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A Multi-Scale Modelling Framework for Assessing Environmental Impacts of Pumped Hydro Energy Storage

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The transition to a decarbonized society necessitates innovative approaches to energy generation, storage, and distribution. Pumped hydro energy storage (PHES) presents a promising solution, functioning as a large-scale battery by cyclically transferring water between two reservoirs of significantly different elevations. This process stores surplus energy—generated through renewable sources such as solar and wind—and releases it during periods of high demand. However, the environmental implications of such large-scale hydrological operations, particularly on surface water quality, require rigorous assessment prior to implementation. Impacts occur across a range of spatial and temporal scales (e.g., outlet structures and hours of water pumping) to large scales (e.g., the whole catchment and the accumulation of pollutants over years), requiring an assessment to represent multiple scales.

This study presents a bespoke multi-scale modelling framework designed to evaluate potential changes in surface water quality associated with PHES infrastructure, using a proposed pumped hydro system in Australia as a case study. The framework integrates three distinct modelling domains, each employing specialized software tools, that are then all linked to represent impacts at various scales. Near-field processes (small spatial and temporal scale) are resolved using Computational Fluid Dynamics (CFD), specifically OpenFOAM, to capture fine-scale hydrodynamic behaviour. Mid-field dynamics (medium scales) are addressed through coupled hydrodynamic and water quality modelling using TUFLOW FV, which simulates mixing and transport processes. Far-field impacts (large scales) are assessed using catchment-scale hydrological modelling via Source, which captures broader catchment dynamics. To ensure a comprehensive understanding of system-wide impacts, these models are dynamically linked to represent all scales, allowing a robust assessment of all impacts and demonstrating how small-scale processes propagate to large-scale impacts.

Several key challenges have been addressed in the development of this framework. One major challenge involves harmonizing spatial and temporal resolutions across the modelling platforms, which range from sub 1 metre CFD grids to lumped catchment models with extents in the squared kilometres, and time steps varying from seconds to days. Aligning water quality parameters across platforms was another challenge overcome in this framework, particularly in translating CFD-derived energy metrics into mid-field water quality indicators, and subsequently reconciling these with far-field sediment and nutrient representations in catchment models. Ensuring numerical stability during rapid water transfers between reservoirs required iterative adjustments to model characteristics, such as mesh resolution, Courant numbers, and geometry, while maintaining computational efficiency. Additionally, selecting appropriate vertical layering schemes—such as z-layers for stratification or sigma-layers for wet-dry transitions—has been critical for accurately representing thermocline dynamics under operational conditions involving water level fluctuations of up to 10 metres.

Using this framework to assess the proposed PHES, scenario-based simulations were employed to evaluate both unmitigated and mitigated outcomes, supporting informed decision-making prior to construction. These scenarios captured a range of variability in the hydrodynamic modelling, including water transfer regimes, storage capacities and climatic conditions, along with bank stabilisation and rock scour protection. The hydrological modelling primarily consisted of variability in climatic context of the project.

Ultimately, this modelling was able to quantify the changes to water quality due to the system in various states. It has indicated that the larger the system, the bigger the impact, although mitigation measures provide a function to reduce this impact.

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