# Introduction to Environmental Engineering

(ENV-167, A.Y. 2025-2026)

4 ETCS, Bachelor course

**W**hat **A** **T**antalizing
**E**nvironmental **R**esource!
(WATER!)

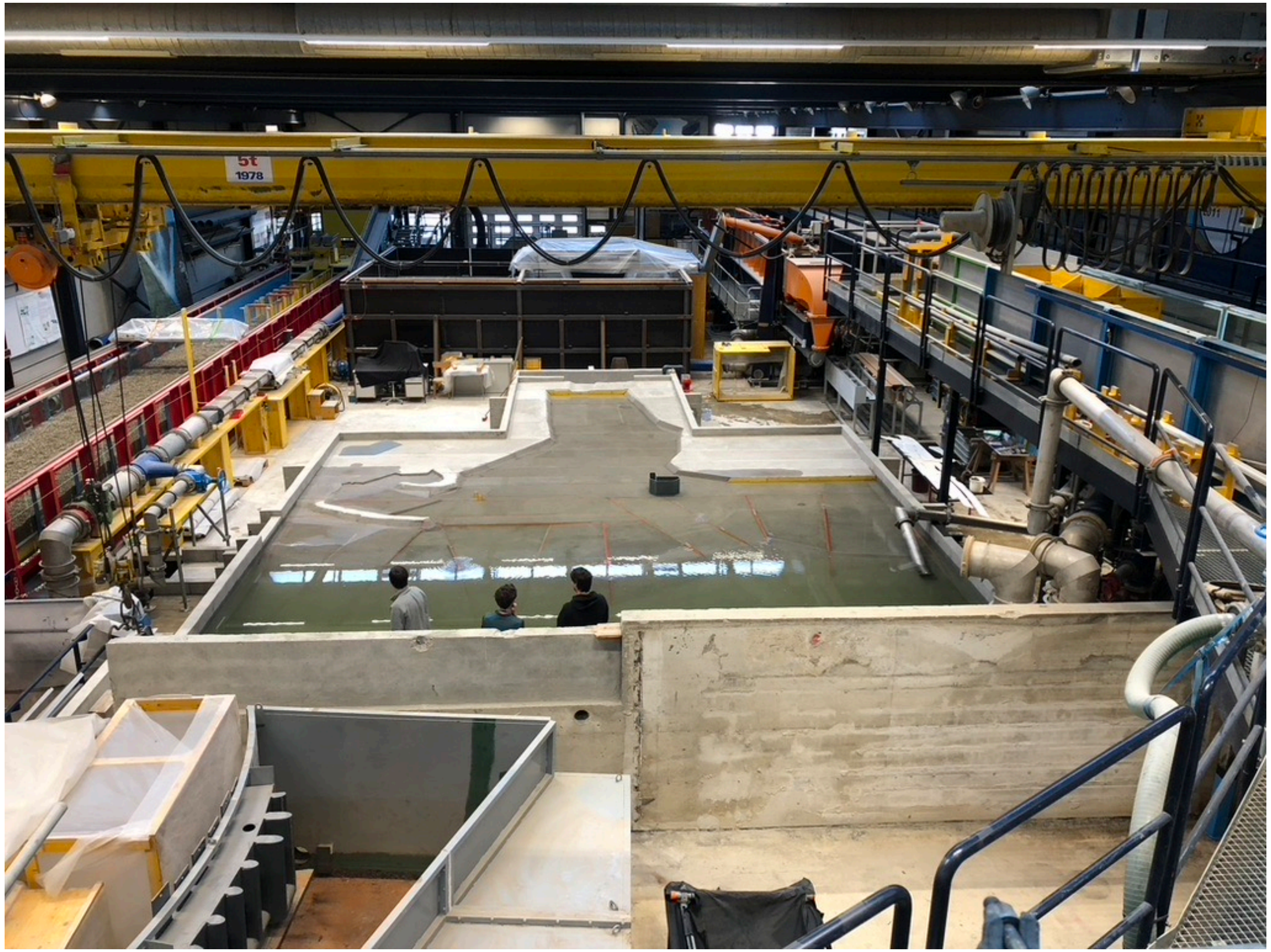
**Prof. P. Perona**
Platform of Hydraulic Constructions

# Who we are

Prof. **Paolo Perona**

Head of the Platform of Hydraulic Constructions (PL-LCH)

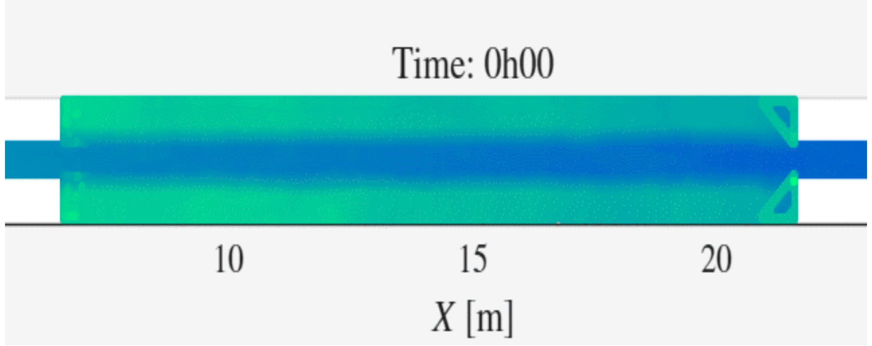
*“We study (via experiments and models) water resources engineering and hydraulics problems for sustainable water use in copying  human and environmental needs” …let’s see…*



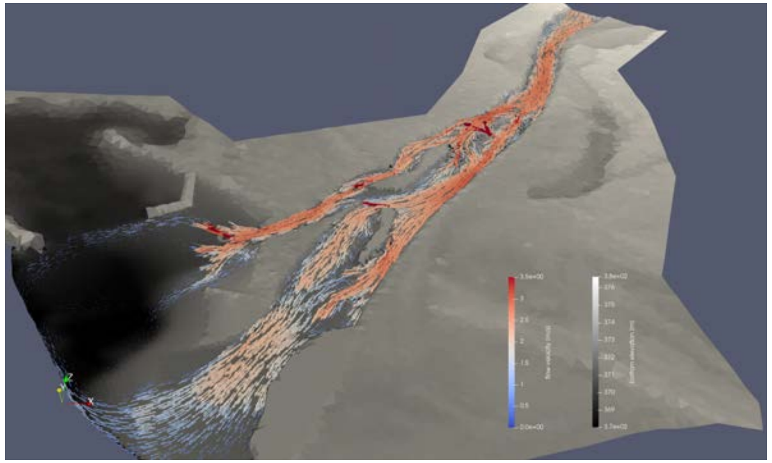
The Hydraulic Hall of the PL-LCH

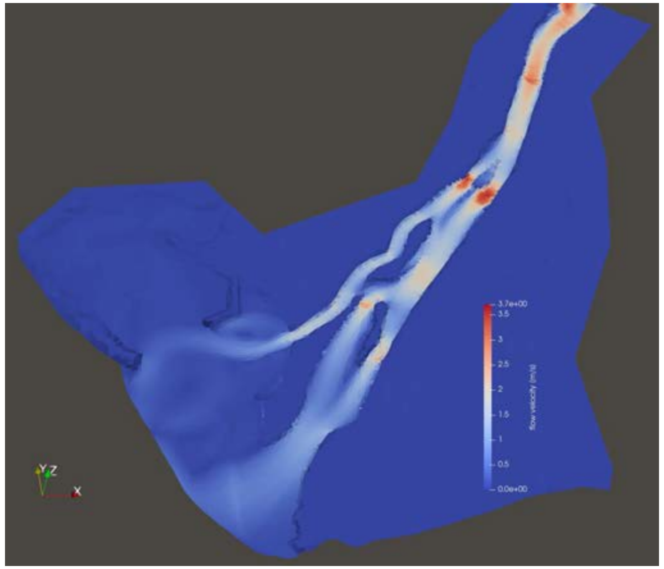
# Applied and fundamental research to solve water eng. problems

Experiments with physical models

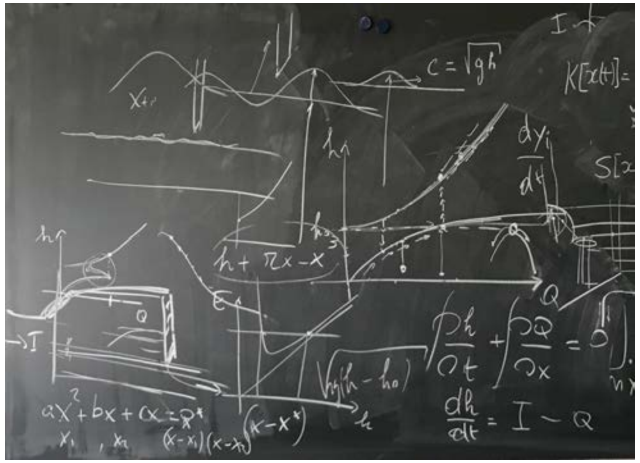


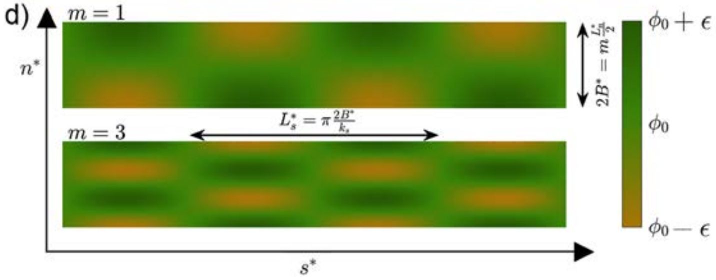
Numerical models





Theoretical models





# Outline of the lecture

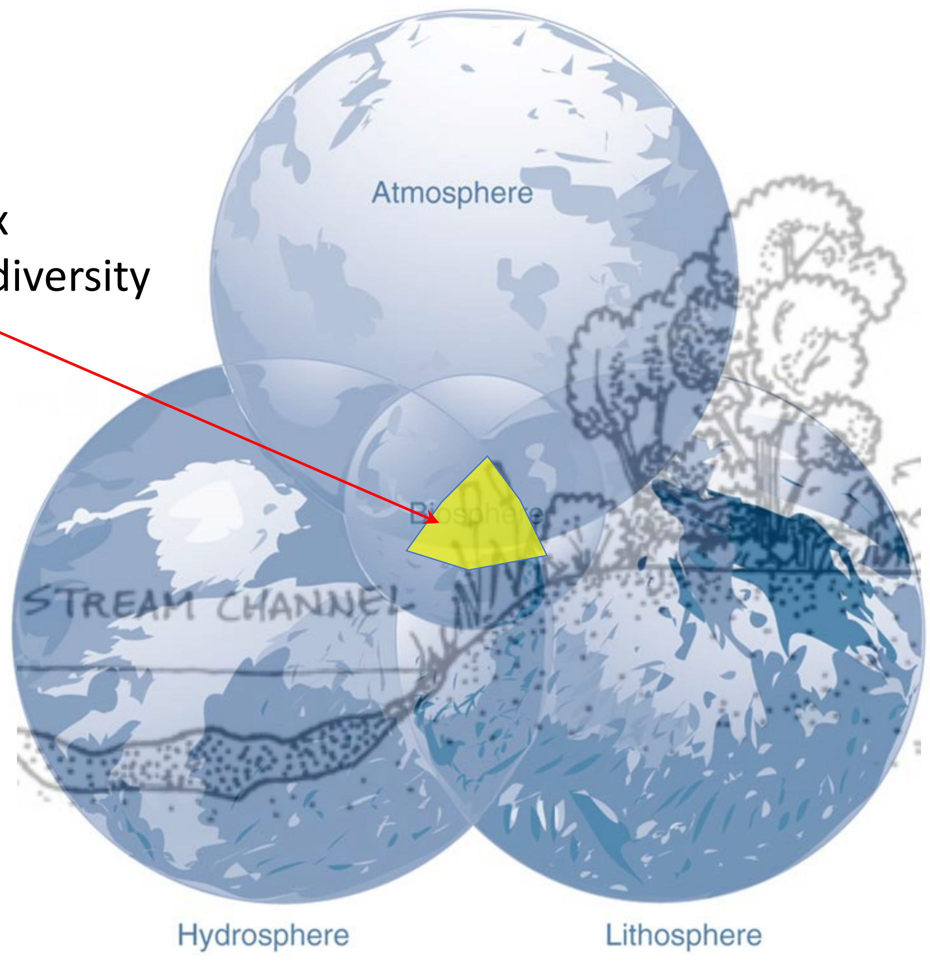
PART 1: processes and uses (propedeutic)

- Water processes (hydrological, hydraulics, transport)
- Water uses

PART 2: impacts and sustainability

- Contribute of water uses to water footprint
- Exemplary research at PL-LCH

  (7 examples concerning river impoundment, sustainable hydropower, irrigation, urban flooding, river restoration and carbon storage, transboundary conflicts with env. consequences



Max biodiversity

# PART 1: water processes and uses for human and environmental needs

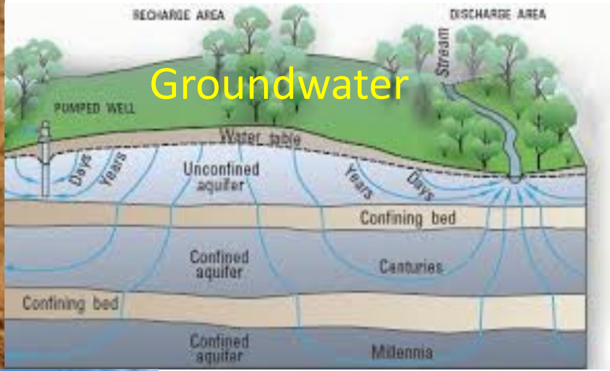
# Environmental engineers are involved in multiple water aspects…

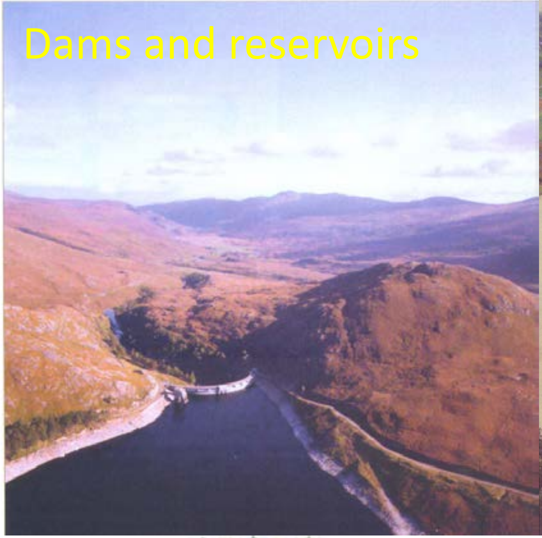

Rainfall

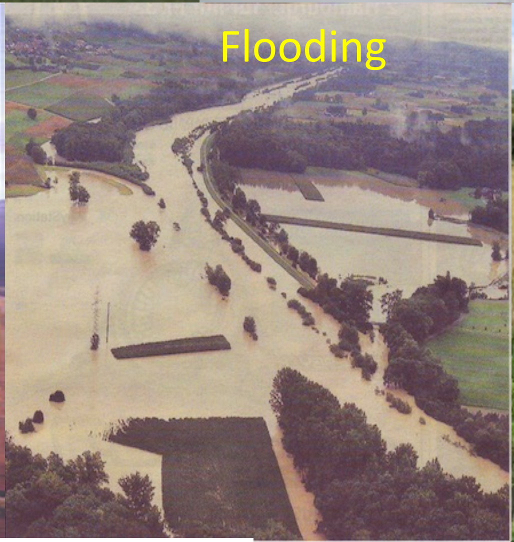

Snowfall


Vegetation and soil moistures


Surface Runoff


Groundwater


Dams and reservoirs

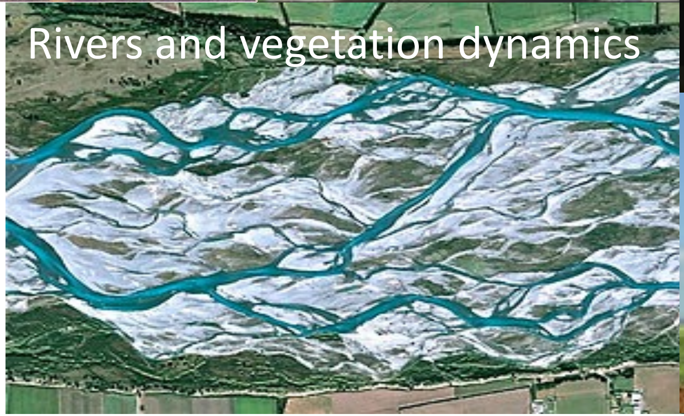

Flooding


Irrigation and drainage systems

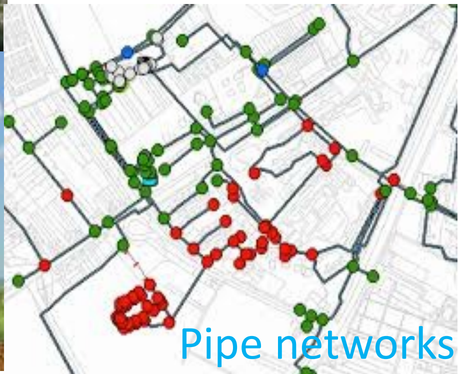

Aqueducts


Sewer systems and water treatment


Hydropower


Rivers and vegetation dynamics


Embankment and protection


Pipe networks

# Water resources and environmental engineers

Education is clearly one of the leading drivers and players are involved in WREM problems at different levels of engagement

A time for opportunities

2010

A time of quandary

2000

1990

A time of new challenges

1980

A time of reality

1970

1960

A time of enlightment

1950

A time of construction

1920 -

PERSPECTIVE: Towards a reconciliation between engineering, environment and society!!

+ ecologists, biologists/ restoration, downstream impacts

+ antropologists/ displaced people

+ geomorphologists/ landscape, instream flows, fish passage

+ sociologists/ social pressure

+ economists/ management

Engineers/ design, operation

A time for education!

GOAL: to make today civil and environmental engineering students interacting with several disciplines!!

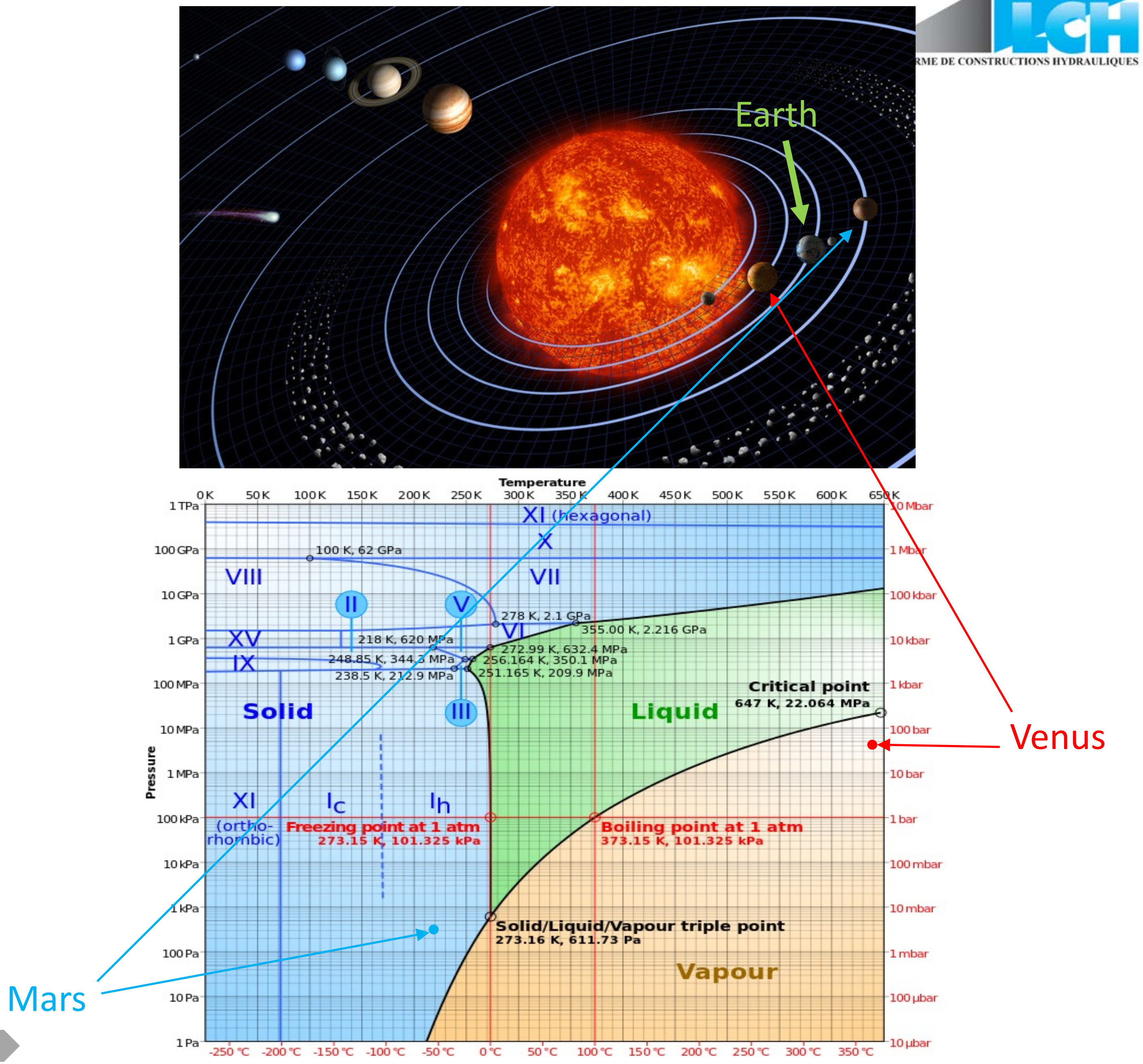
*(Adapted from Hirji et Davis, 2009; Ligget, 2002)*

# Hydrological Processes: from rainfall drops to streamflow to floods

Related courses:
Hydrology for Engineers (ENV 221)

# Water and life: the power of chances

- Life on Earth is sustained by the presence of water, whose existence in his form (e.g., near the critical point of the phase diagram)  is guarranteed by the particular location of our Planet in the solar system
- Compared to our „neighbourest“ planets (e.g., Venus and Mars), Earth is therefore special.
- Water availability throughout Earth is driven by the hydrologic cycle

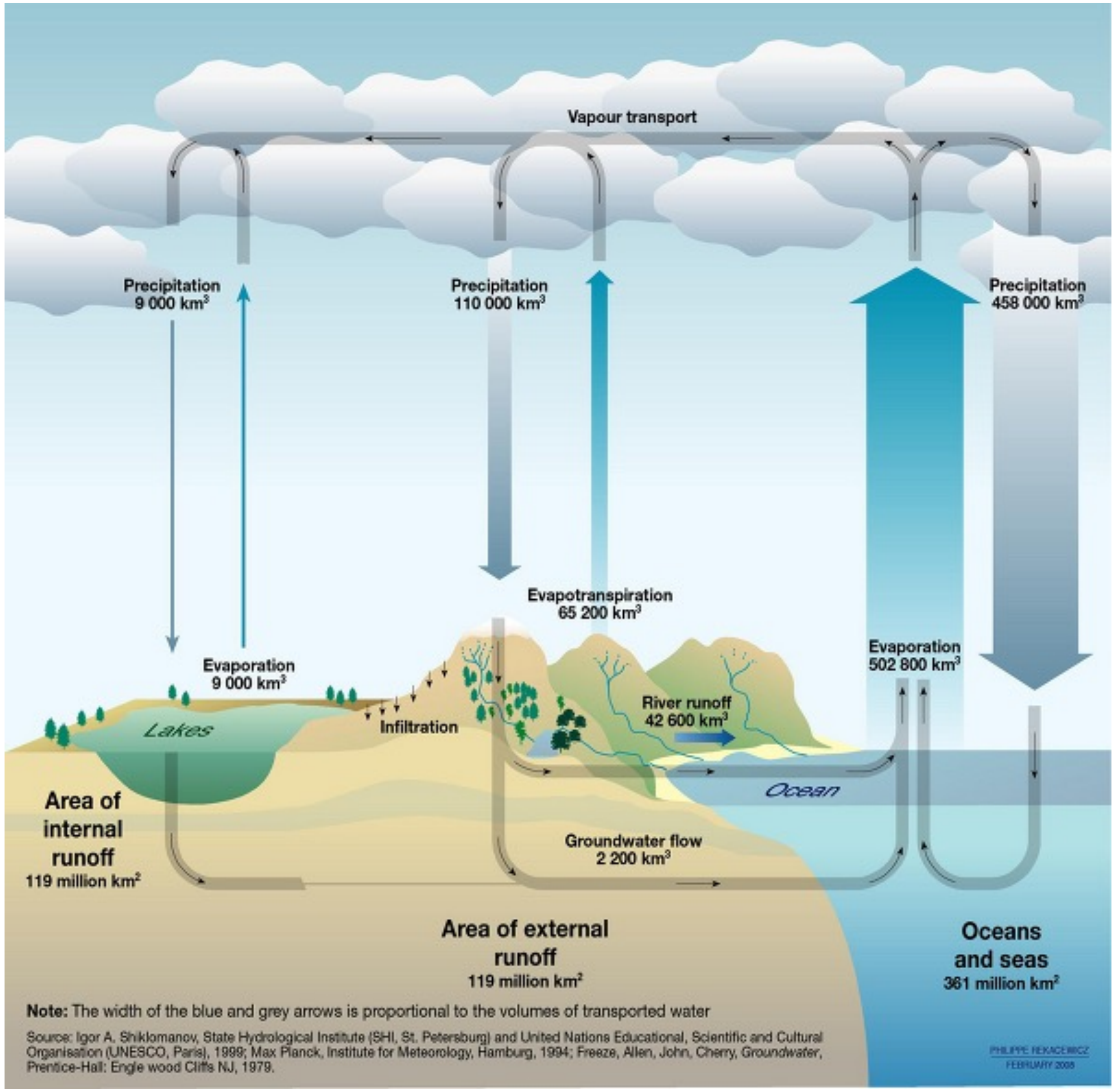


# The hydrological cycle

Water volumes transfer across the globe through transport processes (advection, convection and diffusion mainly).

