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How does coastal groundwater quality evolve over geological time scales? A paleo modeling framework for a coastal groundwater system in Northwestern Germany

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Coastal groundwater systems are critical freshwater resources sustaining millions of people as well as coastal ecosystem health. Thus, their hydrogeochemical state is essential for the sustainability of coastal zones. While it is conceptually understood that coastal groundwater systems reflect the complex legacy of natural and anthropogenic dynamics across various tempo-spatial scales, the broader hydrogeochemical evolution of coastal groundwater systems at the catchment scale and over geological time scales remains poorly constrained. This study addresses this gap by quantifying how Holocene environmental dynamics as well as anthropogenic activities have shaped the hydrogeochemical evolution of a coastal groundwater system in Northwestern Germany, located along the North Sea. 2-D cross-sectional reactive transport models were developed for this purpose, utilizing the parallelized version of the reactive transport simulator PHT3D. The numerical models integrated important hydrological drivers during the Holocene: sea-level rise, paleogeographic evolution, coastal morphodynamics, dyke construction, as well as agricultural drainage. The reaction network of the models regarded the major ion chemistry, redox processes coupled to organic matter degradation, ion exchange processes as well as mineral dissolution/precipitation of relevant mineral phases. These processes were simulated over 9,000 years, capturing transitions from naturally developing salt marshes and swamps to anthropogenic land use. Results demonstrate that the current hydrogeochemical state is a direct archive of the Holocene environmental history. The progressive landward migration of saline water during transgression created long-lasting hydrogeochemical imprints, and sea-level rise as well as paleogeographic evolution were identified as important controls of the major ion and redox chemistry. Hence, our models indicate that hydrogeochemical patterns in coastal groundwater systems cannot be fully resolved without accounting for past boundary conditions and employing reactive modeling frameworks. This underscores the need for process-based reactive transport modeling approaches to reconstruct paleo water quality baselines, serving as important information for the sustainable management of coastal groundwater systems.