Groundwater transport and the freshwater-saltwater interface below sandy beaches

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Abstract

Current conceptual models for groundwater flow in beaches highlight an upper saline plume, which is separated from the lower salt wedge by a zone of brackish to fresh groundwater discharge. There is currently limited knowledge of what conditions allow an upper saline plume to exist and what factors control its formation. We used variable-density, saturated-unsaturated, transient groundwater flow models to investigate the configuration of the freshwater-saltwater interface in beaches with slopes varying from 0.1 to 0.01. We also varied hydraulic conductivity, dispersivity, tidal amplitude and inflow of fresh groundwater. The simulated salinity configuration of the freshwater-saltwater interfaces varied significantly. No upper saline plumes formed in any beach with hydraulic conductivities less than 10 m/d. The slope of the beach was also a significant control. Steeper beach faces allowed stronger upper saline plumes to develop. Median sediment grain size of the beach is strongly correlated to both beach slope and permeability, and therefore the development of an upper saline plume. Prior studies of groundwater flow and salinity in beaches have used a range of theoretical dispersivities and the appropriate values of dispersivity to be used to represent real beaches remains unclear. We found the upper saline plume to weaken with the use of larger values of dispersivity. Our results suggest that upper saline plumes do not form in all beaches and may be less common than previously considered.

1. Introduction

Submarine groundwater discharge (SGD) has been shown to be a major contributor of nutrients, carbon and trace metals to the coastal ocean (Johannes, 1980; Whiting and Childers, 1989; Valiela et al., 1990; Krest et al., 2000; Burnett, 2001; Paytan et al., 2006; Moore, 2010). Sandy beaches and beaches comprised of a mixture of sand and pebble make up approximately 75% of ice-free coastlines (Brown and McLachlan, 2002). Due to the global presence of beaches, groundwater flow in beaches is an integral constituent of near-shore SGD. Significant volumes of water are transported through beach aquifers by tidal pumping (Robinson et al., 2007a; Santos et al., 2010, Santos et al., 2011) and by discharge of fresh groundwater from terrestrial watersheds (Kim and Hwang, 2002; Burnett et al., 2003; Taniguchi and Iwakawa, 2004; Santos et al., 2011). Wave forcing and wave set-up creates hydraulic gradients, also driving significant groundwater flow in the beach aquifer (Longuet-Higgins, 1983; Li and Barry, 2000; Sorenson, 2006; Xin et al., 2010). A distinct freshwater-saltwater interface develops in the beach subsurface where terrestrially derived fresh groundwater and recirculating seawater mix.

Moore (1998) termed the salt-freshwater mixing zone in a coastal aquifer the subterranean estuary, emphasizing similarities between surficial estuaries and the shallow groundwater system with respect to physical and biogeochemical processes. Redox gradients and the availability of dissolved nutrients in the subterranean estuary drive geochemical transformations (Buddemeier, 1996; Moore, 1996; Charette and Sholkovitz, 2002). Short residence times and rapid flow rates of recirculating seawater drive significant mixing in the beach aquifer, driving chemical fluxes across the aquifer-ocean interface (Uchiyama et al., 2000,

Ullman et al., 2002). Further knowledge of the hydrologic processes that occur in these subterranean estuaries is necessary for quantifying coastal geochemical budgets.

The distribution of salinity below beaches is an important indicator of the degree of mixing between fresh groundwater and seawater in the subterranean estuary (Galeati et al., 1992; Xue et al., 1995; Lebbe, 1999; Vandenbohede and Lebbe, 2006). This mixing between groundwater bodies is important as it sets up the potential for geochemical transformations to occur. The classic conceptual model for groundwater flow and solute transport under a beach describes flow of land-derived fresh groundwater toward the ocean, forming a salt-wedge, defined as a Ghyben-Herzberg freshwater-saltwater interface (Fig. 1a). Seaward of this interface, seawater recirculation through the aquifer is driven by differences in fluid density (Ghyben, 1889; Herzberg, 1901; Cooper 1959). Studies as recent as 10 years ago describe a salt-wedge freshwater-saltwater interface with no upper saline plume (Cartwright, 2004; Boehm et al., 2006). Field measurements from a sandy beach in Cape Henlopen, Delaware, suggest the presence of a complex mixing zone and nutrient diagenesis between terrestrial groundwater and recirculating seawater at the lower salt wedge (Ullman et al., 2002).

Other studies have significantly revised this conceptual model. In some beaches an upper saline plume (Fig. 1b) exists adjacent to the classic saltwater wedge, separated by an upward flow zone (freshwater tube) that discharges near the average low tide mark on the beach (Boufadel, 2000; Robinson et al., 2006b). Frequent tidal inundation of the beach surface allows saline water to infiltrate into the subterranean estuary and develop a plume of higher density water above less dense, fresher groundwater below. The upper saline plume is now a fixture of modern conceptual models for groundwater flow below beaches (Bratton, 2010; Santos et al., 2012; Thorn and Urish, 2013).