Atmospheric processes make water distribution spread overall the globe enhancing either <u>equilibrium or non equilibrium processes </u>and local mass exchanges.

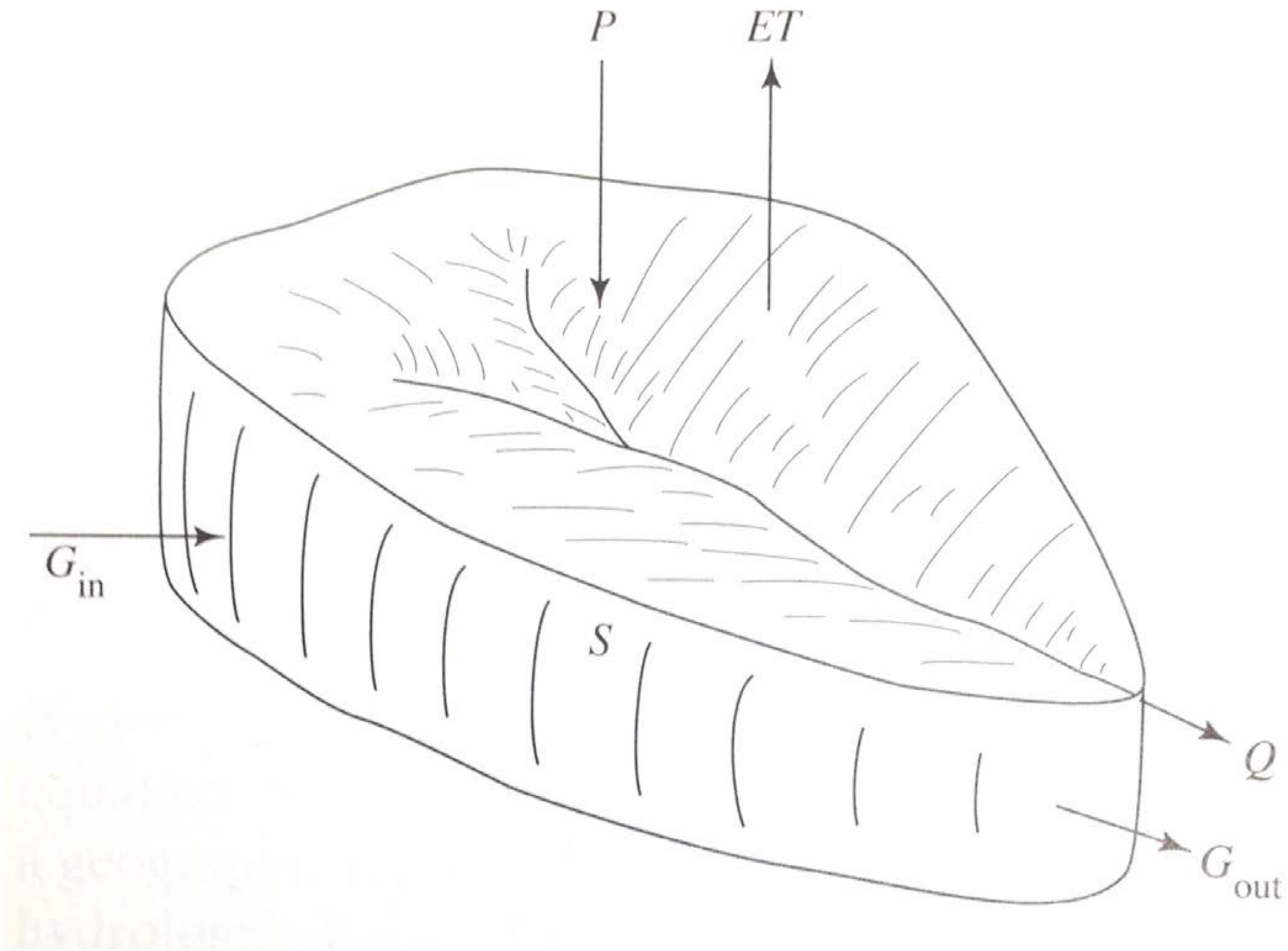
Diseequilibrium conditions are fundamental to maintain active the hydrologic cycle



**Note:** The width of the blue and grey arrows is proportional to the volumes of transported water

Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze, Allen, John, Cherry, Groundwater, Prentice-Hall: Engle wood Cliffs NJ, 1979.

# Hydrological processes and water balance



Continuity equation (mass or volume balance over a given time interval)

$$P - ET + G_{in} - G_{out} - Q = \frac{\Delta S}{\Delta t}$$

Learn me!

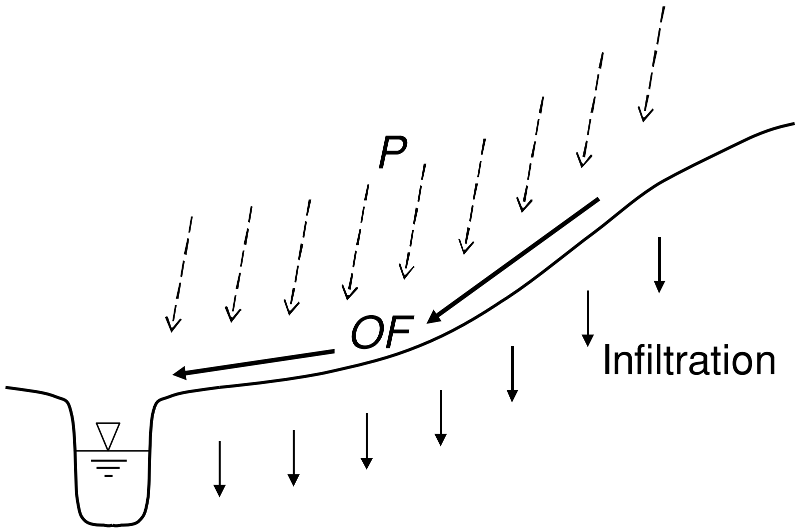
| | |
|---|---|
| $P$ | mean rate of precipitation |
| $ET$ | mean evapotranspiration rate |
| $Q$ | total stream outflow |
| $G_{in}$ | total groundwater inflow |
| $G_{out}$ | total groundwater outflow |
| $S$ | water volume stored in unit area |
| $t$ | time |

# From rainfall to runoff: three mechanisms

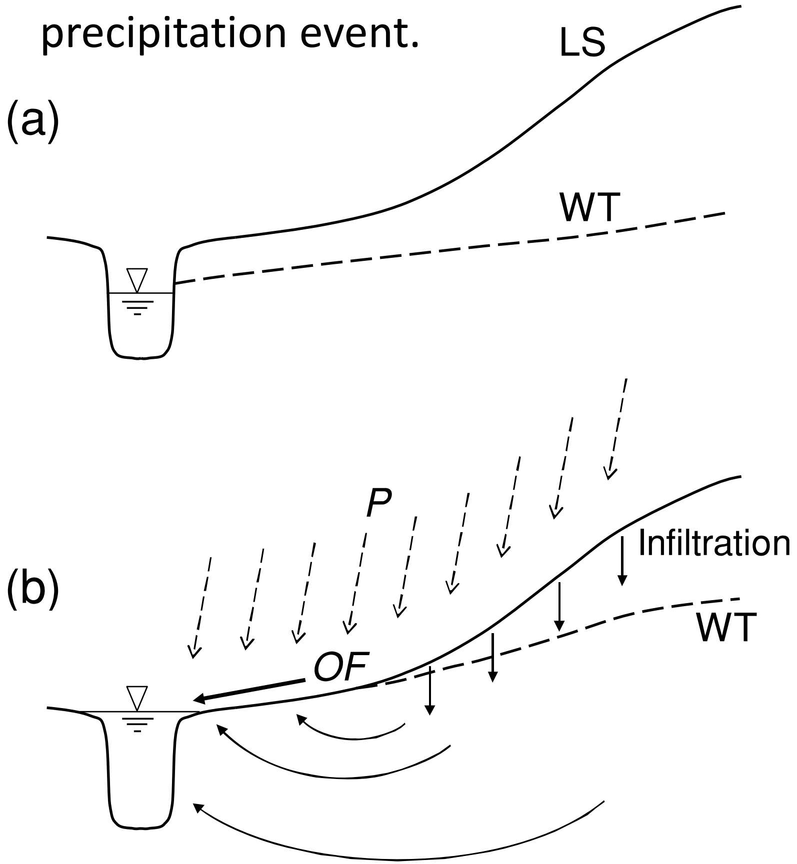
Learn me!

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

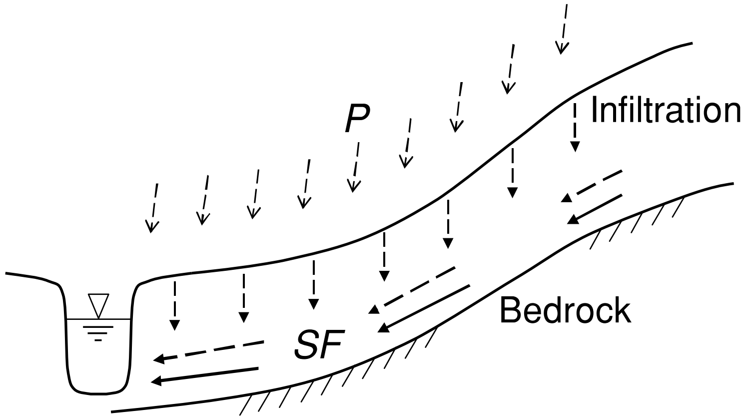
Overland Flow as infiltration excess. The precipitation rate, *P*, exceeds infiltration capacity, and the water table is at the ground surface



Overland Flow as saturation excess. (a) The position of the water table (WT) prior to the onset of precipitation and (b) during the precipitation event.



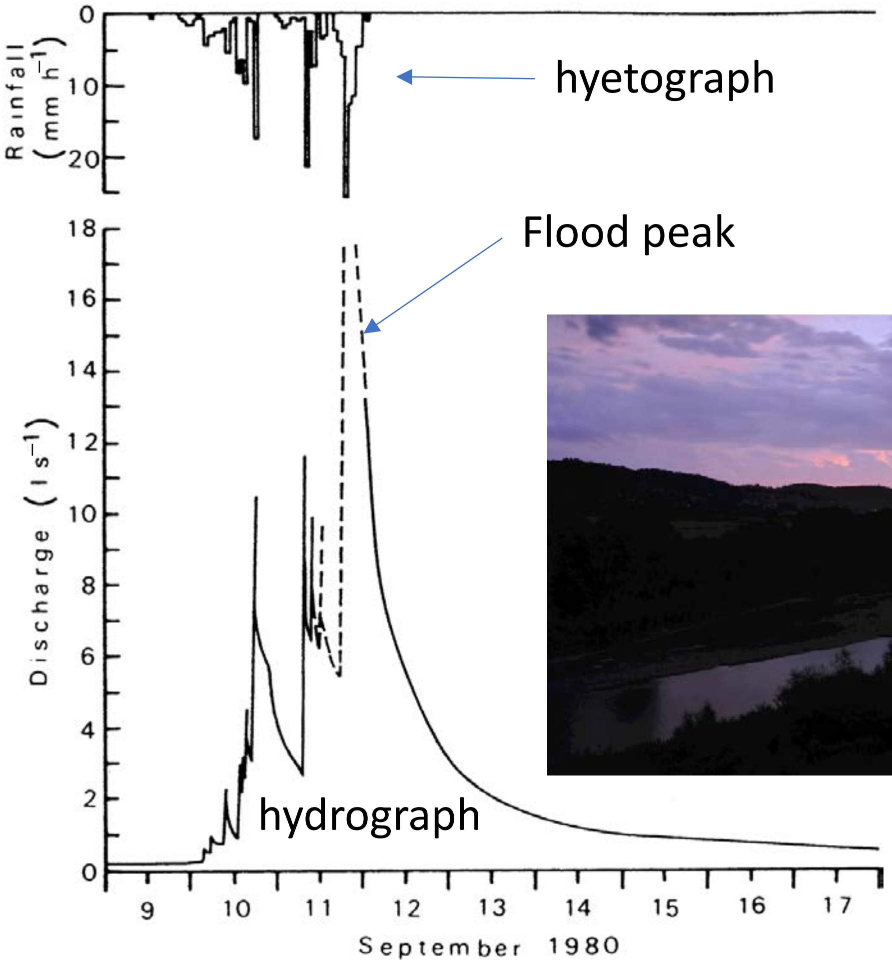
Subsurface storm flow through various types of preferential flow paths, pipes and macropores. The relative amounts of new (dashed arrows) and old (solid arrows) water in the mixing process depend mainly on the precipitation intensity and on the pre-storm soil moisture conditions



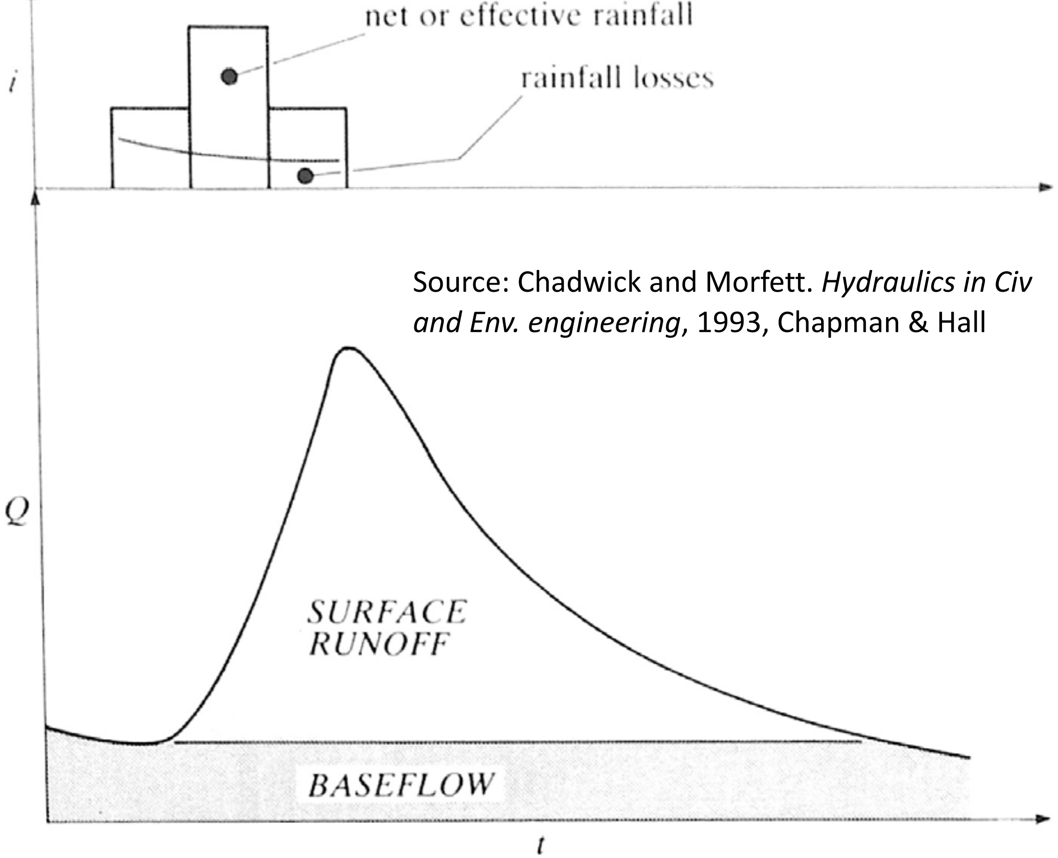
Source: Brutsaert, W. *Hydrology*, Cambridge

# Hydrograph components and flood generation

Typical question:
How do we model streamflow response (e.g., for flooding prevention)?



Precipitation and runoff hydrograph of the event on the catchment aside



Source: Chadwick and Morfett. *Hydraulics in Civ and Env. engineering*, 1993, Chapman & Hall

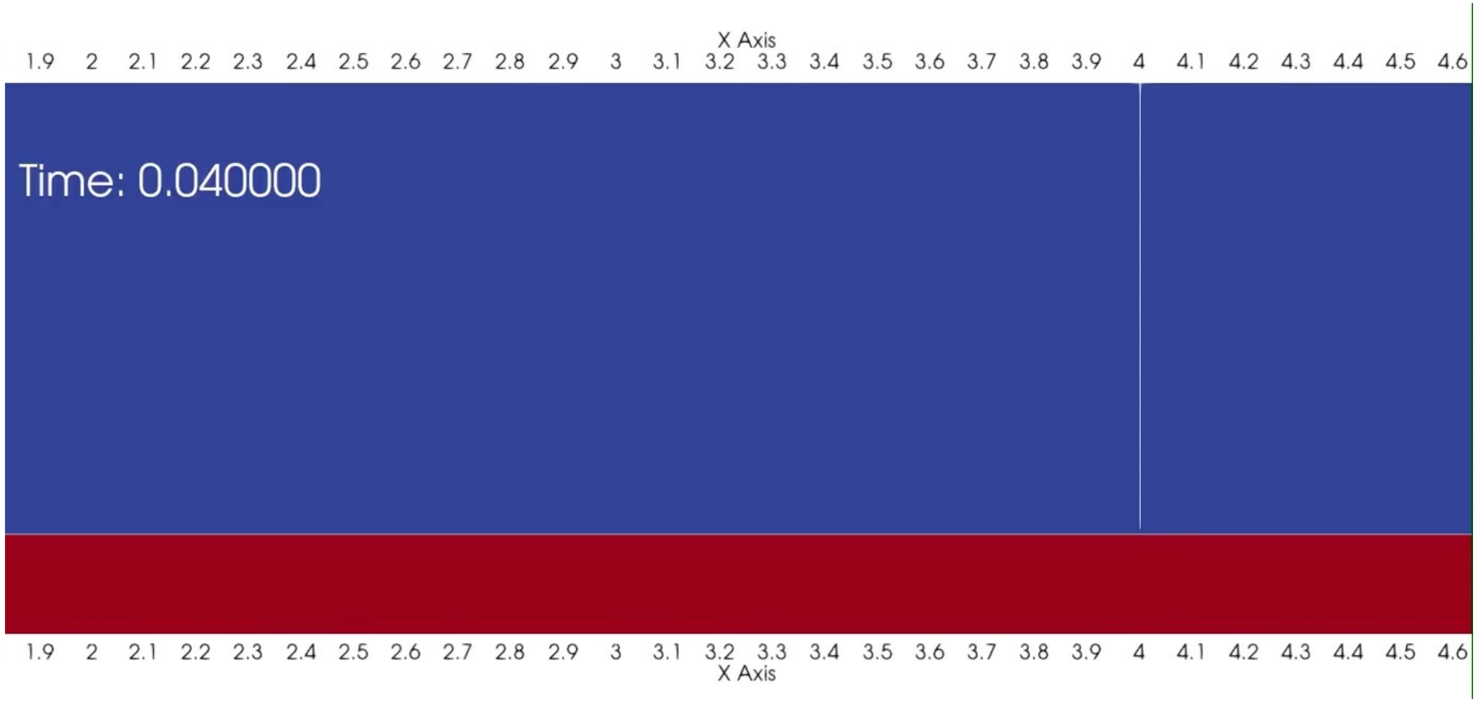
(a) Rainfall and runoff separation

# Hydraulic Processes: free surface vs pressure flow and the beauty of fluid mechanics

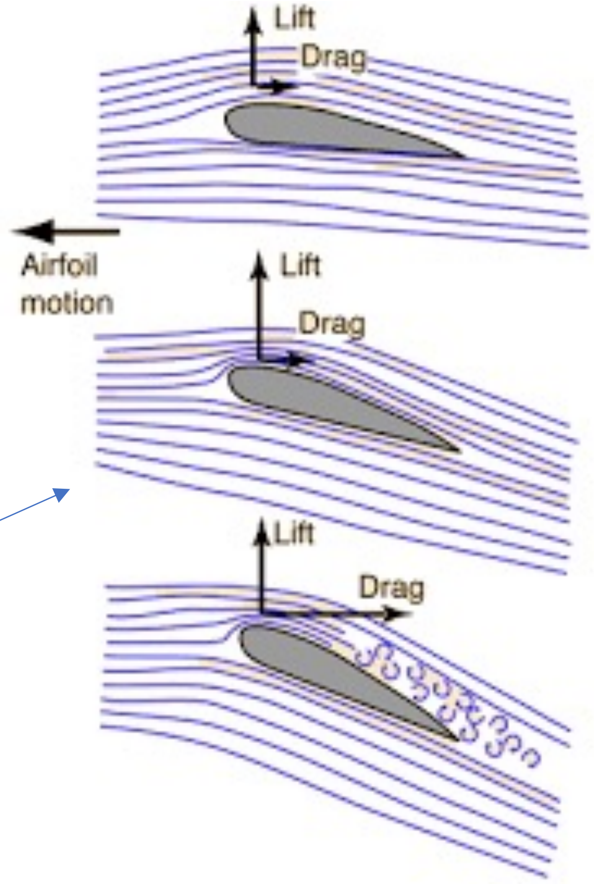
Related courses:
- Fluid Mechanics (ENG 272)
- Hydraulic structures and schemes (CIVIL 312)

# How does water move

Unconfined boundaries
“free-surface flow”



The motion of a fluid continuoum is mathematically described by the Navier-Stokes equations (1822-42), which are amongs the most difficult equations in physics (highly non-linear)

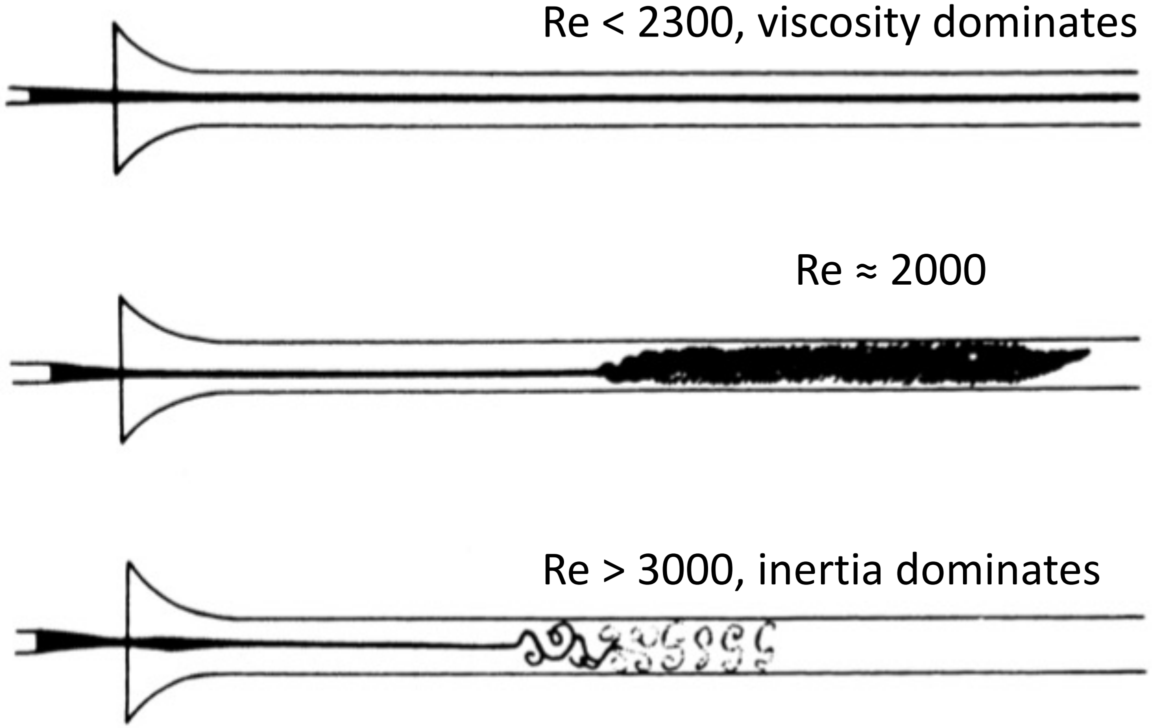


In confined boundaries, e.g. pipes we speak of “pressure flow”, easier to treat than free-surface flow, but also showing interesting shock phenomena (e.g., water hammer)

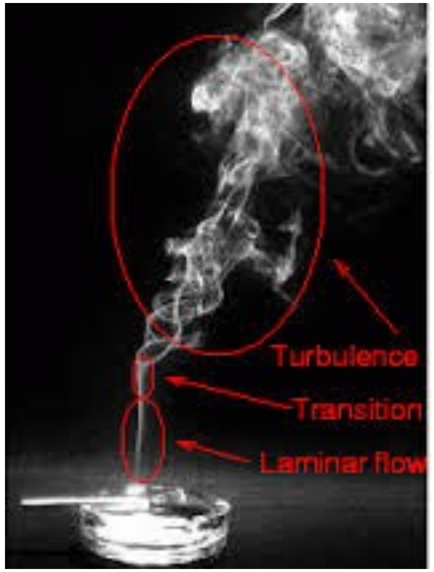
N-S also describes the famous Bernoulli theorem: along a fluid trajectory if pressure increases, the velocity decreases and viceversa

Learn me!

