Earth-Science Reviews 221 (2021) 103800

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Geochemical fluxes in sandy beach aquifers: Modulation due to major physical stressors, geologic heterogeneity, and nearshore morphology

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ARTICLE INFO

Keywords:
Geochemical fluxes
Sandy coastal aquifers
Tides and waves
Geologic Heterogeneity
Shoreline morphology and bathymetry
Vadose zone processes
Evaporation
Submarine groundwater discharge

ABSTRACT

Coastal beach aquifers are biogeochemically active systems that mediate chemical and material fluxes across the land-sea interface. This paper provides a review of major physical stressors and geologic features that influence flow and solute fate and transport in coastal beach aquifers. We outline current understanding of the interactions between these factors and their associated impacts on water and geochemical fluxes within and across these aquifers. The physical processes that control flow, transport, and the formation and distribution of reactive zones in beach aquifers (e.g., tides, waves, density gradients, precipitation, episodic ocean events, and evaporation) operate across overlapping temporal and spatial scales, and present challenges for measuring and modeling physical flow and biogeochemical processes in coastal groundwater systems. Geologic heterogeneity introduces further complexity by modifying flowpaths, mixing patterns, and rates of biotransformation. Interactions between these physical stressors and geological controls are likely to evolve with changes in sea level, climate variability, human settlement, coastal erosion, and other natural and anthropogenic stresses, providing avenues for scientific exploration into the future role of beach aquifers as chemical mediators between the land and ocean.

1. Introduction

Sandy beach aquifers are dynamic environments that constitute more than one-third of the world's ice-free coastline (Brown and McLachlan, 2010; Luijendijk et al., 2018) (Fig. 1). Along sandy coastlines, oceanic forces (e.g., waves, tides, and wind) create highly dynamic zones where seawater and terrestrial groundwater strongly interact (Santos et al., 2012; Robinson et al., 2018). These groundwater-surface water interactions and the associated transport of chemicals and biota across the beach surface promote the formation of biochemically active zones within the beach aquifer that can alter nutrient and other contaminant loads to coastal surface water ecosystems (Moore, 1999; Slomp and Van Cappellen, 2004; Anschutz et al., 2009; Reckhardt et al., 2015; Kim et al., 2017). As the most developed regions worldwide, sandy coastlines are marked by high population density and a plethora of anthropogenic activities that are increasingly threatening nearshore marine resources, coastal ecosystems, and are adversely affecting coastal water quality (Michael et al., 2017; Vousdoukas et al., 2020). Thus, appropriate assessment and management of coastal resources are essential for preserving biodiversity and achieving coastal sustainability. Because coastal beach aquifers can play an important role in maintaining healthy coastal ecosystems, it is critical to understand their physical and geochemical responses to the complex and interacting driving mechanisms acting at the shoreline.

Multiple driving mechanisms affect coastal groundwater dynamics and associated fluxes of water and chemicals across the land-sea interface (Boufadel, 2000; Michael et al., 2005; Moore and Wilson, 2005; Li et al., 2008; Geng and Boufadel, 2015c) (Fig. 2). Buoyancy forces caused by the density difference between fresh and saline groundwater transport large quantities of saltwater upward along the lower freshwater-

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https://doi.org/10.1016/j.earscirev.2021.103800
Received 24 November 2020; Received in revised form 1 September 2021; Accepted 2 September 2021
Available online 4 September 2021

saltwater interface and are an important driver of mixing between fresh and saline groundwater at the coastline (Glover, 1959; Bear et al., 1999; Michael et al., 2005; Werner et al., 2013). Additional driving forces including the terrestrial hydraulic gradients, tides, waves, evaporation, and precipitation interact to create dynamic spatial and temporal patterns of exchange of water and solutes across the coastal land-sea interface (Robinson et al., 2006; Heiss and Michael, 2014; Heiss et al., 2015; Geng and Boufadel, 2017b; Yu et al., 2017; Shen et al., 2018). Foreshore topography and its tempo-spatial change by aeolian sediment transport, storm-induced erosion, and anthropogenic beach-nourishments play a significant role in altering coastal groundwater-seawater interactions and chemical exchange (Shibuo et al., 2006; Yu et al., 2016; Huizer et al., 2019). Subsurface heterogeneity adds additional complexity to groundwater-seawater interactions in coastal aquifers (Simmons et al., 2001; Barlow and Reichard, 2010; Lu et al., 2013; Pool et al., 2015; Michael et al., 2016; Kreyns et al., 2020).

Coastal aquifers are simultaneously exposed to the aforementioned driving forces; the integrated effects of these driving forces on coastal groundwater flow and transport processes are nonlinear (Santos et al., 2009b; Geng and Boufadel, 2015c; Wilson et al., 2015; Xin et al., 2015). Short-term or long-term environmental change (e.g., storm surge, tsunami, sea-level rise, and glacier retreat) and anthropogenic activities (oil spills, onshore and offshore freshwater pumping, and terrestrial pollutants derived from agriculture and industrial activities) also play a critical role in altering coastal groundwater dynamics, and therefore affect submarine groundwater discharge (SGD) and associated chemical input from aquifers to the ocean over different time scales (Violette et al., 2009; Li and Boufadel, 2010; DeFoor et al., 2011; Knee and Paytan, 2011a; Ferguson and Gleeson, 2012; Sanders et al., 2012; Michael et al., 2013; Robinson et al., 2014; Geng et al., 2015; Personna et al., 2015; Seidel et al., 2015; Yu and Michael, 2019; Geng and Michael, 2020).

