Salinity and groundwater flow below beaches

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1. Introduction

High rates of exchange between seawater and fresh groundwater in beach sediments drive significant chemical reactions, but the groundwater flow that controls this is poorly understood. Current conceptual models for groundwater flow in beaches highlight an upper saline plume, which is separated from the traditional freshwater-saltwater interface by a zone of brackish to fresh groundwater discharge (Fig.2b).

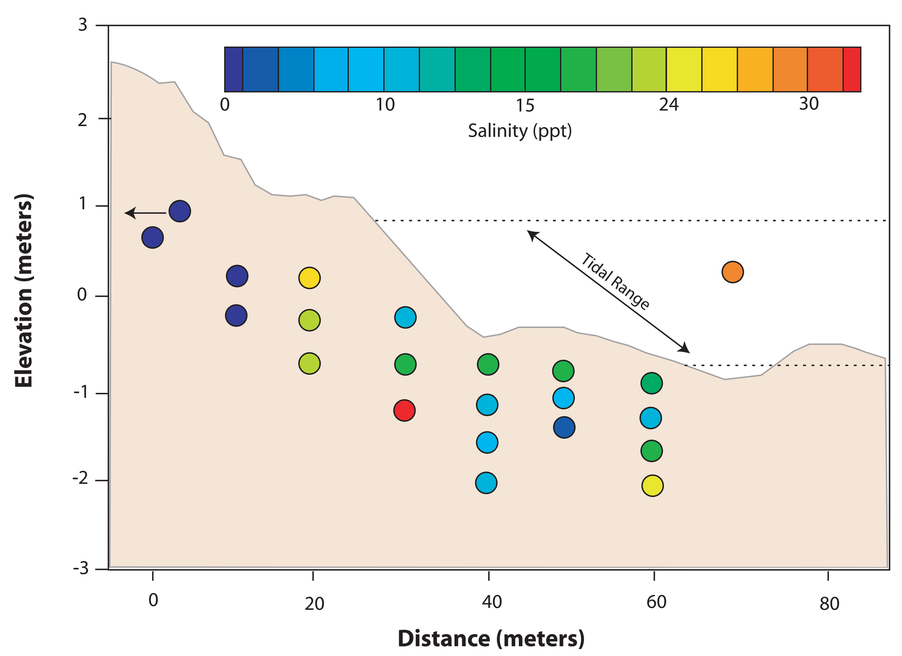


Figure 1. Salinity distribution of pore water in a beach on Cape Henlopen, Delware. After *Ullman et al.* (2003). Field measurements to delineate nutrient diagenesis and groundwater discharge in a sandy beach in Cape Henlopen, Delaware suggest the presence of a complex mixing zone between groundwater masses, but no distinct upper saline plume (Ullman et al., 2003).

Motivated by the absence of an upper saline plume at our field site in Southeastern Georgia, we questioned whether or not an upper saline plume exists in all beaches.

2. Conceptual Model

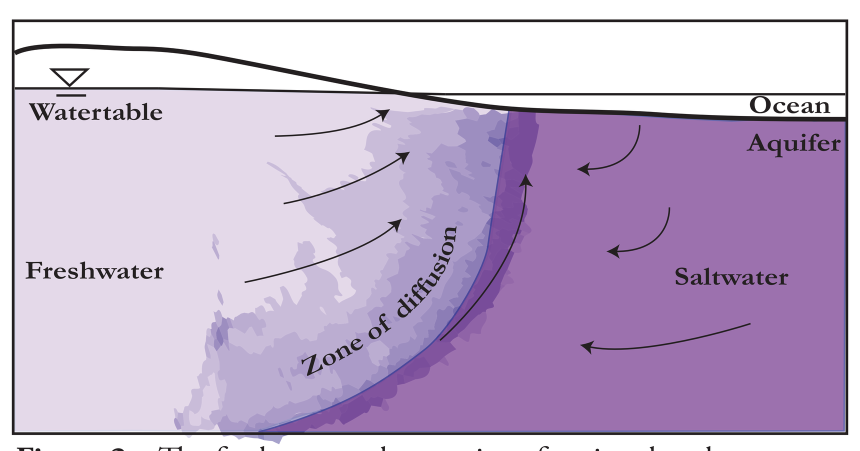


Figure 2a. The freshwater-saltwater interface in a beach. After *Cooper* (1959).