# Laminar vs turbulent regime



Osborne Reynolds experience (1883) to demonstrate laminar to turbulent transition in pipe flow



Key parameter: Reynolds number

$$Re = \frac{\varrho U L}{\mu}$$

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$\rho$= fluid density [kg m$^{-3}$]

$\mu$ = dynamic viscosity [kg m$^{-1}$ s$^{-1}$]

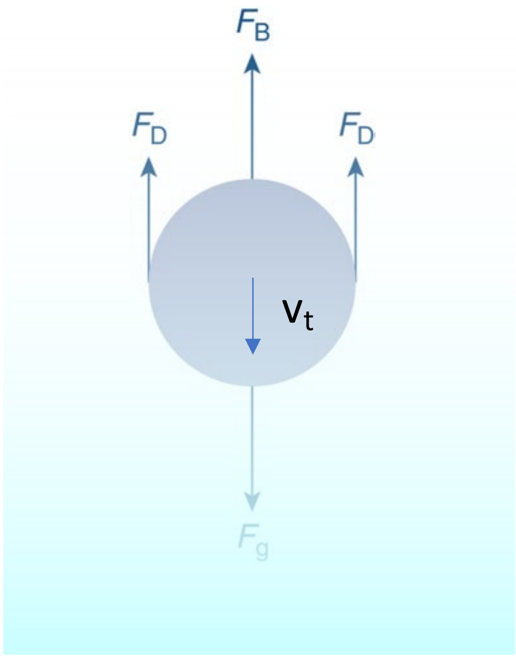
U = mean flow velocity [m s$^{-1}$]

L = characteristic length scale [m] in relation to U. For pipes L=Diameter

Re < 2000 → Laminar flow is stable
Re > 2000 → Laminar flow is unstable
(degenerates into turbulence, Re>4000)

# Interaction with particles

## Falling particles (Stokes law)



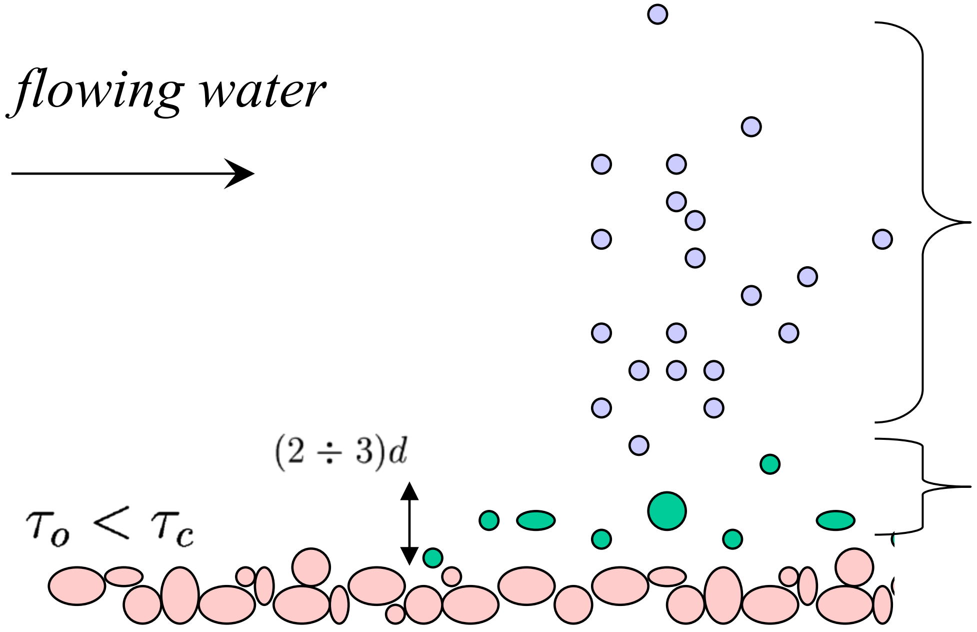
In the Stokes's regime,
$C_d = 24/Re_p = 24\mu/(\rho_f d_p v_t)$

Learn me!

$$\boxed{v_t = \frac{g(\rho - \rho_f)d_p^2}{18\mu}}$$

Falling velocity

## Movement and transport of particles (Shields and Bagnold laws)



$\tau_o > \tau_s$

**suspended load** transported in suspension

$\tau_c < \tau_o < \tau_s$

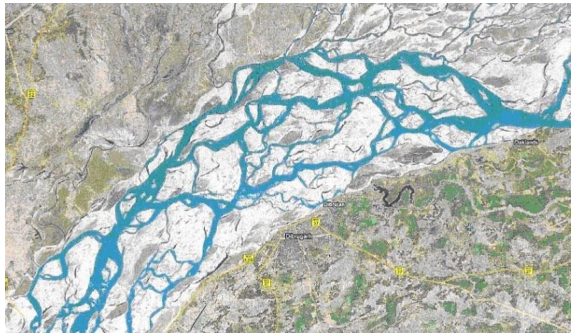
**bed load** transported in contact with the stream bed (by saltating, rolling)

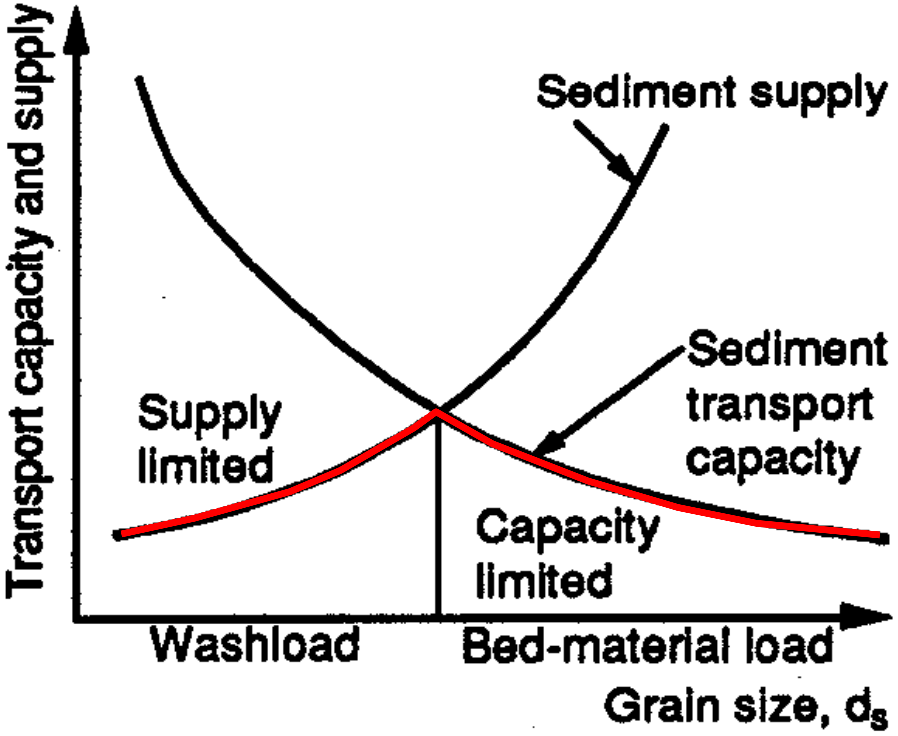
$$\tau_* = \frac{\tau_0}{(\rho_s - \rho)gd} = f(Re_p)$$

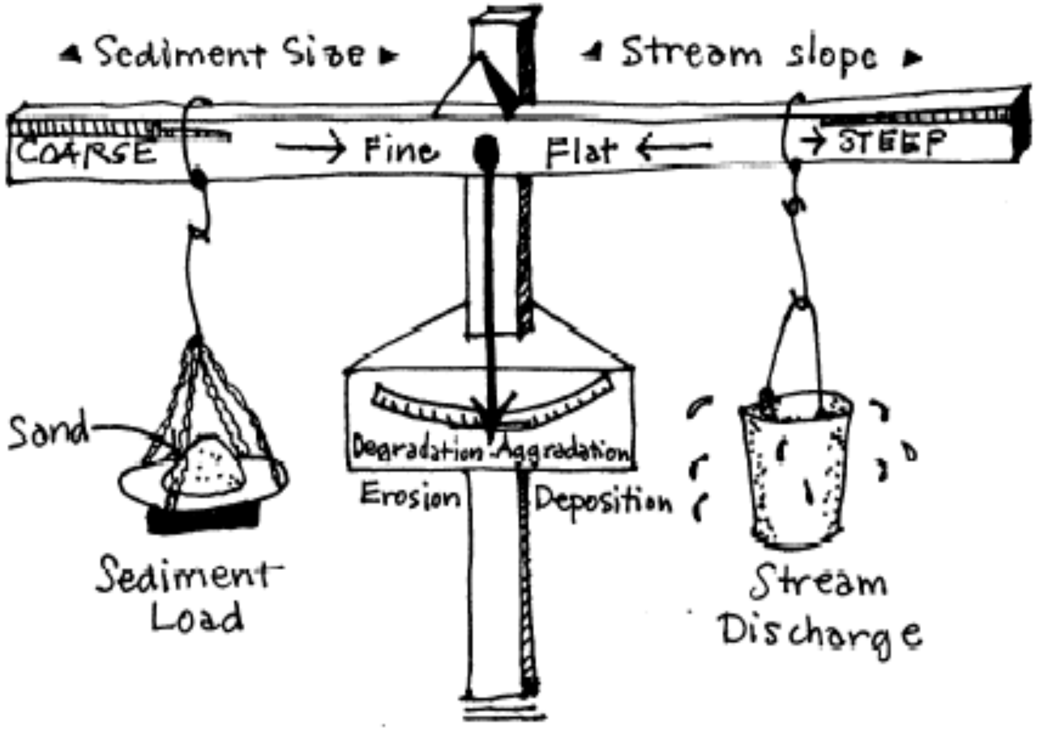
The shear stress $\tau_0$ acting on the particles must exceed a critical value $\tau_c$ for particles to begin moving (incipient motion, bed load). This can be represented in a dimensionless plot $\tau_* = f(Re_p)$ [Shields]

# River mechanics and morphodynamics

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES





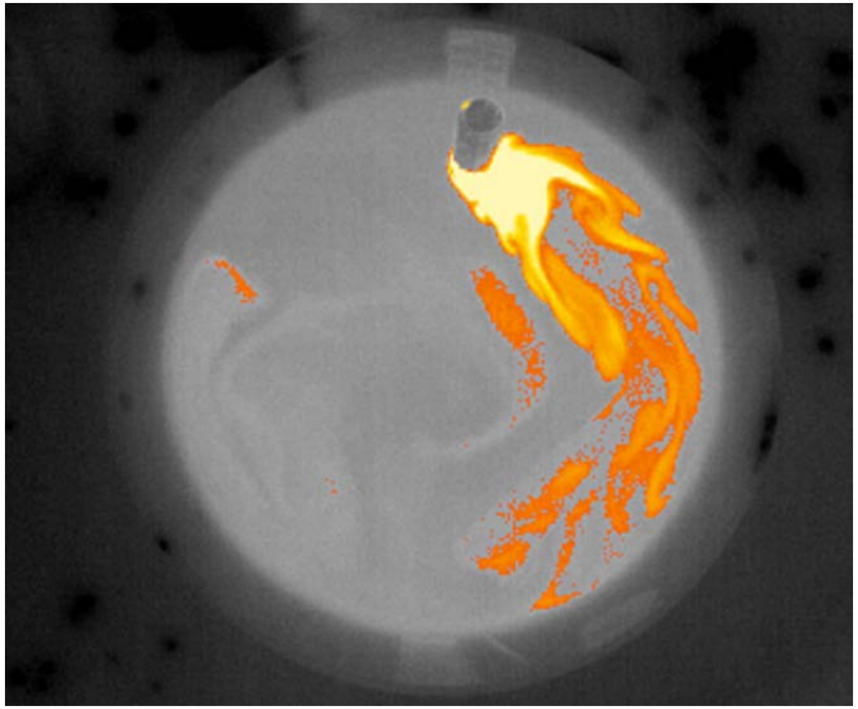


**Lane's equation (non physical!):**

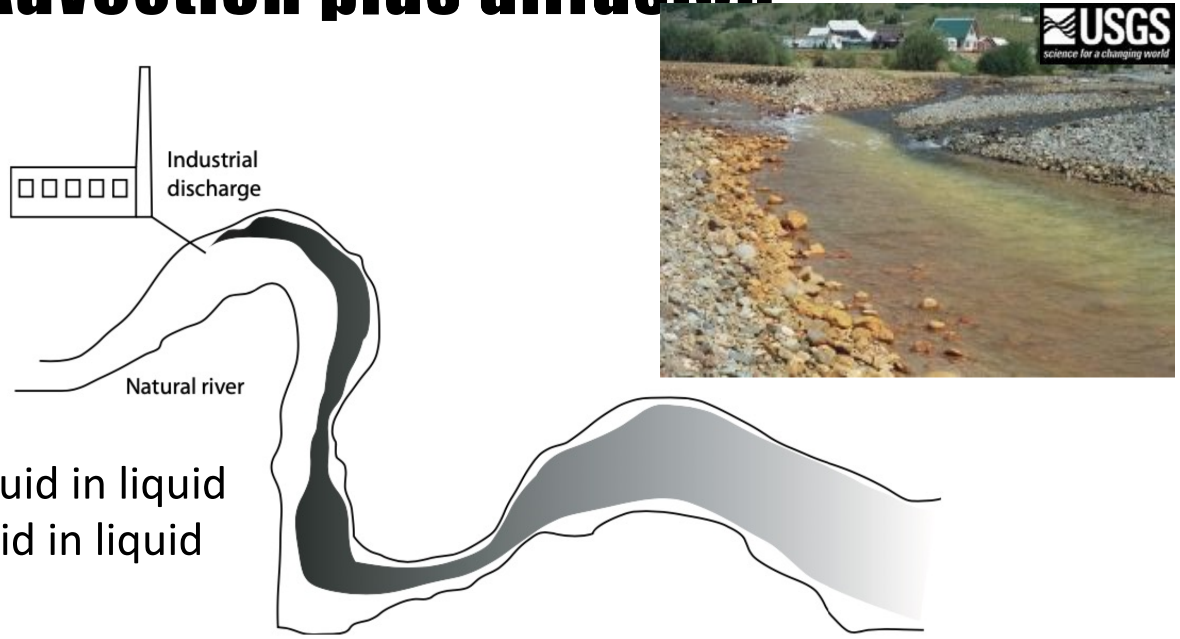
$$Q_s\, d_s = Q\, S$$

# Mixing processes: molecular *vs* turbulent mixing

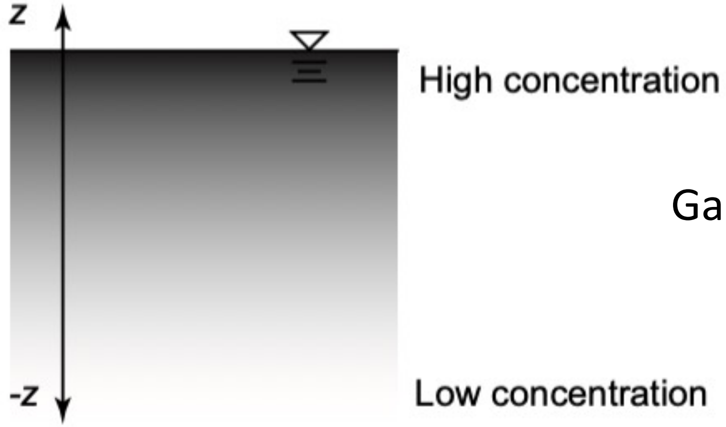
Related courses:
- Environmental Trasport Phenomena (ENV 420)
-



# Advection plus diffusion

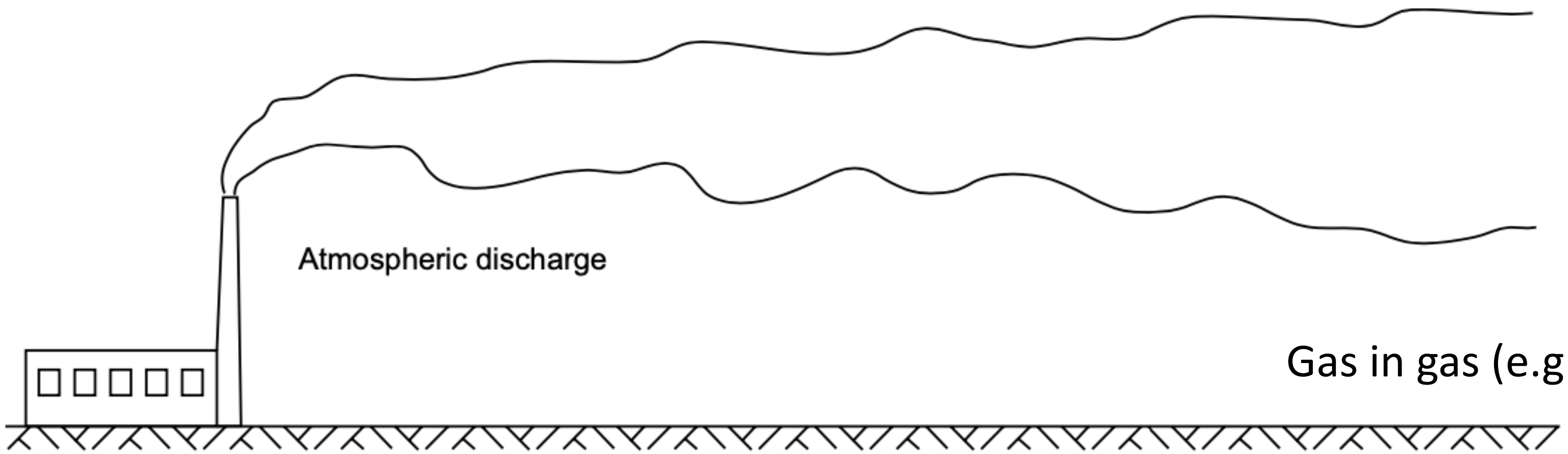


Liquid in liquid
Solid in liquid

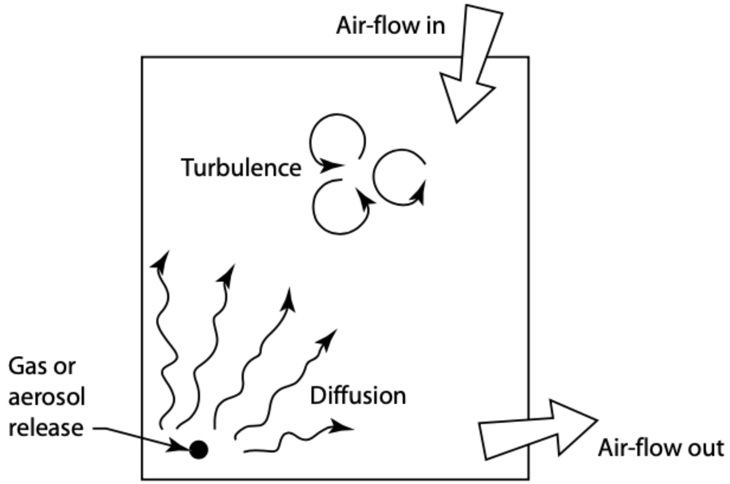


Gas in liquid

Diffusion of oxygen through air-water interface



Gas in gas (e.g. air)



# Diffusion (molecular)

Molecular diffusion is a transport process driven by the random motion of particles from regions with higher towards lower density regions

Because the motion is due to molecular agitation, it is a very slow process

Important parameters: molecular Diffusion coefficient, $D_m$ [$m^2/s$]

It depends on the phase, temperature and size of molecules

Solutes in water $D_m \approx 2 \cdot 10^{-9}$ $m^2/s$
Dispersed gases $D_m \approx 2 \cdot 10^{-5}$ $m^2/s$

Diffusive length scale

$L \propto \sqrt{D_m t}$

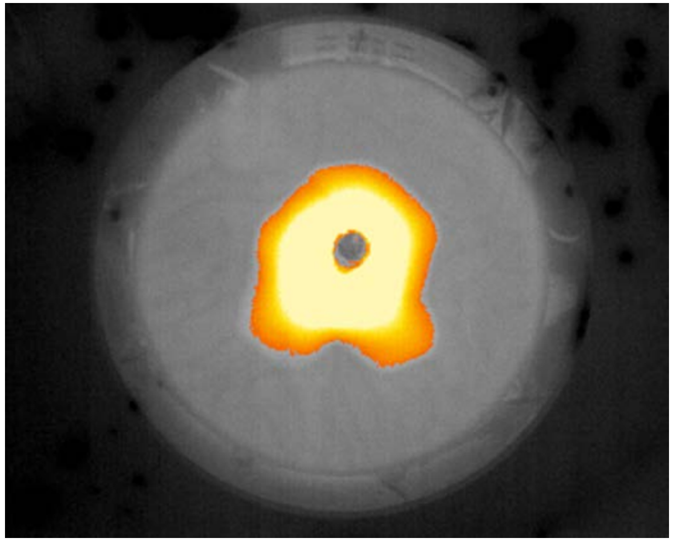
Learn me!

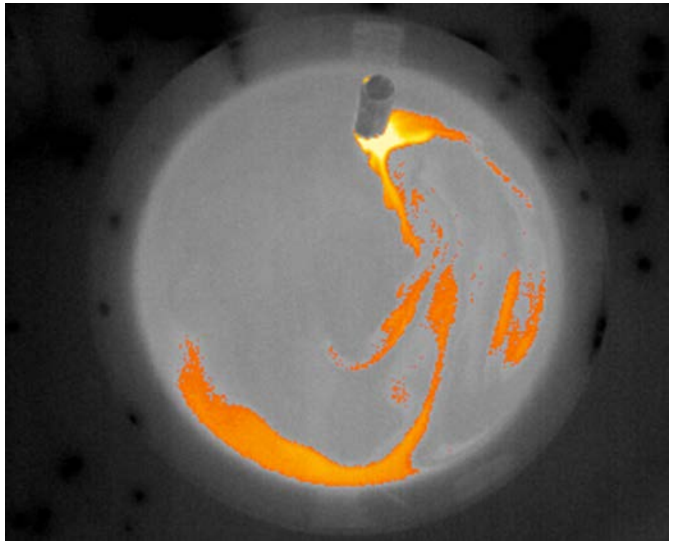
Diffusion + advection velocity (U) → advection-diffusion

Control parameter (Péclet number): $Pe = \frac{D_m}{U^2 t}$

>1 diffusion dominates

<1 advection dominates





# Turbulent diffusion (turbulent mixing)

Turbulent fluctuations of particles accelerates the diffusion process, in which case we speak of turbulent diffusion. The turbulent diffusion coefficient, $D_t$

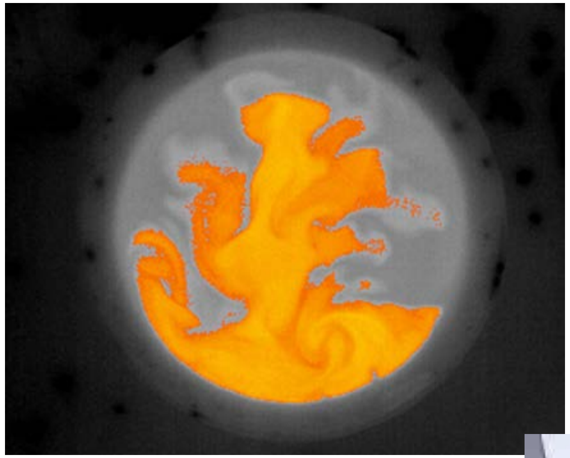
$D_t >> D_m$

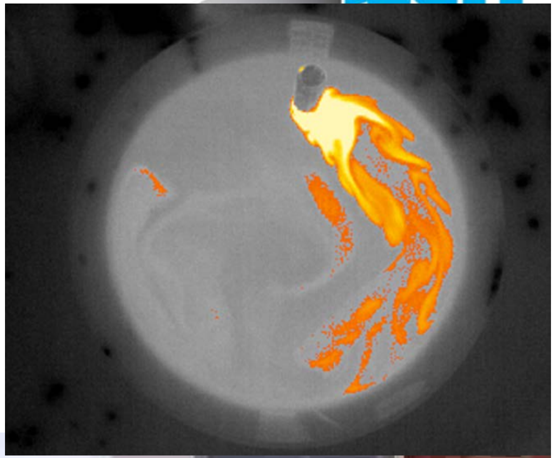
Diffusive Length scales becomes then $L \propto \sqrt{D_t t}$

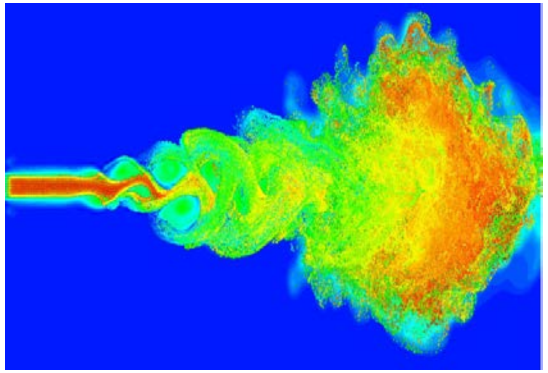
The sum of advection plus turbulent diffusion produces advection-diffusion (turbulent)

By adding non-uniform advection we obtain a process called <u>dispersion by shear</u>, very relevant to mixing in river flow

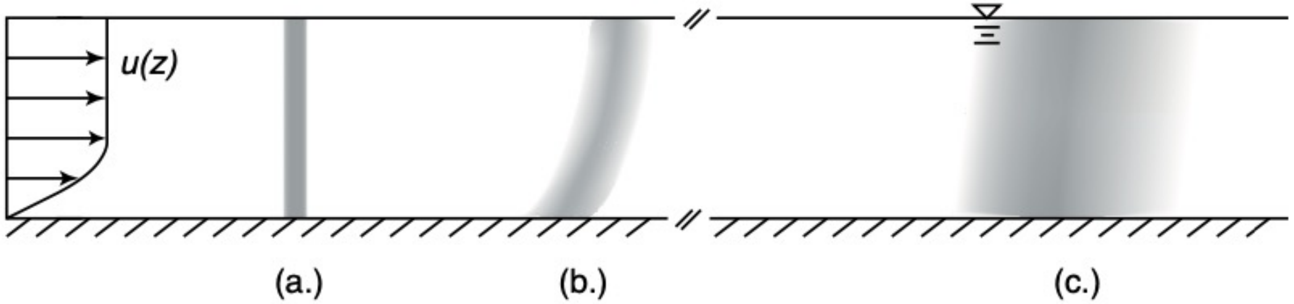
$$D_{t,z} = 6.4 \cdot 10^{-4}\ \mathrm{m^2/s}$$
$$D_{t,y} = 5.7 \cdot 10^{-3}\ \mathrm{m^2/s}$$
$$D_{t,x} = 5.7 \cdot 10^{-3}\ \mathrm{m^2/s}.$$







Side view of river:



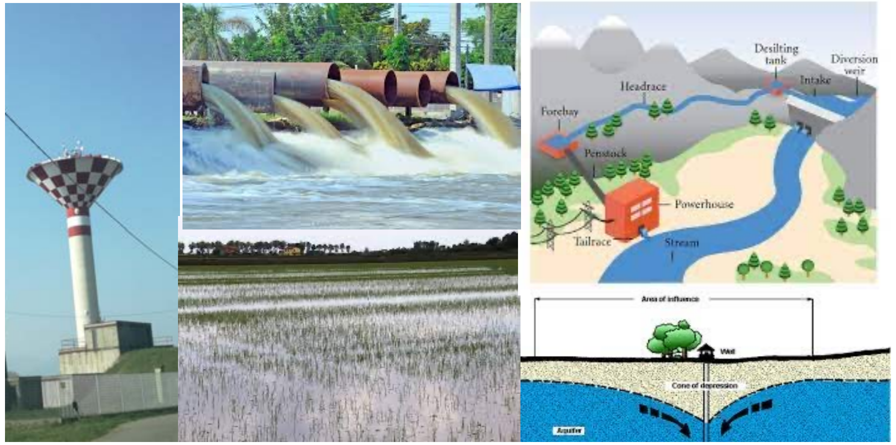
# Water uses

Related courses:

- Water Resources Engineering and Management (CIVIL 466)
- Irrigation and drainage engineeering (ENV-549)
- Hydraulic structures and schemes (CIVIL 312)
- Water and wastewater treatment (ENV-405)
- Groundwater and soil remediation (ENV-504)
- Analyse des polluants dans l'environnement (ENV-300)

# Definition of water uses: consumptive and non-consumptive

- Consumptive water use: any use of water which may change its quality or availability to next users, e.g. return flow coefficient <1 (e.g., urban water, industrial water, irrigation, hydropower with diversion*, etc.)



