Session HS8.2.5
EGU 25-7027

Confined aquifers: a need for an adaptation of sustainability concepts

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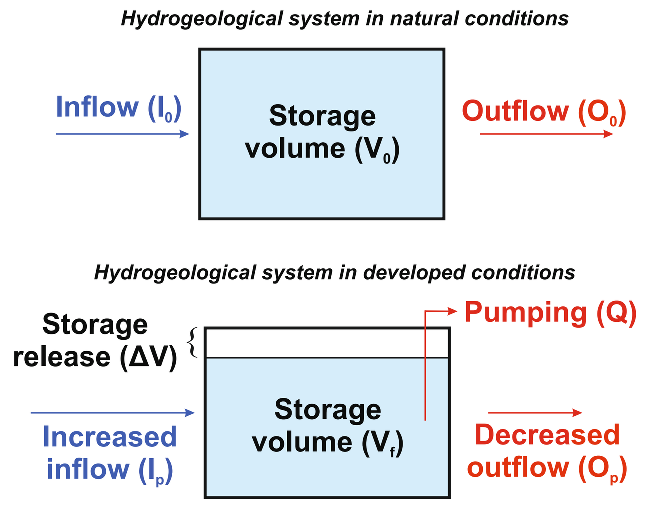
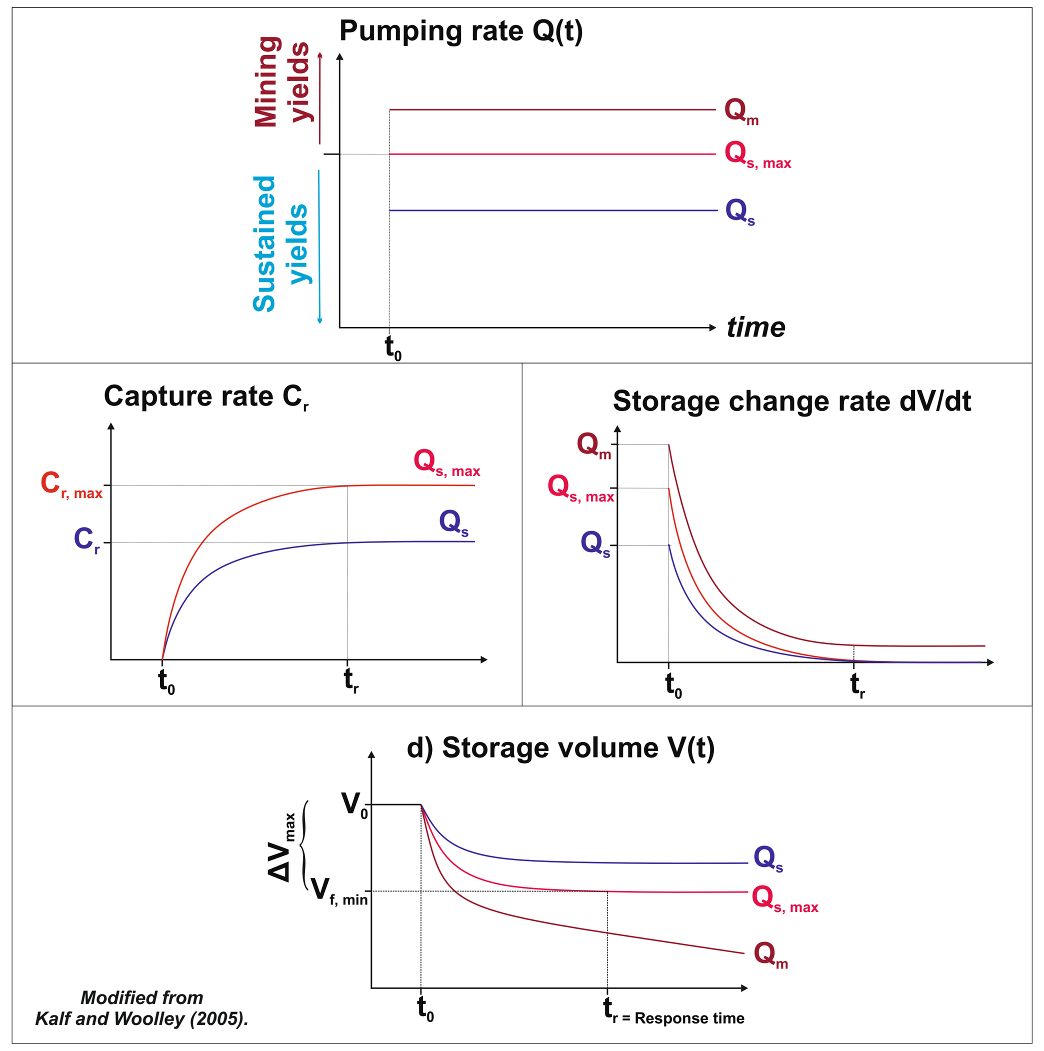
1. How much water can we pump from an aquifer?

