Operational Flood Forecasting System in Denmark – Integrating Groundwater and Surface-water

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Abstract

Most operational flood forecasting systems provide predictions of pluvial and fluvial floods, often neglecting groundwater flooding processes. Groundwater flooding occurs when natural drainage system cannot drain water away quick enough, causing the water table to rise above ground. This study presents an operational integrated flood forecasting system that combines surface water and groundwater components. It provides key variables - such as river discharge and shallow groundwater levels - for assessing flood risk in Denmark. During the winter of 2024, the system predicted relative shallow groundwater levels with an average error of 0.27 m at a 5-day lead time at selected wells. Moreover, the system effectively captures peak flows in rivers alongside high groundwater levels, as exemplified for a specific local flood event in Varde in January 2024. This work demonstrates how groundwater flooding, often neglected in operational forecasting, can be included at the national scale.

Introduction

Floods are among the most devastating natural disasters worldwide, causing substantial socio-economic damage (Tellman et al. 2021). *While fluvial and pluvial floods are well-recognized and investigated for decades due to their immediate and visible impacts* (Merz et al. 2021), *flooding caused by rising groundwater is often overlooked* (Behzad and Nie 2024; Kreibich et al. 2009). *Groundwater flooding occurs when natural drainage systems cannot remove water quickly enough, causing the water table to rise above the ground* (Parkin 2024; Becker et al. 2022). *It can develop more gradual, often persists for weeks or months, feedback to surface waters, and can also cause long-term damage - particularly to below-ground infrastructure such as basements, tunnels, and sewage systems. The British Geological Survey estimates that groundwater flooding is responsible for approximately £530 million in damages annually in the United Kingdom, representing around 30% of the country's total economic loss due to flooding* (Allocca et al. 2021).

Flood forecasting systems play a critical role in reducing the societal impacts of floods by supporting early warning, emergency planning, and climate adaptation strategies (L. J. Speight et al. 2021). *Many countries have developed national and regional forecasting frameworks, such as the National Water Prediction Service in the United States* (NOAA 2016), *the European Flood Awareness System* (Smith et al. 2016), *the Australian Flood Warning Services* (Pagano et al. 2016), *and the British Flood Alerts and Warnings* (L. Speight et al. 2025). *These systems vary in capabilities and tend to focus on surface water processes, with limited attention to integrated surface water - groundwater interactions. Such forecasts may underestimate the full extent and severity of a flood event without accounting for groundwater processes (e.g., low infiltration buffer in saturated soils and groundwater exfiltration). This is particularly problematic in low-lying areas or places with shallow water tables, where groundwater can emerge to the surface even without heavy surface runoff* (Becker et al. 2022). *Conventional surface water-focused systems often miss slow-onset groundwater floods. These events may not trigger standard warning thresholds, leading to delayed or absent alerts for communities vulnerable to prolonged flooding of basements, roads, or critical infrastructure. Rising groundwater level induced floods can persist for a longer duration and emergency planning and allocation measures will be inefficient when groundwater contributions are neglected in flood warning systems* (Parkin 2024).

Denmark, where both surface water and groundwater flooding pose recurring risks, experiences considerable annual flood-related economic losses (Halsnæs, Larsen, and Drenck 2022). *Responding to this need, the Geological Survey of Denmark and Greenland (GEUS) has developed a real-time, operational flood forecasting system that integrates both surface water and groundwater processes. This system is designed to provide short-, medium-, and long-term forecasts of fluvial and groundwater floods at a national scale. In this study, we present the development and initial performance of this integrated forecasting system under operational conditions. We carry out an initial event-based evaluation of its predictive capabilities with focus on shallow groundwater dynamics, discuss limitations, and explore future directions. By highlighting Denmark's experience, this work aims to contribute to the global advancement of integrated flood forecasting and to offer guidance for similar initiatives in other countries that are exposed to groundwater flood risk.*

