Supporting information for the paper:

Field-scale modelling reveals dynamic groundwater flow and transport patterns in a high-energy subterranean estuary

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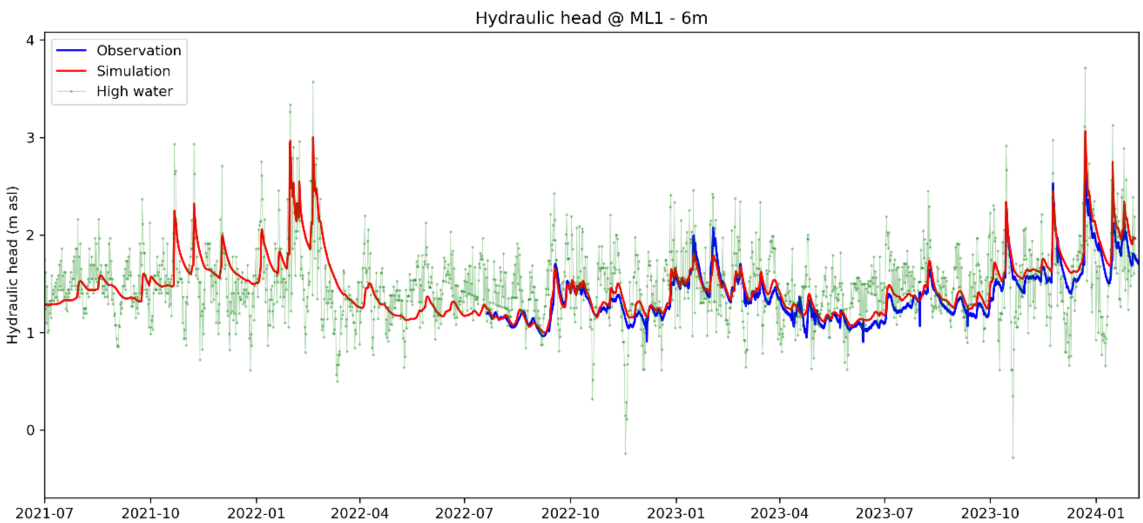

Figure S1: Simulated (red) and observed (blue) hydraulic heads at ML1-6m, and high water level (green) as sum of high tide and wave setup.

Calculation of the monthly groundwater recharge

Groundwater recharge information for Spiekeroog Island was available from the regional water balance model mGROWA22 (Hajati et al., 2022) only until 2020, which calculated an annual recharge of 400-450 mm/a for the area upstream (i.e. south) of the investigated field site. In order to cover the entire simulation period, especially the period where detailed field data exists (July 2022 - February 2024), available monthly climatic water balance data from the nearby barrier island Norderney (30 km west of Spiekeroog) provided by the German Weather Service (DWD) was used in conjunction with the mGROWA22 estimated average groundwater recharge. For that the following assumptions were made: (i) For a negative climatic water balance (i.e., precipitation is less than potential evapotranspiration), no loss of groundwater due to evapotranspiration occurred and the monthly groundwater recharge was set to zero. This is justified as the mGROWA-calculated loss related to evapotranspiration during the summer was less than 2% of the total annual groundwater recharge. (ii) if positive, the climatic water balance on Norderney, scaled by the mGROWA-based average annual recharge of 425 mm/a on Spiekeroog, reflects the monthly groundwater recharge on Spiekeroog.