The configuration of the salinity distribution of the freshwater-saltwater interface has important implications for groundwater mixing and geochemistry in the subterranean estuary. *Robinson et al.* (2006a) showed that a beach with an upper saline plume can support a more dynamic zone of mixing in the subsurface than beaches with no upper saline plume. Oxygenated, recirculated seawater mixes with reduced groundwater and sets up a redox/pH potential for chemical transformations (Slomp and Cappellen, 2004; Spiteri et al., 2005). Fully defining the impact of upper saline plumes will require additional field monitoring, which in turn requires the ability to predict where an upper saline plume is likely to develop.

Motivated by the absence of the upper saline plume in several studies, as well as our own field site on Sapelo Island, Ga, we hypothesized that upper saline plumes do not exist in all beaches and their formation is controlled by major hydrogeologic properties such as beach slope, permeability, tidal amplitude, dispersion and fresh groundwater input. We constructed variable-density, saturated-unsaturated, transient groundwater flow models to perform a sensitivity analysis of the major factors controlling groundwater flow and salinity distribution in beaches.

1.1 Groundwater exchange below beaches

Although previous studies have not directly tested the effects of flow on the configuration of the salt distribution of the freshwater-saltwater interface, they have investigated the driving forces for flow through a beach. *Robinson et al.* (2007a) studied the rate of water exchange across the aquifer-ocean interface as driven by tidal pumping. They performed a sensitivity analysis of major nondimensional parameters related to tidally driven and density driven

recirculation (TDR and DDR, respectively) in beach aquifers. TDR pertains to flow through the subterranean aquifer that is driven by tidal forcing across a sloping beach face and is defined as the ratio of total infiltration due to tidal forcing to terrestrially-derived groundwater flux. DDR refers to density-driven convection of seawater through the beach aquifer driven by the strength of salinity gradients and is similarly defined as the ratio of total infiltration due to density-driven convection to terrestrially-derived groundwater flux. Of particular interest here is the nondimensional ratio of the width of the intertidal zone to tidal propagation distance (Li et al., 2000; Robinson et al., 2007a):

$$\varepsilon = A \cot(\beta) \lambda \quad (1)$$

where A is tidal amplitude, β is beach slope and λ is the tidal propagation distance:

$$\lambda = \sqrt{\frac{n_e \omega}{2KH}} \quad (2)$$

where n_e is effective porosity, ω is tidal period, K is hydraulic conductivity and H is aquifer depth. The distance described by equation (2) reflects the amplitude dampening of a tidal groundwater wave as it propagates into a beach aquifer (Nielsen, 1990). *Robinson et al.*, (2007a) held all parameters in equation (1) constant except beach slope (β) and tidal amplitude (A), both of which changed the horizontal shoreline excursion. Increasing the beach slope (decreasing ε) generally decreased TDR rates in the beach aquifer and increased DDR. The effect of changing ε on pore water salinity distribution and the resulting type of freshwater-saltwater interface was not explicitly examined, but we hypothesized that ε largely controls the development of an upper saline plume in the subterranean estuary.

2. Numerical models

Simulations of tidally influenced flow and solute transport processes were conducted using SUTRA (Voss and Provost 2002). SUTRA is a finite element groundwater modeling program that simulates variable-density, saturated-unsaturated fluid flow and transport of a single solute. We used a modified version to account for changes in total stress associated with tidal fluctuations (Wilson and Gardner 2006). The governing equation in the models is a form of the Richards equation

$$\nabla \cdot [K(\Psi)\nabla h] = S_w S_s \frac{\partial h}{\partial t} + \varphi \frac{\partial S_w}{\partial t} - \alpha_s S_w \frac{\partial \sigma_T}{\partial t} \quad (3)$$

where K is hydraulic conductivity, Ψ is negative pressure head, h is hydraulic head, S_w is water saturation, φ is porosity, σ_T is total stress and S_s is the specific storage,

$$S_s = \rho g (\alpha_s + \varphi \beta) \quad (4)$$

where ρ is the density of water, g is gravity, α_s is sediment compressibility and β is fluid compressibility.