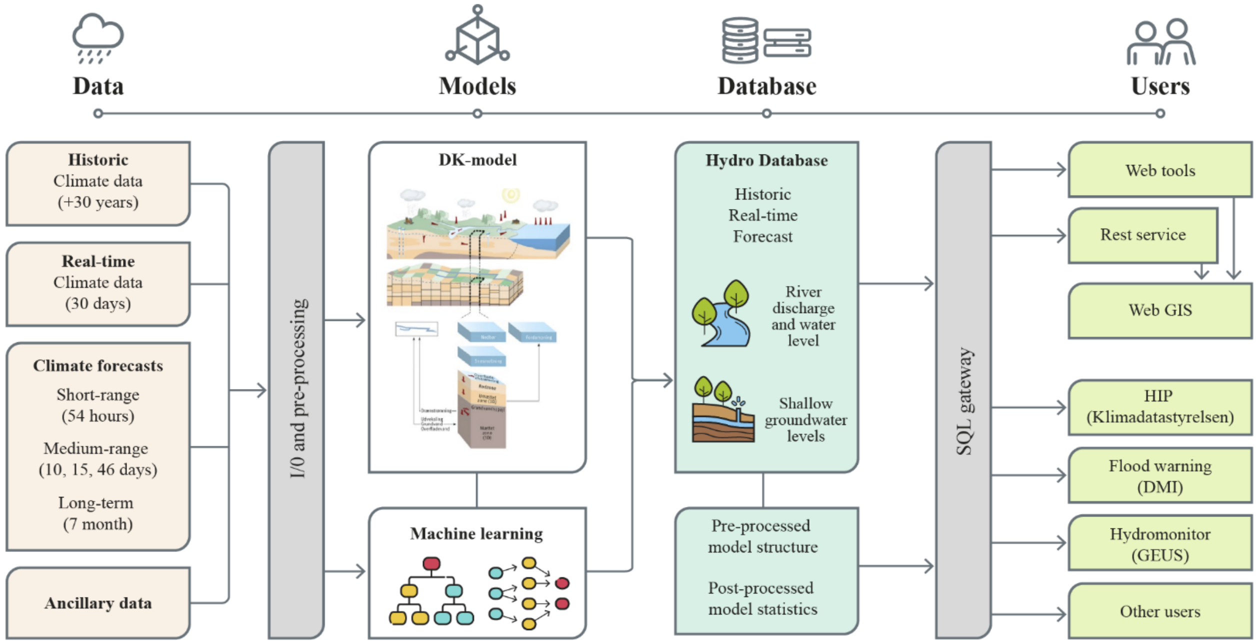

Figure 1. *Process flow of the flood forecasting system.*

Overview of the forecasting system

GEUS' flood forecasting system is an operational surface water - groundwater modelling system that integrates weather forecast downloading and preprocessing with pre-trained forecasting models, e.g., physically based hydrological model and machine learning (ML) models, and data *management. The overall architecture of the forecasting system is illustrated in Figure 1. The process begins with downloading various near real-time and forecasted weather data from meteorological archives, which are then processed to the input formats required by the hydrological forecasting models. The models are then updated and run to predict water dynamics. Upon completion, the flood-relevant variables (discharge, depth to phreatic surface, etc.) are delivered to a database for data management, which serves as the backend for web viewer and sharing to users. The following sub-sections provide detailed descriptions of these components.*

