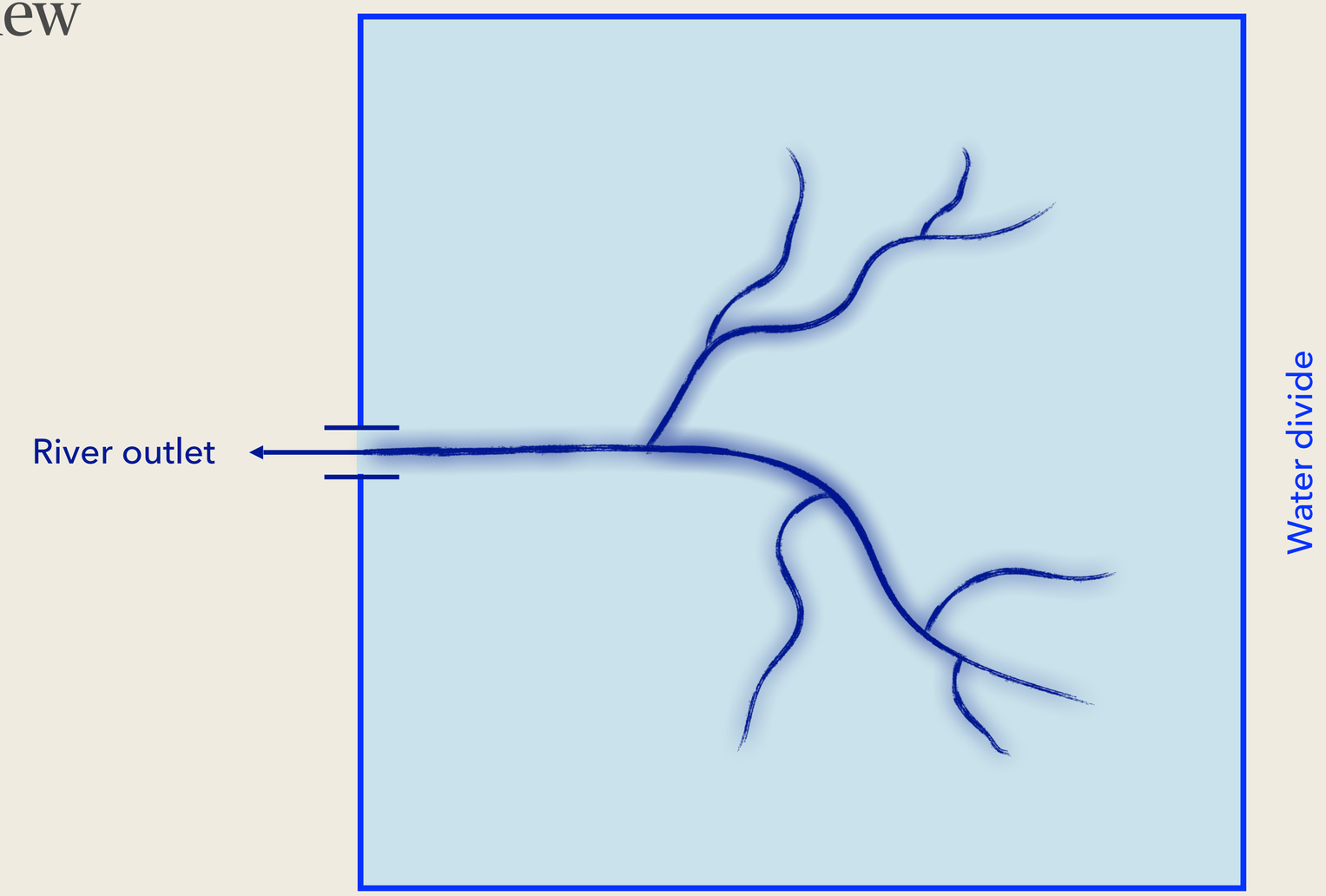
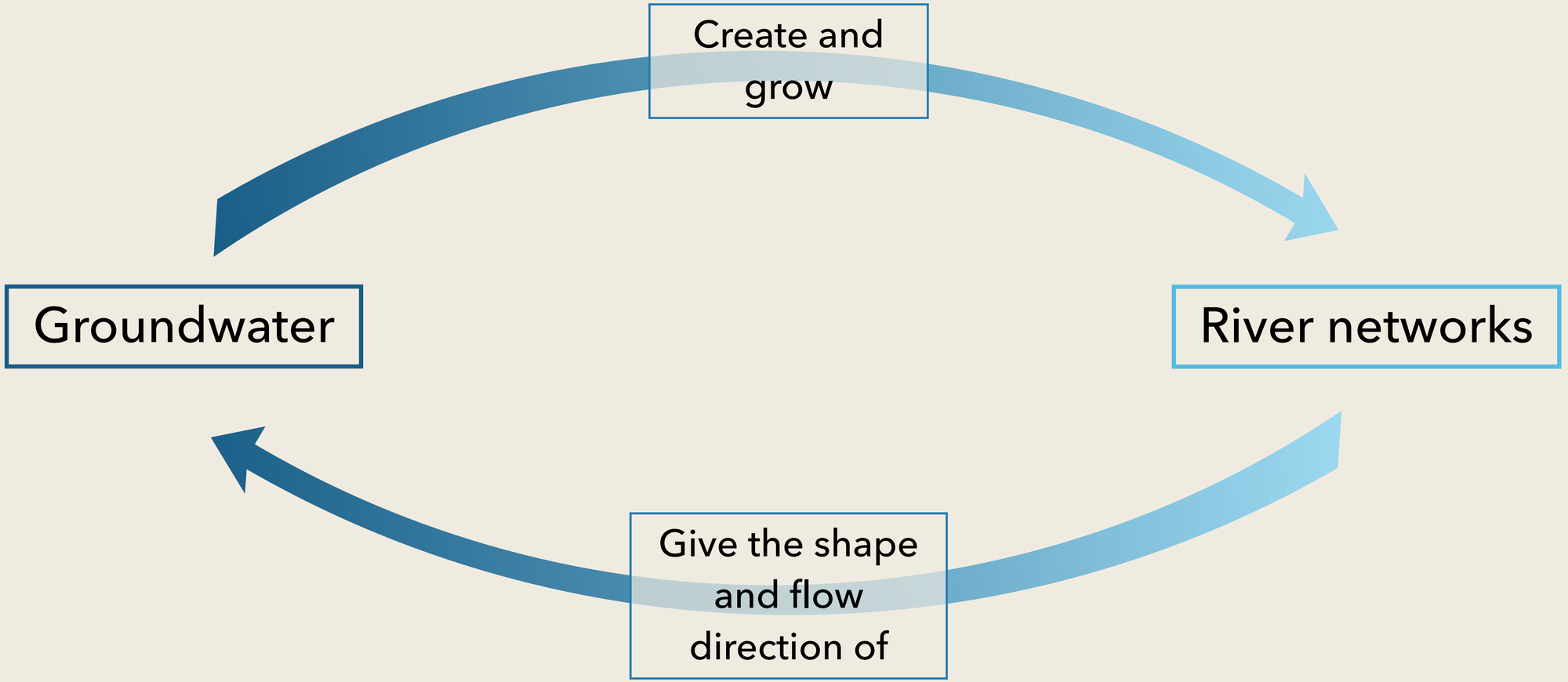
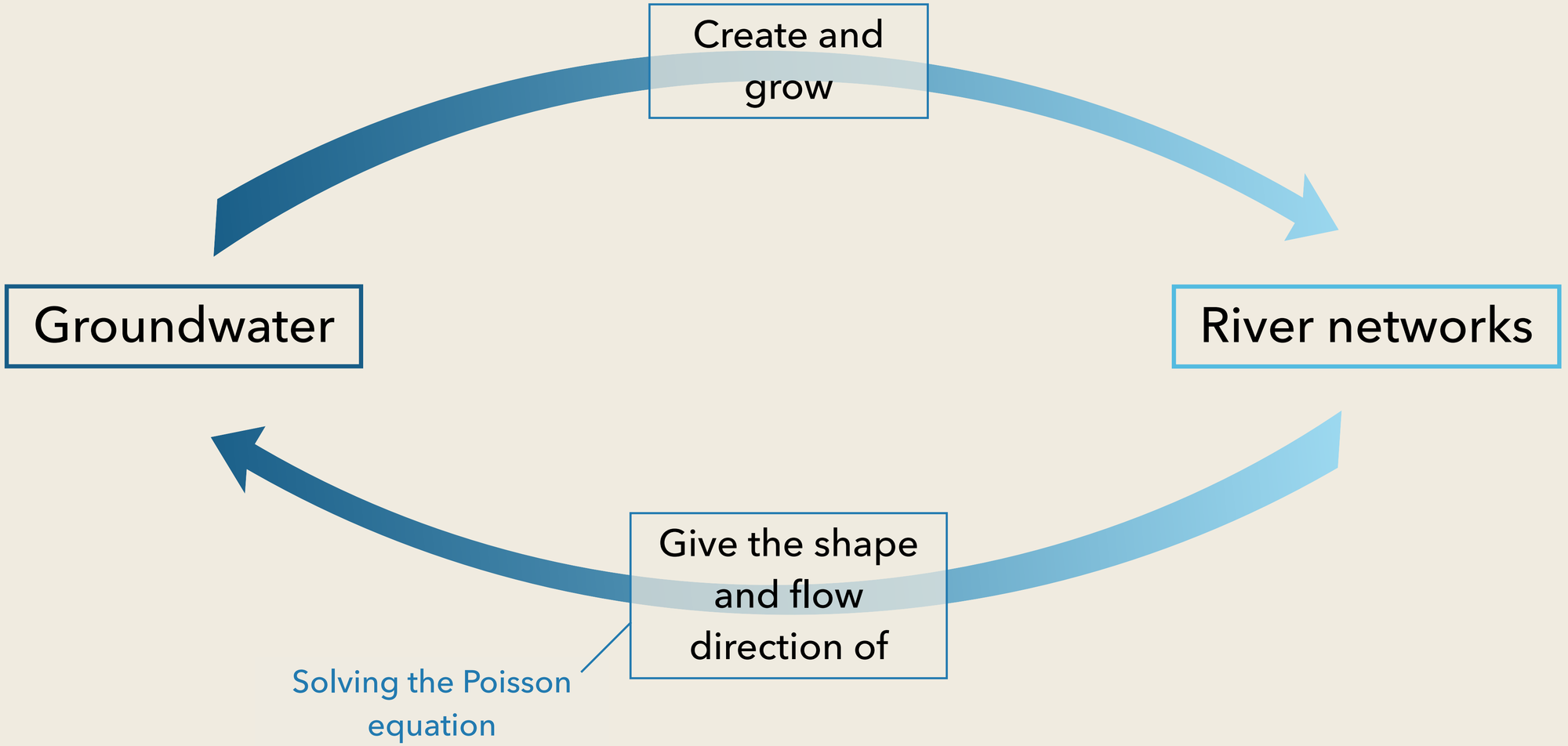
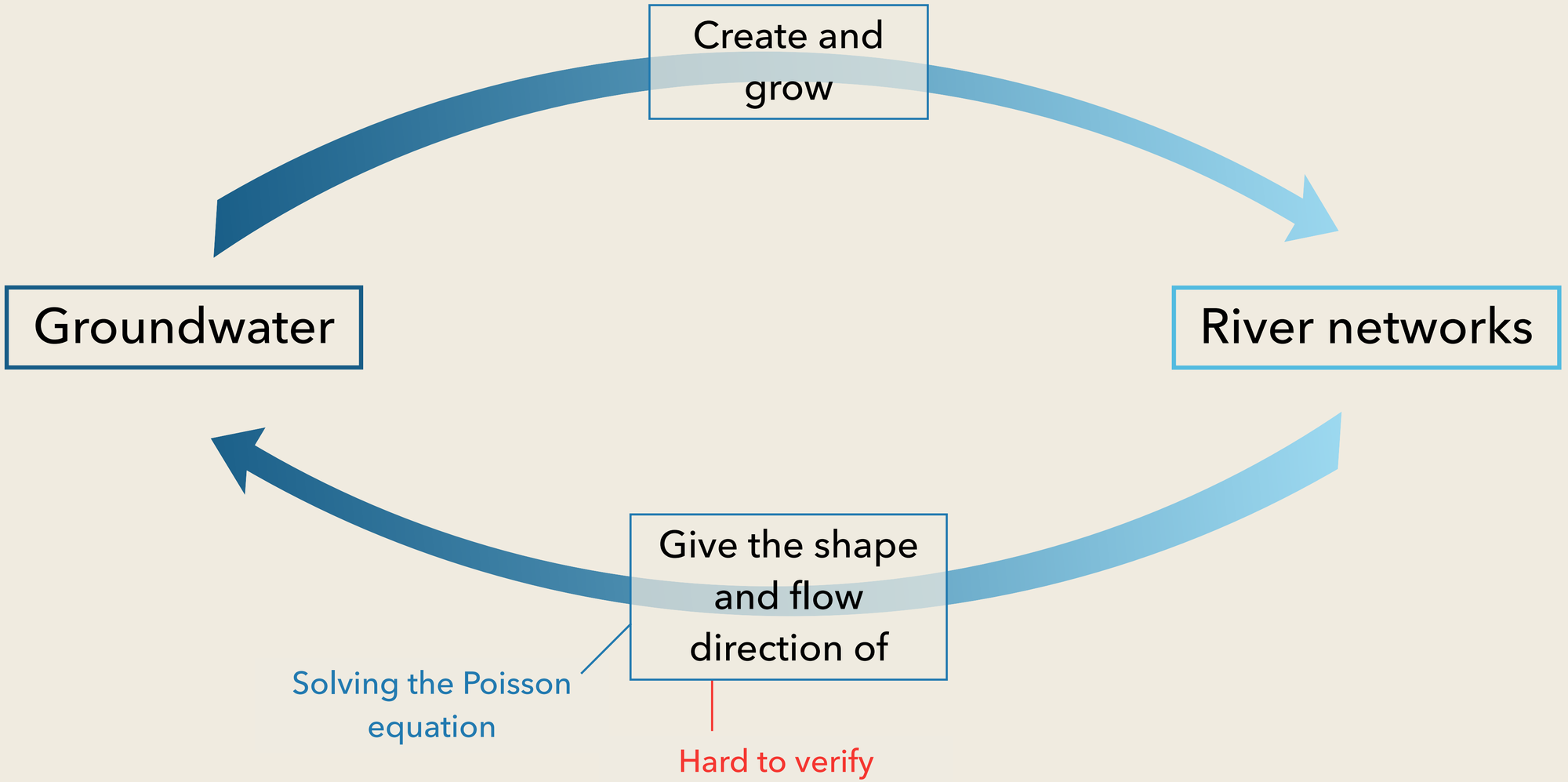