Five model domains were created with beach slopes across the intertidal zone of 0.01, 0.025, 0.05, 0.075 and 0.1 to determine the effect of beach slope on groundwater flow and salt transport. This range of beach slopes was chosen to be representative of a range of real beaches (Bascom, 1959; Creed et al., 2000; McLachlan and Dorvlo, 2005). The five simulation domains contained a number of nodes ranging from a maximum of 11,707 and a minimum of 8,215. The number of elements ranged from a maximum of 11,443 to a minimum of 7,962. Element size

varied from a maximum of 1 m to a minimum of 50 cm in the intertidal zone, where flow rates were the greatest, to ensure the Peclet and Courant criteria were met. The baseline simulation had a porosity value of 0.43 and permeability of $1.2 \times 10^{-11} \text{ m}^2$, which is equivalent to a hydraulic conductivity of approximately 10 m/d. Tidal amplitude was 1 m and the beach slope was 0.5. We chose a baseline freshwater flux of $7.6 \times 10^{-7} \text{ m}^3/\text{s}$, which was also used in Robinson *et al.* (2007a). Longitudinal and transverse dispersivity for the baseline simulation were 10 and 1 m respectively. All of the five domains were then run through a sensitivity analysis that included a range of values for tidal amplitude, dispersivity, inflow of fresh water and permeability (Table 1). The values of the parameters tested were again selected to be representative of those found in real beaches. Permeability values for sandy beaches are likely to vary from approximately 10^{-12} to 10^{-10} m^2 (Wilson *et al.*, 2008). We tested longitudinal dispersivity values that ranged from 0.5 to 10 m and held α_L/α_T constant at a value of 10 (Gelhar *et al.*, 1992; Robinson *et al.*, 2006b; Robinson *et al.*, 2007a). We varied tidal amplitude from 0 to 1.5 m. In our simulations, temperature remained constant; therefore dynamic viscosity was also constant. There is slight variability in the hydraulic conductivity due to variations in density between fresh and saline pore water, but this difference is negligible. Hereafter, we report values as hydraulic conductivities in this paper. We assumed the sediments were homogenous and isotropic.

Boundary conditions for the model domains consisted of a no-flow boundary on the bottom, a specified fluid flux on the landward vertical boundary and a time-variable, combined specified fluid pressure and flux along the surface boundary of the domain (Fig. 2). For sections of the surface boundary that were never inundated by the tide, the boundary condition is no-flow. For areas that were inundated, boundary conditions were specified based on tidal height similarly

as described in *Wilson et al.*, [2006]. Inundated areas were assigned a pressure based on the depth of the overlying water column. When inundated surface nodes had saturations less than 1, a specified flux boundary was applied. If a node along the surface of the domain was exposed and the sediment was fully saturated, a seepage face formed. A theoretical semi-diurnal tide with a period of 12 hours and baseline amplitude of 1m was used. Tidal amplitude was one of the parameters systematically tested in the experiment. Mean water level for the tidal signal was set to be 0 m.

Model domain dimensions were chosen to balance the need for accurate simulation results and computational efficiency. The boundary source of freshwater was positioned far enough away from the intertidal zone to avoid artifacts and boundary effects. The model was extended far enough offshore that the seaward no flow boundary did not interfere with development of the freshwater-saltwater interface. Final model domains ranged from 300 – 800 m in length by 32 m deep.

Initial conditions were handled by assigning pressure equivalent to a hydraulic head of 1m throughout the domain. Salinity was handled by assigning all nodes landward of the center of the intertidal zone as 1 part per thousand (ppt), and all nodes seaward as 34 ppt to represent seawater. Initial conditions did not affect the results because all simulations ran until they reached a quasi-steady state. A total of 105 separate simulations were developed for a model time of approximately 548 days. Time steps of 10 min were required to effectively capture hydraulic responses to tidal fluctuations.

We explored three measures to rank the strength of the upper saline plume in each simulation. The first was a saline plume salinity gradient (SPSG) measured parallel to the upper

boundary of the model from the center of the upper saline plume on the beach surface to the center of the freshwater tube directly seaward (Fig. 1). The SPSG measurement was made at high tide in every model. Both concentration measurements were made at a depth of 1 m below land surface, representative of a typical piezometer depth in a beach. This depth also reaches below the zone of shallow mixing induced by waves, which were not considered in our simulations. Calculated this way, the SPSG is easily measureable in field settings. We classified “strong” upper saline plumes as having an SPSG greater than 0.15 ppt/m. “Moderate” upper saline plumes had SPSGs between 0.05 and 0.015 ppt/m, and “weak” upper saline plumes had SPSGs lower than 0.05 ppt/m. A complete lack of an upper saline plume was characterized by an SPSG of 0.