What happens when we pump?

Pumping acts as a hydraulic perturbation, triggering a transient response. The **response time (t_r)** describes the duration over which the effects of pumping become negligible, as the system approaches a new dynamic equilibrium.

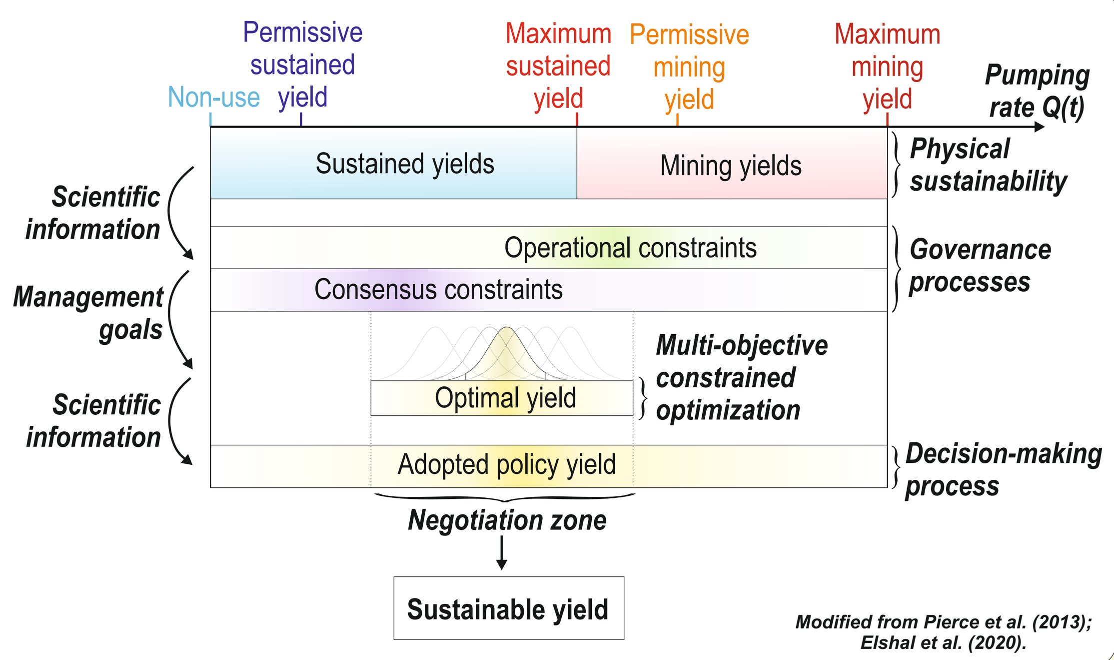




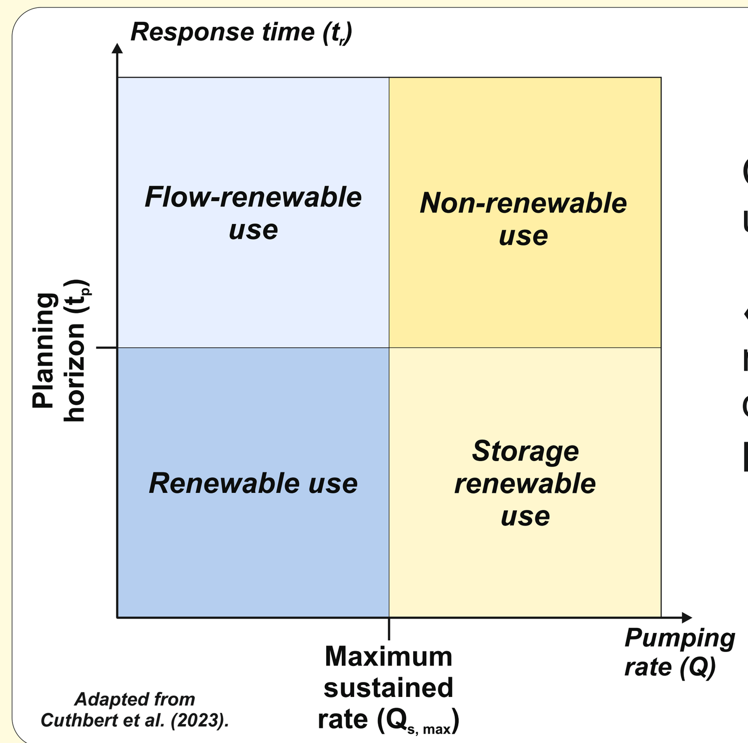
What is groundwater sustainability?

According to Gleeson et al. (2020):

« Is the process of maintaining **long-term,** dynamically stable storage and flows of