Climate data

The climate forcings, including precipitation, air temperature, and potential evapotranspiration, used in the system consist of both observational data and weather forecasts. Observation-based historical and real-time climate data are sourced from national gridded datasets provided by the Danish Meteorological Institute (DMI). These datasets, available at daily resolution, extend back to 1989 (Scharling 1999a; 1999b; DMI, n.d.). *Real-time data is available via the DMI Open Data API (https://opendatadocs.dmi.govcloud.dk/DMIOpenData). The variables are based on data from a network of in situ weather stations distributed throughout Denmark. Air temperature is measured at a height of 2 meters above ground, and potential evapotranspiration is estimated using a modified Makkink's equation* (Plauborg et al. 2002) *. Operational precipitation gauges are typically installed 1–1.5 meters above ground level and are subject to wind-induced turbulence, which causes a systematic undercatch of precipitation. To correct for this bias, an empirical correction is dynamically applied based on rainfall intensity, wind speed, and temperature, distinguishing between solid and liquid precipitation* (Simon Stisen et al. 2011; Allerup, Madsen, and Vejen 1997; S Stisen et al. 2012).

Climate forecasts used in the system are sourced from two providers: DMI's Weather Model (HARMONIE) for DINI (Denmark, Iceland, the Netherlands and Ireland) and the European Centre for Medium-Range Weather Forecasts (ECMWF, (Palmer et al. 1990). *The HARMONIE model delivers local high-resolution short-term forecasts with a lead time of up to 56 hours. ECMWF provides a suite of forecasts at various temporal scales: medium-range forecasts with lead times of 10 to 15 days, extended-range forecasts up to 46 days, and long-range seasonal forecasts* *extending up to 7 months. These forecasts support both short- and long-term hydrological modeling and enable comprehensive flood risk assessments.*

Forecast models

The forecasting system uses two types of models: the physically based National Hydrological Model (DK-model) and data-driven machine learning (ML) models. The DK-model is an integrated surface water – groundwater model that covers most of Denmark's land area - approximately 43,000 km² and has been under continuous development over almost three decades (H J Henriksen et al. 2021; Højberg et al. 2013; Koch et al. 2021; Schneider et al. 2022; Hans Jørgen Henriksen, Ondracek, and Troldborg 2023). *It is implemented in the MIKE SHE modelling framework* (Abbott et al. 1986; DHI 2020)*, which fully couples a finite-difference 3D subsurface flow model with 2D overland flow, a simplified two-layer representation of the unsaturated zone, and 1D kinematic streamflow routing. The model has been calibrated for the period 2000 to 2010 using 304 daily streamflow time series and groundwater head observations from approximately 40,000 intakes across the country, with focus on shallow groundwater and streamflow in the version* (H J Henriksen et al. 2020) *used as part of the forecasting system.*

ML models have demonstrated promising potential for flood forecasting (Nearing et al. 2024)*. To enhance both accuracy and computational speed of discharge predictions, we developed a hybrid ML post-processing model based on Long Short-Term Memory (LSTM) neural networks* (Liu et al. 2024)*. Trained on historical data, this model incorporates real-time climate information and DK-model simulations to generate 10-day discharge forecasts, taking into account weather predictions during the forecasting period. The current ML system provides discharge forecasts for approximately 3,000 catchment outlets across Denmark* (Liu et al. 2025)*. A similar ML post-processing model for groundwater level forecasting is currently under development.*

Data management

Operationally, the models begin with real-time simulations that incorporate a 30-day look-back period each day. These simulations provide the most up-to-date estimates of shallow groundwater levels and discharges, ensuring comparability with historical runs (also backup in *the database) in terms of climate forcings and model configurations. The 30-day look-back period is set based on GEUS' experience to maintain stability of the DK-model and real-time climate data. The real-time simulations are submitted to the database but also serve as initial conditions for forecast runs.*

The forecasts start after real-time simulations. Short-range forecasts (54 hours) and medium-range forecasts (10, 15, and 46 days) are generated once per day. Long-term forecasts (up to seven months) are produced monthly, which will be available at the start of each month but depend on the availability of ECMWF monthly weather forecasts. The medium-range forecasts use ensemble modeling with 51 ensemble members. All simulations provide streamflow estimates for up to 60,000 river points and shallow groundwater levels (represented by depth to the top phreatic surface) at 100m and 500m resolutions. As of the completion of this paper, short-range and 10-day ahead deterministic forecasts are available, while operational forecasts with ensembles and long-term forecasts are under development.

