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Groundwater transport and the freshwater–saltwater interface below sandy beaches

Tyler B. Evans *, Alicia M. Wilson

Department of Earth and Ocean Sciences, University of South Carolina, 701 Sumter Street, EWS 617, Columbia, SC 29208, United States

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SUMMARY

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, in the absence of waves. 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 through beaches (SGD) has been shown to be a major contributor of nutrients, carbon and trace metals to the coastal ocean (Burnett et al., 2001; Johannes, 1980; Krest, 2000; Moore, 2010; Paytan et al., 2006; Valiela et al., 1990; Whiting and Childers, 1989). 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., 2007c; Santos et al., 2011, 2010; Sun, 1997) and by discharge of fresh groundwater from terrestrial watersheds (Burnett et al., 2003; Kim and Hwang, 2002; Santos et al., 2011; Taniguchi and Iwakawa, 2004). Wave forcing and wave swash in the intertidal zone create strong hydraulic gradients, also driving groundwater flow and salt transport in the beach aquifer (Bakhtyar et al., 2013; Li et al., 2000; Longuet-Higgins, 1983; Robinson et al., 2014; Sorensen, 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 (Charette and Sholkovitz, 2002; Moore, 1996). Short residence times and rapid flow rates of recirculating seawater drive significant mixing in the beach aquifer and enhance discharge, driving chemical fluxes across the aquifer-ocean interface (Uchiyama et al., 2000; Ullman et al., 2003). 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; Lebbe, 1999; Xue et al., 1995). 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

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* Corresponding author.

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fresh groundwater toward the ocean, above seawater migrating inland, forming a Ghyben-Herzberg freshwater–saltwater interface (Fig. 1A). Seaward of this interface, seawater recirculation through the aquifer is driven by differences in fluid density (Cooper, 1959; Ghyben, 1889; Herzberg, 1901). Studies as recent as 10 years ago describe a salt-wedge freshwater–saltwater interface with no upper saline plume (Boehm et al., 2006; Cartwright et al., 2004). 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., 2003).

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., 2006). 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. (2007b) 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 Van Cappellen, 2004; Spiteri et al., 2006). Fully defining the impact of upper saline plumes will require additional field monitoring, which in turn requires the ability to predict if, when and where an upper saline plume is likely to develop.

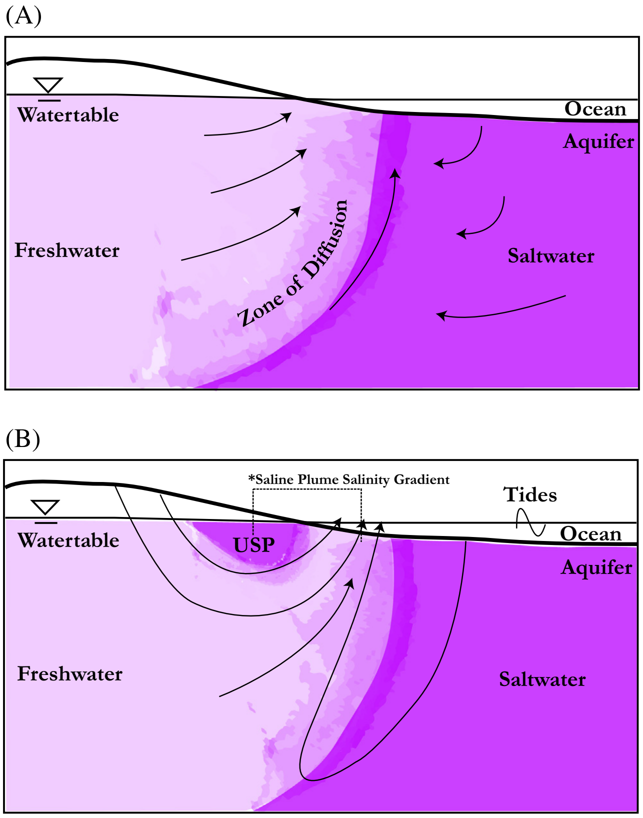

Fig. 1. (A) Conceptual model of the freshwater–saltwater interface in a beach. After Cooper (1959). (B) The upper saline plume and associated flow paths. After Robinson et al. (2006). A saline plume salinity gradient (SPSG) was measured from the center of the upper saline plume to the center of the adjacent seepage face in every simulation. The darker color indicates higher groundwater salinity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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. (2007c) 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 is the flow of seawater driven into the beach by tides, normalized to the terrestrially derived fresh groundwater flow into the beach. DDR refers to density-driven convection of seawater into the beach normalized to the terrestrially derived fresh groundwater flow. 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., 2007c):

$$\varepsilon = A\cot(\beta)\lambda \tag{1}$$

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

$$\lambda = \sqrt{\frac{n_e\omega}{2KH}} \tag{2}$$

where n_e is effective porosity, ω is tidal period, K is hydraulic conductivity and H is aquifer depth. The tidal propagation distance described by Eq. (2) describes the reduction of the amplitude of the tide as it propagates into and through the beach aquifer (Nielsen, 1990). Robinson et al. (2007c) held all parameters in Eq. (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 groundwater salinity distribution and the resulting type of freshwater–saltwater interface was not explicitly examined. A primary goal of the current paper was to test the hypothesis 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