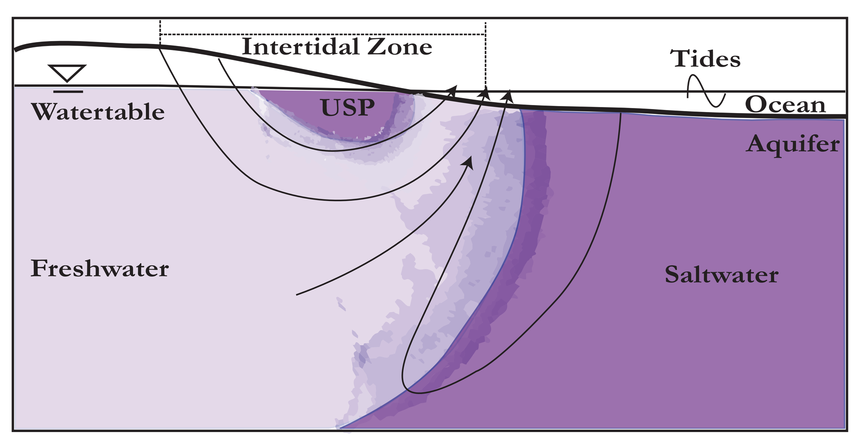


Figure 2b. The upper saline plume and associated flow paths. After *Robinson et al.* (2006).

3. Purpose

The lack of an upper saline plume at our study site led us to ask whether the plume exists in all beaches and what hydrogeological features control its formation. We wanted to show that an upper saline plume is not present in every beach. Major hydrogeologic properties such as hydraulic gradient, beach slope, permeability, dispersion and fresh groundwater flux control whether or not a beach can sustain an upper saline plume.

4. Methods

Simulations of semi-diurnal tidal fluctuations in five beach domains were conducted using SUTRA (Voss and Provost, 2002). We used variable-density, saturated-unsaturated, transient groundwater flow models to investigate the geometry of the freshwater-saltwater interface in beaches with slopes varying from 0.1 to 0.01. We also varied hydraulic conductivity, dispersivity, tidal amplitude, inflow of fresh groundwater and precipitation. In these simulations, we solved a modified version of the Richards equation that handles changes in overlying stress due to tidal loading (Wilson and Gardner, 2006).

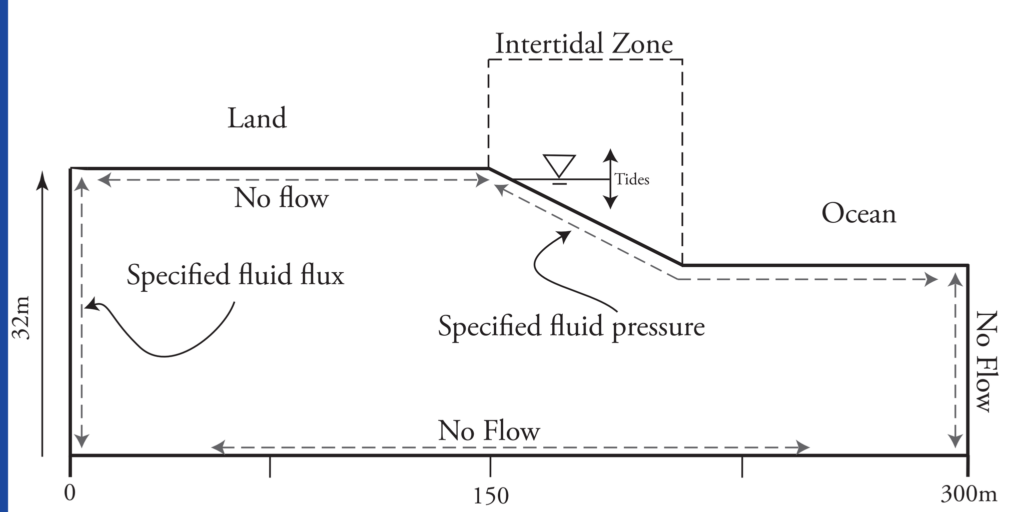
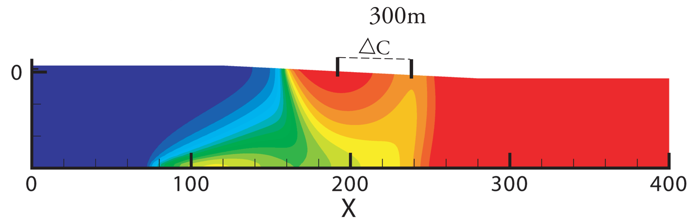