Once the real-time simulations and forecasts are completed, the results are uploaded to a centralized database called HydroDB, which supports data storage, statistical analysis, visualization, and user sharing. HydroDB stores historical simulations spanning 30 years (including river discharge and depth to top phreatic surface, additional data is available upon request), updated annually to reflect newly available data. Real-time simulations and forecast outputs are updated daily and backed up for around one year. The current model structure data, e.g., river network, geological- and calculation layers, is stored in the database.

Using historical records, along with the most recent real-time and forecast data, statistical analyses are conducted to assess current and forecasted conditions relative to historical baselines (e.g., how wet or dry a period is). Through a REST api, the selected part of the data can be accessed and visualized, eg. the webviewer at GEUS Hydromonitor (https://data.geus.dk/hydromonitor/) and through an Structured Query Language (SQL) -gateway registrated users, such as Danish Agency for Climate Data (KDS) can access HydroDB. KDS uses access to stores a local copy for direct external access to real-time data through the Hydrological Information and Prognosis System (HIP, https://hipdata.dk/).

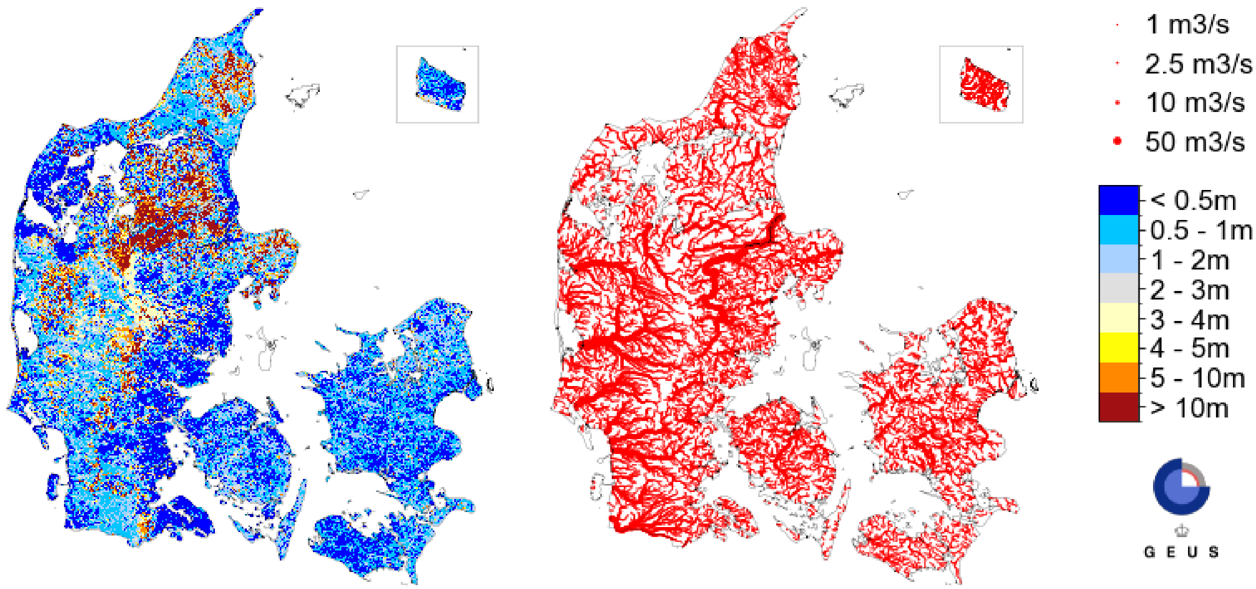

Figure 2. *Example of forecasted absolute shallow groundwater (left) and discharge (right) on January 23, 2025. Shallow groundwater levels are presented as a raster map at 100 m resolution. The system also provides discharge forecasts at 62,728 points (from the 100m model, shown as red dots with size indicating discharge values) along nearly all river channels in Denmark. The up-to-date forecasting are available via GEUS Hydromonitor (https://data.geus.dk/hydromonitor/)*