- Non Consumptive water use: any use of water which preserves quality and availability, e.g., return flow coefficient = 1 (e.g., hydropower run-of-river, flood protection, environmental uses, recreational uses, etc.)

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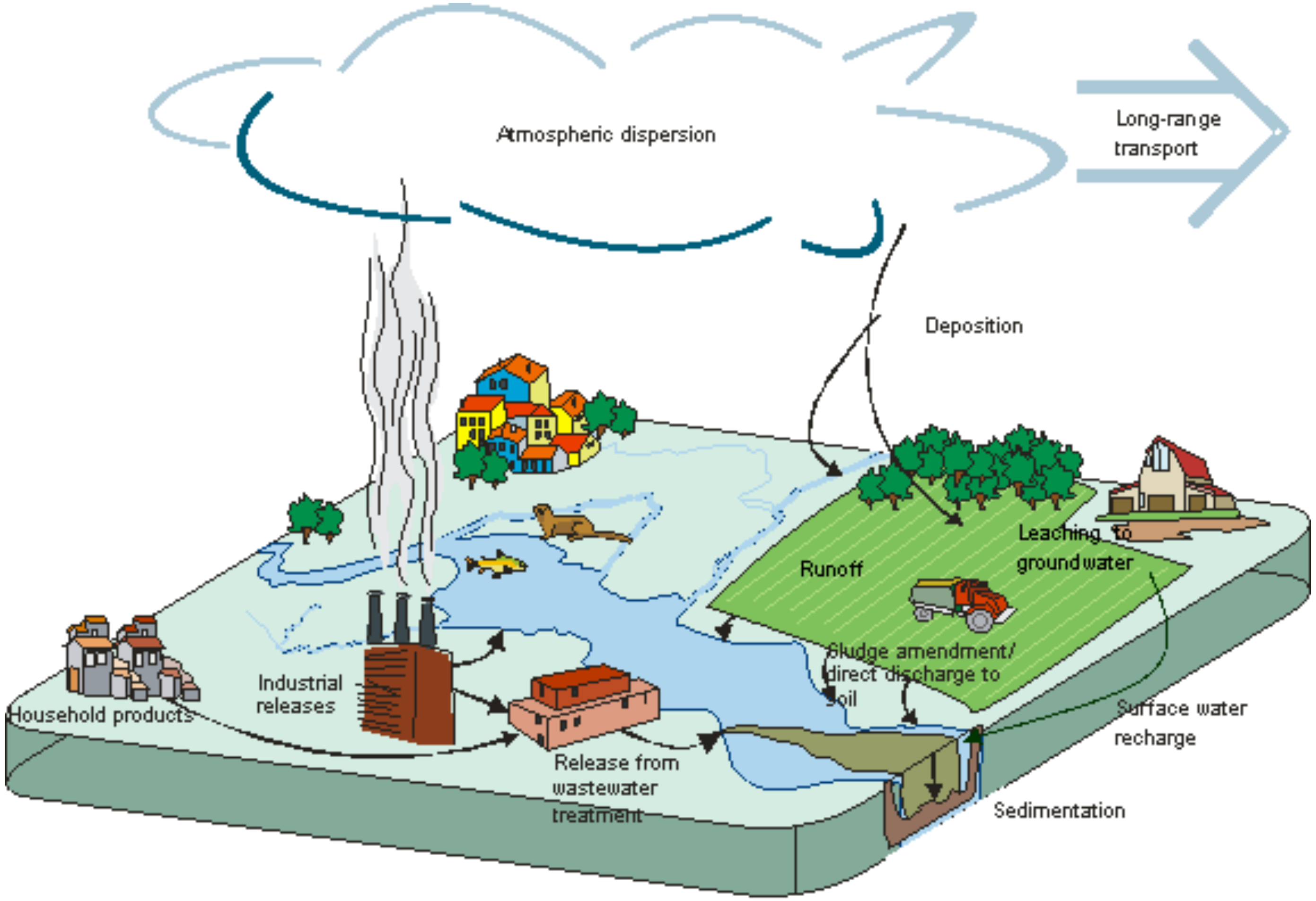
*The case of hydropower is peculiar as it changes return flow coef only locally, i.e. within the impounded reach

# Water uses affecting the water cycle



Courtesy of Dr. A. Semiao, The University of Edinburgh

- Dams and reservoirs
- Irrigation diversions and drainage returns
- Potable water supply
- Wastewater treatment (controversial)
- Changes in land use
- Flood mitigation
- Changes in climate conditions
- Domestic use (pollution)
- Agricultural use (use and pollution)
- Industrial (use and pollution)

Consumptive Non-consumptive

# PART 2: Environmnetal impact following water use

Related courses:

- Sustainability (ENV-101)
- Water Resources Engineering and Management (CIVIL 466)
- Irrigation and drainage engineeering (ENV-549)
- Hydraulic structures and schemes (CIVIL 312)
- Water and wastewater treatment (ENV-405)
- Groundwater and soil remediation (ENV-504)
- Analyse des polluants dans l'environnement (ENV-300

# Water availability on Earth: why to worry?

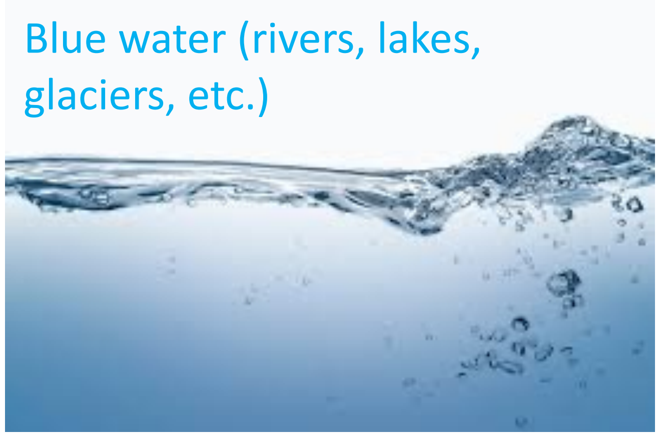
Only 0.0075% of the total water is directly accessible

Learn me!

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

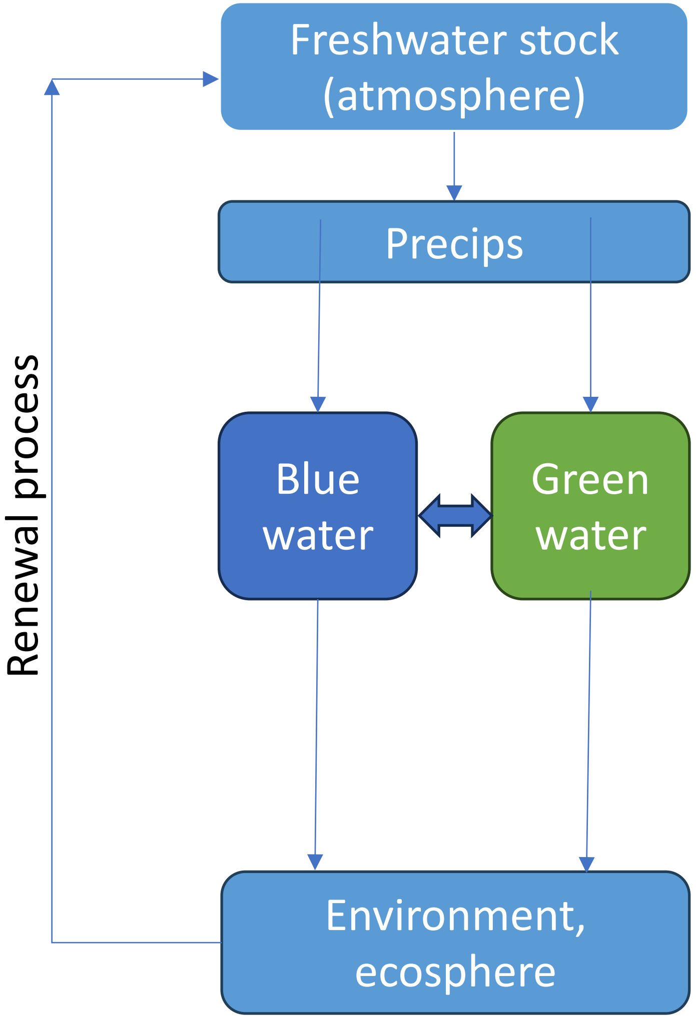
- Total water is the amount of all forms of water some of which are not accessible at all
- Renewable water is the amount that is being renewed either annually or along longer durations
- Available water is the amount that humans can access and use for their consumpion

# The colors of water: natural cycle

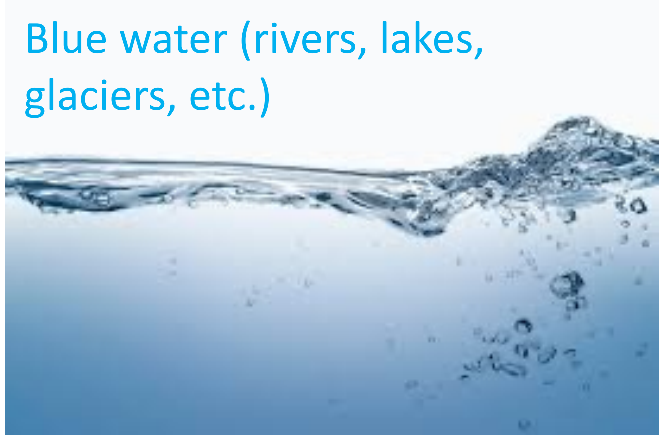


Blue water (rivers, lakes, glaciers, etc.)

Green water (forests, soil moisture, cultures, etc.)



# The colors of water: anthropic influence on water cycle


Blue water (rivers, lakes, glaciers, etc.)


Green water (forests, soil moisture, cultures, etc.)


Grey water(domestic use, commercial, industrial, etc.)







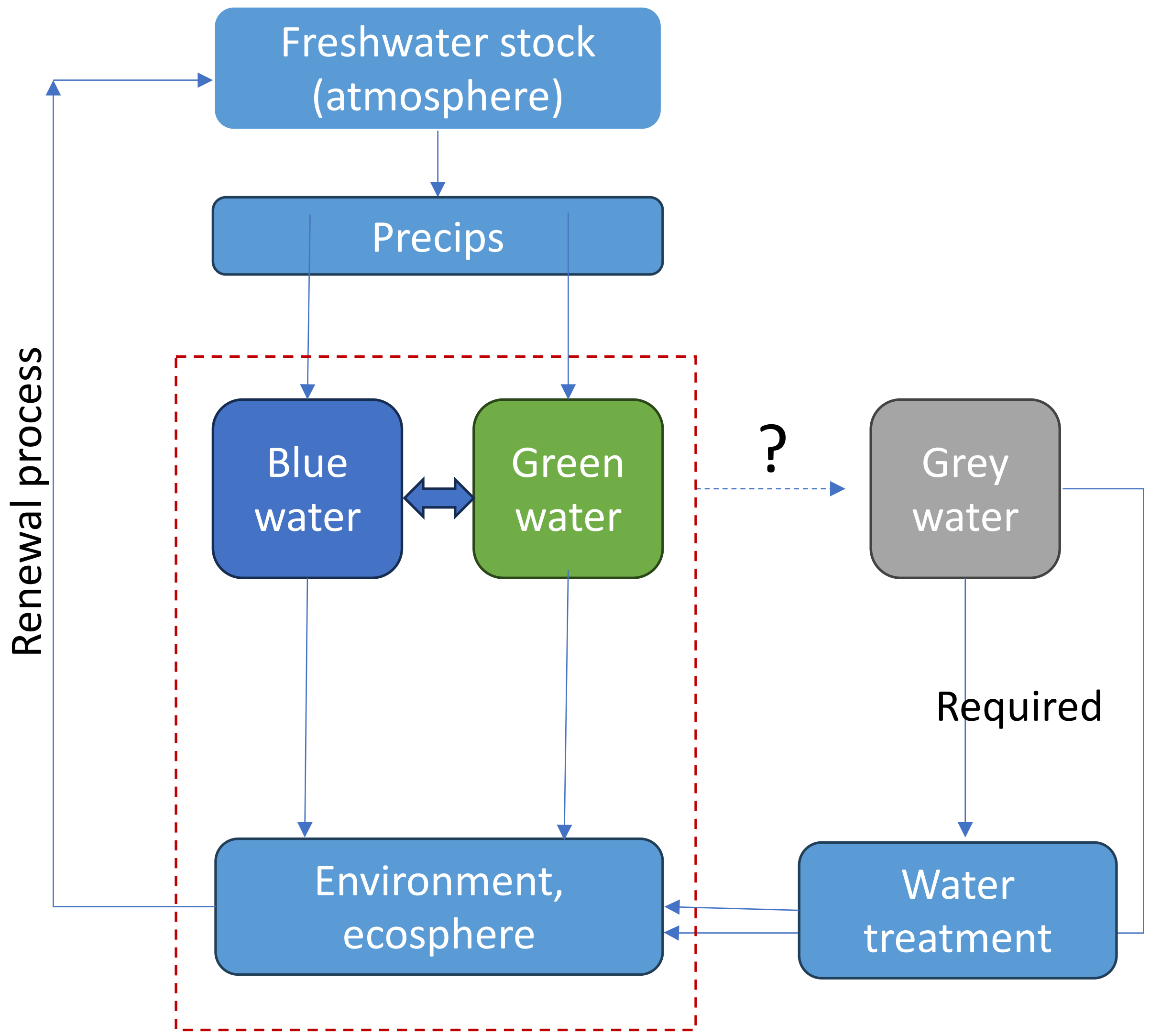




Water footprint:

The amount of blue, green and grey water used for a certain product/action

# Anthropic influence on water cycle (water uses)



The anthropic use of water reduces its quality and transforms it into Grey water

Grey water formally represents a reduction of directly available water in terms of quantity and quality

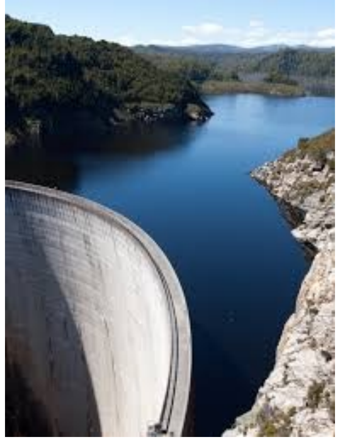
Grey water needs to be treated before it can be returned to the environment and this requires time and energy

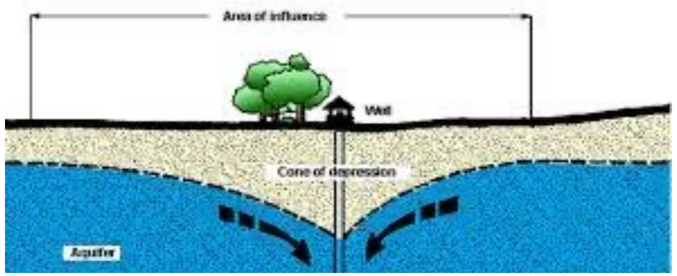
Not all grey water is treated and when it returns to the environment it pollutes it (e.g. leakege of chemicals from agricultural soil)

# Type of impact

## Use of the resource

## Environmental impacts





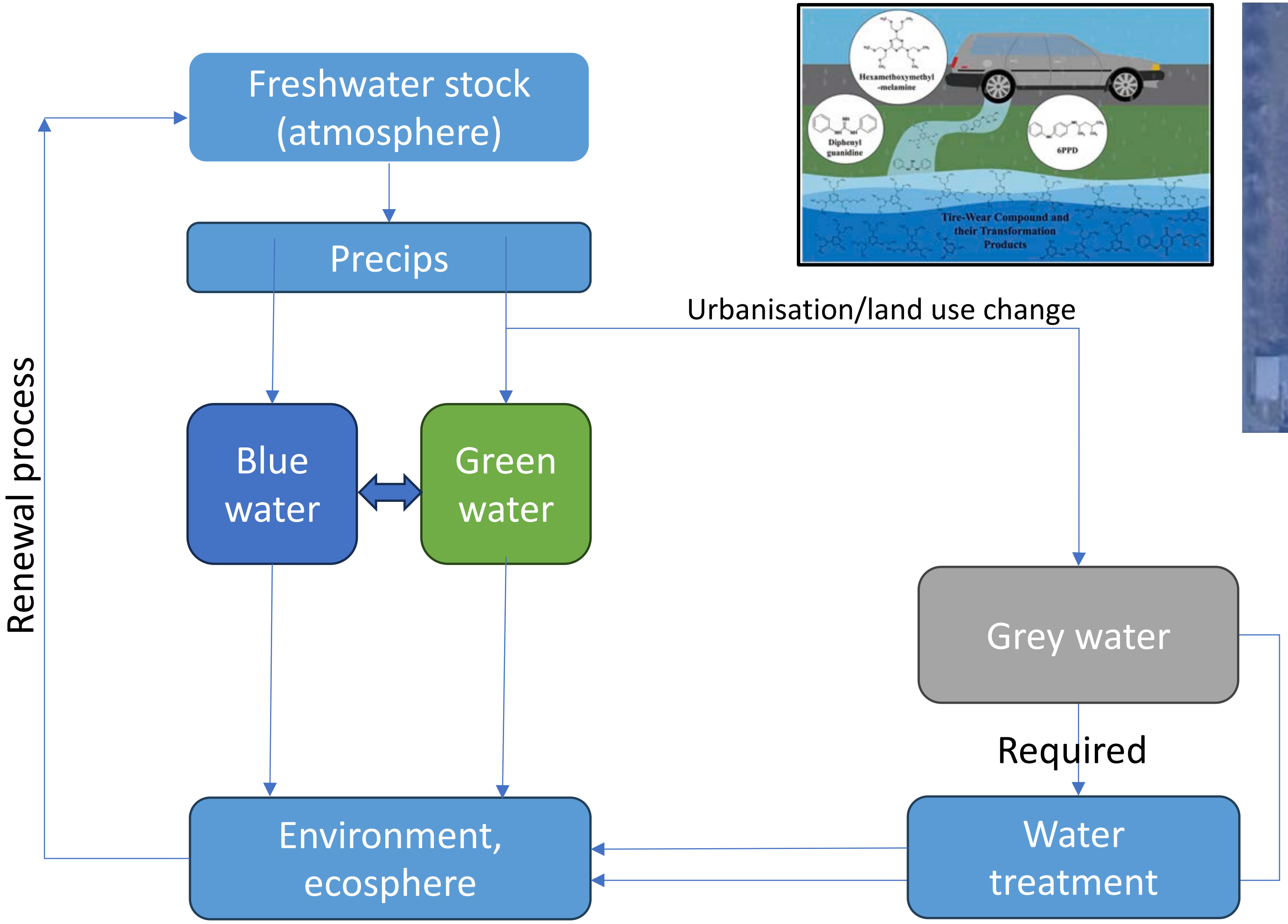
Physical impact: e.g., diverting water from a water course reduces its quantity downstream, alters sediment transport, etc.

Chemical impact: e.g., the use of water changes its quality because of chemical, physical, biological pollution

Biological impact: pathogens proliferation and spreading by vectors into water-borne diseases (malaria, onchocerciasis, Schistosomiasis)

# Contribute of different water uses to water footprint

# Urbanisation and land use/change



Freshwater stock (atmosphere)

Precips

Urbanisation/land use change

Blue water

Green water

Grey water

Required

Water treatment

Environment, ecosphere

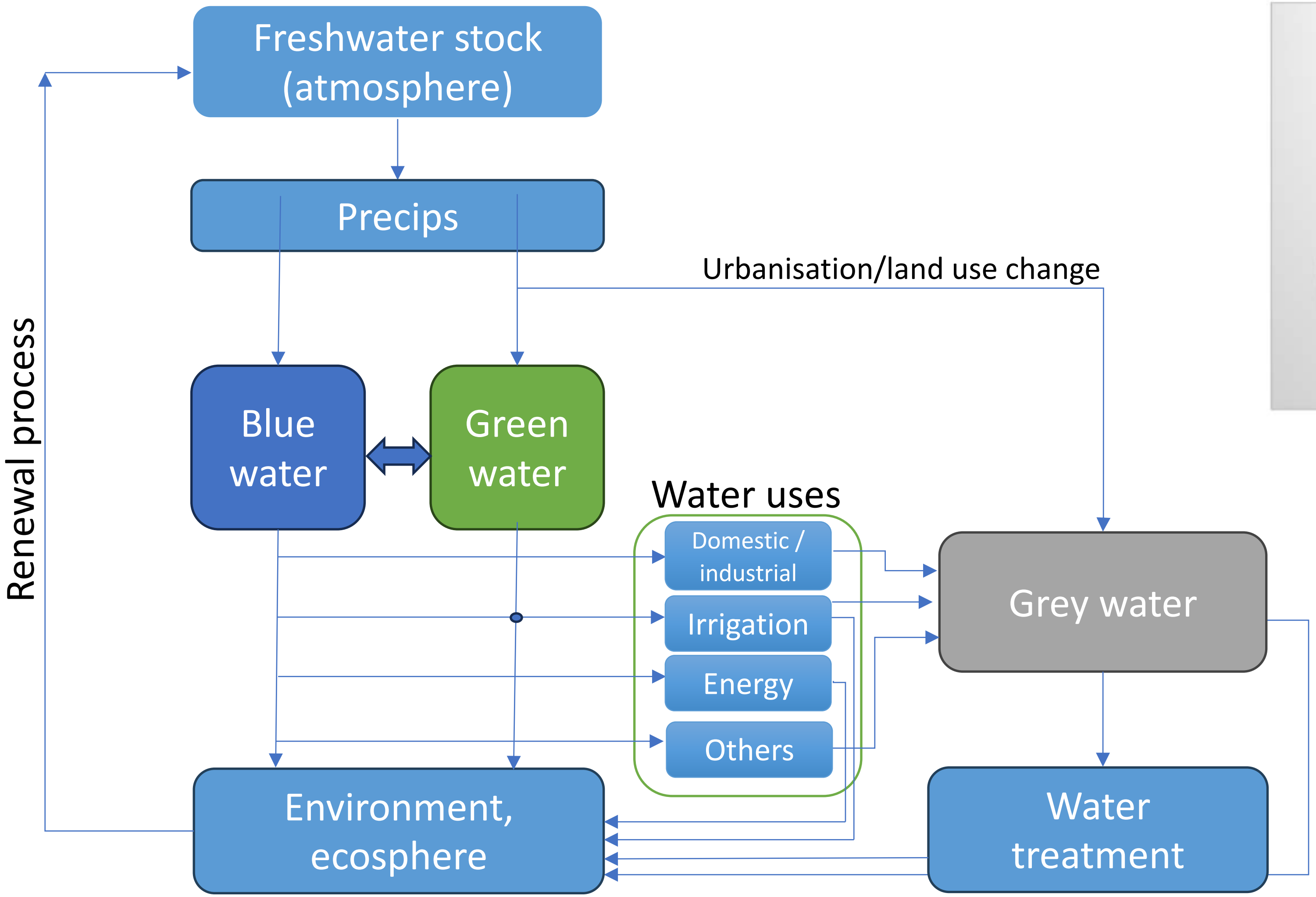
Renewal process

Permeable surfaces retain water (still green water if soil is non contaminated)

Sponge city concept

+ permeable area
+ green water
- grey water

# Effects of major water uses



Freshwater stock (atmosphere)

