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Submarine groundwater discharge and solute transport under a transgressive barrier island

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ABSTRACT

Many recent investigations of groundwater dynamics in beaches employed groundwater models that assumed isotropic, numerically-convenient hydrogeological conditions. Real beaches exhibit local variability with respect to stratigraphy, sediment grain size and associated topographic profile, so that groundwater flow may diverge significantly from idealized models. We used a combination of hydrogeologic field methods and a variable-density, saturated-unsaturated, transient groundwater flow model to investigate SGD and solute transport under Cabretta Beach, a small transgressive barrier island seaward of Sapelo Island, Georgia. We found that the inclusion of real beach heterogeneity drove important deviations from predictions based on theoretical beaches. Cabretta Beach sustained a stronger upper saline plume than predicted due to the presence of a buried silty mud layer beneath the surface. Infiltration of seawater was greater for neap tides than for spring tides due to variations in beach slope. The strength of the upper saline plume was greatest during spring tides, contrary to recent model predictions. The position and width of the upper saline plume was highly dynamic through the lunar cycle. Our results suggest that field measurements of salinity gradients may be useful for estimating rates of tidally and density driven recirculation through the beach. Finally, our results indicate that several important biogeochemical cycles recently studied at Cabretta Beach were heavily influenced by groundwater flow and associated solute transport.

1. Introduction

Surface water-groundwater interactions at the land-sea interface drive significant chemical reactions and contribute dissolved metals, carbon and nutrients to the coastal ocean (Bowen et al., 2007; Burnett et al., 2003, 2001; Charette and Sholkovitz, 2002; D'Elia et al., 1981; Johannes, 1980; Krest, 2000; Paytan et al., 2006; Whiting and Childers, 1989). A major portion of these surface water-groundwater interactions occur in sandy beaches (Bokuniewicz et al., 2004; Li et al., 1999), which occupy about 75% of the world's ice-free coastlines (Brown and McLachlan, 2002). Heiss and Michael (2014) reviewed the four major driving forces for groundwater flow through beaches: (1) an inland hydraulic gradient and associated discharge of fresh groundwater (Glover, 1959; Kim and Hwang, 2002; Taniguchi and Iwakawa, 2004) seaward of a saline circulation cell (Boufadel, 2000; Michael et al., 2005; Robinson et al., 1998); (2) convective mixing due to density gradients between fresh and saline groundwater (Cooper, 1959; Groen, 2002; Kohout, 1960); (3) tidal pumping (Abarca et al., 2013; Li et al., 2000; Robinson et al., 2007a,b; Sun, 1997; Vandenbohede and Lebbe, 2006); and (4) wave setup and swash (Bakhtyar et al., 2013; Heiss et al., 2014; Longuet-Higgins, 1983; Robinson et al., 2014; Sorensen, 2006; Xin et al., 2010; Fig. 1). These forcing factors for groundwater flow in the beach are non-linear in time and space (King, 2012; Xin et al., 2015, 2014). This combination of driving forces in permeable beach sediments leads to rapid flow (0.1–10 m d^{-1}), which drives chemical transformations and exports dissolved constituents to the ocean (Huettel et al., 2014; Slomp and Van Cappellen, 2004).

Previous studies have reported a wide range of biogeochemical reactions in beach sediments. The mixing and chemical exchange that occurs in coastal aquifers, termed the subterranean estuary (Moore, 1998), is significant and has garnered much scientific interest. Charette and Sholkovitz (2002) observed iron oxide coated sands in the subterranean estuary at the freshwater-saltwater interface, where reduced pore water containing dissolved Fe(II) was in contact with oxidized seawater. These iron oxide coatings were shown to prevent phosphorus from discharging to the coastal ocean through adsorption, exemplifying the importance of groundwater mixing at the freshwater-saltwater interface for geochemical processes. Ullman et al. (2003) showed

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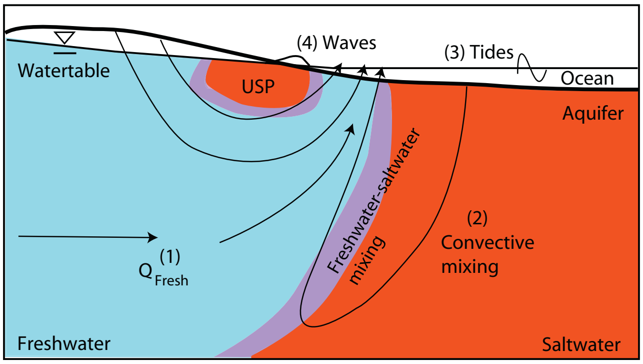

Fig. 1. Conceptual model for the driving forces for groundwater flow under a beach.

that beaches serve as reservoirs for particulate matter and remineralized reactive organic matter from the coastal ocean, which drives higher rates of nutrient fluxes from the beach than could be sustained by upland discharge alone. Furthermore, fluxes of dissolved organic matter and nutrients from the subterranean estuary to the coastal ocean are sensitive to tides (Santos et al., 2009). Schutte et al. (2015) hypothesized that a zone of rapid nitrogen cycling and subsequent nitrous oxide production in a beach in southern Georgia was controlled by periodic spring tide inundation. At the same field site, a confined aquifer system under the beach was hypothesized to facilitate methane export to the coastal ocean, but flow rates in this aquifer and the integrity of the confining unit were relatively unknown (Schutte et al., 2016). The hydraulic feasibility of these proposed groundwater dynamics in the beach requires further investigation. These biogeochemical processes, like those in other subterranean estuaries, are likely transport-limited and may be sensitive to salinity, which indicates the need for a better understanding of groundwater flow below beaches.