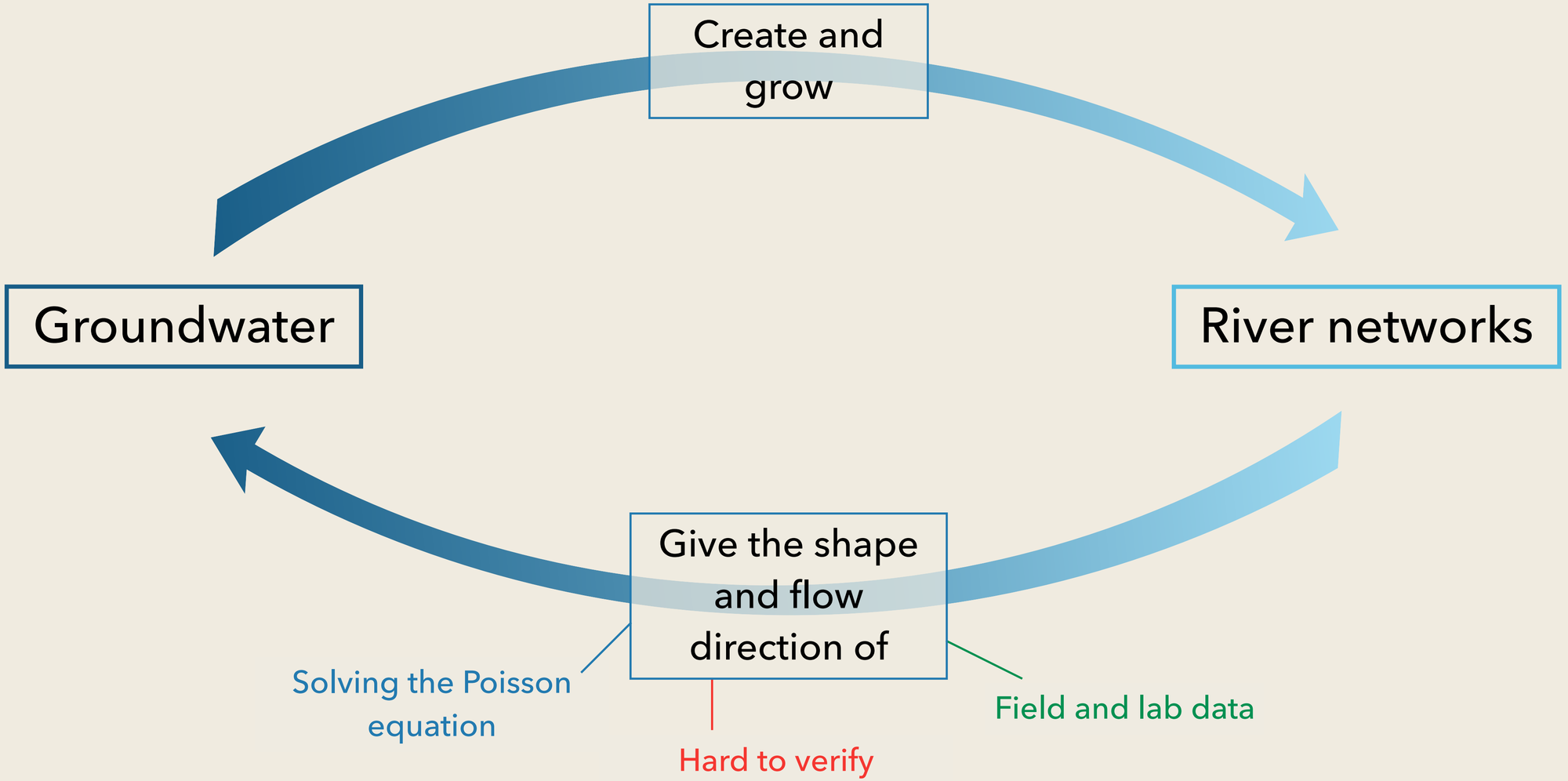


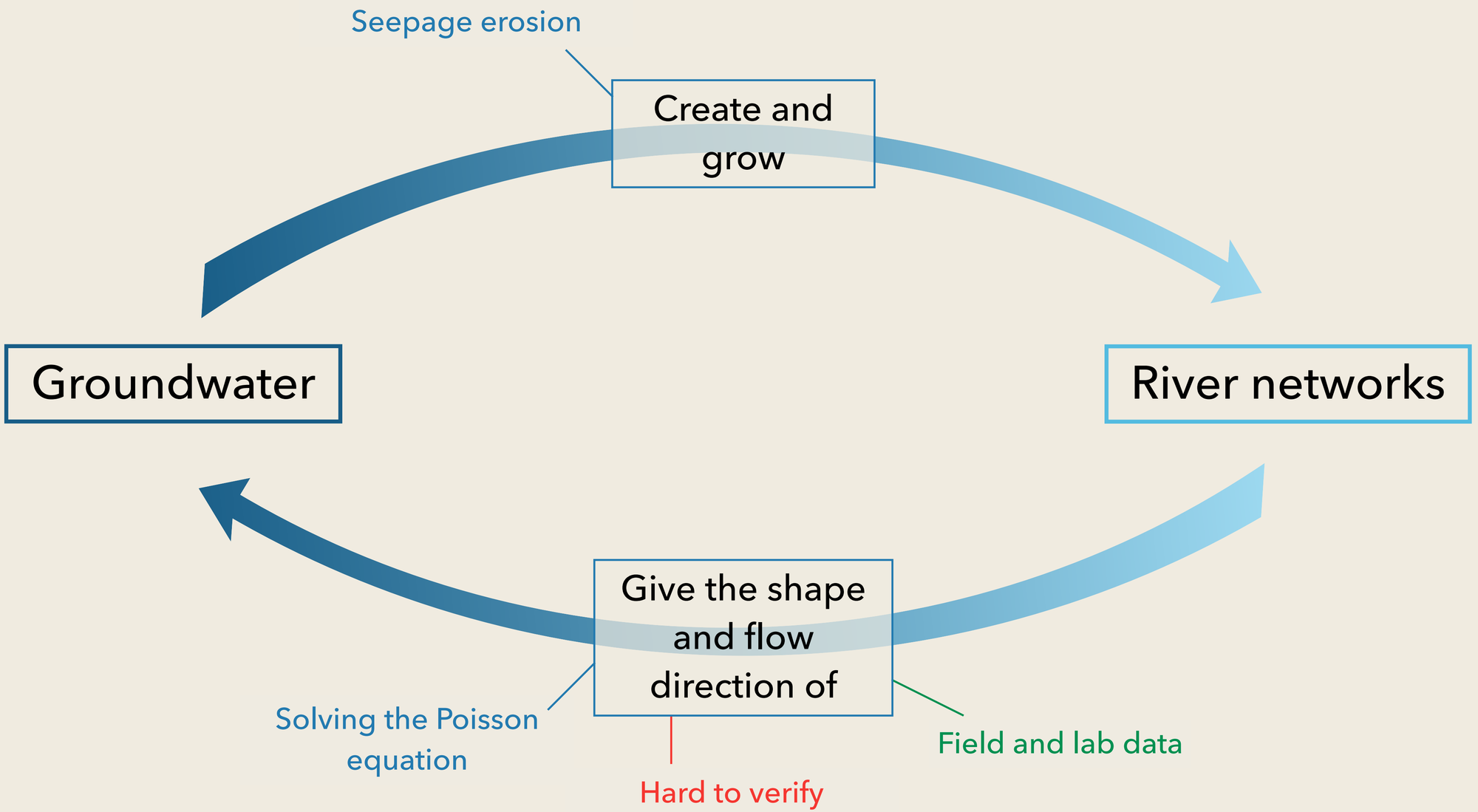
Sorry, wait for next year


Create and grow
Groundwater
River networks
Give the shape and flow direction of


