Simulating groundwater systems beneath artificial dunes: Balancing historical insights and future projections

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Coastal regions face escalating threats from sea-level rise, storm surges, and saltwater intrusion due to climate change. To mitigate these risks, artificial dune systems are increasingly explored as nature-based solutions for enhancing coastal resilience. This research develops a groundwater model tailored to the Belgian coast, integrating historical data and innovative modelling techniques. The study focuses on evaluating past equilibrium conditions, assessing the effectiveness of engineered dunes in protecting freshwater resources, and exploring future scenarios under changing climatic and hydrological conditions.

The model is built using MODFLOW 6, refined through Python-based FLOPY, and initialized with a geological voxel model derived from extensive borehole data from the study area. Historical datasets play a critical role in parameterization, with inputs including well data dating back to 2010 and studies that examined the Belgian coast's hydrogeological systems. These datasets are supplemented with more recent measurements, such as recharge estimates, electrical resistivity tomography (ERT) data, and well-monitoring results. Boundary conditions are iteratively refined to ensure the model accurately reflects the current state of the groundwater system. Particular attention is given to the effects of recent coastal nourishment activities, which have influenced subsurface hydrological dynamics.

The research adopts a staged modelling approach. A steady-state baseline model forms the foundation of the study, representing current conditions and serving as a benchmark for historical equilibrium analysis. This baseline investigates whether equilibrium states were disrupted by natural or anthropogenic events, such as coastal nourishment or historical suppression activities near the beach. Once the baseline is established, transient simulations explore the system's response to dynamic changes over the next century, using stress periods of 10 years from 2000 to 2100.

Future scenarios are developed to account for sea-level rise, recharge variability, and storm surge impacts. Regional projections align with the IPCC-AR6 scenarios (RCP 2.6 and RCP 8.5) and the "Kustvisie" framework, simulating sea-level rises of +1, +2, and +3 meters by 2125. Historical storm data, including events like Storm Corrie, inform the modelling of storm surges and their hydrological consequences. These scenarios are complemented by sensitivity analyses to quantify the groundwater system's response to specific changes, such as shifts in recharge rates or variations in boundary conditions. This multi-scenario approach provides a comprehensive understanding of the system's resilience under diverse conditions.

The primary objective is to evaluate the role of the freshwater lens beneath engineered dunes as a barrier against saltwater intrusion. This has significant implications for protecting vital resources such as agricultural water supplies, drinking water, and coastal infrastructure. Additionally, the model integrates land surface inundation data derived from tidal and wave dynamics to assess the broader hydrological impacts of climate change on coastal systems.

While similar research has been conducted in larger coastal regions like Spiekeroog and the Sand Engine, this study uniquely applies the approach to a compact, heavily engineered coastline. The Belgian coast presents distinct challenges, including its relatively small scale and the complexity of balancing natural and human-influenced processes. By addressing these challenges, the study contributes novel insights into the application of engineered dune systems as a nature-based solution.

Preliminary findings emphasize the importance of steady-state analysis in establishing baseline conditions and understanding autonomous salinization processes. The transient simulations demonstrate the potential for the freshwater lens to enhance resilience against saltwater intrusion, even under significant sea-level rise scenarios. These results underscore the importance of iterative calibration and scenario testing in building reliable models that can inform policy and engineering interventions.

This research highlights the critical role of groundwater modelling in advancing coastal resilience strategies. The study offers a replicable framework for addressing groundwater challenges in vulnerable coastal regions worldwide by integrating historical data with robust calibration techniques and future projections. Its findings provide actionable insights for managing freshwater resources and mitigating the impacts of climate change through innovative, nature-based solutions.

Keywords
Groundwater Modelling; Coastal Resilience; Engineered Dune Systems; Belgian Coast; Climate Projections; Saltwater Intrusion; Freshwater Lens; Sea-Level Rise