Precips

Urbanisation/land use change

Renewal process

Blue water

Green water

Water uses

Domestic / industrial

Irrigation

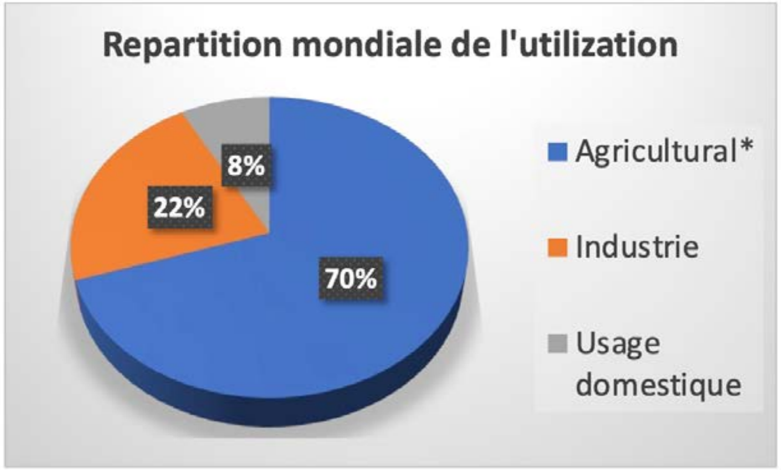
Energy

Others

Grey water

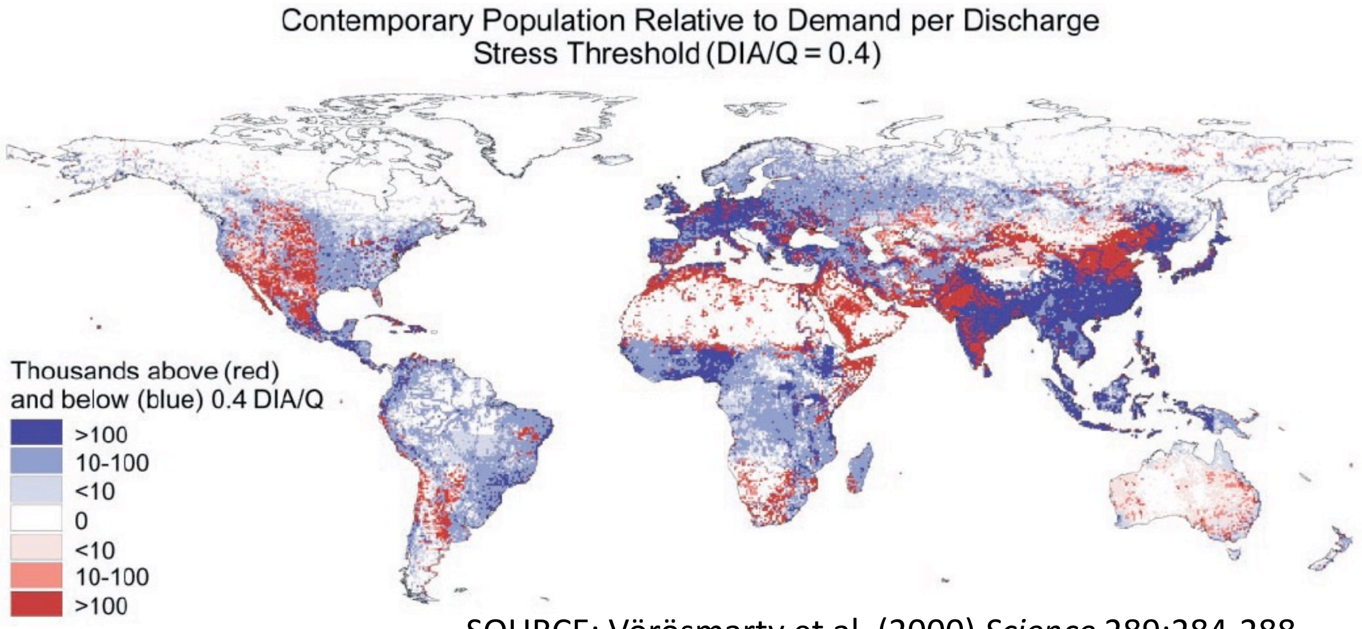
Environment, ecosphere

Water treatment



Repartition mondiale de l'utilization

# Demand vs availability: water stress distribution worldwide



Contemporary Population Relative to Demand per Discharge
Stress Threshold (DIA/Q = 0.4)

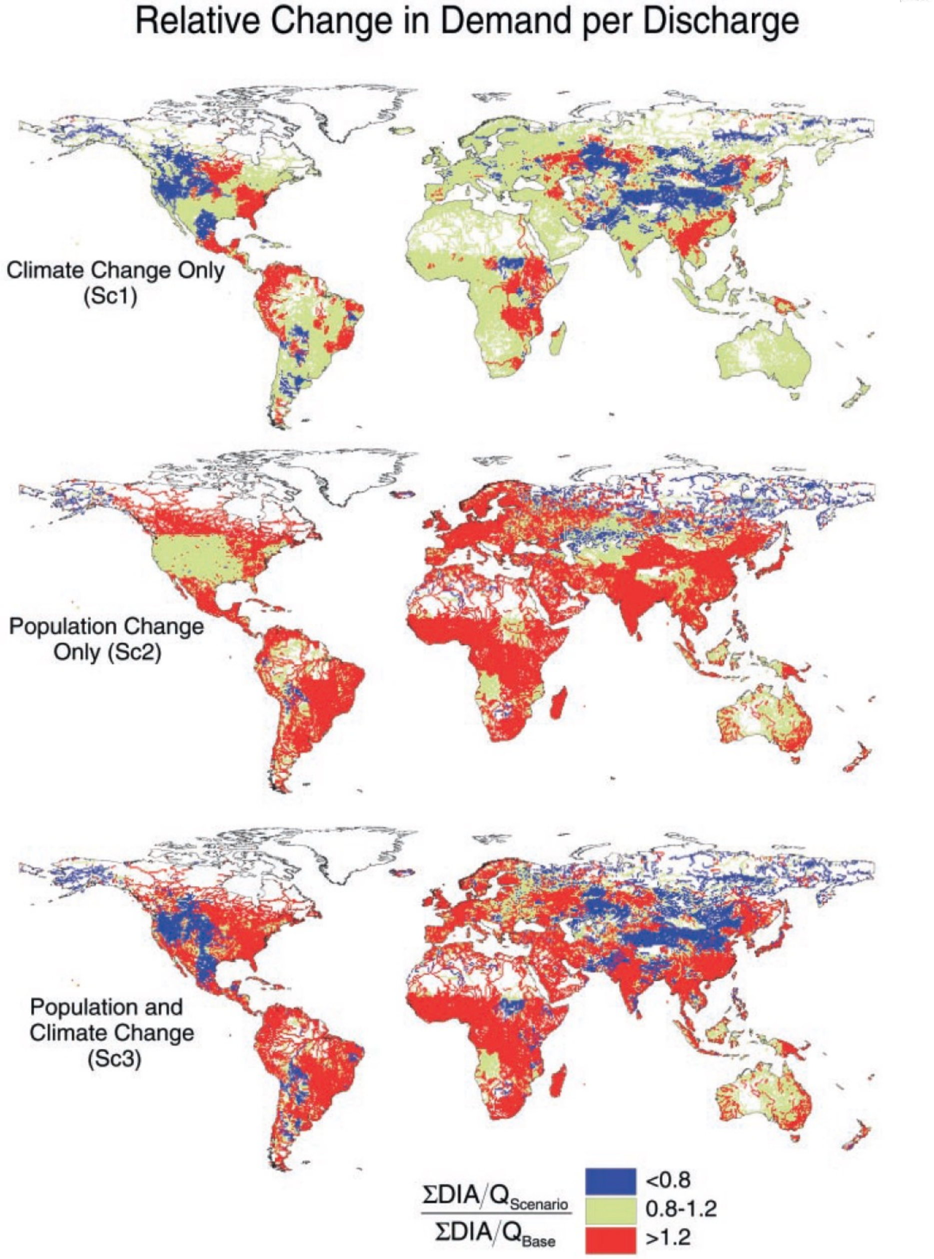
SOURCE: Vörösmarty et al. (2000) *Science* 289:284-288

DIA=Domestic + Industrial + Agricultural uses

Q = River discharge for a given basin

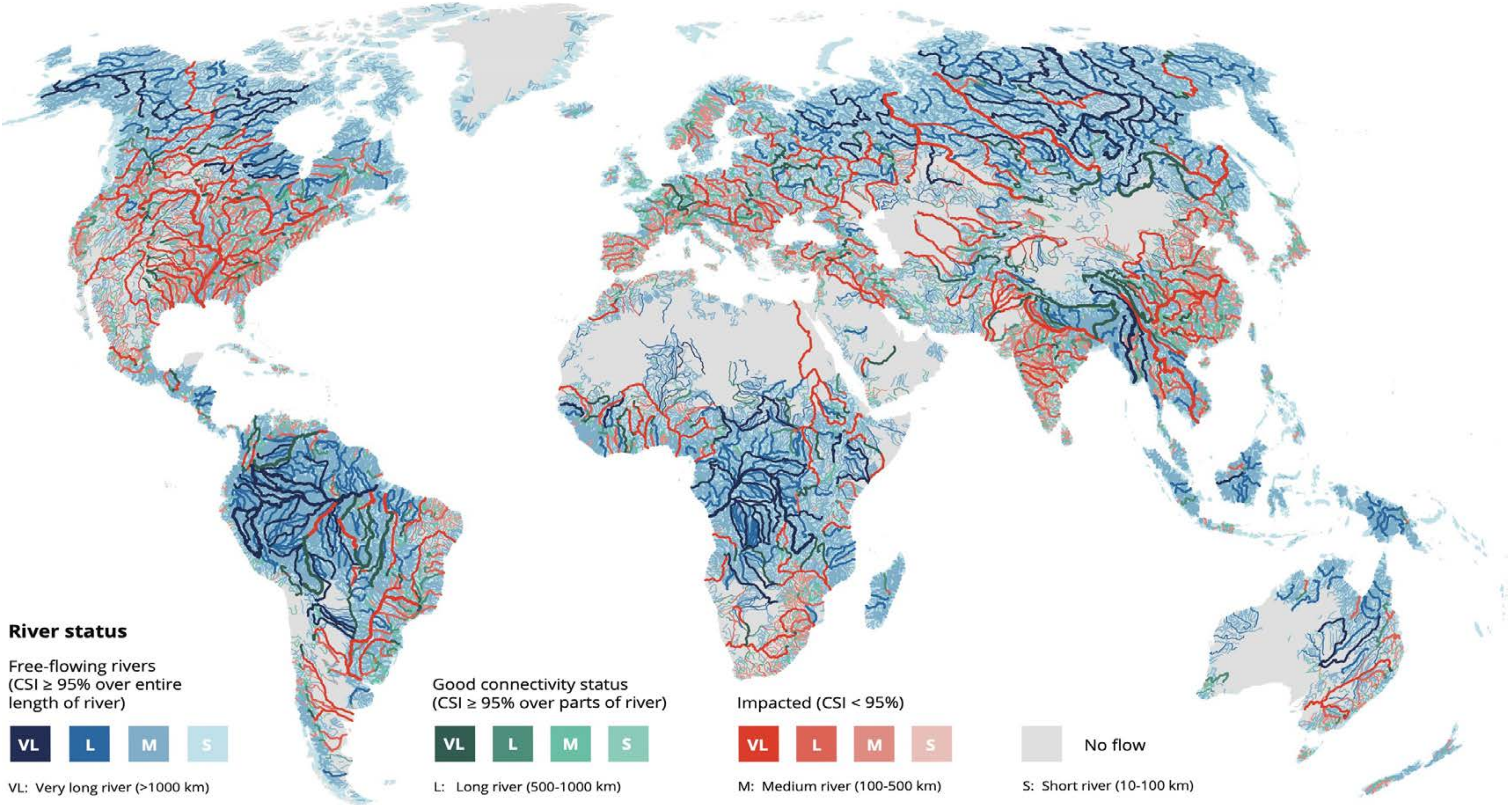
A ratio DIA/Q=0.4 is considered as a threshold for water stress (use of 40% of directly available water)

The estimate done in the year 2000 for 25 years ahead (today) suggested that population increase would impact water stress more than climatic changes. Unfortunately both are worst than predicted



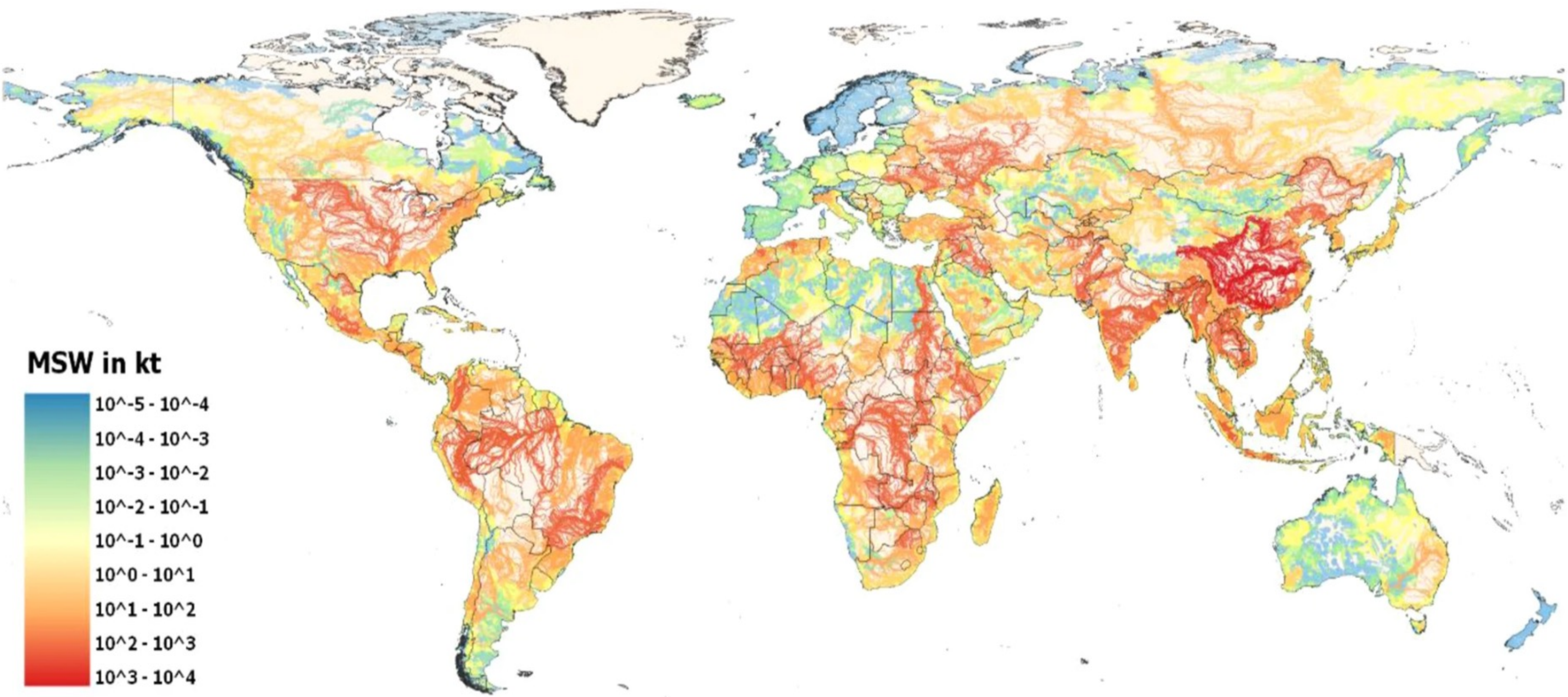
Relative Change in Demand per Discharge

# Status of free-flowing rivers in the world (water quantity impact)



Source:Grill, G., Lehner, B., Thieme, M. *et al.* Mapping the world's free-flowing rivers. *Nature* **569**, 215–221 (2019).©

# Leakage of solide municipal wastes (water quality impact)



*Gómez-Sanabria, A., Lindl, F. The crucial role of circular waste management systems in cutting waste leakage into aquatic environments. Nat Commun 15, 5443 (2024), CC-BY 4.0.*

**Carte des fuites potentielles de déchets municipaux solides (Municipal Solid Waste MSW) dans les rivières en 2020**

# Sustainable Water Resources Management

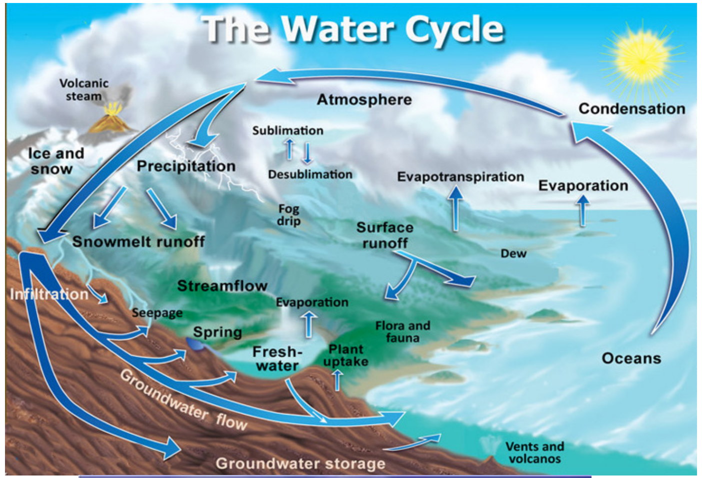
Today WRM‘ policies imply dealing with complex problems

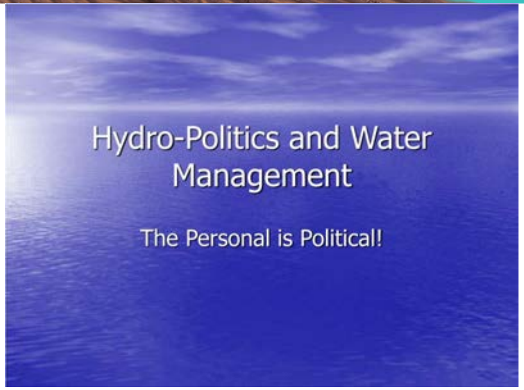
This may imply dealing with deep conflicts

WR manager requires skills well beyond technical training (e.g., pure engineering, science, management, or law)

WR manager must be able to communicate, cooperate in teams, speak other languages, work with other cultures, understand environmental problems and resolve conflicts via cooperation

The goal is to reduce compromising the available water for future generations (sustainability)




Hydro-Politics and Water Management

The Personal is Political!

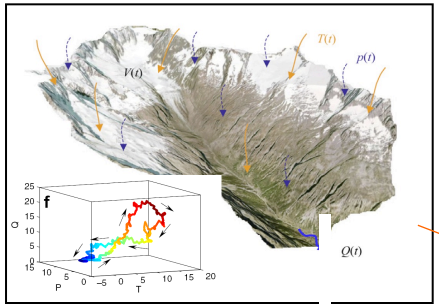

# Exemplary research activites at the PL-LCH

# River catchment scale

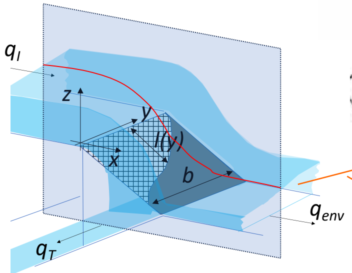
PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

**GOAL**: Pursuing a sustainable use of the freshwater resource to reconcliate anthropic and environmental uses

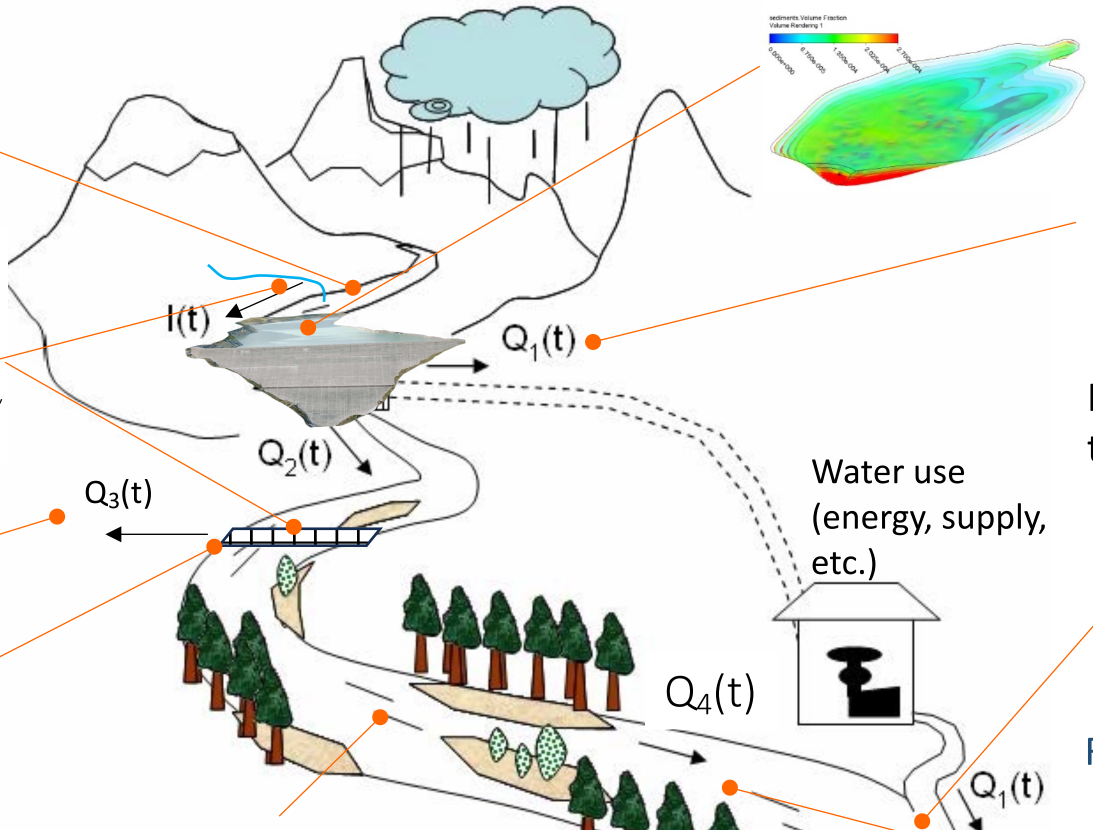
Water resource availability



Zero-energy hydrodynamic based solutions

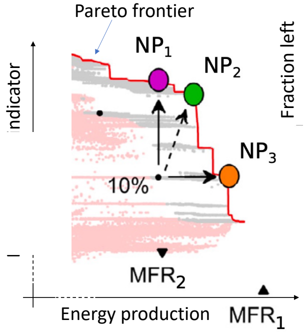


Lake sedimentation and management



Water use (energy, supply, etc.)

