Tidal, spring-neap, and seasonal dynamics of a saltwater-freshwater mixing zone in a beach aquifer

James W. Heiss[1] and Holly A. Michael[1,2]

[1]Department of Geological Sciences, University of Delaware, Newark, DE, USA

[2]Department of Civil and Environmental Engineering, University of Delaware, Newark, DE USA

ABSTRACT

The fate of chemicals discharging to the marine environment through submarine groundwater discharge may be influenced by physical flow and transport processes in the beach aquifer. A more comprehensive understanding of beach hydrodynamics over a range of time scales will thus aid in more accurately estimating chemical fluxes to coastal surface waters. The combined effects of tidal stage, tidal amplitude, and seasonal upland water table oscillations on the salinity distribution and flow dynamics in a tide-dominated sandy beach were investigated over one year using field measurements and variable-density numerical modeling. Measurements and simulations revealed an intertidal saline circulation cell with a structure and cross-sectional mixing zone area that varied over tidal, spring-neap, and seasonal time scales. Seasonal upland water table oscillations were the most important factor controlling the size of the mixing zone, followed by tidal amplitude and tidal stage. The size of the circulation cell expanded as the upland water table declined. The expansion of the cell displaced the fresh discharge zone and offshore interface seaward. The saltwater circulation cell shifted from below the upper beachface to the low tide mark in response to a change in tidal amplitude over a spring-neap cycle. Tidal stage had minimal effect on the salinity distribution in the intertidal zone over a semidiurnal tidal cycle. Seasonal variation of mean sea level did not appear to influence intertidal salinity. Salinity measurements one day following Hurricane Sandy suggest that the beach aquifer adjusted quickly after a moderate storm surge and enhanced terrestrial fresh groundwater inflow from rainfall. The highly transient nature of beach aquifer salinity over multiple time scales may have important implications for the types and rates of chemical transformations that occur in groundwater prior to discharge to the ocean.

INTRODUCTION

The intertidal and nearshore zones of beach aquifers host a significant proportion of total SGD [Li et al., 1999] and a biogeochemically active mixing zone [Charette and Sholkovitz, 2002]. These reactive environments can affect the fate of land-derived chemicals discharging to the nearshore zone. [see review in Slomp et al., 2004]. Since biogeochemical reactivity in the intertidal zone may be linked to subsurface salinity [e.g. Ullman et al., 2003], a better understanding of physical flow and transport processes in the beach aquifer will aid in more accurately predicting chemical fluxes to the coastal ocean.

A brackish to saline circulation cell forms beneath the intertidal zone as waves and tides drive seawater into the beach aquifer [Lebbe, 1999; Michael et al., 2005; Robinson et al., 2006]. The resulting hydraulic head gradients cause seawater to circulate, initially downward and then seaward above a region of terrestrial fresh groundwater that discharges at the base of the beach. A freshwater-saltwater mixing zone forms along the perimeter of the circulation cell due to hydrodynamic dispersion. Field and numerical modeling studies demonstrate that the circulation cell can respond to tidal stage [e.g. Befus et al., 2013], tidal amplitude [Robinson et al., 2007; Abarca et al., 2013] and precipitation, however the importance of seasonal osillations in terrestrail freshgroundwater inflow have not been investigated in the field. Further, the combined affects of these driving mechansisms (tidal stage, tidal amplitude, and seasonal terrestrial freshwater gradients) have not yet been combined into a continuous variable-density numerical model.

METHODS

Field measurements were combined with a variable-density numerical to identify the physical forcing conditions and time scales that are most important for affecting intertidal salinities. The study was conducted in the intertidal zone of a tide-dominated sandy beach at Cape Henlopen, USA. Pore water was sampled for salinity in the intertidal zone over one continuous year to obtain profiles over a tidal cycle (n=7), spring-neap cycle (n=7), seasonal cycle (n=14), and one day following the landfall of Hurricane Sandy (n=1). Water table elevation 33 m behind the dune was recorded every 15 minutes over the one year timeframe. Tide levels were taken from a nearby (<1 km) tide gauge station (NOS tidal station 8557830, Lewes, Delaware). The variable-density groundwater flow and solute transport code SEAWAT (*Langevin et al*., 2008) was combined with the Periodic Boundary Condition package [Post, 2011] to simulate flow and transport in the beach aquifer. The boundary conditions of the cross-sectional model were a time-varying head boundary along the landward boundary to represent seasonal water table fluctuations, and a 5-constituent tidal signal along the aquifer-ocean interface (bottom panel; Figure 1). Aquifer parameters and the amplitude of the head fluctuation at the landward boundary was adjusted until simulated heads and concentrations over the year timeframe, and groundwater velocities at the time of the tracer test reasonably matched field measurements. The aquifer-ocean interface was set was zero-concentration gradient for outflow and a constant concentration (28) for inflow. The landward boundary was a constant concentration (0).