high-quality groundwater using inclusive and equitable **long-term** governance . »



What is groundwater renewability?



Cuthbert et al (2023) define renewable groundwater use as:

« The management strategy that allows for a dynamic re-equilibration of groundwater storage, flows, and quality within relevant human timescales: **the planning horizon (t_p).** »

$$t_r \sim \frac{L^2}{D}$$

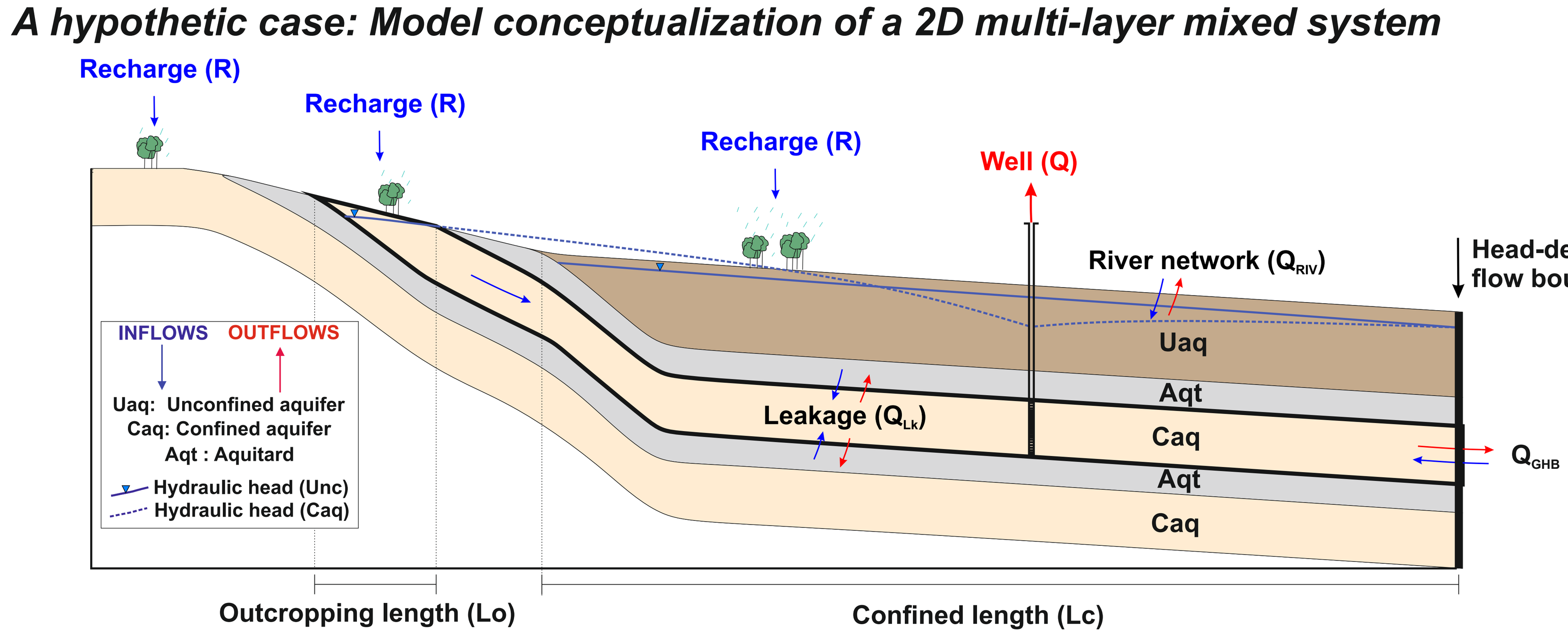
t_r: Response time
L : Characteristic flow length
D : Hydraulic diffusivity