Sustainable blue water allocation



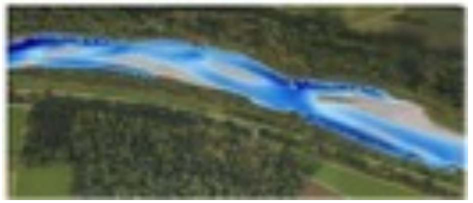
Hydropeaking vs thermopeaking

Sustainable green water use

Fish mobility

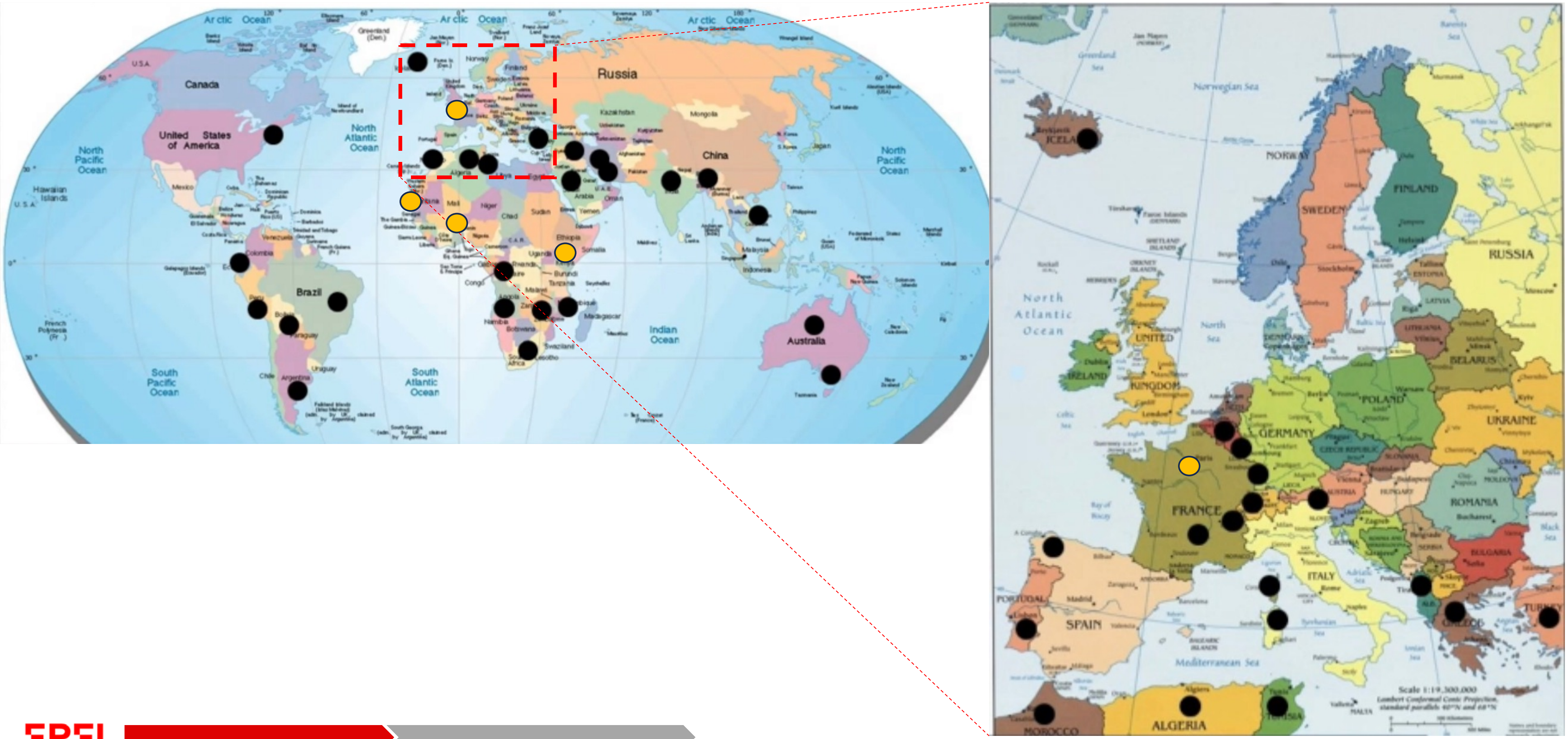
Sediment budget and connectivity

River habitats modelling/restoration



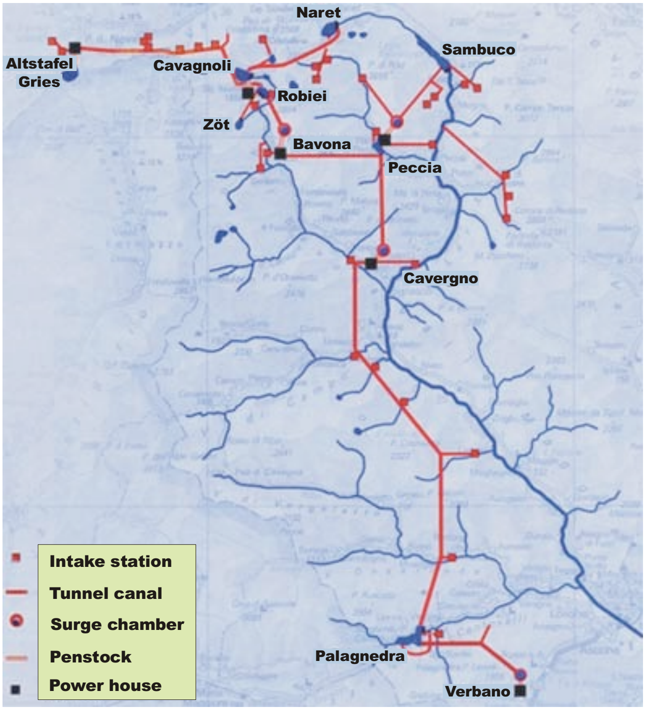
EPFL

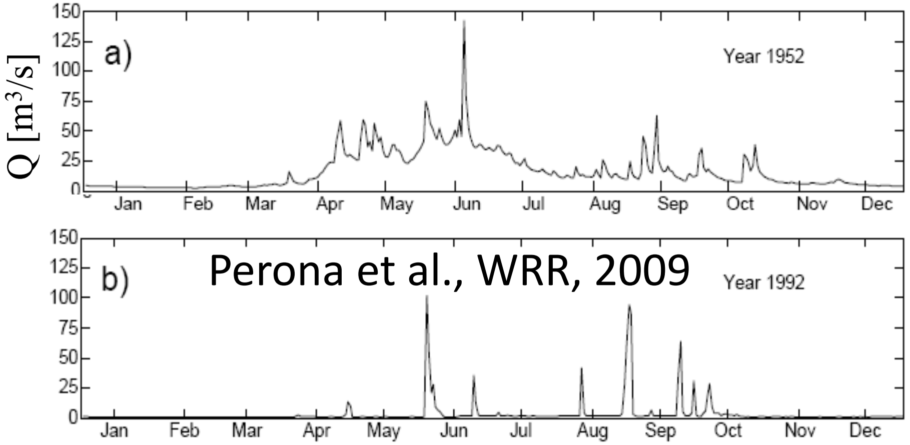
# PL-LCH projects on water resources eng. and hydraulics



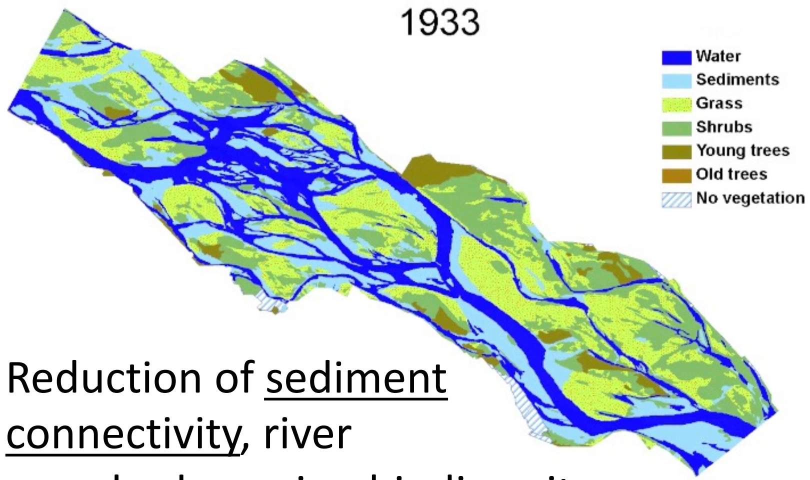
# Example 1: Impact of river impoundment and regulation

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

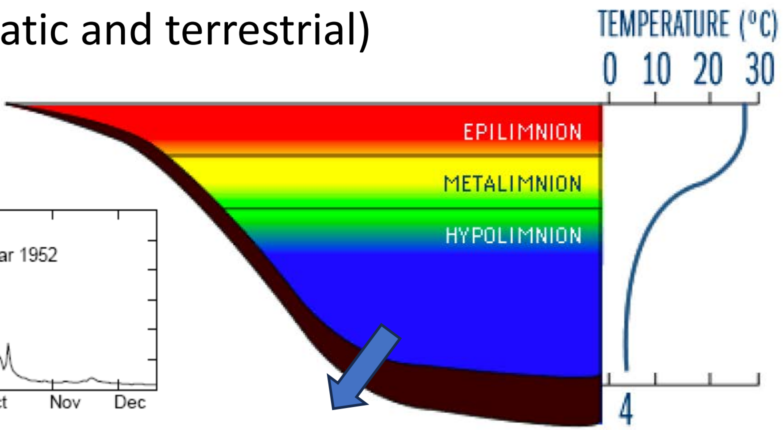




Perona et al., WRR, 2009



Reduction of <u>sediment connectivity</u>, river <u>morphodynamics</u>, <u>biodiversity</u> (aquatic and terrestrial)

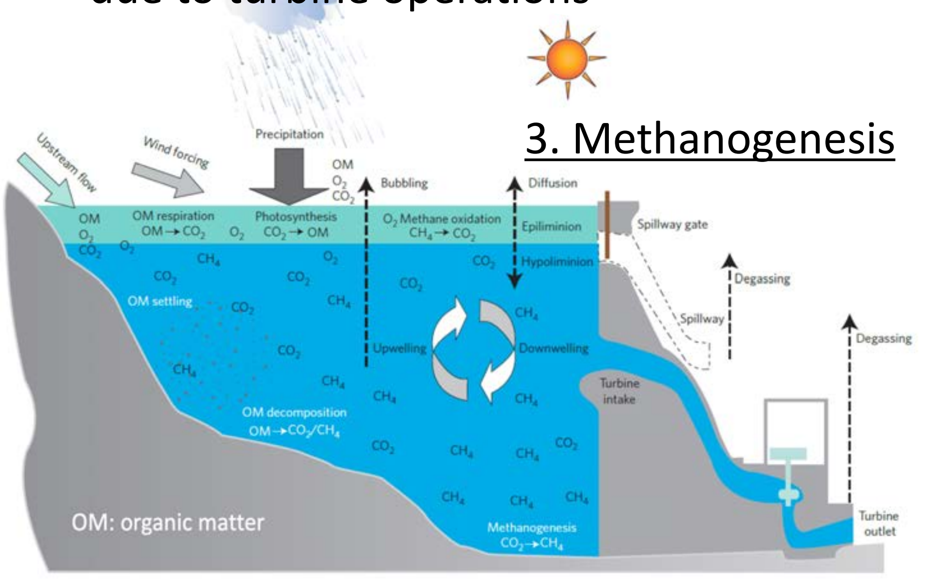


<u>1. Thermregulation</u>, loss of seasonal variability due to thermal stratification

<u>Other impacts</u>

<u>2. Hydropeaking</u> and thermopeaking due to turbine operations

<u>3. Methanogenesis</u>

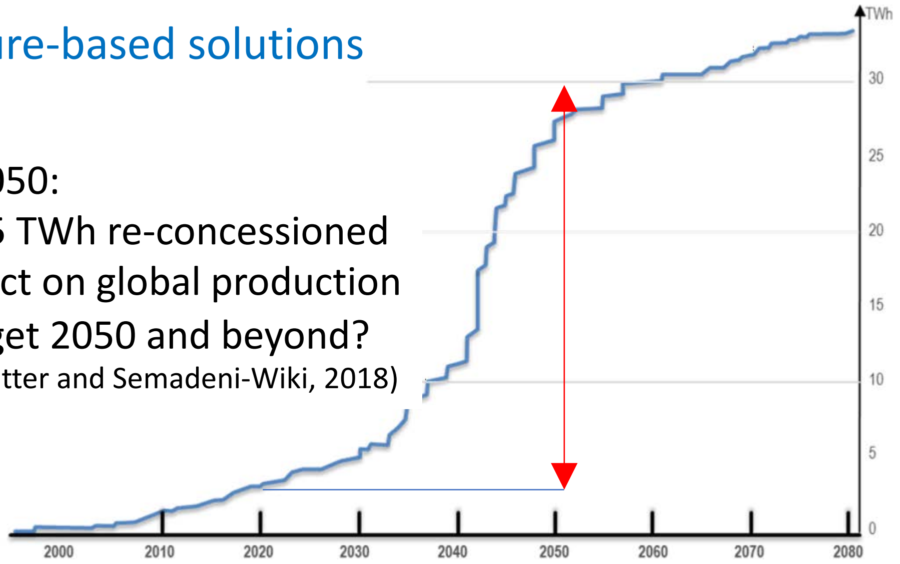


# Example 2: Sustainable hydropower

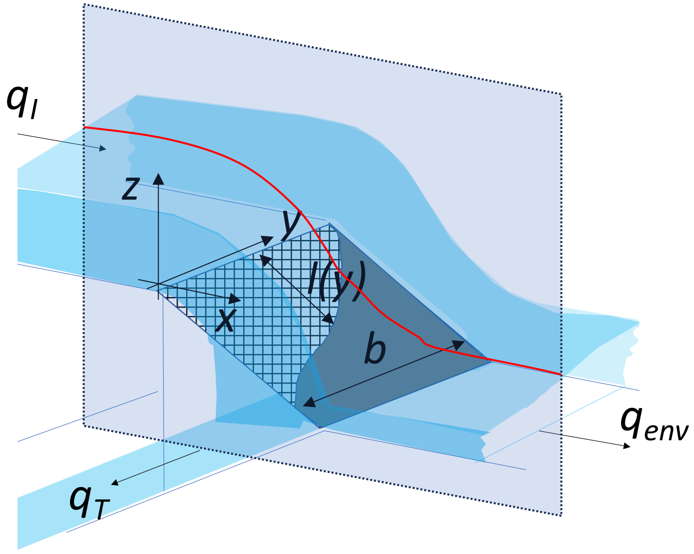
## Nature-based solutions

By 2050:
- ~25 TWh re-concessioned
- effect on global production
- Target 2050 and beyond?

(Pfamatter and Semadeni-Wiki, 2018)



Note: Taken from Barry et al. (2015) and based on ASAE (2012), SWV (2012b); modified graph.

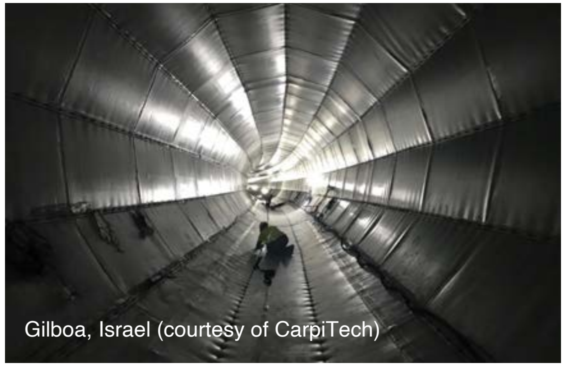


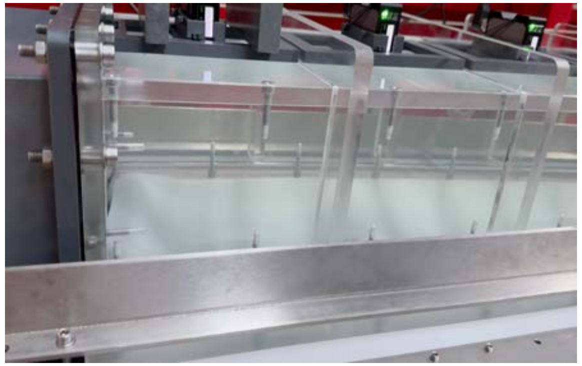
Static env. Flows are responsible for river biodiversity reduction

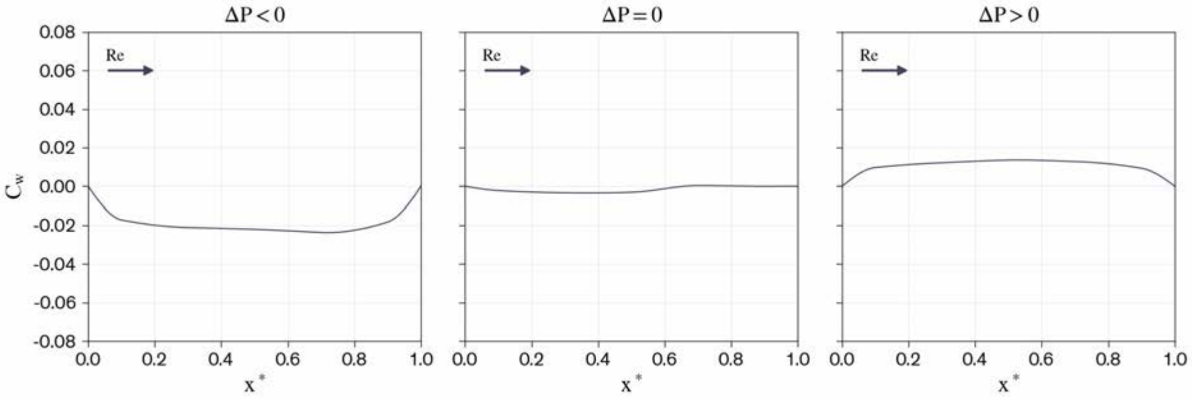
Dynamic Environmental Flows

Martel et al., 2023

## Use of membranes in pressure tunnes to increase hydropower efficiency (reduction of leakage, friction losses), see Vorlet, EPFL PhD thesis 2025


Gilboa, Israel (courtesy of CarpiTech)



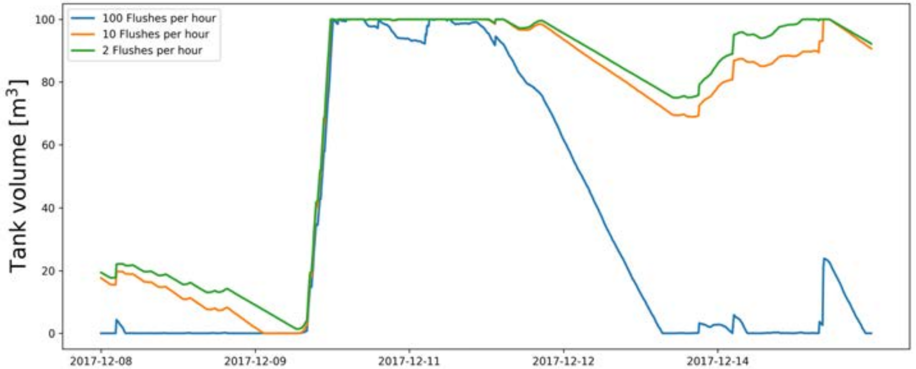


Membranes deforms under the action of the flow and may break (cyclical mechanical fatigue), detach, and be transported to the turbines. Catastrophic damage!

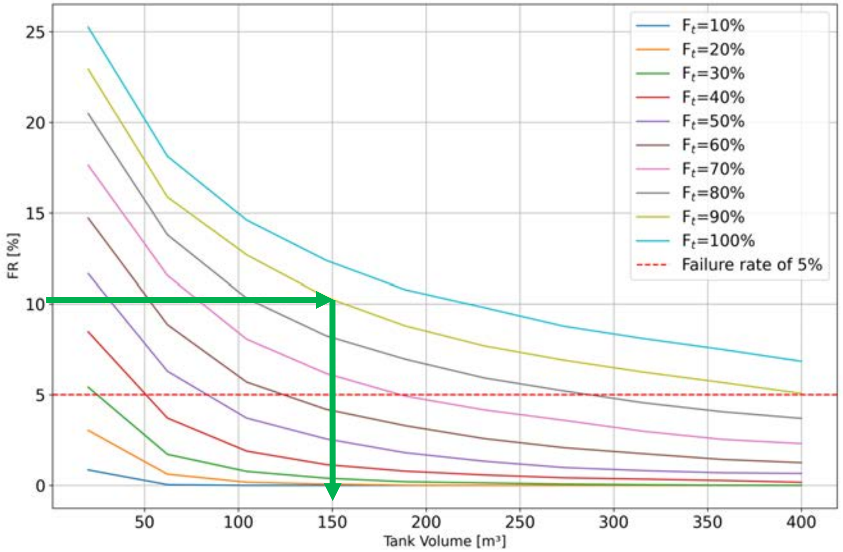
# Example 3: Urbanisation and land use/change (sponge city concept)

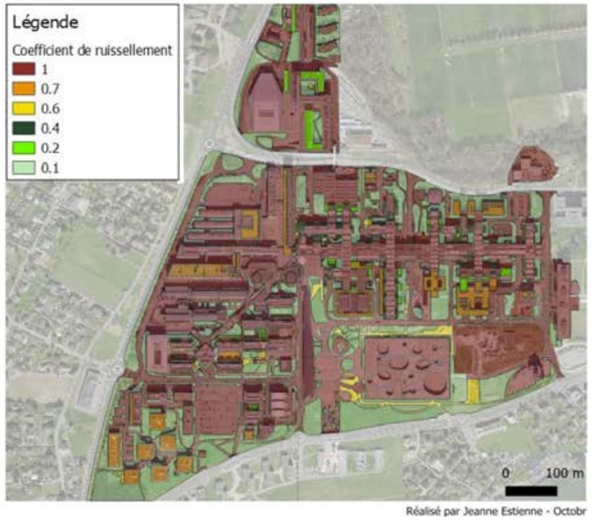
[https://water-portal.epfl.ch](https://water-portal.epfl.ch)

Which reservoir size, which water policy use? Which runoff coefficient?



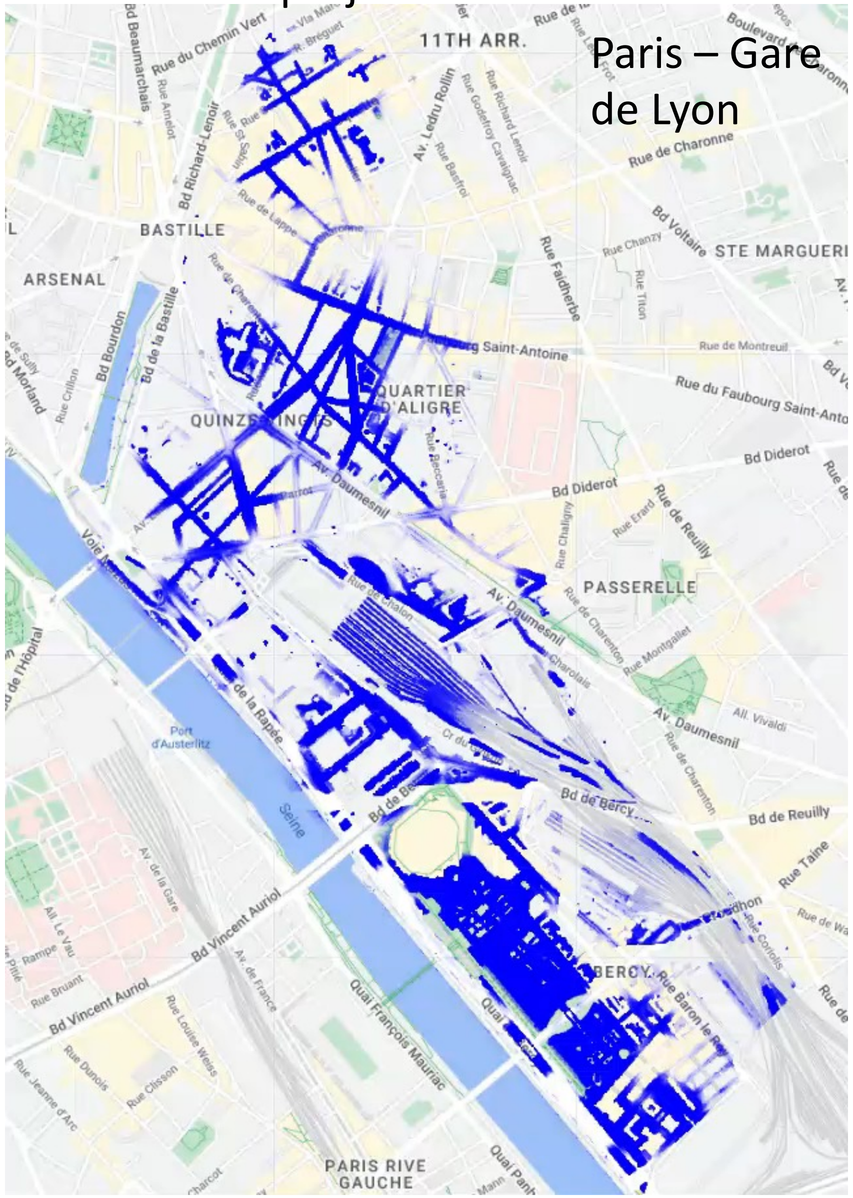
Failure rate FR is a function of Tank volume for different roof interception fraction (water to the tank) $F_t$





Andersson et al., in prepar.

Atlas de Paris project

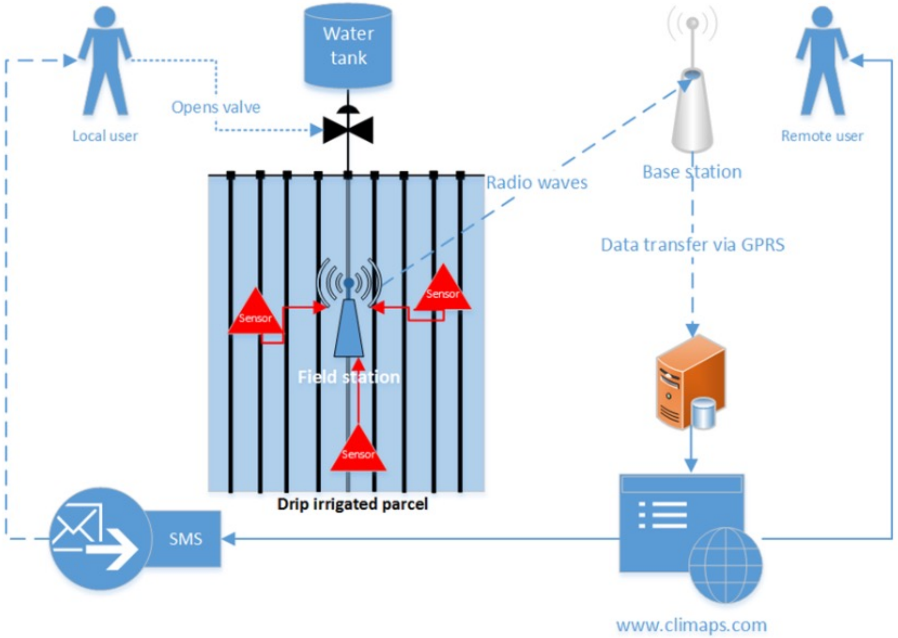


# Example 4: sustainable irrigation in Burkina Faso

Irrigation global efficiency is the ratio between net plant water need, $B_n$ and the effectively provided one, B (i.e., including loss compensations

