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Next-Generation Decision Support System for Equitable River Basin Water Management

Amir Rouhani, Michael Rode, and Seifeddine Jomaa
Department of Aquatic Ecosystem Analysis and Management, Helmholtz Centre for Environmental Research - UFZ, Magdeburg, Germany (amir.rouhani@ufz.de, michael.rode@ufz.de, seifeddine.jomaa@ufz.de)

In recent years, the Bode River Basin has experienced prolonged droughts accompanied by widespread forest dieback, intensifying trade-offs between ecosystem protection, agricultural production, and drinking water supply. The Bode basin represents one of the best-monitored meso-scale catchments in Europe, offering a unique opportunity to develop more comprehensive and evidence-based decision-making capabilities. This study leverages this data-rich environment, advanced modelling approaches, and accumulated knowledge on ecological boundaries to develop and demonstrate an integrated digital twin platform as a next-generation decision support framework. The framework is explicitly co-designed to support equitable and multisectoral water allocation among multiple stakeholders under changing hydrological conditions.

The Bode Digital Twin Platform integrates advanced process-based modelling, and data-driven methods within a unified digital architecture. The platform assimilates more than 15 years of high-frequency water quality observations (part of TERENO Observatory), together with meteorological forcing from the German Weather Service (DWD) and hydrological data from the regional flood protection agency (LHW). Furthermore, the platform integrates state-of-the-art modelling capabilities, by coupling fully distributed hydrological and water quality modelling (mHM-Nitrate) with groundwater level simulations (MODFLOW) and machine-learning-based ecological modules. To this end, water temperature and dissolved oxygen concentrations were predicted with high accuracy using a random forest algorithm (R^2= 0.93 and 0.75, respectively). This hybrid framework allows, for the first time in the Bode Basin, a consistent cross-scale representation of surface water, groundwater, and key ecosystem indicators. These components are complemented by short-term forecasting modules that support proactive management by anticipating hydrological extremes and water quality risks. A fully automated data ingestion pipeline, based on advanced application programming interfaces (APIs), enables continuous updates and near real-time system operation. This design ensures transparency, transferability, and adaptability to diverse governance contexts and stakeholder needs. We argue that this approach offers a replicable pathway towards more equitable, climate-resilient water governance and long-term water security.

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