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Geologic effects on groundwater salinity and discharge into an estuary

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SUMMARY

Submarine groundwater discharge (SGD) can be an important pathway for transport of nutrients and contaminants to estuaries. A better understanding of the geologic and hydrologic controls on these fluxes is critical for their estimation and management. We examined geologic features, porewater salinity, and SGD rates and patterns at an estuarine study site. Seismic data showed the existence of paleovalleys infilled with estuarine mud and peat that extend hundreds of meters offshore. A low-salinity groundwater plume beneath this low-permeability fill was mapped with continuous resistivity profiling. Extensive direct SGD measurements with seepage meters ($n = 551$) showed fresh groundwater discharge patterns that correlated well with shallow porewater salinity and the hydrogeophysical framework. Small-scale variability in fresh and saline discharge indicates influence of meter-scale geologic heterogeneity, while site-scale discharge patterns are evidence of the influence of the paleovalley feature. Beneath the paleovalley fill, fresh groundwater flows offshore and mixes with saltwater before discharging along paleovalley flanks. On the adjacent drowned interfluve where low-permeability fill is absent, fresh groundwater discharge is focused at the shoreline. Shallow saltwater exchange was greatest across sandy sediments and where fresh SGD was low. The geologic control of groundwater flowpaths and discharge salinity demonstrated in this work are likely to affect geochemical reactions and the chemical loads delivered by SGD to coastal surface waters. Because similar processes are likely to exist in other estuaries where drowned paleovalleys commonly cross modern shorelines, the existence and implications of complex hydrogeology are important considerations for studies of groundwater fluxes and related management decisions.

1. Introduction

Submarine groundwater discharge (SGD), the flow of any and all water on continental margins from aquifers into the coastal ocean (Burnett et al., 2003), can be an important source of solutes to coastal waters (Johannes, 1980; Moore et al., 2008; Simmons, 1992; Taniguchi et al., 2002). Elevated SGD-borne nutrient loads, for example, have been associated with harmful effects to ecosystems (e.g., Johannes, 1980; Bowen et al., 2007; Slomp and Van Cappellen, 2004). SGD is primarily composed of two components: saline water derived from coastal surface waters and freshwater from terrestrial sources. The fresh component of SGD contributes new nutrients to coastal waters (e.g., Johannes, 1980; Kroeger and Charette, 2008; Weinstein et al., 2011), exchange of saline surface water across the seafloor can mobilize recycled nutrients and alter shallow porewater chemistry (e.g., Santoro, 2010; Santos et al., 2008; Santos et al., 2012), and mixing zones are active regions for biogeochemical transformations (e.g., Beck et al., 2007; Moore, 1999; Roy et al., 2013; Spiteri et al., 2008). Thus, quantification of fresh, saline and brackish components of SGD is important for estimation and understanding of nutrient loads in coastal environments.

Geologic heterogeneity on a variety of scales has been shown to affect coastal groundwater flowpaths (e.g., Bokuniewicz et al., 2008; Mulligan et al., 2007) and related chemical fluxes (e.g., Weinstein et al., 2011). Groundwater chemistry can be altered along flowpaths from land to sea due to interactions with sediments and mixing processes (Bratton et al., 2004; Kroeger and Charette, 2008; Santoro, 2010). Thus, understanding geologic controls on flowpaths and subsurface salinity distributions is important for predicting geochemical evolution. Despite its importance, the

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impacts of large- and small-scale geologic heterogeneity on coastal groundwater flowpaths, subsurface salinity distributions, and submarine groundwater discharge have not been well explored.

To understand the relationships among geology, groundwater flowpaths, and discharge, the geologic framework, porewater salinity distributions, and SGD patterns must be characterized together across a range of spatial scales. Seismic tools have been used to image contacts between fine- and coarse-grained sediments on the site scale (e.g., Cross et al., 2010). Offshore resistivity surveys have mapped porewater conductivity (e.g., Manheim et al., 2004; Simonds et al., 2008; Swarzenski and Izbicki, 2009), which may be used as a proxy for zones of fresh discharge and shallow saltwater exchange (e.g., Stieglitz et al., 2008a). Data from these geophysical tools have been correlated to examine the relation between geology and porewater salinity (Krantz et al., 2004; Viso et al., 2010). However, directly linking the geologic framework to rates and distributions of fresh and saline groundwater discharge is challenging due to the diffuse and heterogeneous nature of SGD. Natural tracers have been widely used to infer fresh and saline SGD rates (e.g., Cable et al., 1996; Ganju, 2011; Moore, 1996; Paytan et al., 2006). However, characterizing site-scale variability in SGD with these tools can be challenging and spatial and temporal variability in groundwater end-member concentrations can make it difficult to determine a representative end-member value, leading to potential inaccuracy in the SGD estimate (e.g., Burnett et al., 2007; Dulaiova et al., 2008; Michael et al., 2011; Santos et al., 2009a). SGD may be measured directly with seepage meters, which have been used in a wide range of settings (e.g., Israelsen and Reeve, 1944; Lee, 1977; Santos et al., 2009b; Taniguchi et al., 2008). Seepage meters can also be used to characterize heterogeneous patterns of fresh and saline flux (see review in Rosenberry et al., 2008) that can be linked to geology (e.g., Bokuniewicz et al., 2008; Connor and Belanger, 1981; Stieglitz et al., 2008b), though many concurrent measurements are necessary to overcome ubiquitous small-scale heterogeneity in the rate (e.g., Michael et al., 2003; Rosenberry et al., 2008) and salinity (e.g., Martin et al., 2007; Michael et al., 2005; Taniguchi et al., 2006) of SGD. Measurement artifacts may occur due to hydrodynamic interactions with the seepage meter (e.g., Rosenberry, 2008; Shinn et al., 2002; Smith et al., 2009); however, these can be minimized if measurements are limited to low-energy conditions (e.g., Cable et al., 2006).