We also calculated TDR and DDR for each simulation, as indications of the volume of water that circulated through the beach. To do so, we calculated tidally driven (Q_t) and density driven (Q_d) recharge rates in the beach aquifer. We defined Q_t to be all recharge into the beach above the elevation of low tide and Q_d to be all recharge at elevations lower than that of low tide. These volumetric fluxes were then divided by the rate of fresh water inflow into the model (Q_f) and multiplied by 100 to yield nondimensional TDR and DDR. *Robinson et al. (2007a)* segregated TDR from DDR by the location of the freshwater discharge tube, which corresponds very closely to the elevation of low tide. We did not use the location of the freshwater discharge tube specifically because it did not exist in every simulation. This approach does not measure density-driven recirculation that occurs when density gradients center around the high tide line, but our purpose was to identify the presence and importance of the freshwater tube.

We note that the saline plume salinity gradient, as defined above, provides an indication of whether an upper saline plume exists at a site, as determined by whether an identifiable

freshwater tube is present. TDR and DDR are instead measures of how much water flows through the system. DDR has the potential to co-vary with the measured SPSG because higher salinity gradients in the upper saline plume may correspond to larger density gradients surrounding the lower salt water wedge. These gradients in turn drive DDR. TDR is clearly required if an upper saline plume is to form, but the relationship between TDR and strong upper saline plumes is not well defined.

3. Results

Our baseline simulation was used as a point of comparison for subsequent simulations due to the moderate parameter values used and upper saline plume that developed (Fig. 3a-e). The maximum pore water salinity in the upper saline plume was approximately 33 ppt, and the minimum salinity of pore water discharging from the adjacent freshwater tube was approximately 29 ppt. In this simulation, the SPSG between the center of the upper saline plume and the adjacent freshwater tube was 0.11 ppt/m. This indicates a moderate saline plume. TDR for the baseline simulation was 55.9% and DDR was 9.6%. Groundwater flow velocities in the intertidal zone were greatest during low tides and least during flood tides (Fig. 3b-e). Seawater circulated through the beach aquifer on each tidal cycle, where it mixed with fresher pore water. In general, saline pore water infiltrated into the aquifer during high tides and was discharged to the coastal ocean during low tides. Groundwater discharge from the beach aquifer was focused at the level of the tide as it moved across the beach. The maximum rate of discharge over a tidal cycle occurred directly landward of the lowest extent of the tide on the beach (low tide).

All 105 simulations showed that a freshwater-saltwater interface developed below the intertidal zone, but the width and configuration of the salinity distribution was highly variable. The maximum salinity of the upper saline plume ranged from 28 to 34 ppt in each model, and the salinity of pore water discharging from the freshwater tube varied from 6 ppt to 34 ppt. For a hydraulic conductivity of 10 m/d, the maximum measured rate for TDR was 85.33% and the minimum was 6.05%. The maximum rate for DDR was 43.77% and the minimum was 1.56%. The salinity distribution remained stable throughout the tidal cycle. The configuration of the salinity distribution of the freshwater-saltwater interface was also highly variable between separate simulations; some models contained an upper saline plume, while others showed only a lower salt wedge.

The slope of the intertidal zone of the beach was found to be a major controlling factor for the development of an upper saline plume and for flow through the beach in general. For the cases simulated, higher beach slopes supported a greater SPSG, greater DDR and greater TDR than lower beach slopes (Table 2). When beach slopes fell below 0.05, the upper saline plume weakened significantly and could not support density gradients high enough to drive significant rates of DDR. This relationship is illustrated very clearly in a subset of simulations where tidally averaged flow rates are compared directly to the subsequent salinity configuration (Fig. 4). Tidally average flow rates decrease in magnitude with decreasing beach slope. Beach slopes above or equal to 0.05 had larger hydraulic gradients, allowing greater discharge rates from the beach, which in turn allowed greater rates of TDR. No upper saline plume formed in any beach with a slope of 0.01 except when the hydraulic conductivity was set higher to 100 m/d.

Density-driven infiltration into the beach aquifer was found to increase with increasing SPSG in all simulations (Fig 5a). Higher groundwater salinity gradients between the saline

plume and freshwater tube, and therefore more distinct upper saline plumes, drove greater rates of density-driven convection under the beach. Rates of density-driven recharge into the beach aquifer could therefore be used as an indicator of the strength of the upper saline plume in a beach, but we ultimately chose to report measured SPSGs because they can be readily measured in the field. Infiltration rates into the beach aquifer are tedious and difficult to measure in a real beach.

Varying the hydraulic conductivity shifted the range of beach slopes that could sustain an upper saline plume (Fig. 6a). A hydraulic conductivity of 100 m/d allowed the formation of an upper saline plume only in beaches with slopes of 0.025 and 0.01. In beaches with slopes greater than 0.025, only a lower salt wedge developed. Only very low-slope beaches allowed a weak upper saline plume at this hydraulic conductivity. A hydraulic conductivity of 10 m/d led to the strongest upper saline plumes (Fig. 6a). With this hydraulic conductivity, seawater could effectively infiltrate the subsurface during inundation, and tidally-averaged flow rates through the beach were high enough to sustain an upper saline plume. No upper saline plumes formed in any beach with hydraulic conductivities less than or equal to 1 m/d because tidally-averaged flow rates through the beach were too low. TDR and DDR rates were proportional to hydraulic conductivity because greater volumes of water moved through the beach aquifers with higher hydraulic conductivities (Supp. 1a; 2a).