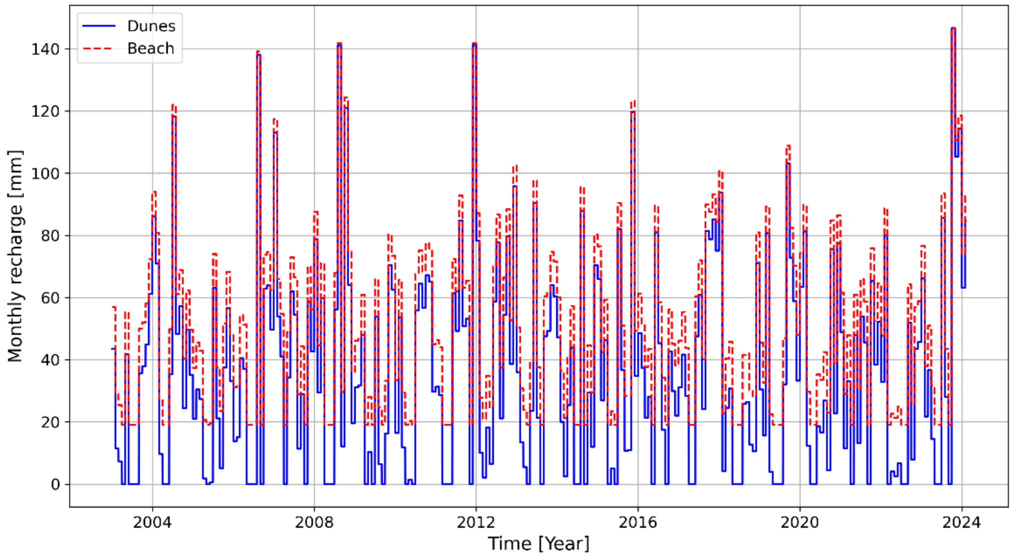

Figure S2: Applied monthly groundwater recharge in dune and beach areas.

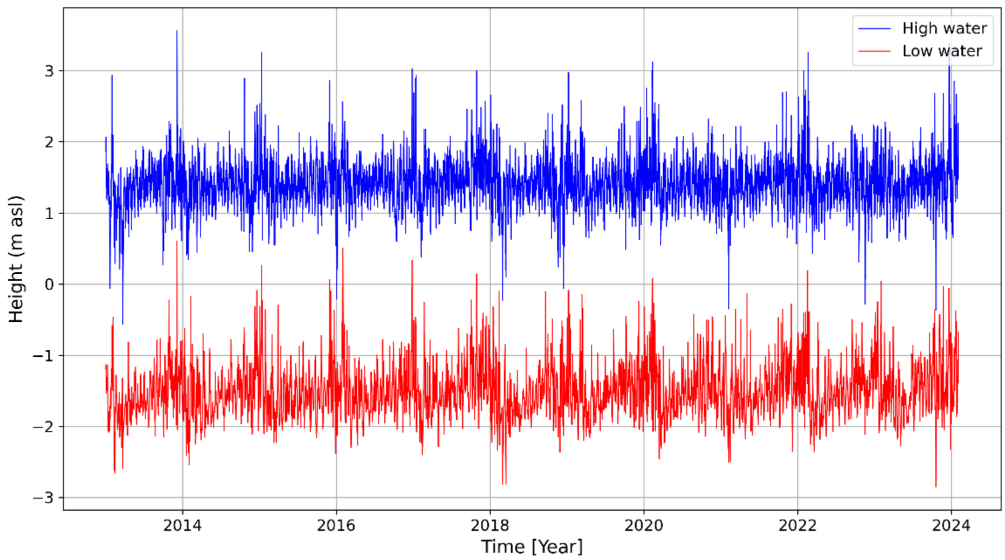

Figure S3: High and low tide level from employed tide time series.

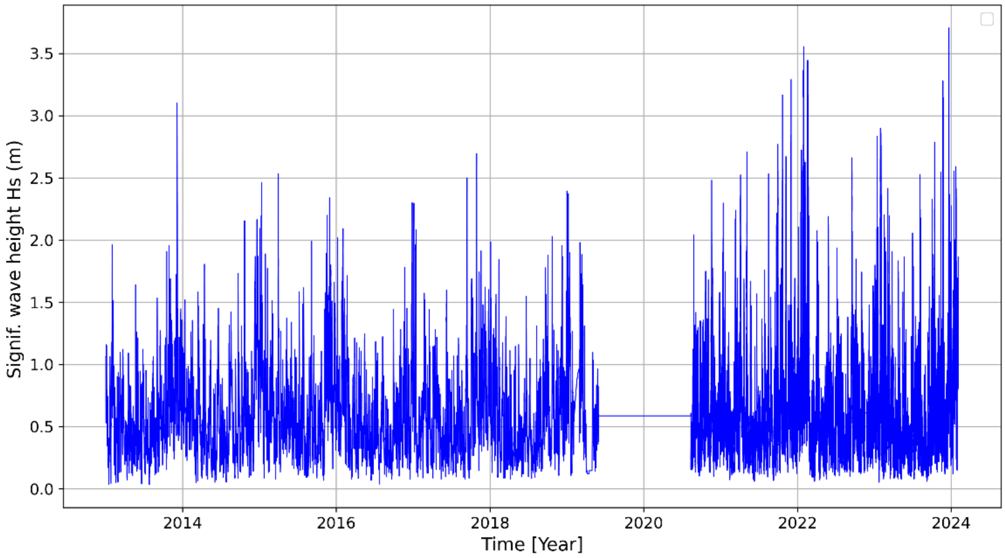

Figure S4: Employed significant wave height for the calculation of the wave set up. Missing data were filled with the mean significant wave height.