Figure 3. An example of one model domain and boundary conditions used for the beach simulations. The surface boundary condition accounts for tidal inundation by specifying a pressure at a point based on the height of the column of seawater above that point. If a node along the surface of the domain is exposed, the pressure is specified according to the saturation of the sediment. This allows for the formation of either a seepage face or the input of precipitation at a defined rate. Groundwater discharges when the water table intersects land surface, infiltration occurs if the water table drops below land surface.

*Average concentration gradients were measured for each simulation from the center of the upper saline plume to the center of the seepage face that developed directly seaward.



5. Sensitivity Analysis

Table 1. Parameters tested in the sensitivity analysis. A total of 105 separate simulations were run until they reached quasi-equilibrium. We tested 5 beach slopes ranging from 0.01 to 0.1 to constrain the effect of intertidal zone slope on the development of an upper saline plume. We also performed a sensitivity analysis on the 5 different model domains, systematically varying tidal amplitude, dispersivity, freshwater inflow and permeability.

Beach Slope	Tidal Amplitude (m)	Dispersivity (m) (α_L, α_T)	Freshwater Flux (m/s)	Hydraulic Conductivity (m/d)
0.01	0.5	(0.5, 0.05)	7.6E-08	0.1
0.025	0.75	(1, 0.1)	7.6E-07	1
0.05	1.0	(2.5, 0.25)	7.6E-06	10
0.075	1.25	(5, 0.5)	7.6E-05	100
0.1	1.5	(7.5, 0.75)	7.6E-04	
		(10, 1)		