Performance and case application

Accuracy of groundwater level forecasts

The forecasting system has been operational since October 2024, providing 10-day ahead forecasts of shallow groundwater levels and river discharge based on ECMWF's 10-day weather forecasts. Figure 3a shows changes in groundwater levels between two dates, i.e., October 15, 2024, and January 9, 2025. On average, groundwater levels increased by 1.70 meters across Denmark during this period, with spatial variation (Figure 3a). We initially evaluated the relative groundwater forecasts by comparing them with measurements from 7 randomly distributed wells in Denmark. The subplots in Figure 3 display the 10-day groundwater level forecasts (blue curves) alongside observed measurements (dotted black curves) relative to the groundwater levels on October 15, 2024. Overall, the simulated relative groundwater dynamics align well with the observations. The root-mean-square-error (RMSE) between observations and 5-day ahead forecasts (marked by red points in the subplots) ranges from 0.11 to 0.64 meters among the 7 wells. Discrepancies persist in absolute groundwater levels, suggesting that further model improvement or post-processing is necessary.

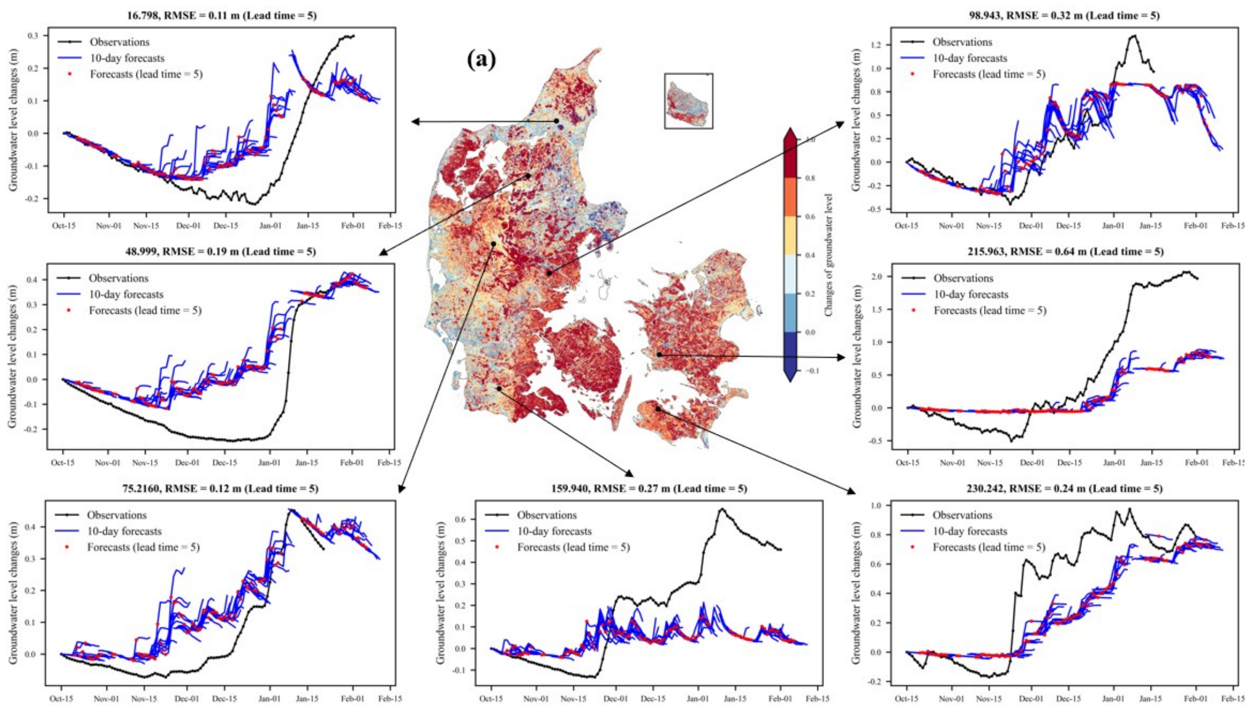

***Figure 3**. Comparison of relative groundwater level forecasts (forced by ECMWF 10-day deterministic weather forecasts) and measurements at 7 wells during October 15, 2024, to February 15, 2025. Subplot (a) shows the differences between October 15, 2024, and January 9, 2025. The remaining subplots show the time series of groundwater level forecasts and measurements.*

Case application