Create and grow
River networks
Give the shape and flow direction of
Groundwater
Solving the Poisson equation


Create and grow
River networks
Give the shape and flow direction of
Groundwater
Solving the Poisson equation
Hard to verify


Create and grow
Groundwater
River networks
Give the shape and flow direction of
Solving the Poisson equation
Hard to verify
Field and lab data


Seepage erosion
Create and grow
Groundwater
River networks
Give the shape and flow direction of
Solving the Poisson equation
Hard to verify
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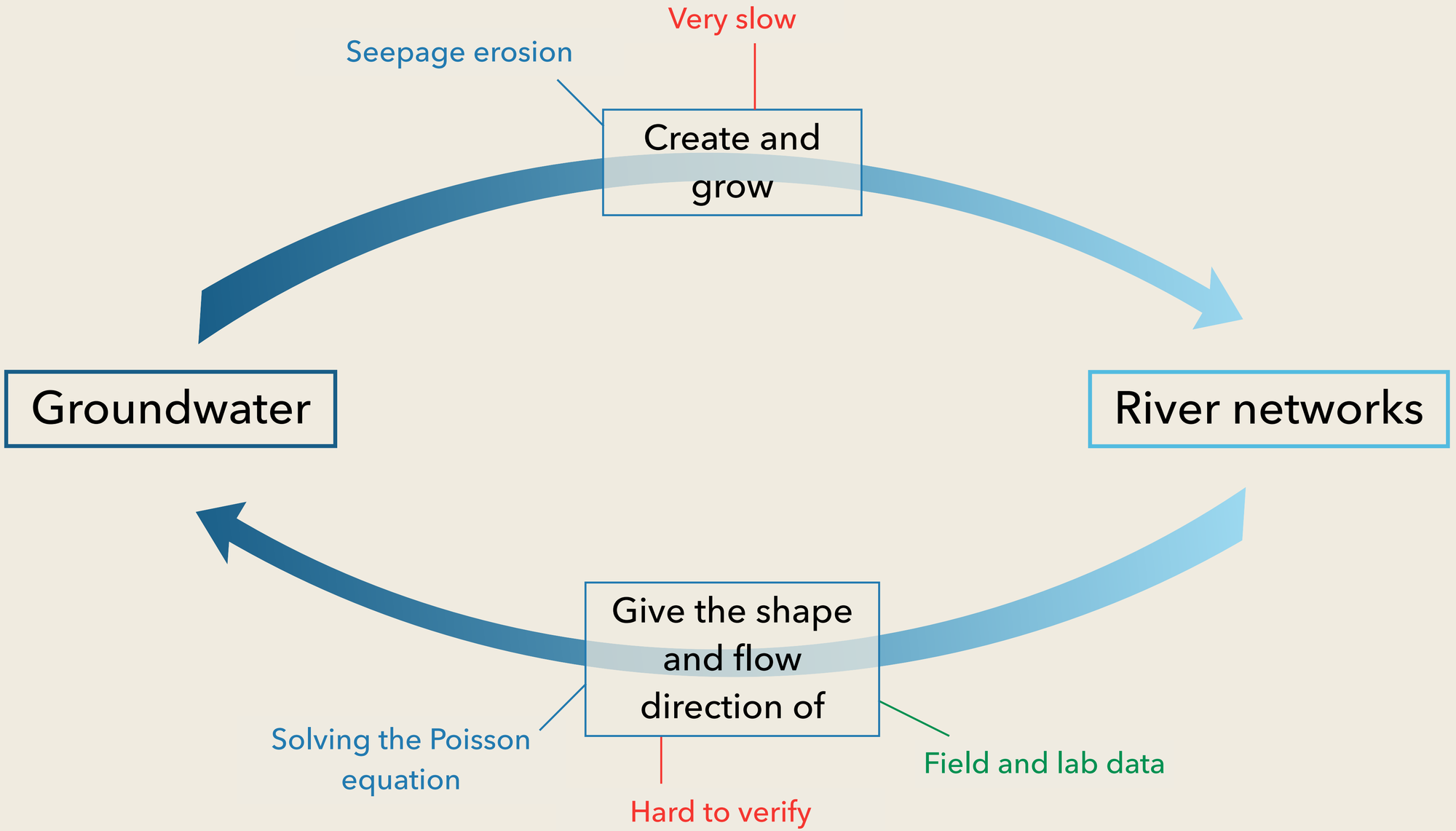
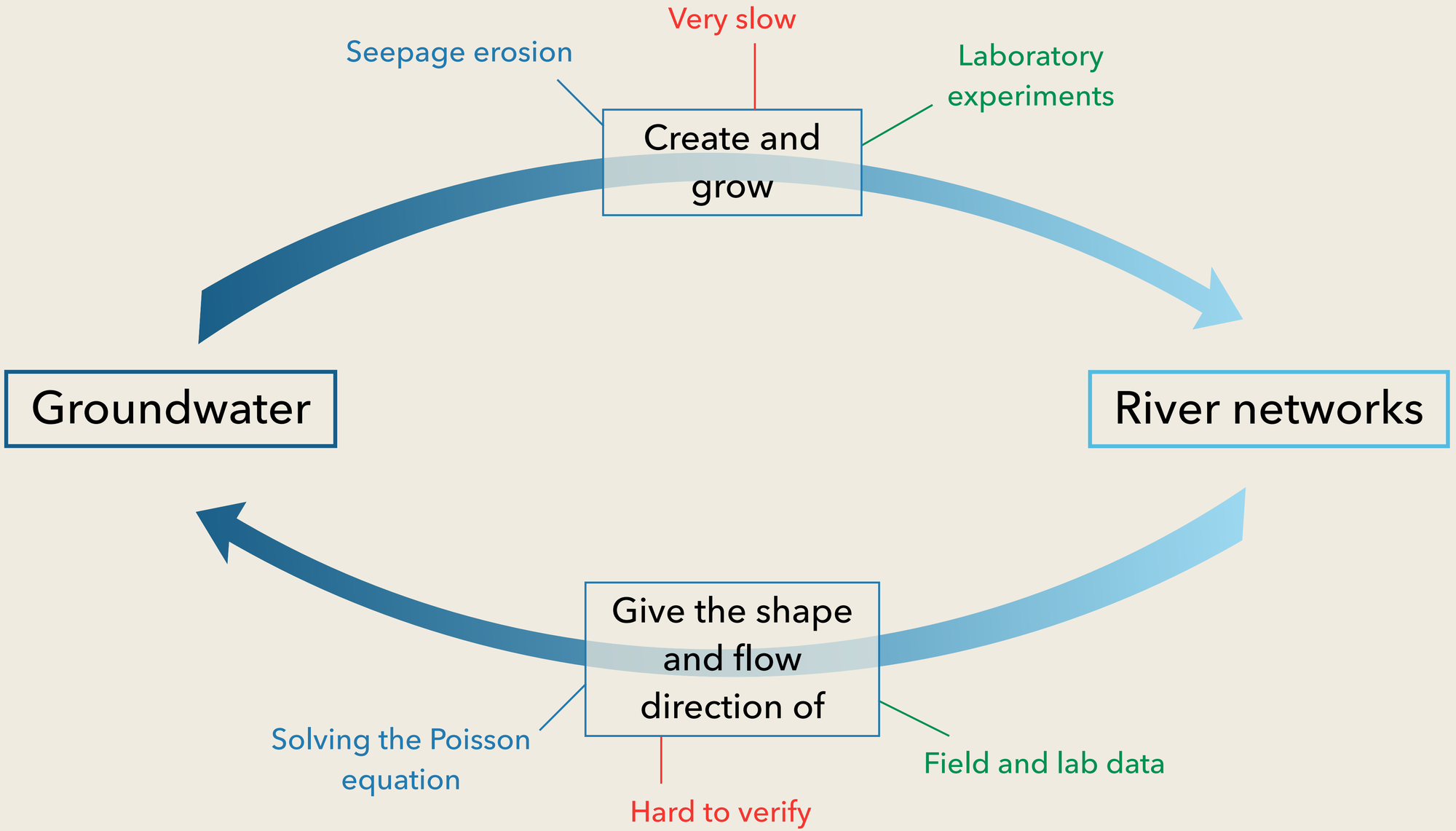

Very slow
Seepage erosion
Create and grow
Groundwater
River networks
Give the shape and flow direction of
Solving the Poisson equation
Hard to verify
Field and lab data


Very slow
Seepage erosion
Laboratory experiments
Create and grow
Groundwater
River networks
Give the shape and flow direction of
Solving the Poisson equation
Field and lab data
Hard to verify

Thank you for your time !