6. Model Results

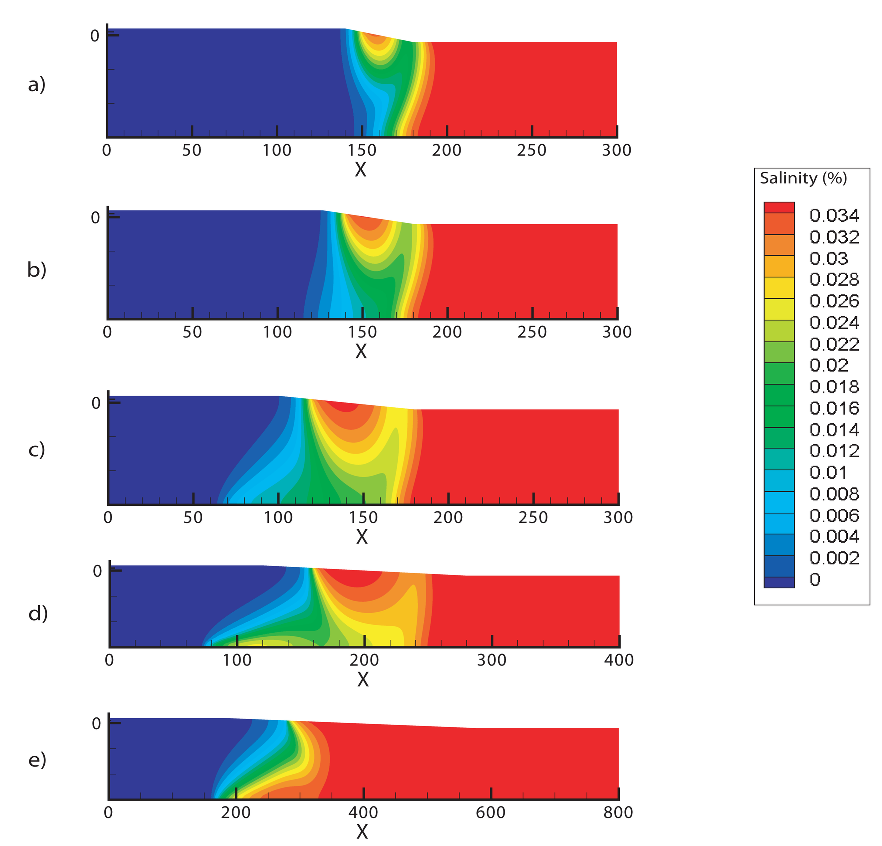


Figure 4. Simulation results for beaches with intertidal zone slopes of (a) 0.1, (b) 0.075, (c) 0.05, (d) 0.025 and (e) 0.01. The magnitude of the concentration gradient decreases with decreasing beach slope. No upper saline plume is present in model (e). Vertical exaggeration is 2:1 for models (a) through (d) and 4:1 for model (e).

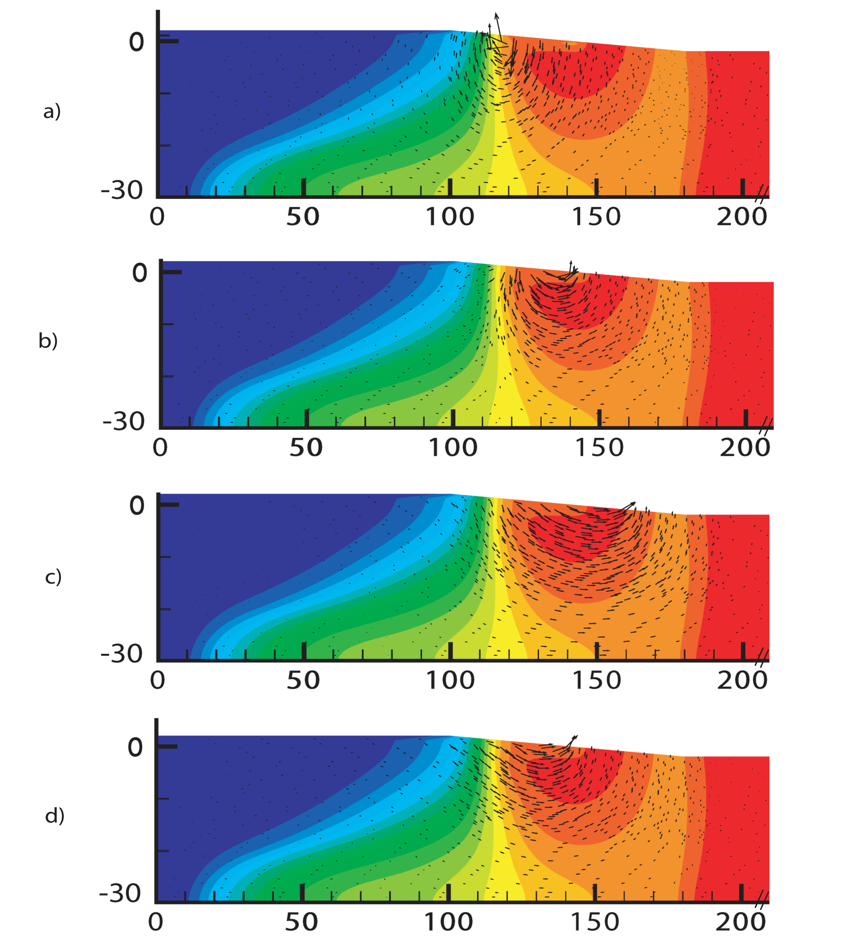


Figure 5. Simulation results for a beach with intertidal zone slope of 0.05 during (a) High tide, (b) Ebb tide, (c) Low tide and (d) Flood tide. Vectors indicate velocity. As indicated by the salinity contours, the concentration gradient between the center of the upper saline plume and the seaward seepage face was small. Water discharging had a salinity of ~31 ppt and the salinity of the upper saline plume was 34 ppt. Pore water salinities did not have a lot of variability throughout the tidal cycle. Seawater circulated into the coastal aquifer when the beach was inundated by the tide and discharged back into the ocean during falling tide.