$$E = {}^{B_n}/_{B}$$

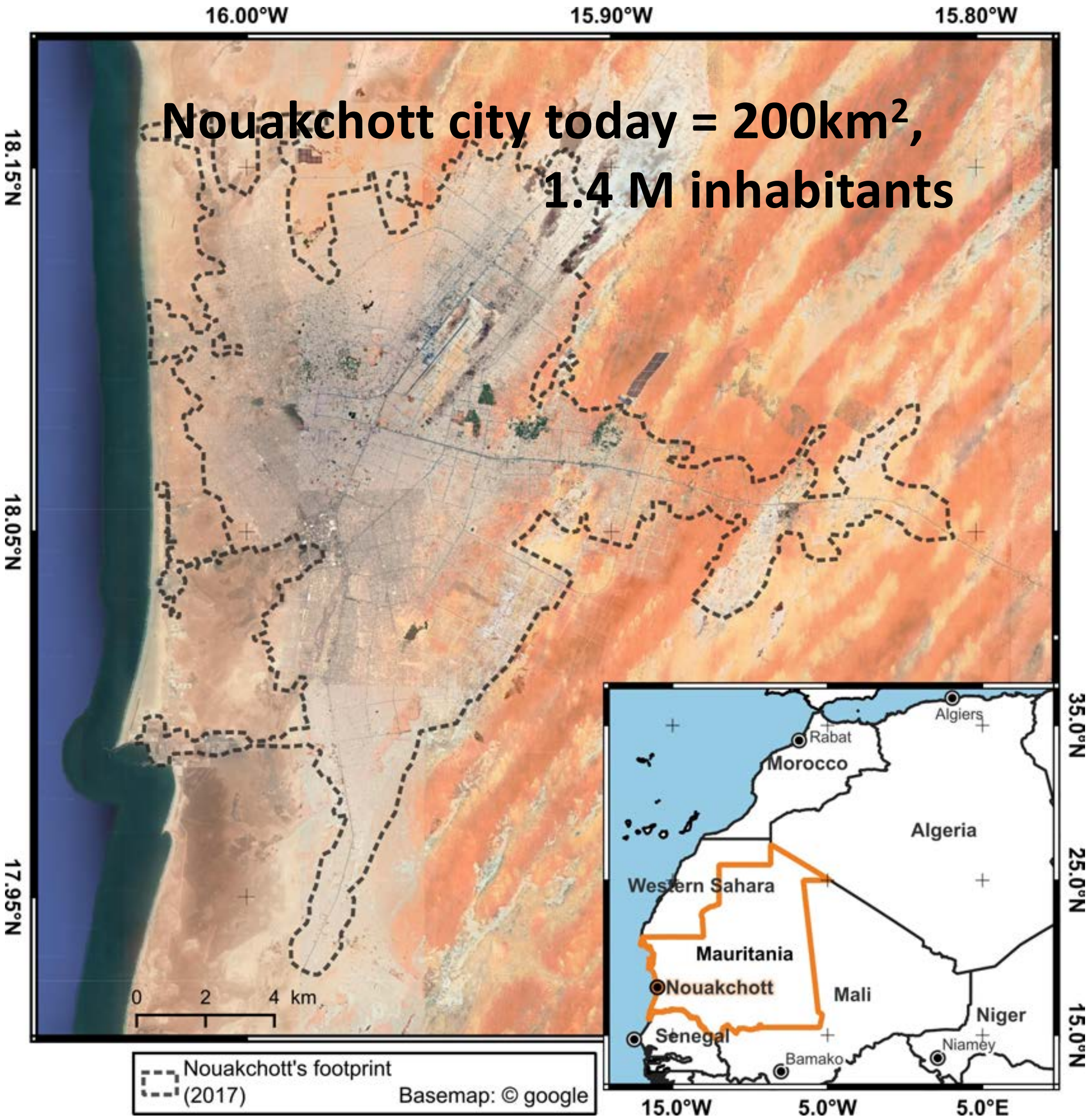
Example: wireless sensor network system

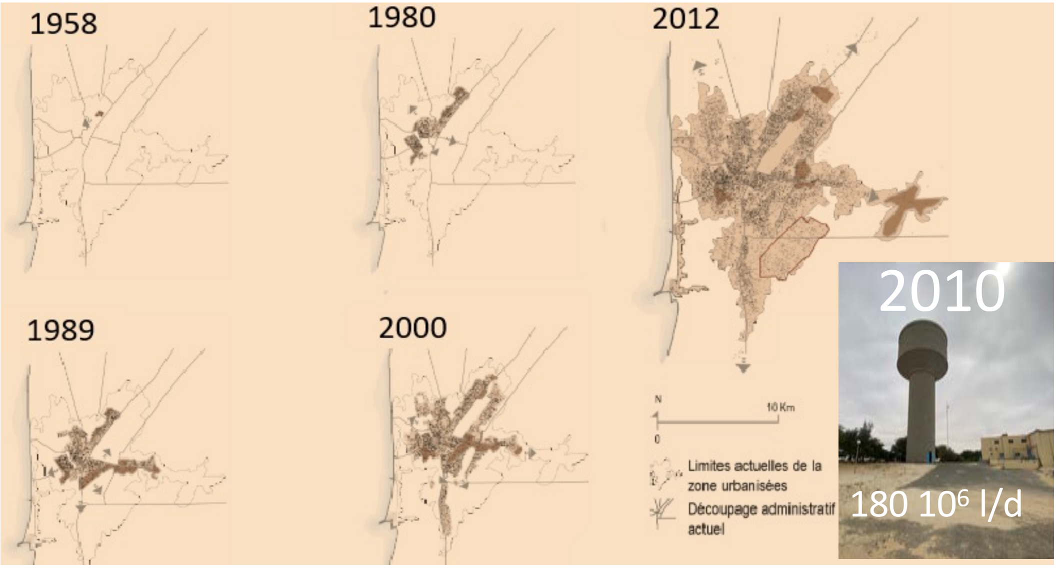


The experiments revealed cultural problems in accepting the scientific method: tanks were operated when receiving the opening signal, but not closed anymore for the fear of providing too less water

In locations where it worked an effective higher efficiency was measured, particularly if provided considering evolving thresholds (see Müller et al., Agric. Wat. Manag, 2016)

# Example 5: flooding due to saturation excess in Mauritania

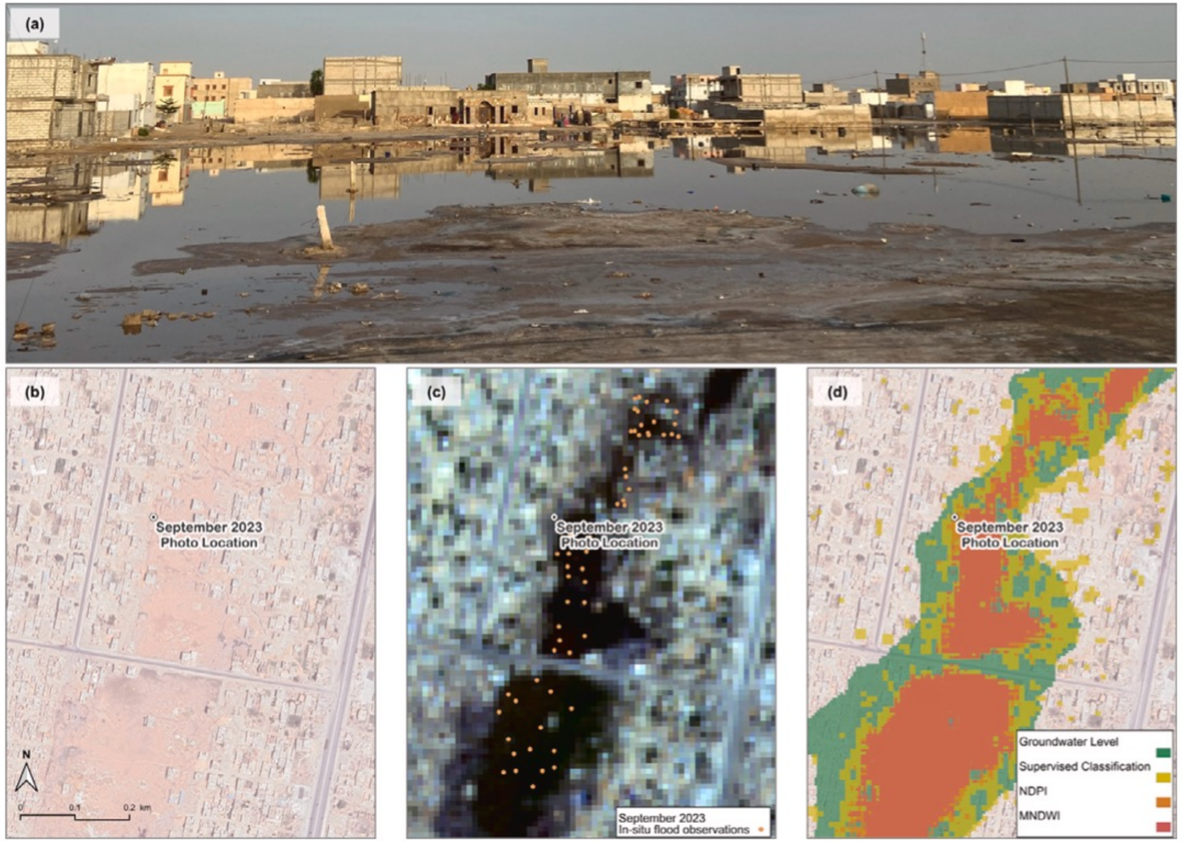

Nouakchott city today = 200km$^2$, 1.4 M inhabitants



No sewers → more infiltration → GW rise

Rainfall→ saturation-excess flooding

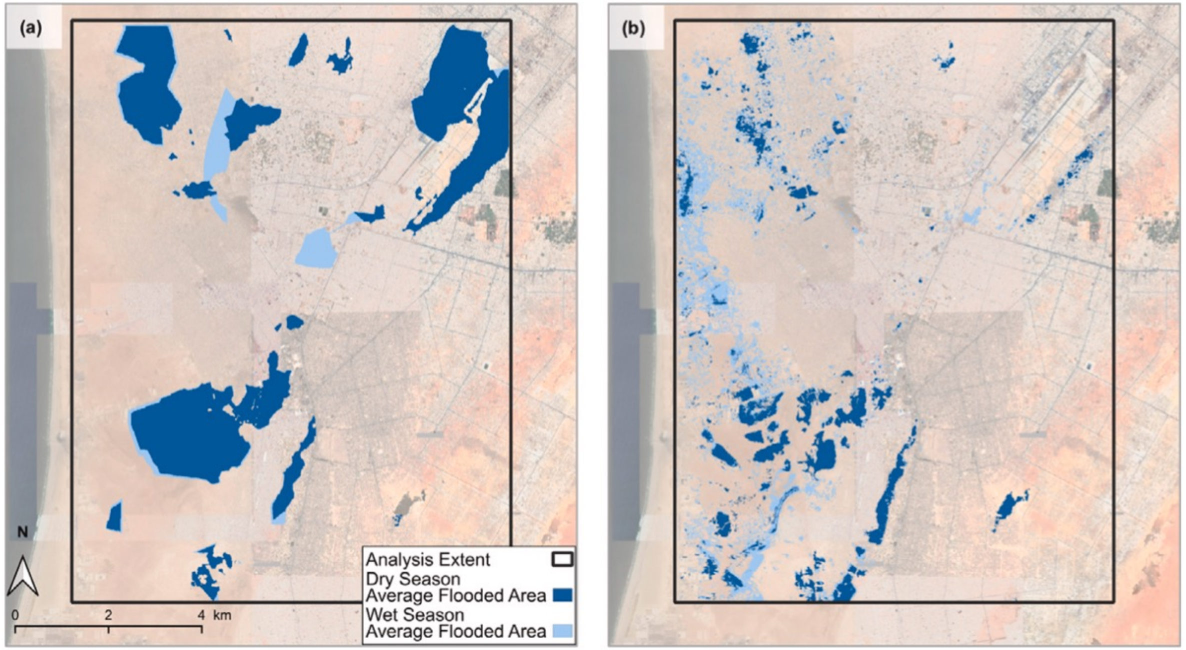
# Detection of water ponding

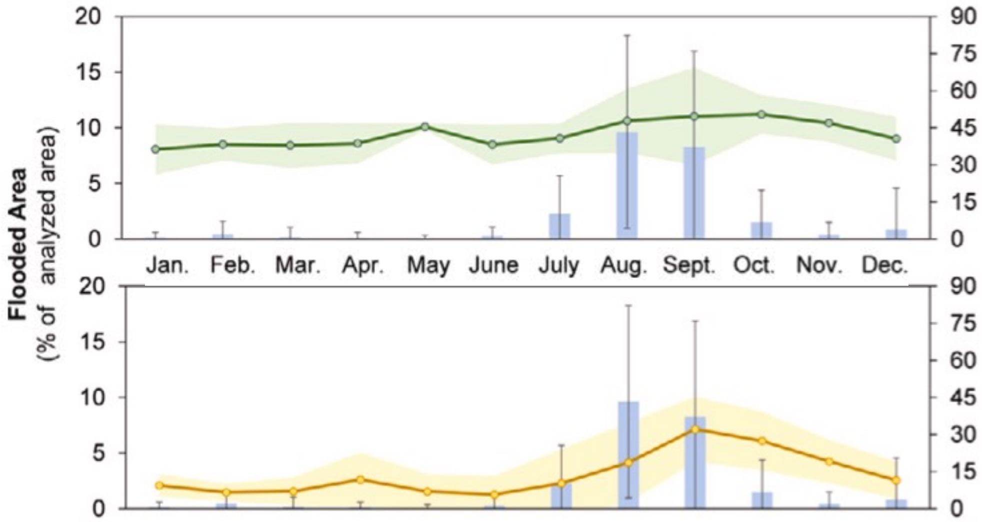


Increase in groundwater levels in Nouakchott between 0.04 m and 0.44 m during the wet seasons produce 10% sparse flooding (i.e. about 20 km$^2$)

GW based

Supervised Classif.



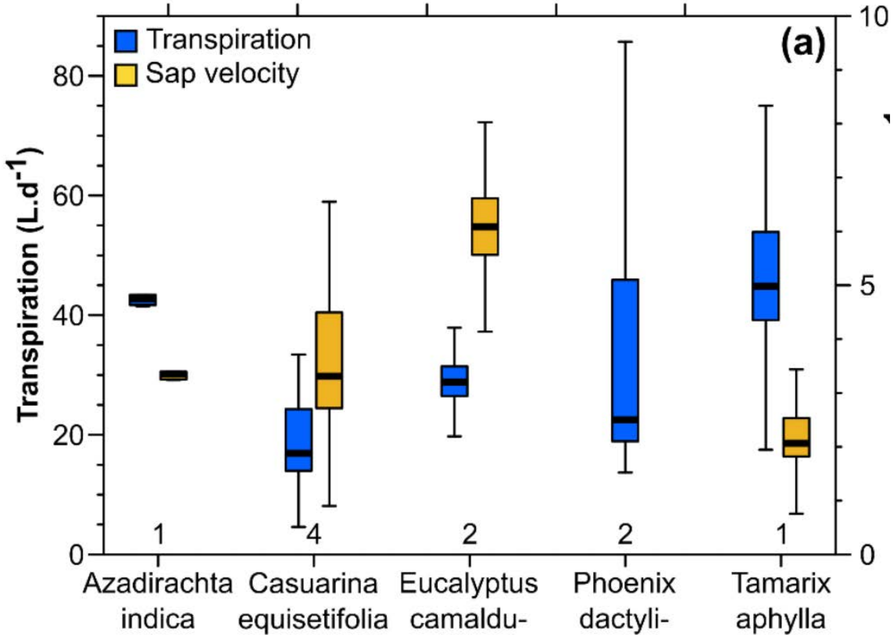


GW

SC

# Afforestation as a sustainable solution

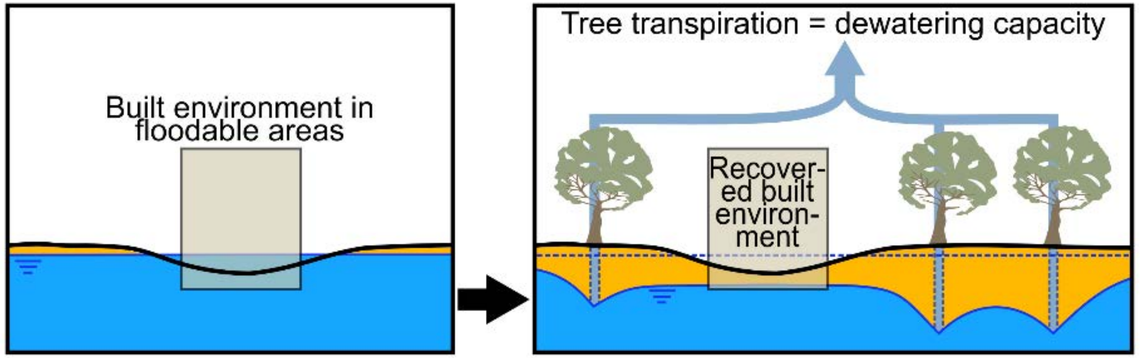
## No topog. gradients → no trad. drainage



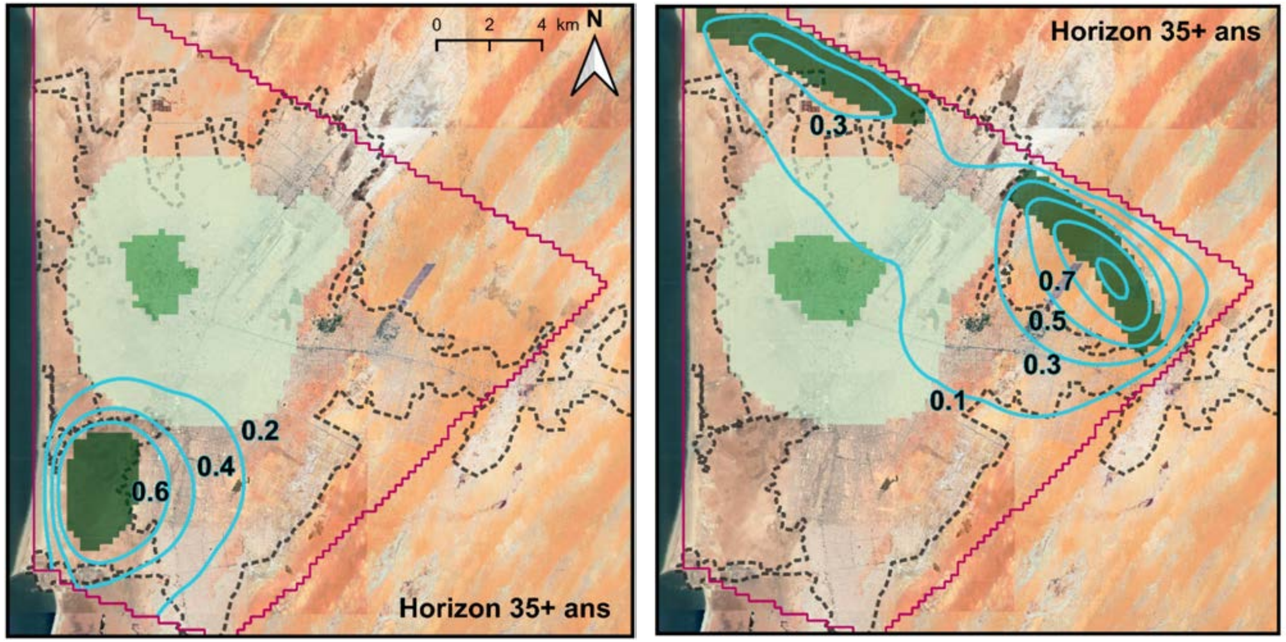
EIRA project

## Afforestation might work !!

Dubois et al., 2024

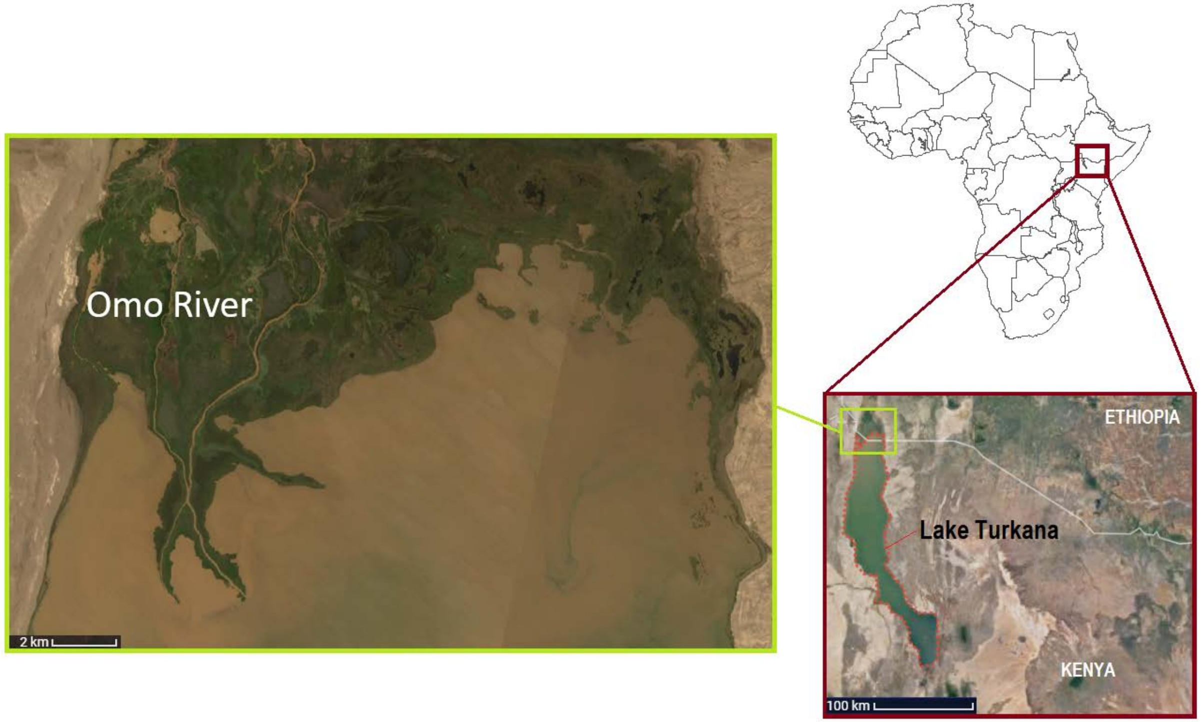


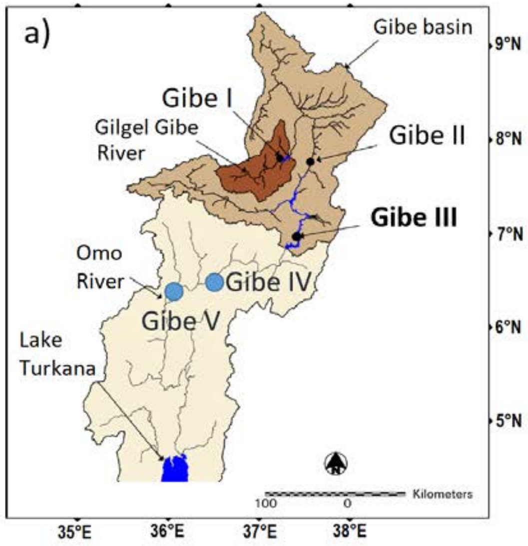
Dubois et al, STOTEN 2024

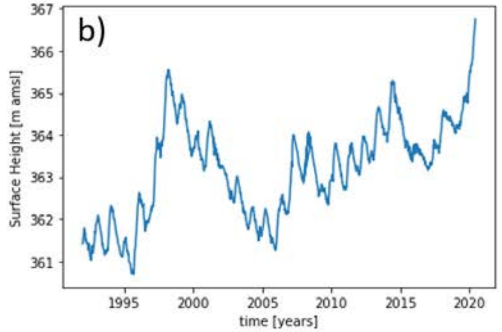


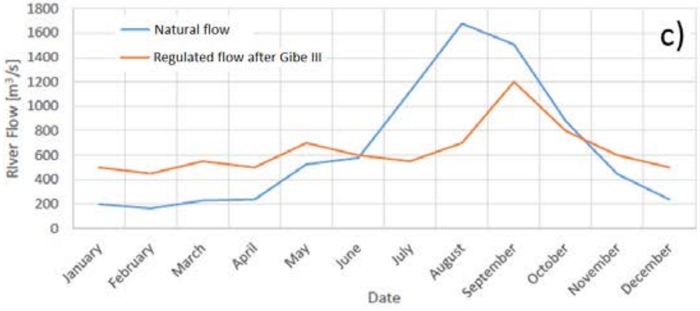
Plant transpiration can induce up to 60-70 cm of GW decrease