The DK-model is developed with moderate spatial resolution (up to 100 m), allowing flood forecasting across scales but computationally manageable. To demonstrate its capabilities for local applications, we present a flood event that occurred downstream of the Varde River in mid-western Jutland on January 23rd, 2024. The flood extent was captured by Sentinel-1 satellite imagery (Figure 4a), which reveals significant inundation across the region (Hansen at al. 2025 under review). River discharge increased from 17.81 m^3/s on January 19th to 31.92 m^3/s on January 23rd (Figure 4a). Our model successfully captured this flood event at the river section, with simulated discharge increasing from 16.07 m^3/s to 32.47 m^3/s. The RMSE of the simulated discharge was 3.99 m^3/s for January 2024 compared to observations, demonstrating the system's promising capability for river flood forecasting.

There are no groundwater well measurements available in this region at the time of interest. Therefore, we compared the simulated groundwater level dynamics during the event to historical averages (1989–2023) to illustrate groundwater behavior during the flood events. As shown in

Figure 4b, groundwater levels are significantly higher than the historical averages across most of the area. Even in the river valley, where groundwater is typically close to the surface, levels were elevated by 0.2–0.4 m compared to the historical baseline.

Figures 4c and 4d present two profiles showing model topography, groundwater levels, flooded areas along the profiles, and the location of the main river channels. These profiles further confirm that during the event groundwater levels (green curves) are consistently higher than the historical averages (blue curves). The flooding is concentrated along the river channel but also extends across the adjacent plains, as indicated by the gray vertical lines representing flooded locations. Notably, the simulated groundwater levels exceed the surface topography in some sections of the profiles, corresponding well with the observed inundation.