We also varied the flux of fresh groundwater from the landward boundary into the models. The magnitude of fresh groundwater input into the model strongly influenced the development of the upper saline plume and associated SPSG (Fig. 6b). SPSGs were very low for inflow velocities of $\sim 10^{-8}$ to 10^{-6} m/s, increasing significantly for velocities of 7.6×10^{-6} m/s and greater (Fig. 6b). A greater inflow of fresh pore water caused a sharper salinity gradient to

develop at the freshwater-saltwater interface because the salinity of water discharging through the freshwater tube was lower. For a given freshwater flow, SPSGs generally increased with increasing beach slope. No upper saline plumes formed in beaches with a slope of 0.01 regardless of the magnitude of fresh groundwater input. Rates of TDR decreased with higher fluxes of terrestrially derived freshwater (Supp. 1b). DDR increased with higher fluxes of terrestrially derived freshwater for beach slopes greater than 0.01 (Supp. 2b).

We found that tidal amplitude exhibited significant control on the strength of the upper saline plume. For beaches with slopes of 0.05 to 0.1, the SPSG and tidal amplitude were approximately inversely proportional (Fig. 6c). Higher tidal amplitudes caused inundation of larger areas of the beach, spreading out the upper saline plume and decreasing the SPSG. The simulations with an intertidal zone slope of 0.025 were particularly sensitive to tidal amplitude; for this slope, the upper saline plume failed to form for tidal amplitudes less than or equal to 0.75 m. For tidal amplitudes of 1 m or greater, the associated SPSG was relatively constant. As previously indicated, no upper saline plumes formed in beaches with a slope of 0.01 regardless of the tidal amplitude. Rates of TDR increased with increasing tidal amplitude as larger areas of the beach were inundated by the tide (Supp. 1c). Rates of DDR increased with decreasing tidal amplitude because stronger salinity gradients developed between the saline plume and adjacent freshwater tube (Supp. 2c).

Dispersivity was also found to be a major controlling factor for the development of an upper saline plume in a beach. Transverse dispersivity was a much more significant control on salinity configuration than longitudinal dispersivity because the salinity gradients developed perpendicular to the dominant flow direction in the beach (vertical). For beaches with slopes of 0.05 or greater, small dispersivities increased the SPSG and allowed more distinct upper saline

plumes to form (Fig. 6d). For beaches with lower slopes, small dispersivities prevented the formation of an upper saline plume. This occurred because a minimum level of mixing was required in the aquifer to allow the formation of an upper saline plume. Varying dispersivities in a beach with a slope of 0.01 did not produce an upper saline plume. Rates of TDR were relatively constant with increasing dispersivities while rates of DDR decreased with increasing dispersivities (Supp. 1d; 2d).

4. Discussion

Our results suggest that upper saline plumes do not form in all beaches. We found that the most significant controls on the development of an upper saline plume in a beach were hydraulic conductivity, the slope of the intertidal zone and fresh groundwater inflow. Additionally, we suggest that the median sediment grain size of the beach is strongly correlated to the development of an upper saline plume in the subterranean estuary.

Sediment grain size is an empirical predictor for the slope of the intertidal zone on an exposed beach (Bascom, 1959):

$$\beta = 0.0045e^{5.3612d} \quad (5)$$

where β is the beach slope and d is the median grain size of the beach sediments. The grain size of sediments deposited on a beach is controlled by the wave energy in the coastal ocean.

Sediments with a larger median grain size can support a steeper slope while sediments with smaller grain sizes build shallower slopes. Due to the relationship between grain size and beach slope, grain size is also correlated to the development of an upper saline plume. *Wilson et al.* (2008) showed that the median grain size of coastal sediments is also a good indicator of

permeability. Sediments with larger grain sizes had higher permeability values in both near-shore and continental shelf samples and can be fit by the following equation:

$$k = 4 \times 10^{-10} d^{1.6} \quad (6)$$

where k is permeability and d is the median grain size of the sediments.

Due to the correlation between sediment grain size and both permeability and beach slope, grain size of beach sediments is also indirectly correlated to the presence/absence of an upper saline plume.

The link between grain size, beach slope and permeability indicates a very specific set of conditions required to have an upper saline plume in a beach. As the median grain size in a beach increases, the permeability and slope of the intertidal zone increase (Fig. 7). Steeper slopes in the intertidal zone support more distinct upper saline plumes, but this is balanced by the fact that permeability values also increase and flushing rates are more rapid. Beaches with shallow slopes have finer sediments with lower permeability values, further reducing the potential for developing an upper saline plume.