Groundwater salinity is simple field measurement and can be used to provide insight into the flow dynamics beneath the beach. In some beaches, two separate saline circulation cells develop: (1) The classic freshwater-saltwater interface (FSI) (Cooper, 1959; Ghyben, 1889; Glover, 1959; Henry, 1959; Herzberg, 1901); and (2) the upper saline plume (USP) (Boufadel, 2000; Lebbe, 1999; Robinson et al., 2006; Fig. 1). The FSI is present in all beaches and is the salinity configuration that forms at equilibrium between flowing land-derived fresh groundwater and circulating saline groundwater (Cooper, 1959; Kohout, 1964). Density-driven recirculation (DDR) of seawater into the beach aquifer is driven by density gradients that form in the freshwater-saltwater transition zone, the width of which is controlled by dispersion. The USP develops through tidally driven recirculation (TDR) of seawater into the beach above a body of discharging fresh groundwater that exits near the elevation of low tide (Boufadel, 2000; Robinson et al., 2006). The shallow beach aquifer fills with seawater during rising tide and discharges during low tide after mixing with land-derived fresh groundwater. After the initial discovery and description of the USP by Boufadel (2000) and Robinson et al. (2006), the established convention was that most beach aquifers contained a USP. Recent studies have shown that the USP may be transient in coastal aquifers and its presence is highly dependent on lunar cycles, fresh groundwater head, beach slope and grain size (Abarca et al., 2013; Evans and Wilson, 2016; Heiss and Michael, 2014). The distribution of salinity in the beach is a direct consequence of the flow dynamics within the beach and can potentially be used to estimate rates of seawater recirculation (Evans and Wilson, 2016).

Evans and Wilson (2016) proposed a field measurement called the saline plume salinity gradient (SPSG) that was shown to vary with rates of TDR and DDR in theoretical studies. The SPSG is calculated by determining the concentration gradient between two points perpendicular to the shore, 1 m below land surface. The first measurement is made at the approximate center of the USP, and the second is collected near the center of the freshwater tube directly seaward. These locations roughly correlate with mean high and mean low water. Stronger USPs had higher SPSGs. Beaches with the strongest USPs had the highest rates of DDR (Evans and Wilson, 2016). TDR was more complex and was dependent on beach slope, tidal amplitude and inland hydraulic head (Robinson et al., 2007b). These hydraulic parameters can be simultaneously expressed in a nondimensional ratio of the width of the intertidal zone to tidal propagation distance (Li et al., 2000; Parlange et al., 1984; Robinson et al., 2007b):

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

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. This analytical index does not include the effects of the vadose zone on the tidal propagation distance in a beach. As described in Kong et al. (2015) the presence of an unsaturated zone above the unconfined beach aquifer has the potential to increase the tidal propagation distance. As a result, our calculations of ε are conservative estimates. In beaches with moderate slopes (0.01–0.1), TDR decreased with increasing values of ε (Evans and Wilson, 2016). More interestingly, SPSG, TDR and DDR are all related to ε, which can be calculated for any beach. Evans and Wilson (2016) hypothesized that rates of TDR and DDR could be estimated using only a measured SPSG and calculated value for ε. Additionally, these theoretical models predicted that SPSG would be higher for lower tidal amplitudes, indicating that neap tides should support weaker USPs than spring tides. Rates of seawater recirculation should be higher during spring tides (Evans and Wilson, 2016). Although these relationships are valid in theoretical beaches, the viability of using a measured SPSG to estimate rates of TDR and DDR in a real beach is unknown. Further study using numerical models calibrated to a real beach is required to test these hypotheses.

Most numerical studies of groundwater flow and solute transport processes in beaches assume homogenous, isotropic sand to depths as great as 30 m below land surface (Abarca et al., 2013; Ataie-ashtiani et al., 1999; Boufadel, 2000; Evans and Wilson, 2016; Heiss and Michael, 2014; Lebbe, 1999; Michael et al., 2005; Robinson et al., 2007b, 2006; Vandenbohede and Lebbe, 2006). The use of homogenous models to describe groundwater flow in beaches ignores interbedded sediments present in a large portion of the world's beaches. In addition, many of these models used a constant single slope for the intertidal zone of the beach. Real beaches have variable topography due to the dynamic impacts of waves and currents. We hypothesize that the inclusion of real-world heterogeneity in beach groundwater flow models will highlight important deviations from these theoretical models and chose a transgressive barrier island beach as a site to test this hypothesis and the potential for estimating TDR and DDR from the SPSG.

We chose a transgressive barrier island beach as a test beach because barrier islands cover 49% of the coastline of passive continental margins and are characterized by complex, heterogeneous stratigraphy (Glaeser, 1978). These environments are extremely dynamic, and their morphology is controlled by wave action and tidal energy (Hayes, 1979). As a result, the beach profile across a barrier island is non-uniform. These beaches are also commonly