Project title: Groundwater Time Series Prediction using Deep Learning
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DKRZ Resource Request Proposal

1 Project Overview - Abstract

Groundwater is a critical resource for drinking water, agriculture, and ecosystems, especially in regions facing increasing climate stress. However, existing groundwater level (GWL) models often fail to capture the full impact of climate change, particularly the acceleration of the hydrological cycle and the increasing occurrence of both dry and wet extremes, such as drought events (DEs) and extreme precipitation events (EPEs). Changes in extremes are strongly linked with synoptic-scale atmospheric blockings (Detring et al. 2021; Lupo 2021) and mesoscale convective systems (MCS) (Schumacher & Rasmussen 2020), with recent studies linking spatially coupled drought–flood events to such atmospheric processes (Brunner et al. 2025). These events are projected to increase worldwide and can drastically disrupt soil moisture dynamics, infiltration rates and groundwater recharge processes, but remain poorly represented in existing models.

This project introduces an innovative deep learning (DL) modeling framework to forecast GWLs on the regional scale under future climate conditions. The key innovation lies in coupling regionally trained DL architectures with the analysis of synoptic-scale atmospheric blocks and mesoscale atmospheric processes, a combination not yet applied in groundwater modeling. Historical atmospheric blocking events will be evaluated regionally using climate reanalysis data and the statistical approach published in Detring et al. (2021). Additional meteorological features will be engineered (e.g., blocking persistence, position, precipitation duration and intensity), to assess GWL response times and lags. Subsequently, the role of MCSs will be analyzed using the Cloud Model 1 (CM1), as they represent a key driver of extreme precipitation in the study region. CM1 is a state-of-the-art, convection-resolving, non-hydrostatic numerical model that allows the study of atmospheric phenomena in idealized setups (Bryan & Fritsch 2002; Bryan 2021; in Schielicke et al. 2024), making it well suited for studying EPEs, thunderstorms, and MCSs. By integrating climate, soil, and hydrological data, the framework bridges meteorology and hydrogeology to capture subsurface processes at the regional scale. This enables the model to better learn the connection between GWL and atmospheric conditions, that translate into DEs and EPEs, enhancing sensitivity to both short and intense versus prolonged rainfall events. Brandenburg, Germany's driest federal state, serves as the initial testbed due to its pressing water scarcity vulnerability and strong data infrastructure.

The project pursues three main work packages (WP), which are subjects of this application:

WP 1) Develop a scalable DL architecture for regional GWL prediction using climate and soil data,

WP 2) Evaluate how the inclusion of DE and EPEs through atmospheric blockings and MCSs improves model responsiveness and identify regions of high sensitivity to DE and EPEs,

WP 3) Improve long-term forecasts using scenario-based training under future climate pathways (e.g., RCPs).

The computational component of this research involves extensive training and benchmarking of DL architectures (e.g., CNN–LSTM hybrids, LSTMs, and Transformer-based models) using high-resolution climate reanalysis data and ensemble simulations. Model development requires iterative hyperparameter optimization, sensitivity analyses, and scenario-based inference under multiple RCP pathways. These tasks demand access to high-performance GPU resources and parallel data processing capabilities, making the DKRZ environment essential for model development, evaluation, and scalability analyses in a computationally efficient and scientifically reproducible way.

References

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