To the authors' knowledge, only 3 beaches exhibit an upper saline plume in published works: Waquoit Bay, Massachusetts (Abarca et al., 2013), Cape Henlopen (Heiss and Michael, 2014) and Moreton Island, Australia (Robinson et al., 2006a and Kuan et al., 2012). All three of these beaches have intertidal zone slopes of approximately 0.09 or greater. *Bascom* (1959) compiled approximately 500 profiles from 40 beaches on the Pacific Coast of the United States. Beach slopes in the intertidal zone ranged from 0.25 to 0.01. *McLachlan and Dorvlo* (2005) categorized 161 sandy beach transects from a wide variety of locations worldwide and found that beach slopes range from approximately 0.2 to 0.0125, with an average beach slope of 0.037. Our model results predict that more prominent upper saline plumes develop and persist in beaches

with greater slopes. Upper saline plumes weakened significantly in beaches with intertidal zone slopes less than 0.5. This suggests that a large portion of the world's beaches do not exhibit a strong, persistent upper saline plume.

We can now consider the relationship between the presence of an upper saline plume and the volume of submarine groundwater discharge. Strong upper saline plumes had high rates of TDR and DDR. Our model results indicate that increasing values of ϵ (lower beach slopes) lead to lower SPSGs in the beach, representative of weak or absent upper saline plumes (Fig. 8a). *Robinson et al.* (2007a) showed that increasing values of ϵ led to increasing rates of TDR for steeper beaches (0.1 to 0.4), and TDR began to behave asymptotically for moderate beach slopes (0.067). Our results show that TDR (Fig. 8b) and DDR (Fig. 8c) drop off significantly for moderate to low slope beaches (0.05 to 0.01). As the beach slope approached the horizontal (increasing values of ϵ), the hydraulic gradient that drives seawater infiltration into the intertidal zone decreased. These relationships indicate that the formation of a stable upper saline plume occurs in beaches where TDR is sufficient to supply the beach with seawater each tidal cycle, and where DDR is high due to strong convective flow associated with a strong salinity gradient. Higher SPSGs form in beaches with higher slopes. Upper saline plumes cannot persist in the subterranean estuary through the tidal cycle when rates of TDR and DDR are low, as they are in beaches with low slopes.

Controls on the formation of an upper saline plume can be further explored by examining the relationship between advection and dispersion in the beach aquifer. We can quantify these relationships by using the Peclet number:

$$P_e = \frac{v_x L}{D} = \frac{L}{\alpha_T} \quad (7)$$

where v_x is groundwater velocity, L is the length scale of interest, D the dispersion coefficient and α_T is transverse dispersivity. Substituting the width of the intertidal zone (equation 1) for L yields:

$$P_e = \frac{L}{\alpha_T} = \frac{A \cot \beta}{\alpha_T} \quad (8)$$

where A is tidal amplitude and β is the slope of the beach. The most significant SPSGs, and therefore the strongest upper saline plumes, occurred with relatively low (< 15) Peclet numbers (Fig. 8d). This relationship suggests that upper saline plumes form when advection is moderate with respect to dispersion. When advection rates are high with respect to dispersion, SPSGs decrease to 0. However, upper saline plumes will not develop when dispersive transfer begins to dominate over advective transfer. In order for an upper saline plume to develop, advection through the subterranean aquifer is necessary.

Anthropogenic modifications to beaches have the potential to alter groundwater flow and exchange. Coastal engineering and beach nourishment are currently active strategies to combat sediment loss due to erosion and longshore drift in beaches. A common practice to reduce sediment loss from beaches with high rates of erosion is to build up the beach face with homogenous sands with larger grain sizes (Delft Hydraulics, 1987; Davidson et al., 1992; California Department of Boating and Waterways, 2002). The larger grain size means that less sediment can be entrained by the local waves due to the increased grain size, leading to a net decrease in erosion. Beach nourishment could artificially increase beach slopes and permeability values, thereby allowing the development of an upper saline plume. Inducing the development of an upper saline plume in a beach could lead to increased rates of nutrient remineralization and potential export to the coastal ocean. If a beach managed in such a way is within a coastal zone that is already experiencing anthropogenic eutrophication and algal blooms, increased nutrient

export to sensitive coastal waters could further reduce water quality. Coastal managers should consider the potential effects of beach modifications on groundwater systems and the fertility of the local coastal ocean.