RESULTS

Hydraulic heads and salinities in the coastal aquifer varied over tidal, spring-neap and seasonal time scales. The water table behind the dune fluctuated between 5 and 10 cm over a tidal cycle, 10-25 cm over a spring-neap cycle, and 30 cm seasonally (top panel; Figure 1). The cross-sectional area of the saltwater-freshwater mixing zone along the perimeter of the circulation cell also varied over the three time scales. Over a tidal cycle, the area fluctuated up to 3 m^2 and was generally largest 3-4 hours after high tide (Figure 2a). The area fluctuated by about 10 m^2 over 14 day spring-neap cycles, with a 4-5.5 day lag between spring tide and the largest area (Figure 2b). The area varied the most in response to seasonal inland water table oscillations, varying up to 115 m^3. The area at this time scale varied inversely with the water table behind the dune; the area was largest when the water table was at its yearly maximum, and largest when the water table was at its yearly minimum (Figure 2c). These results, which show the importance of seasonality on saltwater-freshwater mixing in beach aquifers, were qualitatively supported by the field observations.

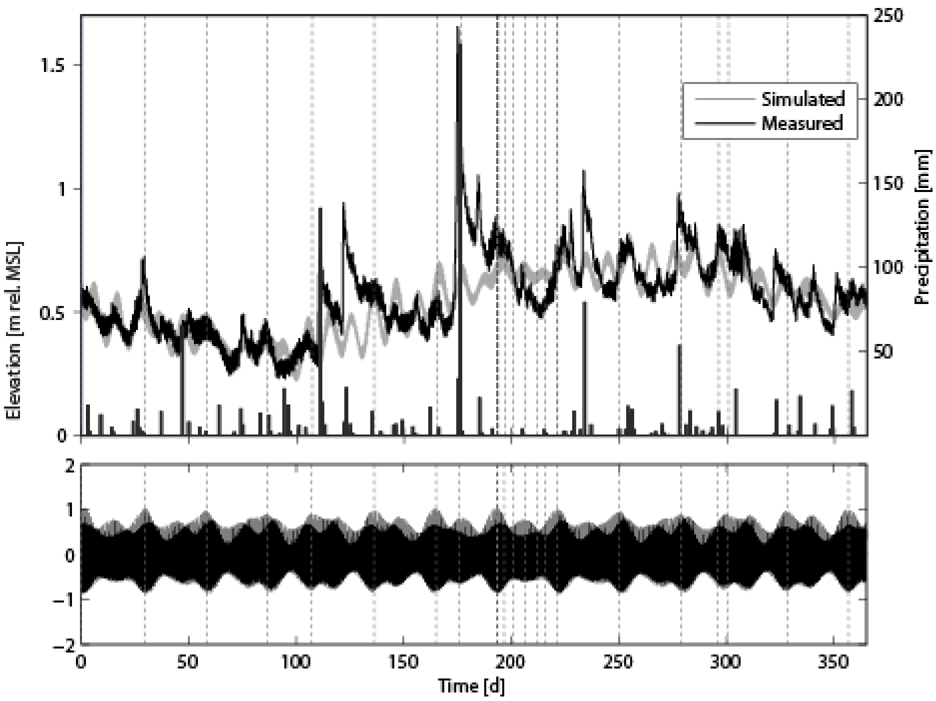

Figure 1. Measured and simulated head 33 behind the dune with precipitation (top panel). Tidal signal used in the model (bottom panel).