# Example 6: Lake Turkana (Kenya) transboundary water conflict

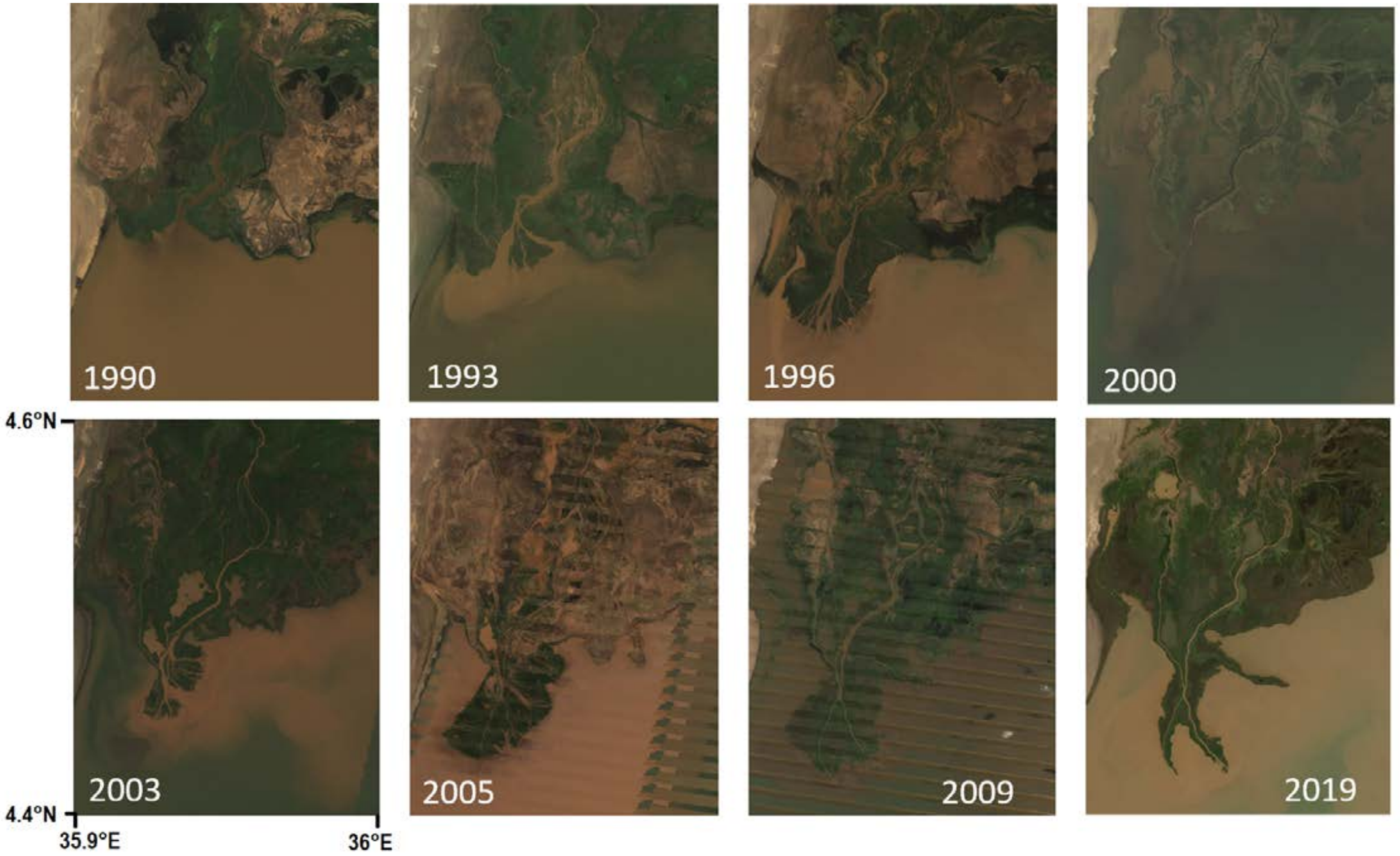


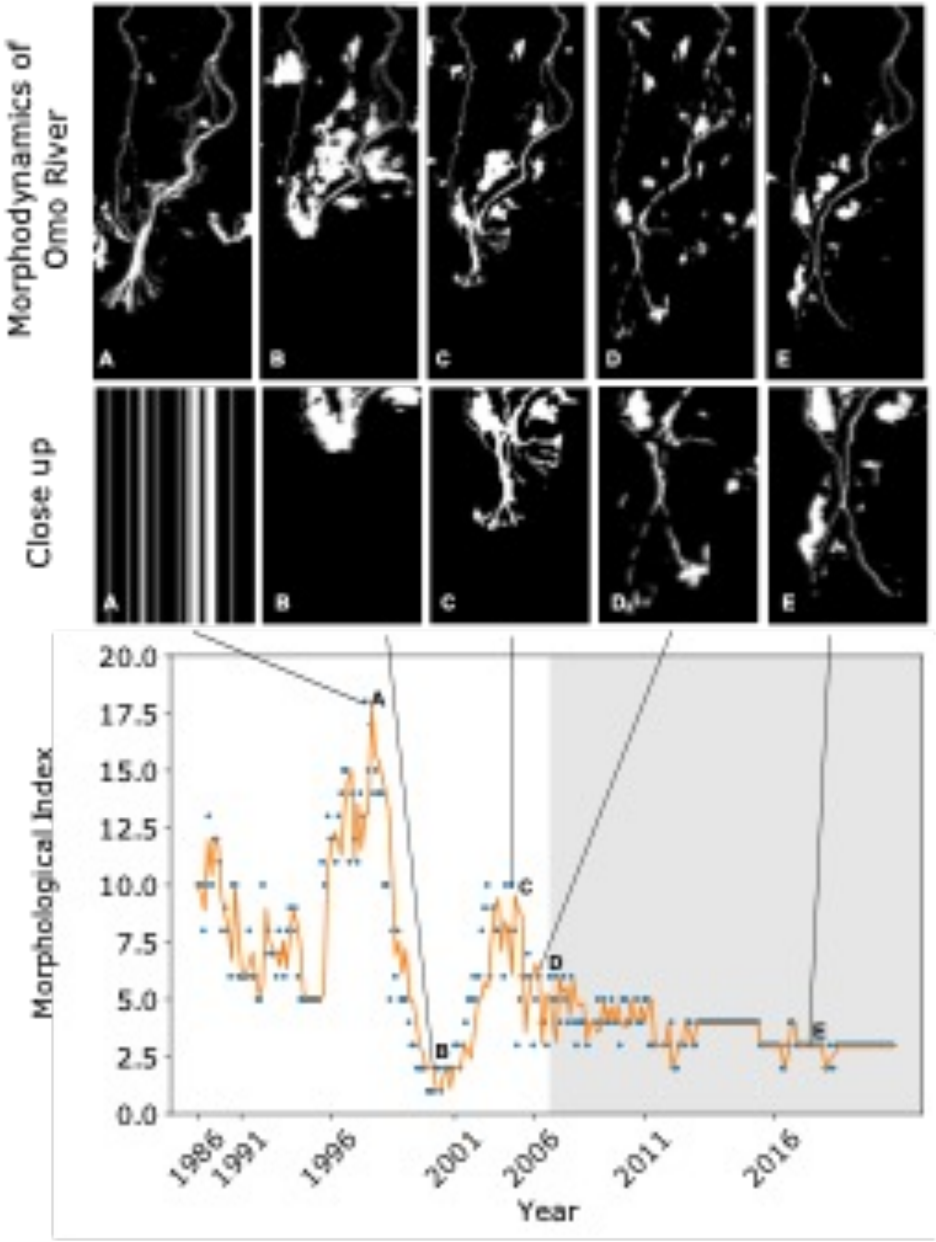






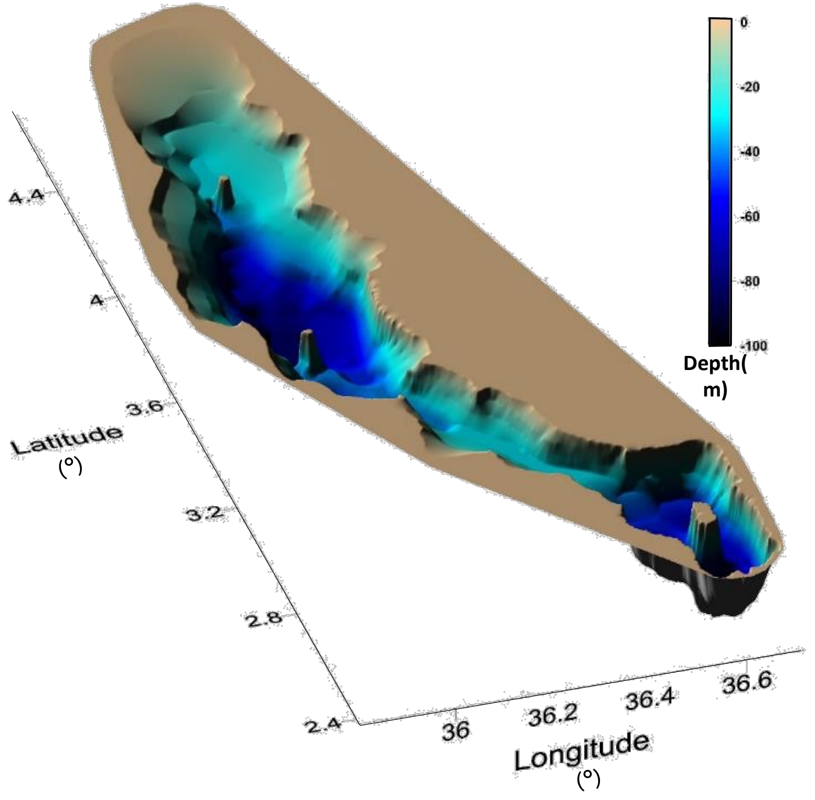
# Sediment impondment causes reduced delta activity



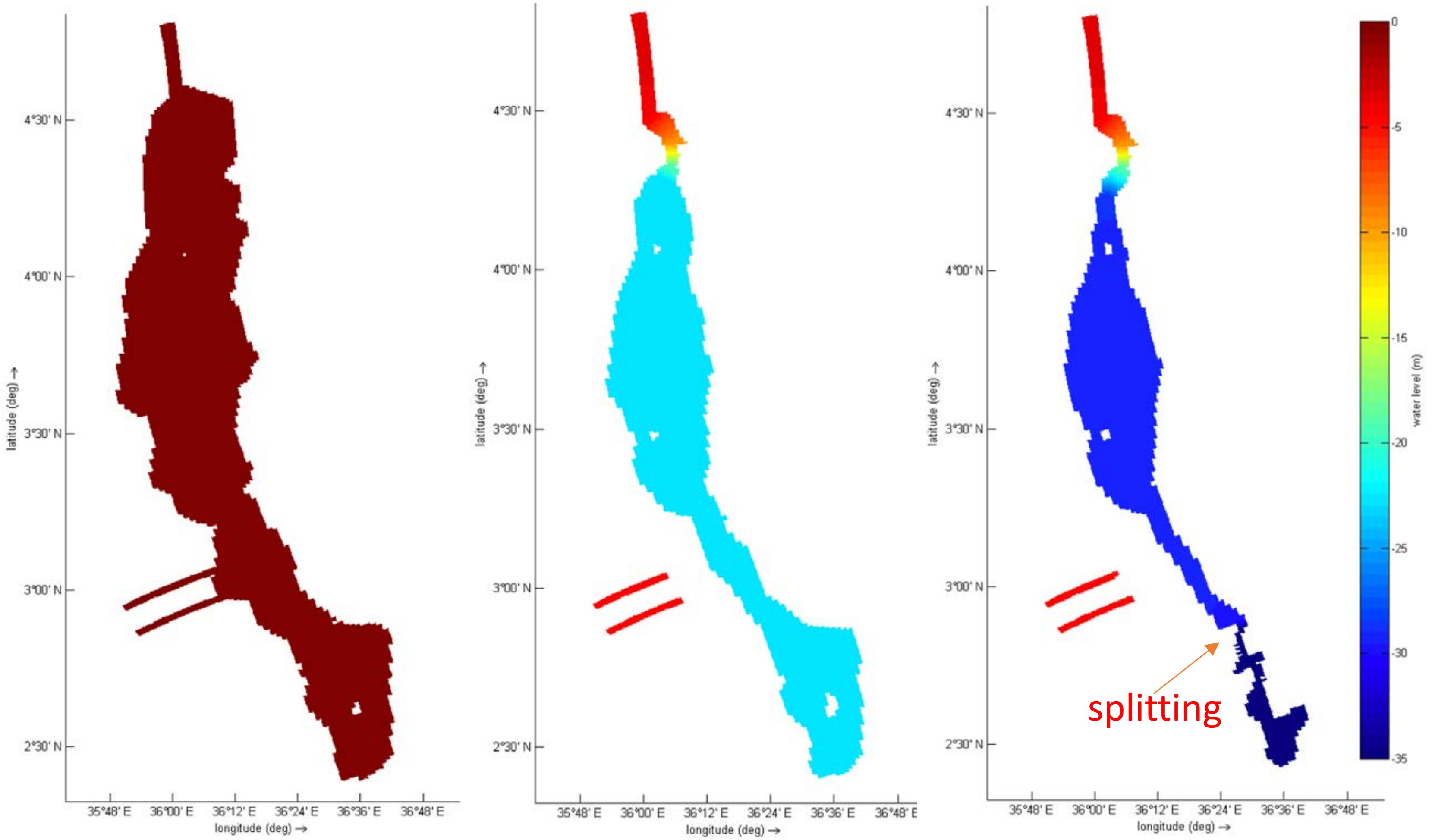


Zen, Perona, Medina-Lopez, Geomorphology, 2023

# Further use for irrigation might threaten lake's existence



Delft 3D numerical model of lake hydrodynamics and water balance



Depending on the level of extraction, a shrink of up to 80 km width might occur over a time horizon of 50 years, with possible lake splitting for extraction levels of 64%

# Example 7. River restoration and vegetation survival

Schirmer et al., HESS, 2014

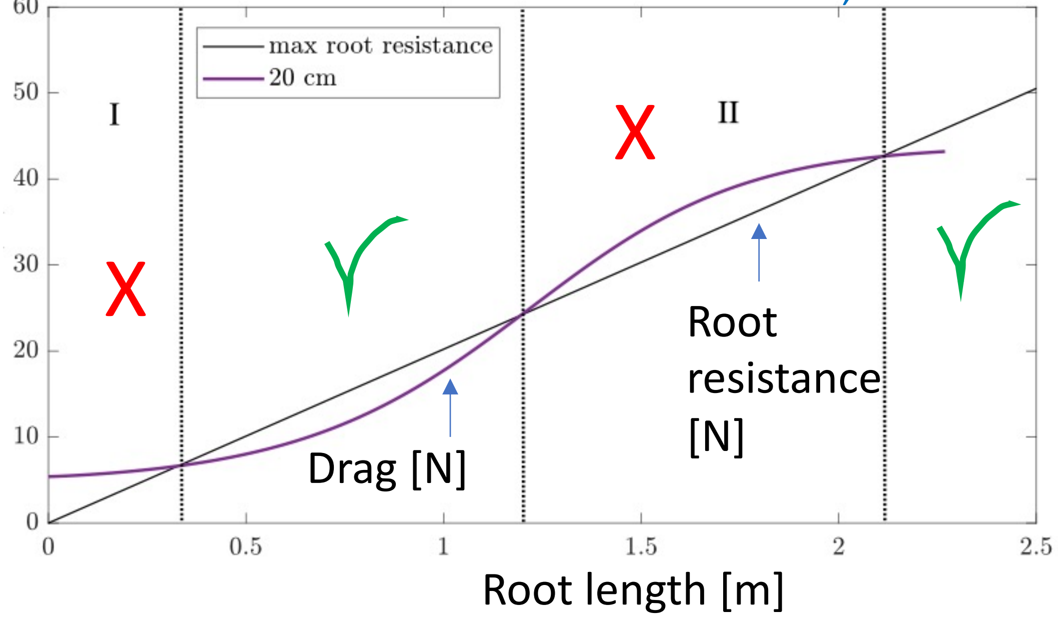
The first instability occurring after restoration is alternate sediment bar formation, which migrate to form point bar and then trig outer bank erosion.

This morphology may reactivate river ecological processes thanks to increasing connectivity.

Careful! River width changes impliy bed slope changes!

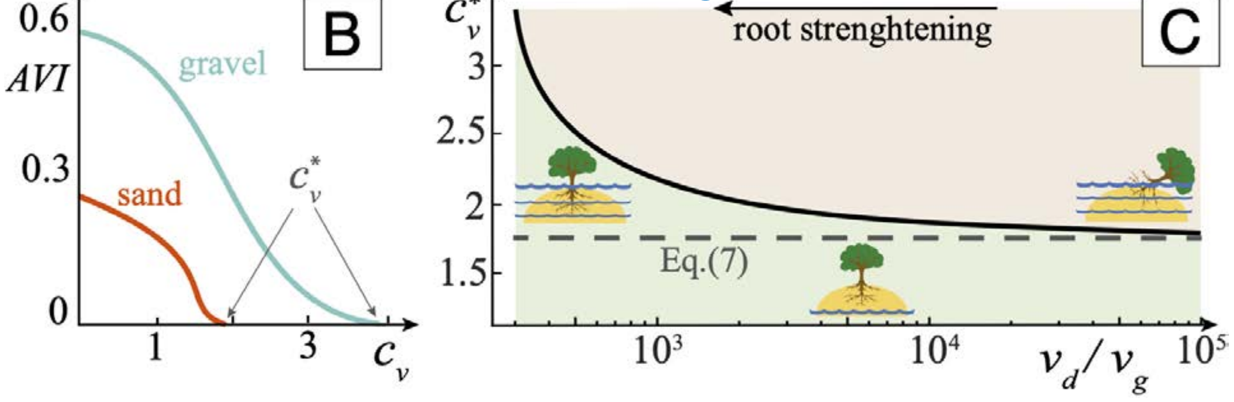
River bars may vegetate according to opportunity windows

Bau et al, JGR 2019

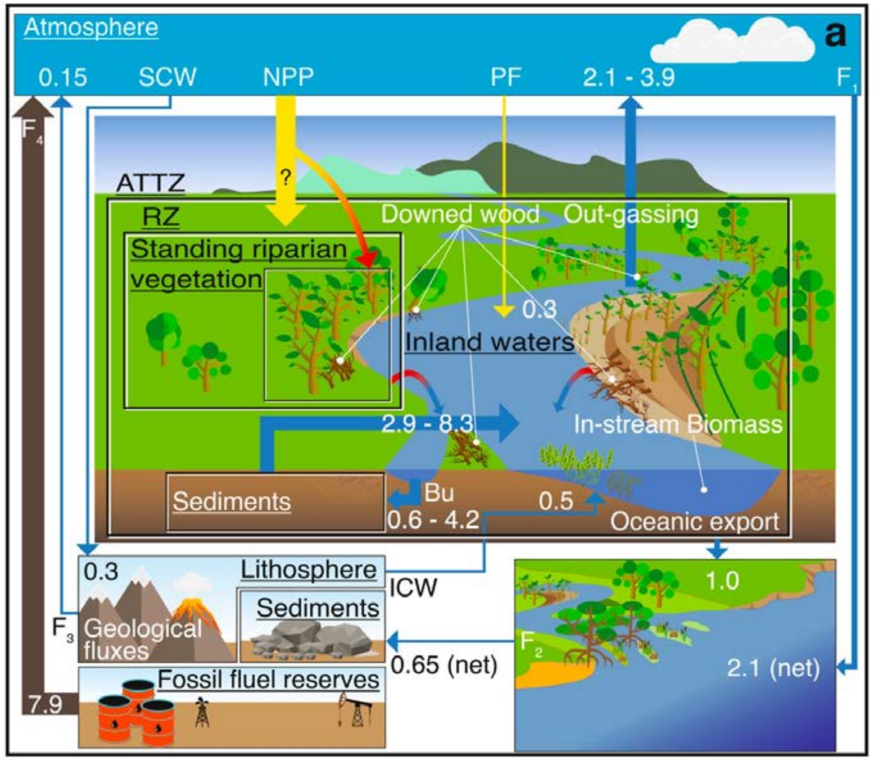


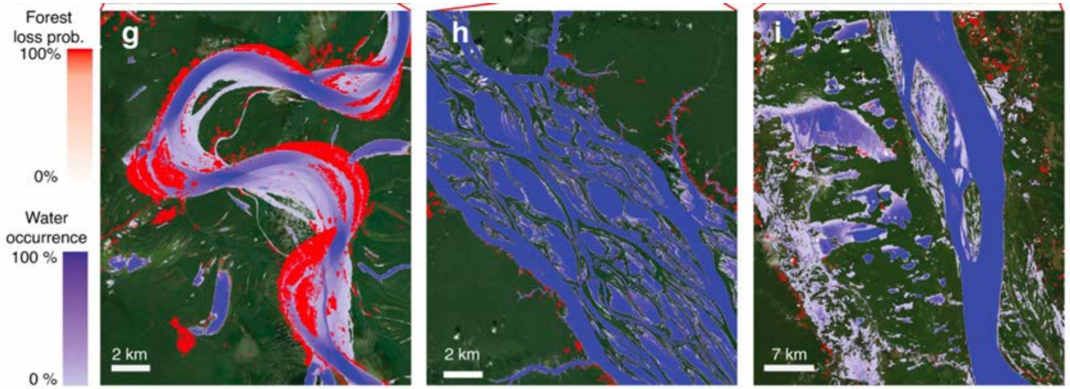
Areal Vegetation Index depends on coeff. of variability of discharges

Bertagni et al., PNAS 2018

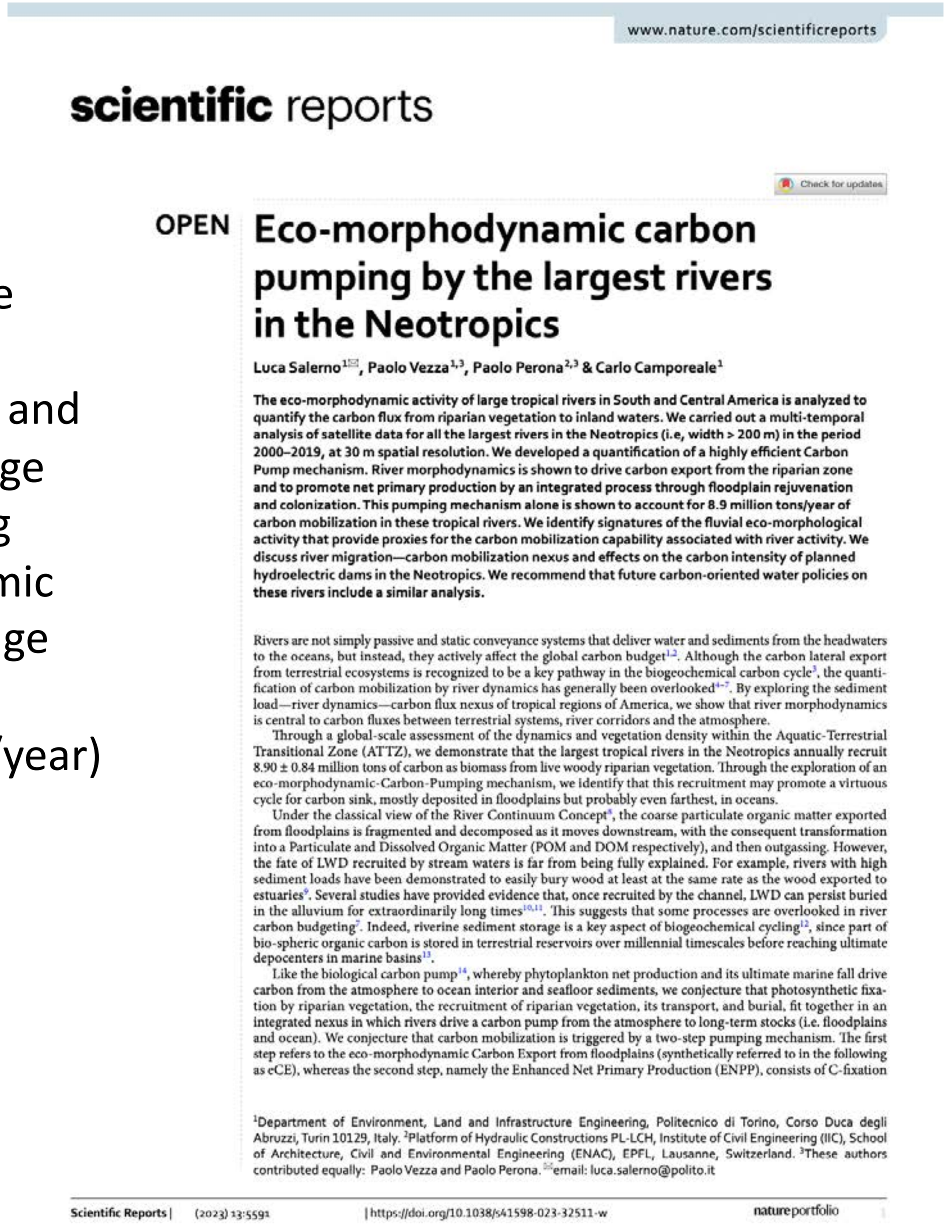


# Example 8: Plant removal by flow erosion helps storing carbon





Dams reduce longitudinal connectivity and river discharge thus freezing morphodyamic carbon storage processes
(up to 9 MT/year)


www.nature.com/scientificreports

**scientific** reports

OPEN

## Eco-morphodynamic carbon pumping by the largest rivers in the Neotropics

Luca Salerno[1]✉, Paolo Vezza[1,3], Paolo Perona[2,3] & Carlo Camporeale[1]

**The eco-morphodynamic activity of large tropical rivers in South and Central America is analyzed to quantify the carbon flux from riparian vegetation to inland waters. We carried out a multi-temporal analysis of satellite data for all the largest rivers in the Neotropics (i.e, width > 200 m) in the period 2000–2019, at 30 m spatial resolution. We developed a quantification of a highly efficient Carbon Pump mechanism. River morphodynamics is shown to drive carbon export from the riparian zone and to promote net primary production by an integrated process through floodplain rejuvenation and colonization. This pumping mechanism alone is shown to account for 8.9 million tons/year of carbon mobilization in these tropical rivers. We identify signatures of the fluvial eco-morphological activity that provide proxies for the carbon mobilization capability associated with river activity. We discuss river migration—carbon mobilization nexus and effects on the carbon intensity of planned hydroelectric dams in the Neotropics. We recommend that future carbon-oriented water policies on these rivers include a similar analysis.**

Rivers are not simply passive and static conveyance systems that deliver water and sediments from the headwaters to the oceans, but instead, they actively affect the global carbon budget[1,2]. Although the carbon lateral export from terrestrial ecosystems is recognized to be a key pathway in the biogeochemical carbon cycle[3], the quantification of carbon mobilization by river dynamics has generally been overlooked[4–7]. By exploring the sediment load—river dynamics—carbon flux nexus of tropical regions of America, we show that river morphodynamics is central to carbon fluxes between terrestrial systems, river corridors and the atmosphere.

Through a global-scale assessment of the dynamics and vegetation density within the Aquatic-Terrestrial Transitional Zone (ATTZ), we demonstrate that the largest tropical rivers in the Neotropics annually recruit 8.90 ± 0.84 million tons of carbon as biomass from live woody riparian vegetation. Through the exploration of an eco-morphodynamic-Carbon-Pumping mechanism, we identify that this recruitment may promote a virtuous cycle for carbon sink, mostly deposited in floodplains but probably even farthest, in oceans.

Under the classical view of the River Continuum Concept[8], the coarse particulate organic matter exported from floodplains is fragmented and decomposed as it moves downstream, with the consequent transformation into a Particulate and Dissolved Organic Matter (POM and DOM respectively), and then outgassing. However, the fate of LWD recruited by stream waters is far from being fully explained. For example, rivers with high sediment loads have been demonstrated to easily bury wood at least at the same rate as the wood exported to estuaries[9]. Several studies have provided evidence that, once recruited by the channel, LWD can persist buried in the alluvium for extraordinarily long times[10,11]. This suggests that some processes are overlooked in river carbon budgeting[7]. Indeed, riverine sediment storage is a key aspect of biogeochemical cycling[12], since part of bio-spheric organic carbon is stored in terrestrial reservoirs over millennial timescales before reaching ultimate depocenters in marine basins[13].

Like the biological carbon pump[14], whereby phytoplankton net production and its ultimate marine fall drive carbon from the atmosphere to ocean interior and seafloor sediments, we conjecture that photosynthetic fixation by riparian vegetation, the recruitment of riparian vegetation, its transport, and burial, fit together in an integrated nexus in which rivers drive a carbon pump from the atmosphere to long-term stocks (i.e. floodplains and ocean). We conjecture that carbon mobilization is triggered by a two-step pumping mechanism. The first step refers to the eco-morphodynamic Carbon Export from floodplains (synthetically referred to in the following as eCE), whereas the second step, namely the Enhanced Net Primary Production (ENPP), consists of C-fixation

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