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7. Synthesis

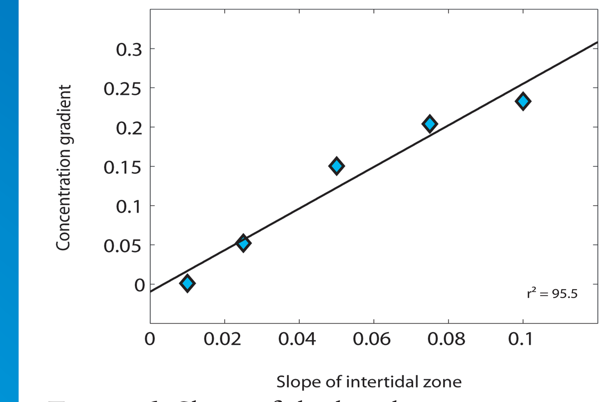

Figure 6. Slope of the beach vs. concentration gradient.

- All simulations showed that a salinity gradient developed between the fresh groundwater and seawater in the subsurface.
  - The magnitude of the gradient was highly variable.
  - The geometry of the freshwater-saltwater interface was also variable.
- An upper saline plume was not present in every model.
- The slope of the intertidal zone was an important control on the development of an upper saline plume (Fig. 5).
  - Higher beach slopes supported higher concentration gradients (more prominent upper saline plumes).
- A permeability of 1.2 x 10^{-11} m^2 allowed the highest concentration gradients to develop in beaches with slopes of 0.05 or greater (Fig. 6a).
  - No upper saline plumes formed in any beach with permeabilities less than 1.2 x 10^{-11} m^2.
  - Beaches with shallow slopes developed weak upper saline plumes with a permeability of 1.2 x 10^{-10} m^2.

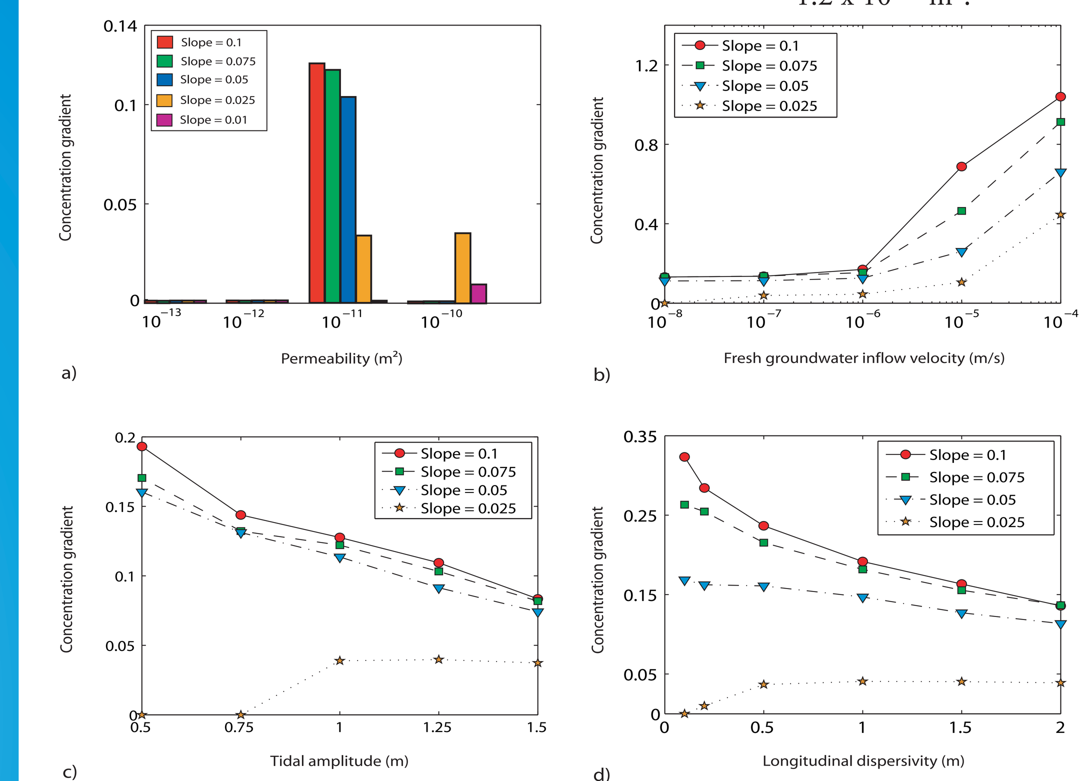

Figure 7. Simulation results for tested parameters vs. concentration gradient.

