Patterns and drivers of large-scale groundwater drought recovery

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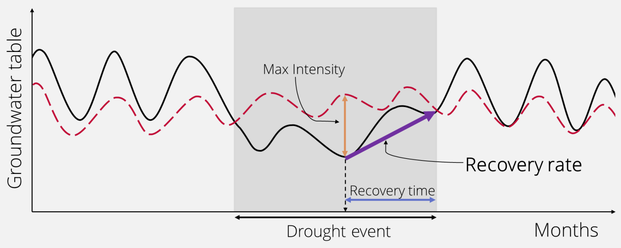
Introduction

Groundwater is one of the biggest freshwater reserves, sustaining people, crops and ecosystems worldwide. Human interventions but also climatic extremes, such as droughts, can have a large influence on groundwater resources. These will likely only increase in the future with climate change and increasing water demand.
The effects of drought on the groundwater, especially the drought recovery in groundwater systems remains still largely unexplored. Hence, this project is trying to uncover the global patterns and drivers of global groundwater drought recovery, to see how aquifers respond to climatic extremes and human pressures.

Drought Recovery definition and Recovery Regimes

Drought recovery

Recovery rate = max intensity / recovery time



Drought event:
based on threshold:
when the groundwater table dips below and above.

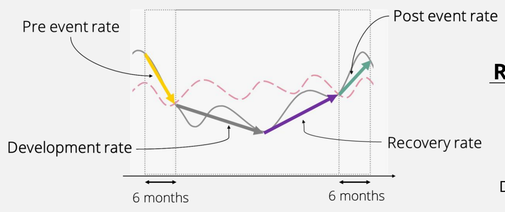
Lowest point:
start of the recovery period,
max intensity

Variable threshold
based on long term timeseries.
Using mean + std as threshold (~16%).

Recovery time
moment of lowest point till end of event.

Recovery Regimes

based on pre - , development, recovery and post drought event rates



Ratios:
Recovery rate (R)
{event} rate

{event} rate:
Pre event rate (PRE),
Development rate (DEV),
Post event rate (POST)

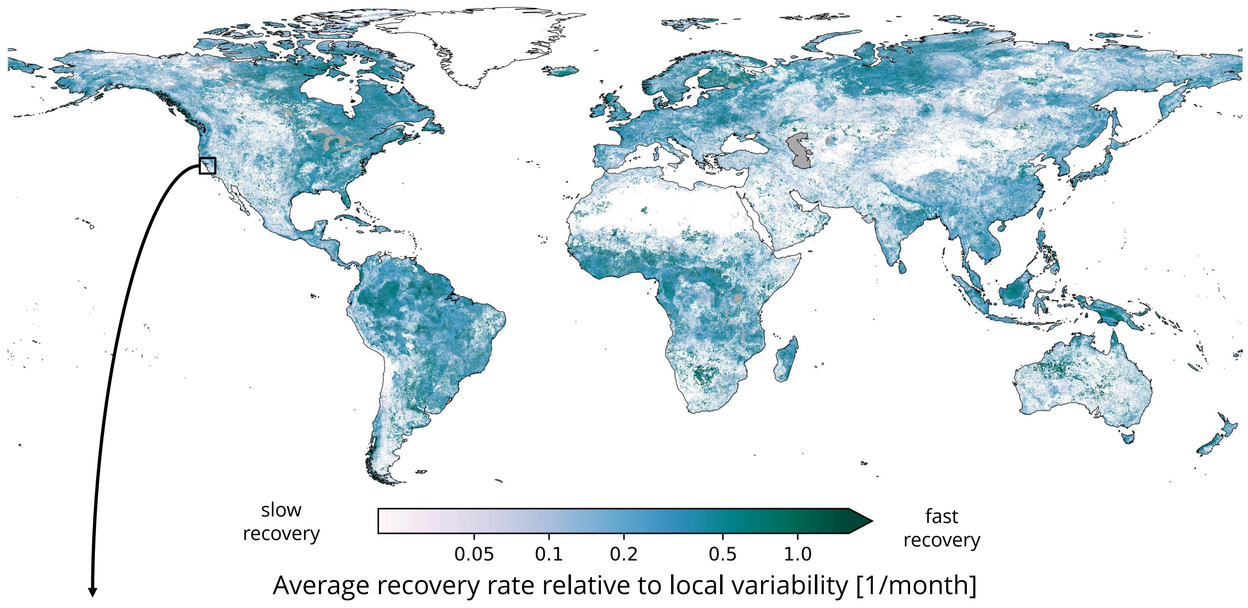
Resilient	Stable	Vulnerable	Unstable
• Rapid rebound, fast dev. but also fast recovery • *R/PRE ≪ −1, R/POST ≫ 1*	• Balanced behaviour (equal dev. and recovery) • *R/PRE ≈ −1, R/POST ≈ 1*	• Fast dev., weak recovery • *R/PRE > −1, R/POST < 1*	• Unstable after recovery • *R/POST < 0*