The goal

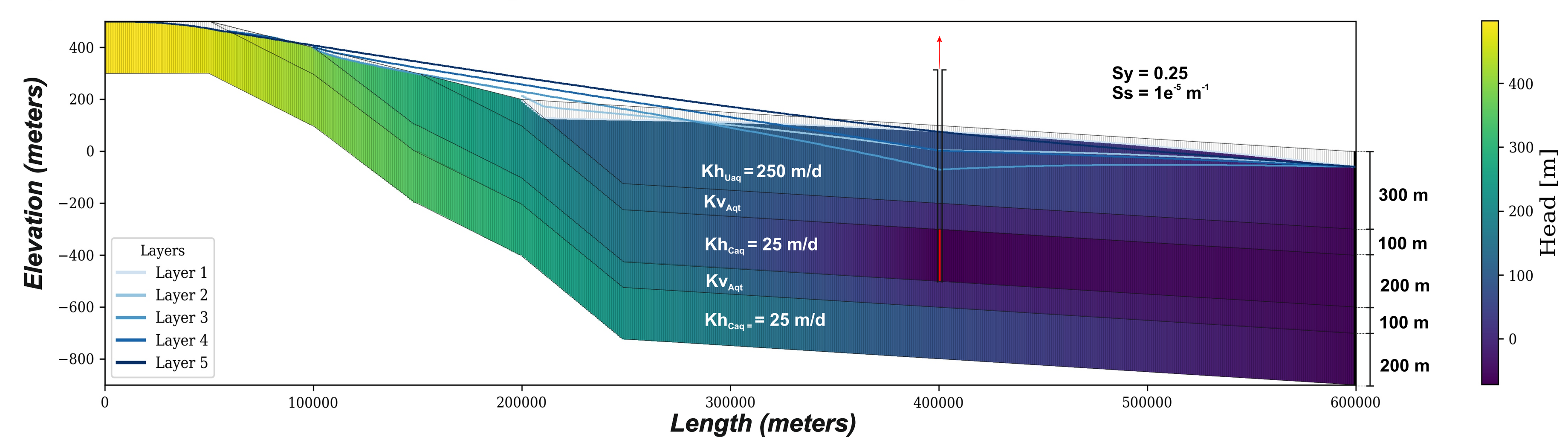
To understand how climatic conditions, the degree of confinement, and the planning horizon influence sustainability considerations and sustainable yield estimations in confined aquifers.