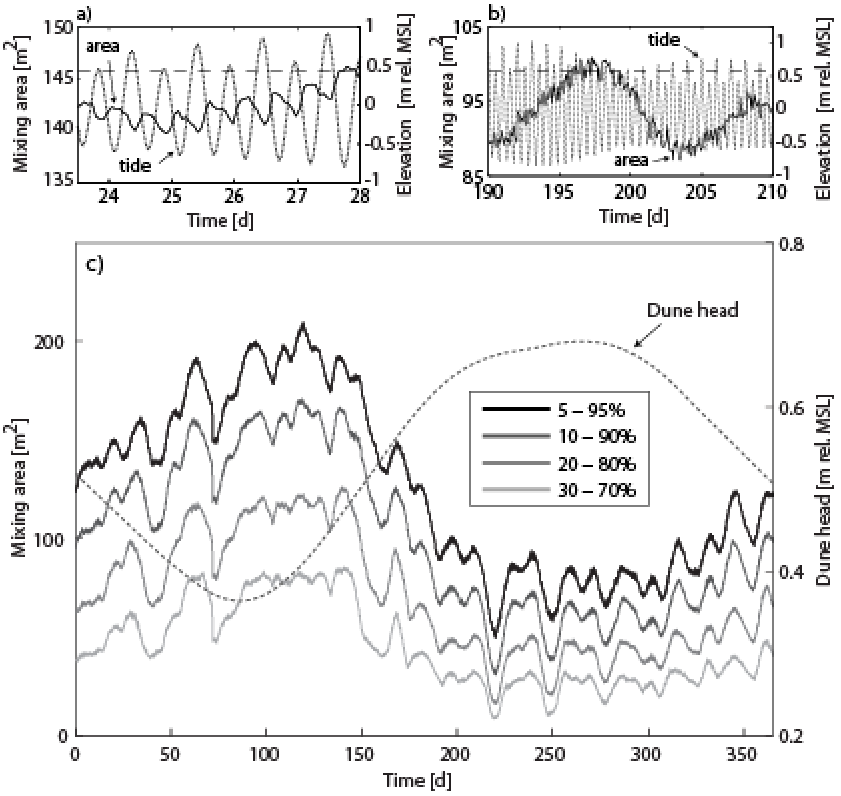

Figure 2. Area of mixing zone over a) tidal cycles; b) spring-neap cycle for the 5 -95% saltwater contours; c) mixing zone area over the one year simulation period for a range of salinity contours.

REFERENCES

Abarca, E., H. Karam, H. F. Hemond, and C. F. Harvey. 2013. Transient groundwater dynamics in a coastal aquifer: The effects of tides, the lunar cycle, and the beach profile, Water Resources Research 49, 1–16, doi:10.1002/wrcr.20075.

Befus, K. M., M. B. Cardenas, D. V. Erler, I. R. Santos, and B. D. Eyre. 2013. Heat transport dynamics at a sandy intertidal zone. Water Resources Research 49(6): 3770–3786. doi:10.1002/wrcr.20325.

Charette, M. A., and E. R. Sholkovitz. 2002. Oxidative precipitation of groundwater-derived ferrous iron in the subterranean estuary of a coastal bay, Geophysical Research Letters 29(10): 1444, doi:10.1029/2001GL014512.

Langevin, C. D., D. T. Thorne Jr, A. M. Dausman, M. C. Sukop, and W. Guo. 2008. SEAWAT version 4: A computer program for simulation of multi-species solute and heat transport, Technical Report, in U.S. Geological Survey Techniques and Methods Book 6, Chapter A22, 39 pp.

Lebbe, L. 1999. Parameter identification in fresh-saltwater flow based on borehole resistivities and freshwater head data, Advances in Water Resources 22(8):791–806.

Li, L., D. A. Barry, F. Stagnitti, and J. Y. Parlange. 1999., Submarine groundwater discharge and associated chemical input to the coastal sea, Water Resources Research 35(11), 3253-3259.

Michael, H. A., Mulligan, A. E., and C. F. Harvey. 2005. Seasonal oscillations in water exchange between aquifers and the coastal ocean. Nature 436: 1145–1148.

Post, V. E. 2011. A new package for simulating periodic boundary conditions in MODFLOW and SEAWAT, Computers and Geosciences 37(11): 1843–1849.

Robinson, C., B. Gibbes, and L. Li. 2006. Driving mechanisms for groundwater flow and salt transport in a subterranean estuary, Geophysical Research Letters 33: L03402. doi:10.1029/2005GL025247.

Robinson, C., B. Gibbes, H. Carey, and L. Li. 2007. Salt-freshwater dynamics in a subterranean estuary over a spring-neap tidal cycle, Journal of Geophysical Research 112(C9): 1–15. doi:10.1029/2006JC003888.

Slomp, C. P., and P. Van Cappellen. 2004. Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact. Journal of Hydrology 295: 64–86. doi:10.1016/j.jhydrol.2004.02.018.

Ullman, W. J., B. Chang, D. C. Miller, and J. A. Madsen. 2003. Groundwater mixing, nutrient diagenesis, and discharges across a sandy beachface, Cape Henlopen, Delaware (USA). Estuarine, Coastal Shelf Science 57: 539-52.

Contact Information: Holly. A. Michael; 302-831-4197; hmichael@udel.edu