Recovery definition closely based on work about hydrological drought termination by Margariti et al. (2019) and Parry et al. (2018)

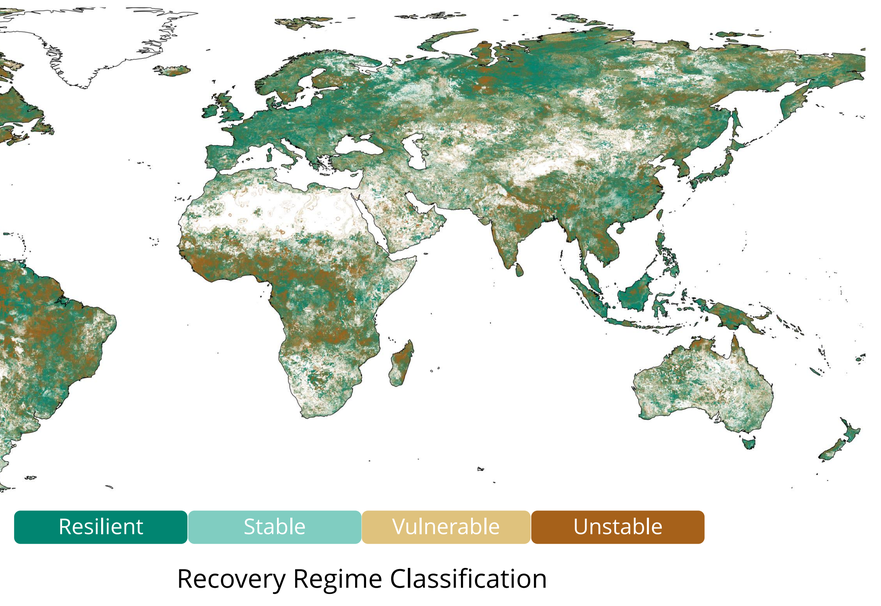
Global Groundwater Model GLOBGM

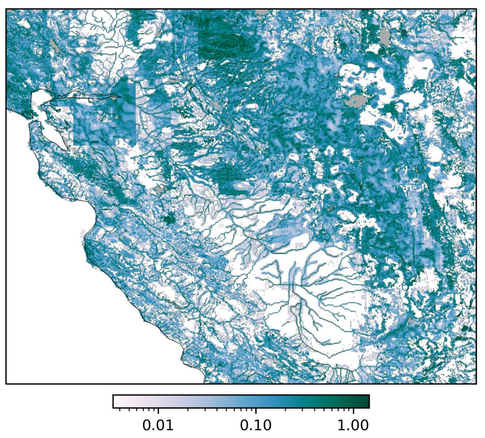
The groundwater drought recovery analysis is based on the groundwater simulations of the Global Groundwater Model (GLOBGM; Verkaik et al., 2024 and van Jaarsveld et al 2025 (submitted)), a transient global groundwater flow model. GLOBGM couples PCR-GLOBWB surface fluxes with a two-layer MODFLOW-6 setup, simulating monthly groundwater heads at ~1 km spatial resolution from 1960-2019. It therefore provides a consistent framework to assess groundwater variability and drought recovery worldwide.