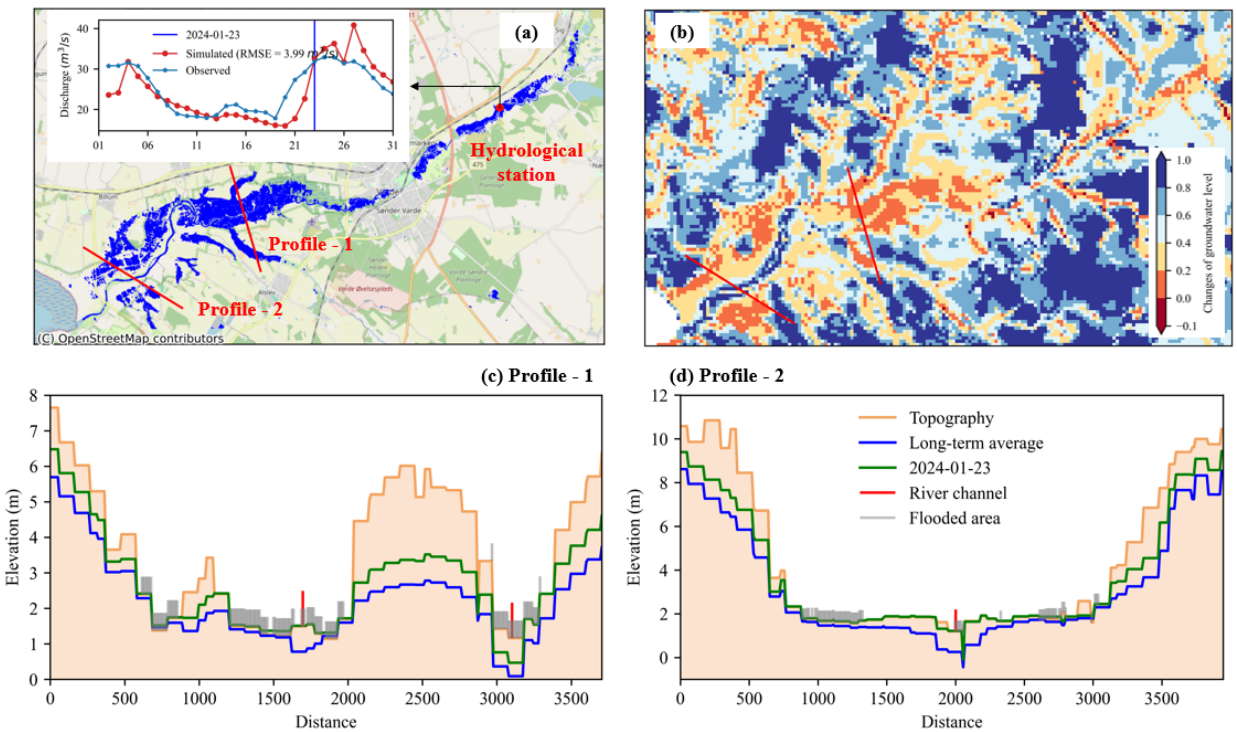

***Figure 4**. Application of the flood forecasting system to a local case study (Varde River). (a) Inundation extent derived from satellite imagery on January 23, 2024, and a comparison of simulated and observed discharge at the hydrological station during January 2024; (b) Relative changes of the groundwater levels on the same date compared to historical reference (mean values of 1989-2023) for the area; (c) and (d) are vertical profiles along two cross-sections across river valley. The curves show model topography, groundwater level dated January 23, 2024, and groundwater level from historical reference. Flooded area from satellite data is indicated in grey, and the river location in red. Please note that the real water surface elevation is unknown, so the grey and read bars do not indicate water depth of the inundated area but the locations.*

Perspectives and conclusions

This study presented the ongoing development of a national-scale operational flood forecasting system for Denmark that explicitly integrates surface water and groundwater hydrological processes. Groundwater is often neglected in operational flood forecasting; hence, its inclusion represents a significant advancement. In groundwater-dominated regions such as Denmark, the integration of groundwater into a forecasting framework enables the prediction of groundwater flooding, a regularly occurring but often overlooked hazard (Parkin 2024). *Additionally, the explicit representation of slower-reacting delayed groundwater processes enhances streamflow forecasts from more conventional rainfall-runoff type models (as e.g. shown by Liu et al. (2024)). Ongoing and future developments of the system aim to further increase forecast skill and expand lead time. These include the integration of ensemble and seasonal weather forecasts. Also, special attention is being paid to improving the accuracy of absolute groundwater level predictions; amongst others by developing Deep Learning post-processors to enhance groundwater level predictions, comparable to the already applied post-processing of streamflow simulations* (Liu et al. 2024). *Nevertheless, relative groundwater levels (e.g. as quantiles or return events) provide relevant information, and such statistical indicators are more robustly simulated than absolute levels* (Seidenfaden et al. 2025). *Finally, derived local scale models are envisaged for particularly vulnerable areas, especially urban areas at the risk of being affected by compound events of flooding from rivers, sea and groundwater* (Seidenfaden et al. 2024) .

The Danish integrated system developed across a range of institutions can serve as a reference for other countries facing similar hydrological hazards. This work highlights that with appropriate data, modeling infrastructure and institutional collaboration, it is feasible to implement such integrated systems at the national scale – ultimately improving preparedness and resilience to a broader range of flood hazards.

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Additional information

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