2. Estimating the sustainable yield of a confined aquifer

2.1. A hypothetic case: Model conceptualization of a 2D multi-layer mixed system



2.2. Synthetic cross-section and groundwater flow modelling: MODFLOW6 on FloPY



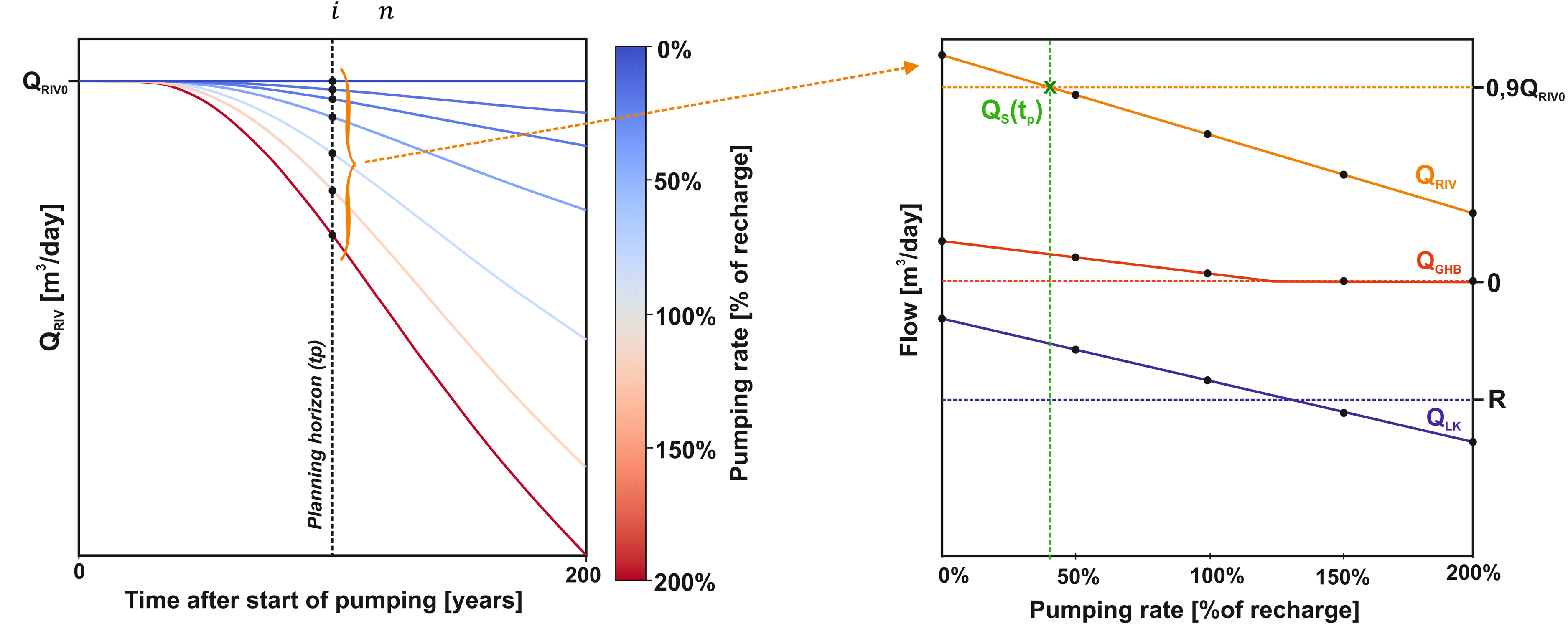
Model scenarios		Vertical hydraulic conductivity of the aquitards - Kv_{aqt} [m/day]							
		10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
Recharge rate	Arid conditions 45 mm/year	Low ← Degree of confinement → High							
	Humid conditions 240 mm/year								

The influence of contrasting climatic conditions was assessed using recharge rates representative of arid and humid settings.

The degree of confinement was explored through scenarios with different vertical hydraulic conductivity of the aquitards.

