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Increasing threat of coastal groundwater hazards from sea-level rise in California

K. M. Befus[1,2] ✉, **P. L. Barnard**[3], **D. J. Hoover**[3], **J. A. Finzi Hart**[3] and **C. I. Voss**[4]

Projected sea-level rise will raise coastal water tables, resulting in groundwater hazards that threaten shallow infrastructure and coastal ecosystem resilience. Here we model a range of sea-level rise scenarios to assess the responses of water tables across the diverse topography and climates of the California coast. With 1 m of sea-level rise, areas flooded from below are predicted to expand ~50–130 m inland, and low-lying coastal communities such as those around San Francisco Bay are most at risk. Coastal topography is a controlling factor; long-term rising water tables will intercept low-elevation drainage features, allowing for groundwater discharge that damps the extent of shoaling in ~70% (68.9–82.2%) of California's coastal water tables. Ignoring these topography-limited responses increases flooded-area forecasts by ~20% and substantially underestimates saltwater intrusion. All scenarios estimate that areas with shallow coastal water tables will shrink as they are inundated by overland flooding or are topographically limited from rising inland.

Over the next century, rising sea levels are predicted to cause widespread inundation of coastal terrestrial areas[1,2], wetland loss[3] and more severe nuisance flooding[4,5]. Relative sea levels are projected to increase for much of Earth's coastlines[6], presenting a wide range of coastal hazards for the ~1 billion people living in low-elevation coastal areas by 2050 (ref. [7]). Along with the increasing exposure of coastal communities to overland flood risk[1,8,9], rising sea levels will cause unconfined coastal groundwater levels (that is, water tables) to rise, leading to inland flooding hazards via subsurface connections to the sea[10]. An improved understanding of the physical controls on the severity of the groundwater hazards caused by sea-level rise (as opposed to human-induced controls, such as pumping causing saltwater intrusion) is therefore urgently needed.

Compared with the impacts of direct marine inundation, the responses of groundwater to sea-level rise may lead to earlier, more severe or longer-term[11] hazards to terrestrial water resources[1,12,13], ecosystems[14,15] and infrastructure[10,16–18] and could contribute substantially to the projected hundreds of millions of people displaced by climate change over the next century[19,20]. Coastal water tables are dynamically connected to sea levels, with inland spatio-temporal responses dictated by the frequency and magnitude of forcing events[21,22]. Unconfined aquifers in hydraulic connection with rising seas experience shoaling of water tables as the higher sea level and the intrusion of denser marine water force water tables higher[10,23]. As water tables rise, groundwater discharge to receiving drainage networks may initiate or intensify[24].

Groundwater systems respond hydraulically to sea-level rise over a continuum between two primary modes[12,13,23]: (1) water tables rise the same amount as sea levels where thick, overlying unsaturated zones can accommodate additional groundwater storage, termed the flux-controlled or recharge-limited mode; and (2) water tables rise less than sea levels and instead discharge some of the original storage to existing or new drainage networks as saline intrusion displaces the fresh groundwater, termed the topography-limited or head-controlled mode. The hydrogeologic setting, which combines geology and climate, controls the hydraulic mode[13] and the vulnerability of the aquifer to seawater intrusion[12,25], the amount of fresh groundwater flowing through the aquifer, and the rate of submarine groundwater discharge and its role in transporting terrestrial chemicals to marine waters[26]. At the global scale, it is estimated that 16–78% of coastal groundwater systems could be topography limited (using one-dimensional analytical solutions with coarse topographic and geologic data)[13], but these estimates have not been refined at smaller scales. Many analyses of coastal groundwater with future sea-level rise adopt the flux-controlled mode[10,16,27,28], but selecting one mode to represent all groundwater can bias the analysis[29], and the implications of this assumption have not been extensively tested.

Here, we use a numerical modelling approach to test how groundwater beneath diverse coastal landscapes responds to rising sea levels. In this initial application to coastal California, the first large-scale, high-resolution analysis of the groundwater hazards resulting from sea-level rise is presented. The extent of future groundwater shoaling along California's coast is forecast, and the prevalence of flux-controlled and topography-limited conditions is then identified. Finally, the relevance of these conditions for future coastal management decisions is discussed. The focus is on the California coast, but the modelling approach is flexible and can be applied to coastal settings worldwide.

Approach

Modelled forecasts for present-day and future equilibrium water-table depth conditions used both present-day local mean sea level (LMSL) and mean higher high water (MHHW) tidal datums as end members for the long-term position of the water table at the coast, with sea-level rise added to these datums for the analysed scenarios. Model hydrogeology was conceptualized in a simple manner, with uniform aquifer thickness along the coastline, a horizontal impermeable bottom at −50 m NAVD88 and homogeneous hydraulic conductivity (K). Given unknown aquifer properties, a different value of K (0.1, 1 and 10 m d^{-1}) was used for each of the models run for each tidal datum, allowing the generation of a

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[1] Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY, USA. [2] Department of Geosciences, University of Arkansas, Fayetteville, AR, USA. [3] Pacific Coastal and Marine Science Center, United States Geological Survey, Santa Cruz, CA, USA. [4] Water Mission Area, United States Geological Survey, Menlo Park, CA, USA. ✉e-mail: kmbefus@uark.edu