The goal of this work is to characterize the effects of multiple-scale geologic heterogeneity on the spatial and temporal distributions of groundwater salinity and discharge. We hypothesize that large-scale features affect site-scale groundwater flowpaths and salinity distributions, but that small-scale heterogeneity controls point fresh and saline discharge rates. These patterns may be critical for estimating fresh and saline SGD, associated chemical loading, and for predicting the extent of geochemical transformation that may occur in the subsurface prior to discharge. We chose a site in Indian River Bay, Delaware as an example of a location with paleovalley features typical of drowned estuaries along the Mid-Atlantic coast of the USA and in other coastal systems. We employed geophysical tools (chirp seismic and electrical resistivity) to map the paleovalley feature and an associated fresh groundwater plume extending offshore. The salinity and spatial patterns of SGD across and away from the large-scale geologic feature were directly characterized with porewater sampling and seepage meter measurements collected at a sample density sufficient to capture both small-scale heterogeneity and large-scale trends. The data set allows interpretation of a hydrogeologic framework in which flow systems and salinity distributions are highly influenced by geologic heterogeneity–complexities that have implications for understanding and predicting subsurface geochemical transformations and design of field campaigns appropriate for geologic settings. The processes associated with this paleovalley feature are likely occurring along similar geologic features widely identified in coastal environments and wherever shallow confining units exist offshore of shorelines worldwide.

2. Study site

Indian River Bay, Delaware is a shallow estuary (mean depth 2 m; Wong, 2002) that is representative of estuaries on the Atlantic Coastal Plain (Fig. 1). Unconsolidated sediments more than 2.5 km thick form the aquifer system in the region (Benson, 1984). The shallow (<60 m) aquifer system is primarily hosted in sandy beds of the Upper Pleistocene to Lower Pleistocene Beaverdam Formation, a highly heterogeneous estuarine deposit that consists of a series of fining upward depositional sequences (Andres and Klingbeil, 2006). Following deep incision of paleo-river valleys during the Wisconsin glacial period, reworked fine-grained tidal channel, tidal flat, and marsh fill were deposited into the incised river valleys during the Holocene (Chrzastowski, 1986). These infilled paleovalleys were ultimately capped by fine-grained and presumably low-permeability peat and mud deposited in marshes fringing the retreating bayshore prior to submergence by rising water of the estuary. Most of the topographic elevation within the watershed is within 7 m of sea level. The surrounding watershed has a predominantly agricultural history with 32% of the land area currently used for agriculture (Bason, 2011) and widespread ditching to enhance drainage. An average annual precipitation of 1.1 m is evenly distributed throughout the year with changes in recharge primarily determined by seasonal evapotranspiration patterns (Johnston, 1976). Temperatures average between 2 °C and 25 °C for the 12 months (NOAA/NCDC, 2010). We measured a 0.25 m average daily tidal range over a full year at the study site. Terrestrial water table elevations can vary by several meters during a year due to changes in precipitation and evapotranspiration (Martin and Andres, 2008). Numerous studies have aimed to characterize the geology, nutrient cycling, and water fluxes of the watershed in an attempt to understand and manage stresses caused by agricultural and residential development that have negatively impacted the Indian River Bay ecosystem (e.g., Andres, 1991; Bratton et al., 2004; Ullman et al., 2002).

This study is focused on Holts Landing State Park (HLSP), located on the south-central shore of Indian River Bay (Fig. 1), as a regionally representative section of shoreline. A previous study at HLSP mapped paleovalleys and a related fresh groundwater plume by using seismic and continuous resistivity profiling (CRP) geophysical studies (Bratton et al., 2004; Krantz et al., 2004; Manheim et al., 2004). The study showed that a 30-m thick section of the Beaverdam Formation is overlain by three shore-perpendicular mud and peat-filled paleovalley features at the site (Krantz et al., 2004). These paleovalleys are incised 1–4 m near shore and extend approximately 1 km offshore where they intersect the thalweg of the Indian River paleovalley. The study identified high resistivity zones, indicating fresh groundwater extending offshore of the coastline beneath the paleovalleys, which suggested that complex groundwater flowpaths and circulation patterns are present at the site (Bratton et al., 2004; Manheim et al., 2004). Temporary coreholes at four locations allowed examination of the geology (Krantz et al., 2004) and measurement of porewater chemistry in core samples during a single field season (Bratton et al., 2004). However, the impacts of the geologic heterogeneity on the spatial patterns of groundwater discharge and salinity were not investigated.

In this study we conducted a more detailed geophysical survey to achieve improved spatial coverage and to more accurately delineate the paleovalley features, the thickness of the low