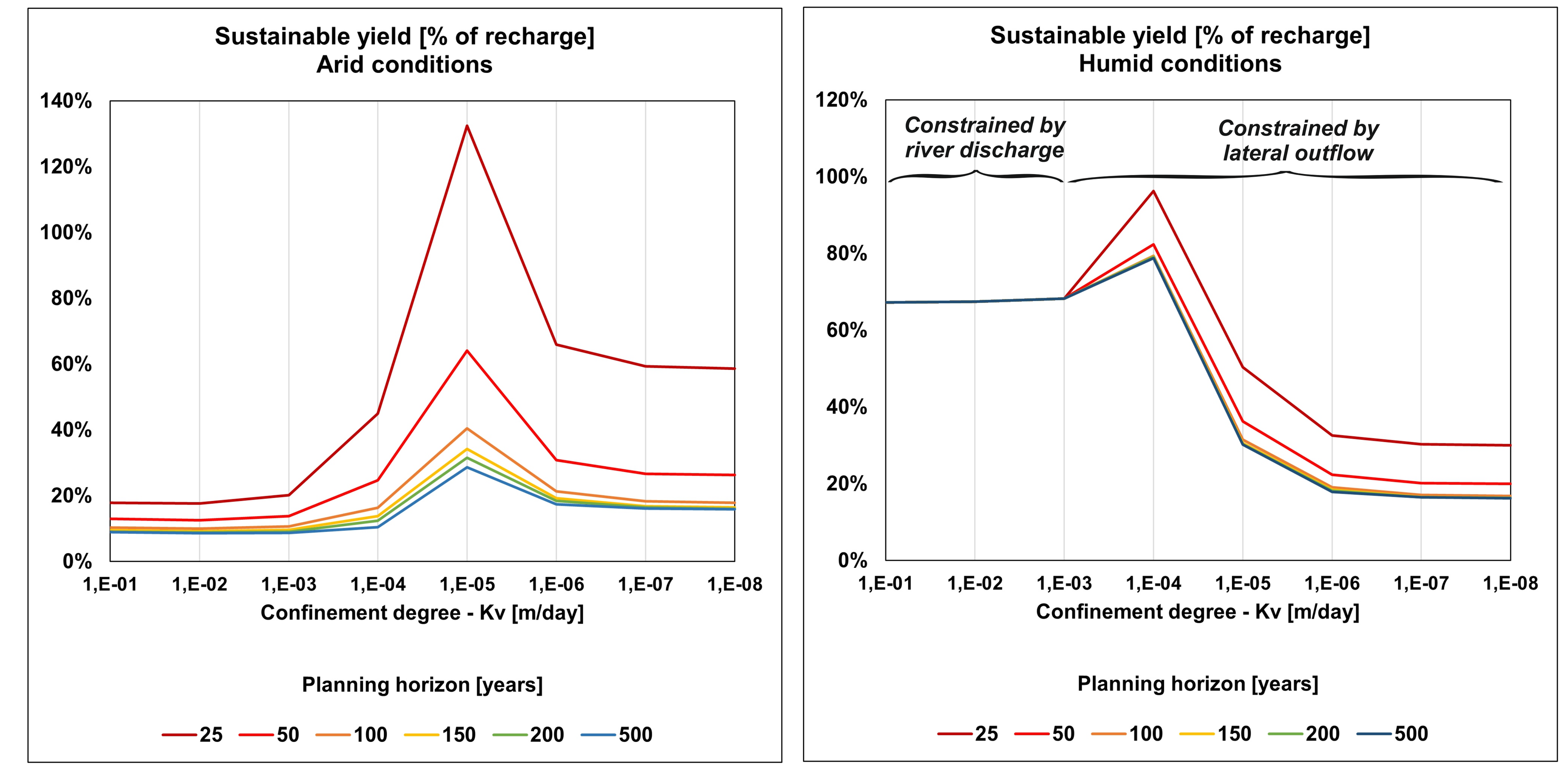
2.3. Sustainable yield estimation: Constrained optimization problem

$$Qs(t_p) = max\ V = \sum_i \sum_n Q\,\Delta t \quad subject\ to \quad Q_{GHB(t)} \geq 0,\ \ Q_{LK(t)} \leq R,\ \ Q_{RIV(t)} \geq 0{,}9Q_{RIV0}\ \ for\ t \in [0, t_p]$$



The sustainable yield was estimated by iteratively running a transient model with increasing constant pumping rates. For each planning horizon, net flow values constraining the optimization were extracted as a function of the pumping rate. The sustainable yield is the rate at which the first constraint is violated.