It is important to consider that real beaches exhibit variability in sediment grain size and therefore permeability and beach slope. Some beaches have multiple slope breaks along their profiles where small, localized upper saline plumes could develop. Beach profiles are also dynamic with respect to season, experiencing increased rates of erosion during winter months and increased sediment accretion during summer (Aubrey, 1979). Beaches on transgressive barrier islands can have relic marsh muds buried in the subsurface (Anderson et al., 2000), leading to complex stratigraphy and permeability anisotropy. Although quantifying these effects is beyond the scope of the current paper, these effects clearly warrant future investigation.

In our simulations, we used a simulated tidal signal to represent tidal forcing. Real tidal signals that include variations in mean water level, sea level and lunar cycles such as spring-neap tides are likely to yield variable results. *Abarca et al.* (2013) showed that real tides, even with small tidal amplitudes, can create significant variability in fluxes in a beach aquifer. Spring-neap tidal cycles also cause the upper saline plume to expand and contract in response to changes in tidal amplitude (Robinson et al., 2007b). Field studies with a goal of delineating an upper saline plume in a beach should span an entire lunar tidal cycle to capture the variability in both groundwater fluxes and salinity distribution.

TDR and DDR rates are important data for understanding SGD, but are difficult to measure in the field and often require computational methods to estimate. Salinity distribution in a beach aquifer is a useful indicator of groundwater flow dynamics. Measuring the salinity of groundwater is simple, and often the first step in identifying the configuration of the freshwater-

saltwater interface in a beach. A saline plume salinity gradient can be measured by installing piezometers in the intertidal zone of a beach, near the average elevation of low tide and mean sea level. By also measuring the median grain size of beach sediments, the beach slope, the tidal amplitude and elevation of mean sea level at a field site, it is then possible to estimate general rates of TDR and DDR. For example, density-driven recirculation rates are related to the strength of the measured SPSG between the saline plume and the freshwater discharge tube, located near the average low-tide line. The salinity gradient increases with increasing beach slope. In general, the fresher the water in the discharge tube, the greater the rates of DDR in the beach. TDR rates are largely dependent on the slope of the beach, tidal amplitude and permeability. Beach slopes between 0.5 and 0.1 had the greatest rates of TDR, while rates decreased significantly for lower beach slopes where the hydraulic gradient across the ocean-aquifer interface was low. When both TDR and DDR rates are low, there will be no distinct upper saline plume, and the SPSG in the beach will be close to 0. Flow velocities through the beach are slowest in beaches with shallow slopes.

5. Conclusion

Our results suggest that the upper saline plume may be an uncommon phenomenon that only occurs in beaches with the appropriate combination of beach slope, hydraulic conductivity and fresh groundwater flux into the beach. The development of an upper saline plume under a beach requires high rates of TDR which create strong salinity gradients and therefore high rates of DDR. Steeper beach slopes supported higher SPSGs in the beach aquifer and therefore had more distinct upper saline plumes. No upper saline plumes formed in any simulations when the

hydraulic conductivity was below 10 m/d. Sufficient volumes of seawater could not infiltrate the beach aquifer during high tide. Upper saline plumes were less distinct for hydraulic conductivities greater than or equal to 100 m/d because pore water was flushed through the beach too rapidly, leading to the development of a lower salt wedge only. Increasing the fresh groundwater flux into the model decreased the salinity of groundwater that discharged seaward of the upper saline plume, increasing the SPSG.

Dispersivity also had an important effect on the distribution of salinity in the pore water. Lower transverse dispersivities allowed higher SPSGs to develop in the simulations. Prior studies of groundwater flow and salinity in beaches have used small dispersivities (Robinson et al., 2007a). We found that the upper saline plume became much less distinct when larger dispersivities were used, because more mixing occurred in the simulations. Real beaches are highly mixed environments, with waves, heterogeneous sediments and geologic layering. Longitudinal dispersivity can vary by an order of 2 within a single field site, adding additional complications to simulating field data of salinity distribution (Gelhar et al., 1992). The appropriate magnitude of dispersivities to be used in modeling groundwater in beaches remains unclear (Smith, 2004).

The median grain size of beach sediments has the potential to be an indicator of whether or not a beach will have an upper saline plume because of the correlations between grain size and both beach slope and permeability. In order for a beach to contain a prominent upper saline plume, the sediment grain size must allow a steep beach face to develop with permeability values high enough to allow sufficient infiltration of seawater but not too high to prevent strong salinity gradients from developing. Because of this relationship, wide, gently sloping beaches with fine grained sands will not support distinct upper saline plumes.

