Coupled surface-water and groundwater modeling approach to optimize drinking-water dam management under climate change impacts

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Abstract

In crystalline bedrock regions, groundwater resources are inherently limited and challenging to exploit, making surface reservoirs essential components of drinking water management systems despite their vulnerability to climate change. Our research quantifies water volume availability stored in these reservoirs in response to changing hydrological regimes, with a specific focus on dams exploited for drinking water supply. A physically-based modeling approach is developed to fully couple surface-water and groundwater flows, allowing for comprehensive assessment of reservoir dynamics under climate stress.

For our pilot site, this study focuses on the Chèze dam, a major hydraulic structure providing one-third of the drinking water supply for over 500,000 residents in the Rennes metropolitan area (Brittany, France). This site has been continuously monitored for more than twenty years, making it ideal for studying interactions between anthropogenic management and climate variations. The dam, with a capacity of 13 Mm^3, is situated on a 62 km^2 watershed in a crystalline bedrock domain. Our study employs the ModFlow–LAK/SFR framework, which has been used in the scientific literature to couple exchanges between reservoirs, aquifers and stream networks. Our contribution is distinguished by enhancing its deployability through HydroModPy (Python toolbox), seeking an optimal balance between physical accuracy and operational simplicity. The daily transient model was developed to serve as a decision support tool for water resource managers at Eau du Bassin Rennais water authority. It is fed by meteorological data from Météo-France's SIM2 dataset and operational data. The model continuously simulates bidirectional flows between the reservoir, aquifers, and surface hydrographic network. It also enables climate projections and assessment of their impacts, as well as evaluation of various management strategies.

Primary results highlight groundwater infiltration as a key phenomenon in the system's hydrological balance. This infiltration represents water loss from the reservoir at the dam-bedrock interface, accounting for more than 28% of the reservoir's nominal capacity annually

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(approximately 3.6 Mm^3). The significant subsurface flux was identified using our coupled modeling approach and validated against long-term monitoring data. Measurements indicate this flow maintains consistent patterns throughout the year due to the relatively constant hydraulic head at the outlet, which results from the reservoir's limited water level fluctuations (maximum annual amplitude of 8 m). Previously unquantified, this subsurface component potentially contributes to supporting downstream low flows, complementing the regulatory reserved flow.

Additionally, our approach investigates the deconvolution of reservoir balance components from operational data, leveraging their distinct temporal signatures (seasonal, annual) to separate individual hydrological fluxes. These signal-based findings will be validated against the coupled physical model results. Identifying and characterizing this critical interface between the reservoir and the subsurface environment is important for accurately assessing the system's sensitivity to changes in climate forcing. Our approach thus integrates prospective analysis of system trajectories under various climate change scenarios across different time horizons. These projections, associated with adaptive management scenarios, evaluate the robustness of operational strategies against prolonged/intensified droughts and seasonal flow redistribution.

This methodology will be extended to all operational sites managed by the Eau du Bassin Rennais water authority, with the objective of developing a meta-model. This decision support system will enable short, medium, and long-term optimization of spatiotemporal distribution of withdrawals among different available resources, thus maximizing the overall resilience of the supply network against future climate constraints. The methodological developments carried out within this research provide an easily transferable conceptual and technical framework. This approach considerably simplifies the vulnerability assessment of hydraulic infrastructure in crystalline bedrock contexts, thereby helping improve sustainable water resource management strategies amid regional-scale climate change challenges.