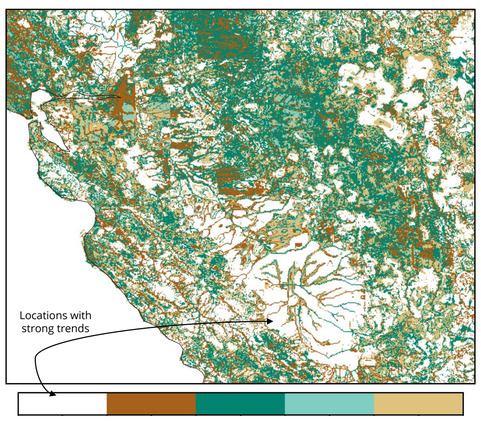
How quickly do places recover from groundwater droughts?



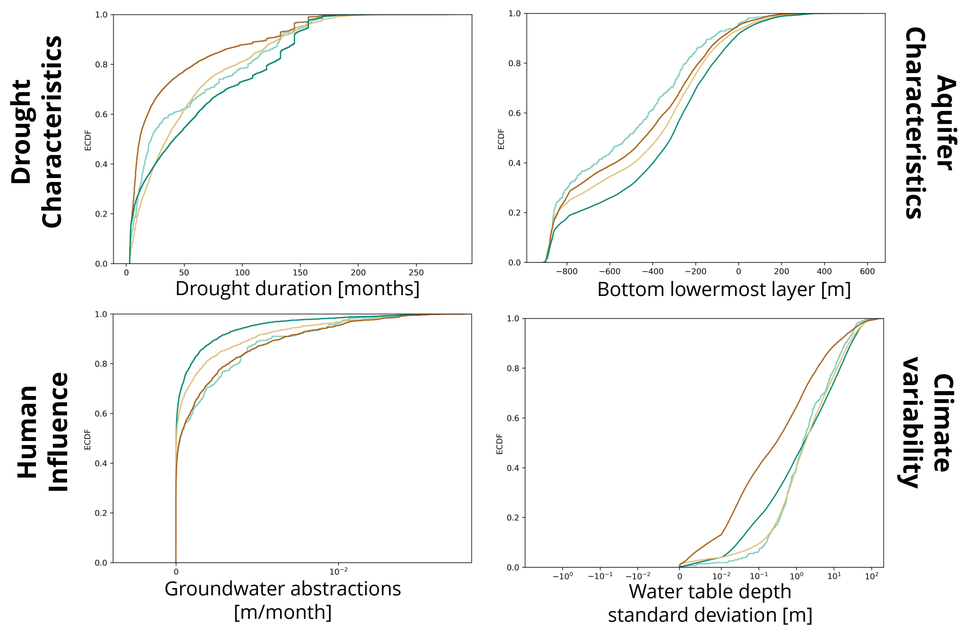
… and how does it relate to the recovery regimes?







Can we detangle this into different drivers?



Conclusions

- Global groundwater drought recovery patterns are highly variable
- Groundwater drought recovery patterns are strongly influenced by climate variability
- Recovery regimes highlight different patterns within areas of fast/slow recovery rate
- Recovery regimes help to indicate potential different drivers in the groundwater drought recovery process
- Comprehensive analysis on drivers between physical and climatic drivers still ongoing

Open Questions – Thoughts welcome!

- Better way to clearly distinguish and attribute drivers (physical and/or climatic) of drought recovery rate?
  → ML for driver analysis (e.g., feature importance of RF or XGB) so far not fully conclusive
  → PCA analysis for dimensionality reduction and informed ML input
- Lots of locations with water table depth trends (either climate and/or human influence) – currently left out of analysis. Better way to deal with them?

References
Margariti, J, Rangecroft, S., Parry, S., Wendt, D.E. and van Loon, A. (2019): Anthropogenic activities alter drought termination. ElemSciAnth, 7: 27. DOI: https://doi.org/10.1525/elementa.365
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