- Concentration gradients were approximately constant for inflow velocities of ~10^{-8} to 10^{-6} m/s, increasing drastically for velocities 7.6 x 10^{-6} m/s and greater (Fig. 6b).
  - No upper saline plumes formed in beaches with a slope of 0.01 regardless of fresh groundwater flux.
- Tidal amplitude did not have a drastic effect on the magnitude of the concentration gradient (Fig. 6c).
  - Concentration gradients for beaches with slopes between 0.05 and 0.1 were inversely proportional to tidal amplitude.
- For beaches with slopes of 0.05 or greater, dispersivity and concentration gradient were inversely proportional (Fig. 6d).
  - A longitudinal dispersivity of 0.5 m and a transverse dispersivity of 0.25 m were the minimum values in a beach with a slope of 0.025 required to sustain an upper saline plume.

8. Discussion

- The two most important hydrogeological controls on the development of an upper saline plume in a beach are the permeability and the slope of the intertidal zone.
- Grain size of the beach sediments is an important control for both beach slope (*Bascom 1951)* and permeability (*Wilson et al. 2008*).
- Due to the control that sediment grain size has on both the beach slope and permeability, grain size also has a significant effect on whether or not a beach can support an upper saline plume.
- The presence/absence of an upper saline plume in a beach can have implications for pore water exchange in the subsurface and remineralization (Robinson et al., 2007).
  - Fresh groundwater in a beach with no upper saline plume will undergo less exchange with oxygenated, saline pore water.
  - Fresh groundwater in a beach with a well-defined upper saline plume will undergo much greater exchange.
- Beaches without upper saline plumes could discharge less nutrients and dissolved metals to the coastal ocean due to decreased pore water exchange in the subsurface.

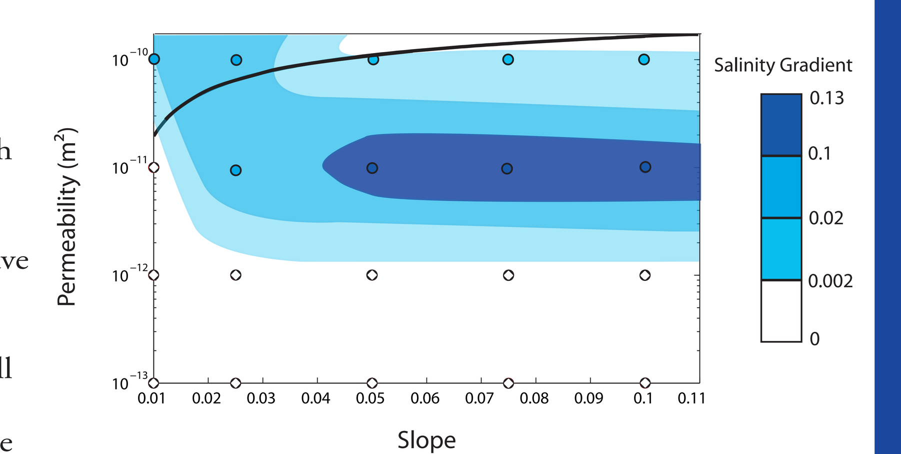

Figure 8. The strength an upper saline plume in a beach, as indicated by salinity gradient. Open circles represent simulation results. The trend line indicates permeability and beach slope associated with median grain size (d50) based on empirical observations (Bascom 1959, Wilson 2008).

9. Conclusions

- Steeper slopes of the intertidal zone on a beach support higher concentration gradients in the pore water and therefore have more distinct upper saline plumes.
- In the models using a permeability of 10^{-11} m^2, no upper saline plumes formed in beaches with a slope less than 0.05.
- The salinity of brackish groundwater that discharges seaward of the upper saline plume became less saline with higher fresh groundwater fluxes into the model.
- Prior studies of groundwater flow and salinity in beaches have used small dispersivities.
  - We found that the upper saline plume becomes much less distinct when larger dispersivities are used.
- Real beaches are highly mixed environments and the appropriate magnitude of dispersivity remains unclear.
- Our results suggest that upper saline plumes may not form in all beaches of the U.S. Southeast, which are characterized by fine-grained sands and moderate slopes.