Calculation of tide-averaged hydraulic heads at the seaside boundary condition

The applied hydraulic head at the seaside boundary was a function of local topographic height, tidal signal and significant wave height, based on the tide-averaging approach of Nuttle (1991). In this approach it is assumed that a location on the aquifer-sea boundary below the high tide mark receives a hydraulic head equal to the topographic height if the tide is lower than the topography at this position. Hence it is assumed that the time to drain the aquifer is not sufficient to significantly lower the groundwater level during ebbing tide. Or in other words, seepage is assumed everywhere along the un-inundated beach face between high water mark and actual sea level position. If the actual tide elevation is higher than the respective location, the hydraulic head is equal to the tidal elevation. Averaging the hydraulic head over time for each position over a tidal period results in a curve that declines from the topographic elevation at the high tide mark to zero at the low tide mark and beyond. The approach of Nuttle (1991) was extended by adding the wave setup using an empirical formulation by Nielsen (2009):

$$\eta = \frac{0.4 H_{RMS}}{1 + 10 \dfrac{D + \eta}{H_{RMS}}} \tag{1}$$

where η is the phase-averaged increase above the still water level (i.e., the actual seawater level without waves) depending on root-mean-square wave height H_{RMS} and still water depth D. The root-mean-square wave height H_{RMS} can be calculated from the significant wave height H_{sig} as $H_{RMS} = 0.5\sqrt{2} H_{sig}$ (Holthuijsen, 2007).

For each minute data the actual hydraulic head was calculated from tide-level and wave setup at a given position, and then averaged over time for a whole tidal cycle by Nuttle’s approach.

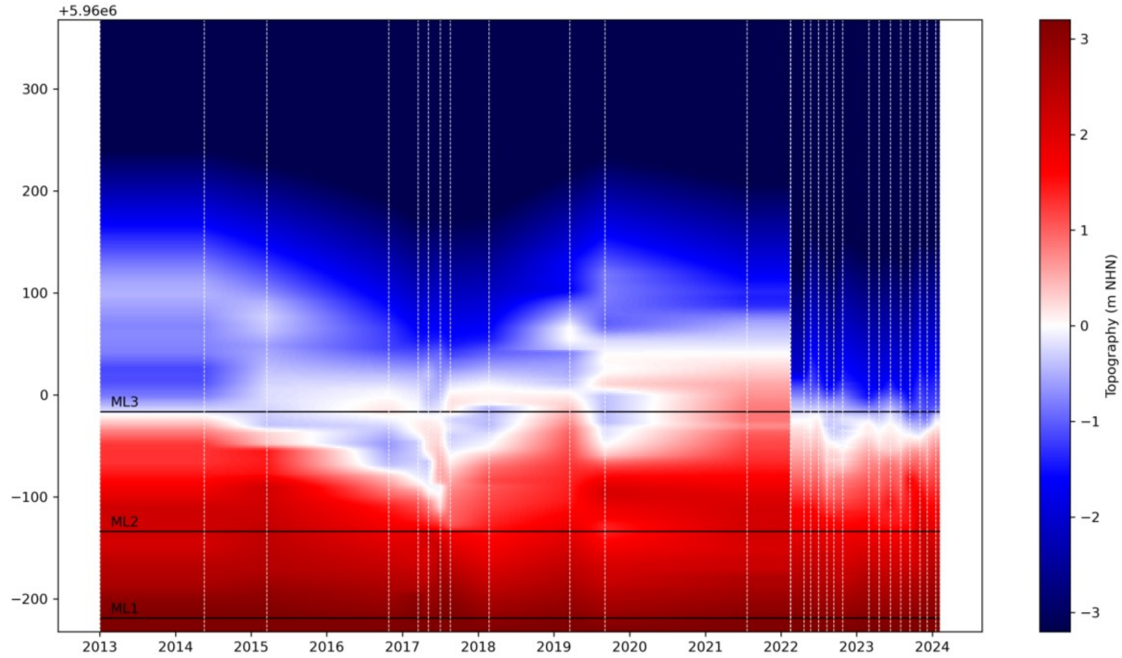

Figure S5: Evolution of beach topography with time. Vertical dashed lines indicate time points of measurements. The y-axis is given in UTM32-North.

Video S1: Animation that shows simulated Salinity, groundwater age and temperature along the modelled cross-section at the study site between July, 2016 and February, 2024.

References

Holthuijsen, L.H., 2007. Waves in Oceanic and Coastal Waters. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511618536

Nuttle, W.K., 1991. Comment on “Tidal dynamics of the water table in beaches” by Peter Nielsen. Water Resources Research 27, 1781–1782. https://doi.org/10.1029/91WR00939