Machine learning for faster estimates of groundwater response to artificial aquifer recharge

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Abstract

Numerical models like AMIGO simulate groundwater systems accurately but are slow and limit scenario evaluations. This study explores machine learning (ML) models as faster alternatives.

The study focuses on the Baakse Beek catchment in the eastern Netherlands, which has high transmissivity Pleistocene sands. Three ML models, Encoder-Decoder, U-Net, and Attention U-Net, were trained using data from the AMIGO numerical model under steady-state conditions. Five hydrological inputs were used to predict how groundwater responds to artificial recharge by focusing on three key groundwater response characteristics: maximum, area, and total response. The ML models were trained on 100, 300, 500, and 1000 recharge sites with varying recharge rates to analyze the effect of training dataset size on model accuracy. Model performance was evaluated using Nash-Sutcliffe Efficiency (NSE).

U-Net performed best, simulating 720 scenarios in 144 seconds versus AMIGO's 11 hours, identifying optimal recharge rates of 11 mm/day and 23 mm/day for the central and eastern regions. However, limitations include underestimation of maximum responses near the surface and reduced accuracy for small responses. Future work should consider transient scenarios to capture seasonal variations and use a coupled surface-groundwater model for better accuracy, despite increased complexity.

This study highlights the efficiency of ML models like U-Net for groundwater response prediction, fast alternative with high accuracy for optimizing recharge strategies.

Keywords: Managed artificial recharge, Machine learning, Drought mitigation, Scenario optimization, Groundwater response.

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Research papers

Machine learning for faster estimates of groundwater response to artificial aquifer recharge

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ABSTRACT

Groundwater models are a valuable tool in optimising the decisions influencing groundwater flow. Spatially distributed models represent the groundwater level in the entire area from where essential information can be extracted, directly aiding in the decision-making process. However, these models are time-consuming, limiting the number of scenarios that can be considered. This study explores different machine learning (ML) models as faster alternatives to predict the increase in steady-state groundwater head due to artificial recharge in the unconfined aquifer while considering a wider spatial extent (832 columns x 1472 rows totalling 765 km^2) than previous ML groundwater models. We trained three ML models (encoder-decoder, U-Net, and attention U-Net) with various hypothetical artificial recharge sites (100, 300, 500, and 1000 sites) in the Baakse Beek catchment (the Netherlands), using a detailed numerical groundwater model, AMIGO. The applied recharge rate along with geo-hydrological properties from the AMIGO baseline run were used as inputs to the ML models. The properties' permutation importance indicated that all properties of the first aquifer were important to predicting the response and were included when training the ML models. All three ML models improved with additional training sites but showed limited benefits from more than 500 recharge sites. Of the three ML models, U-Net and Attention U-Net outperformed the encoder-decoder. These two models achieved Nash-Sutcliffe efficiency (NSE) of more than 0.8 when trained with 300 or more recharge sites. U-Net trained on 1000 recharge sites had the highest overall NSE of 0.95. U-Net better captures input features with highly variable spatial characteristics, such as rivers and drains which influence the maximum height of the groundwater response. The model captured the influence of the input features on the response, reproducing the response patterns across the entire catchment. Finally, we showed that the trained ML models are faster than the numerical model, predicting within 0.24 s (97th percentile), making it ideal for optimising decisions.

1. Introduction

In the context of international policy frameworks like the European Water Framework Directive and Natura 2000, water management authorities have multiple targets they need to meet. The droughts of 2018–2020, which set a new benchmark in Europe (Rakovec et al., 2022), increased the urgency to take appropriate measures (Bartholomeus et al., 2023). Although the events are considered rare in the current climate, future climate change could exacerbate such events (Aalbers et al., 2023; Balting et al., 2021; Lehner et al., 2017; Pronk et al., 2021; van der Wiel et al., 2021). Even in deltas like the Netherlands, droughts cause serious risks for nature, agriculture, infrastructure and drinking water availability, which resulted in drought-related policy actions like "Water and soil leading in land use planning" (Bartholomeus et al., 2023). One of the reasons for this vulnerability is the expansion of the surface drainage network and the increased exploitation of groundwater resources (Ahmadalipour et al., 2019; Bartholomeus et al., 2023; Castle et al., 2014; de Wit et al., 2022a, b; Thatch et al., 2020; Thomas and Famiglietti, 2019; Witte et al., 2018).

The Pleistocene uplands of the Netherlands have recently faced severe rainfall deficits (Brakkee et al., 2022; Philip et al., 2020), increasing the reliance on surface and groundwater for irrigation. This has increased the strain on the limited water available for nature (van den Eertwegh et al., 2021). Long-term structural changes are identified to be

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