Finally, the observation of the presence or absence of an upper saline plume in a beach is important because it allows a conceptual model to be developed with respect to submarine groundwater discharge and seawater recirculation. If a strong upper saline plume is identified in a beach, it can be determined that rates of DDR are high. The presence of a moderate or weak upper saline plume indicates that rates of DDR are lower in that beach. A beach with no upper saline plume will still undergo DDR across the lower salt wedge, but the rates will be significantly lower than in beaches with a USP. TDR is more difficult to determine from the configuration of the salinity distribution alone because TDR is dependent on beach slope, tidal amplitude and inland fresh groundwater head. TDR is highest in beaches with moderate to steep slopes (0.05 to 0.1), large tidal amplitudes and low terrestrial groundwater flux. These types of beaches exhibit moderate/weak upper saline plumes because the SPSG decreases with increasing tidal amplitude and decreasing terrestrial groundwater flux. Therefore, beaches with slopes between 0.05 and 0.1 and no upper saline plume have the highest rates of TDR. Beaches with slopes in this range that have an upper saline plume will likely have moderate rates of TDR. Any beaches with slopes less than 0.05 will have the lowest rates of TDR. High rates of circulation through the beach aquifer are important because they could lead to higher rates of geochemical exchange and transformation. By identifying the salinity configuration in a beach aquifer, powerful hypotheses about flow and geochemical exchange can begin to be developed from a simple measure.

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611

Figures

Figure 1. (a) Conceptual model of the freshwater-saltwater interface in a beach. After Cooper (1959). (b) The upper saline plume and associated flow paths. After Robinson et al. (2006b). A saline plume salinity gradient (SPSG) was measured from the center of the upper saline plume to the center of the adjacent seepage face in every simulation.

Figure 2. An example of one model domain (slope = 0.05) and the subsequent boundary conditions used for every beach simulation.

Figure 3. (a) Salinity distribution for the baseline simulation. The salinity was normalized so that 1 = 34 ppt. The salinity gradient for this simulation was 0.114 ppt/m. Groundwater velocities for the baseline simulation during (b) high tide, (c) ebb tide, (d) low tide and (e) flood tide. Flow velocities were greatest during low tide and lowest during flood tide. Seawater circulated into the aquifer during rising tide.

Figure 4. Salinity configuration and tide-averaged flow for beaches with intertidal zone slopes of (a) 0.1, (b) 0.075, (c) 0.05, (d) 0.025 and (e) 0.01. The fresh groundwater flux in these simulations was 7.6×10^{-7} m/s, hydraulic conductivity was 10 m/d. The magnitude of the concentration gradient decreased with decreasing beach slope. As beach slope decreased, average flow rate decrease in magnitude, driving lower rates of TDR and DDR through the beach. Table 2 describes values for TDR, DDR, average velocity and salinity gradient for each simulation.

Figure 5. (a) Plot of DDR versus SPSG for simulations with baseline hydraulic conductivity (10 m/d). (b) Subset of simulation results above for a beach slope of 0.1 displaying the relationships between DDR and SPSG for fresh groundwater inflow, dispersivity and tidal amplitude.

Figure 6. Simulation results for tested parameters vs. SPSG for each model domain. (a) Hydraulic conductivity, (b) Fresh groundwater inflow, (c) Tidal amplitude and (d) Transverse dispersivity.

Figure 7. The strength an upper saline plume in a beach, as indicated by SPSG. Open circles represent simulation results. The trend line indicates permeability and beach slope calculated from median grain size (d_{50}) based on empirical observations (Bascom, 1959; Wilson, 2008). Permeability is likely to vary significantly in beaches, and reasonable values may fall below the line. Only permeability and beach slope were varied in these simulation results; the remaining parameters were equivalent to the baseline simulation.

Figure 8. (a) The ratio of horizontal shoreline excursion to tidal propagation distance (ϵ) versus SPSPG. (b) TDR vs. ϵ . (c) DDR vs ϵ . (d) Peclet number vs. SPSPG. Hydraulic conductivity is 10 m/d for each case. Intertidal zone slopes (β) were 0.1, 0.075, 0.05, 0.025 and 0.01. Tidal amplitudes range from 0 to 1.5 m and transverse dispersivity was 1 m. Note that increasing slopes result in decreasing values of ϵ .

Table 1. Parameters used in base model and subsequent beach simulations

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

^{*}Baseline simulation parameters.

Table 2. Simulation results specific to Figure 4 (a-e)

Model	Beach Slope	TDR	DDR	Max Average Velocity (m/d)	SPSG (ppt/m)
a	0.1	61.92%	28.03%	1.24	0.129
b	0.075	59.49%	18.02%	1.14	0.122
c	0.05	55.86%	9.56%	0.784	0.114
d	0.025	42.09%	3.20%	0.411	0.039
e	0.01	16.18%	2.50%	0.253	0.0

A)

B)

Figure 1

Figure

Figure 2

Figure

Figure 3

Figure

Figure 4

Figure

Figure 5

Figure

Figure 6

Figure

Figure 7

Figure

Figure 8