3. Results and discussion



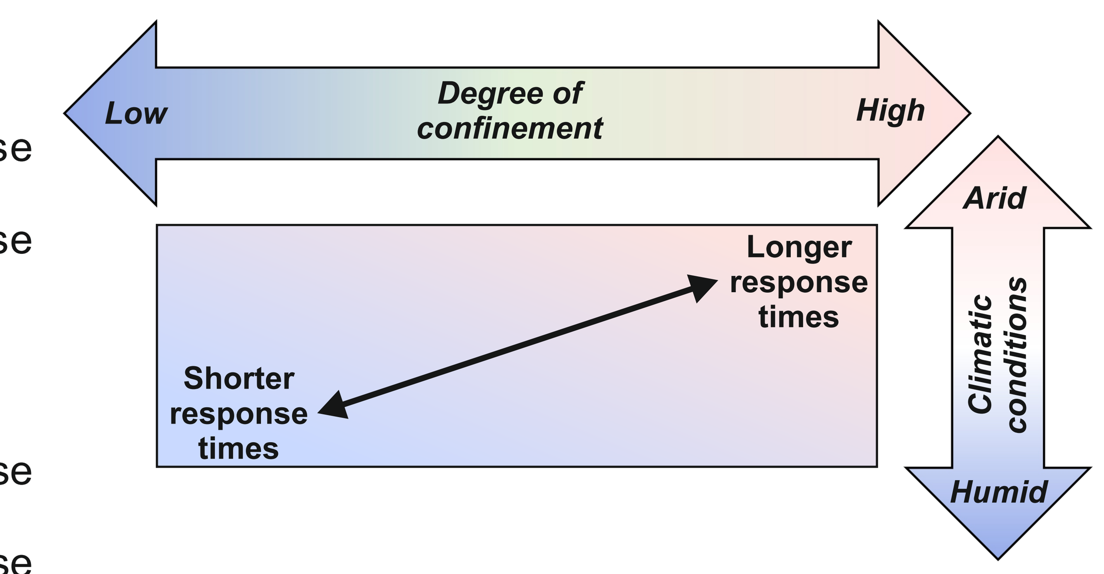
Estimated sustainable yields for humid and arid conditions under different degrees of confinement and planning horizons.

Response times and climatic conditions

- **Arid settings:** Longer response times, less surface connectivity.
- **Humid settings:** Faster response times, more surface connectivity.

Response times and degree of confinement

- **High confinement:** Longer response times, more buffering by aquitards.
- **Low confinement:** Faster response times, less buffering by aquitards.



4. Conclusions

- Estimated sustainable yields are highly dependent on the **chosen constraints**, **planning horizon,** and **model characteristics**, making it a case-specific optimization problem that requires an explicit solution in real-world applications.
- Intermediate confinement degrees, or **semi-confined aquifers**, tend to support higher yields, likely due to an optimal balance between vertical connectivity and buffering, enhancing their capacity to redistribute pumping impacts.
- The **vertical diffusivity of aquitards** should not be overlooked in response time estimations of multi-layer systems.
- In confined aquifers, sustainability is shaped by long system responses and the buffering role of confining units, **calling for long-term, context-specific, and adaptive management**. These systems challenge current sustainability concepts: **what we consider sustainable depends on when we decide to evaluate it.**

Acknowledgements

This study was conducted in the frame of the French **PEPR OneWater DEESAC** project **ANR-22-PEXO-0010**

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