A large number of studies over the past two decades have investigated the effects of the various driving forces on flow and associated geochemical fluxes in coastal aquifers. Review papers have been published on this subject, which in general can be classified into two categories: one focused primarily on quantification of SGD and associated chemical input into the ocean (Burnett et al., 2001; Taniguchi et al., 2002; Burnett et al., 2003; Taniguchi et al., 2003; Slomp and Van Cappellen, 2004; Knee et al., 2010; Moore, 2010), and the other focused on the underlying driving mechanisms of water and chemical fluxes across the land-sea interface (Horn, 2002, 2006; Santos et al., 2012; Robinson et al., 2018). Other relevant reviews of coastal flow and transport processes were conducted with major interest on saltwater intrusion (Werner et al., 2013; Ketabchi et al., 2016). Significant impacts of aquifer heterogeneity on coastal groundwater-seawater mixing dynamics have been identified since the 1990s (Dagan and Zeitoun, 1998; Held et al., 2005; Nofal et al., 2015; Michael et al., 2016; Geng et al., 2020d). However, a comprehensive review of the effects of geologic heterogeneity on coastal subsurface flow and transport processes, particularly integrating with major physical stressors uniquely featured for coastal marine systems, has not been conducted. Here, we provide a review of major terrestrial/oceanic driving forces affecting groundwater flow in beach aquifer systems. While driving forces act on a range of spatial scales and these can be difficult to tease apart, we are primarily focusing on beach aquifers and the fluxes through these shallow unconfined systems. We review how these factors modulate SGD and associated chemical fluxes across the land-sea interface to improve current understanding of integrated effects of major physical stressors, geologic heterogeneity, and shoreline morphology and bathymetry on coastal flow and transport processes. The layout of the paper is as follows: first we review the key concepts and measurement approaches of SGD and associated geochemical fluxes across the land-sea interface (Section 2). Then, we review the current understanding of major physical stressors on coastal flow and transport processes, geologic heterogeneity, and shoreline morphology and bathymetry, and how these driving mechanisms and system features affect discharge of water and chemical fluxes from coastal aquifers to the ocean (Sections 3-5). Some key concepts derived from those influencing mechanisms along with representative references are listed in Table 1. Finally, we highlight key knowledge gaps and challenges that must be addressed to improve understanding of flow and chemical exchange between land and the sea (Section 6).

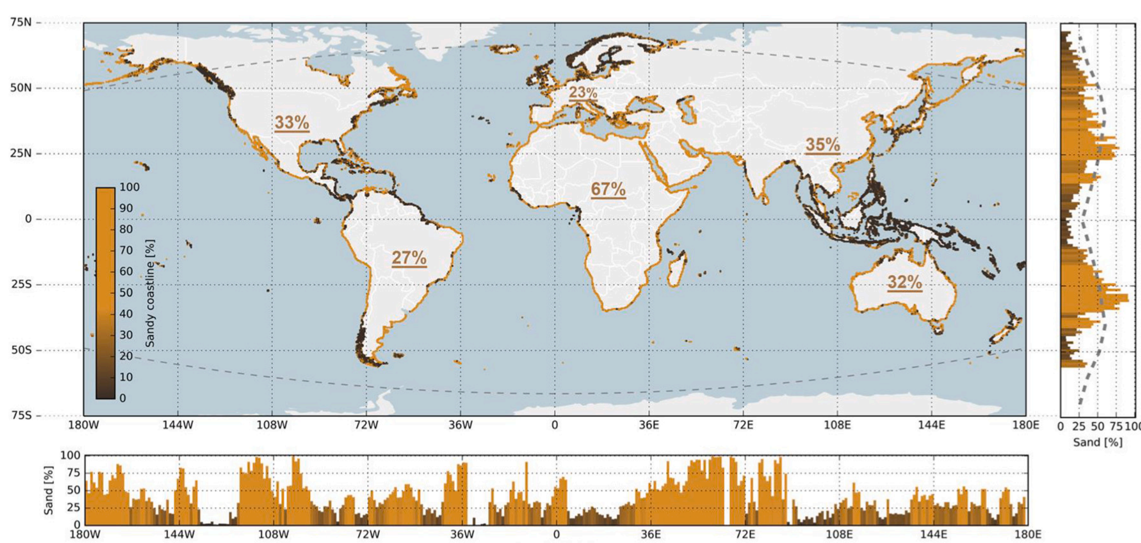

Fig. 1. Global distribution of sandy shorelines; the color contour along the world's shoreline represents the local percentage of sandy shorelines (orange is sand, dark brown is non-sand). The subplot to the right presents the relative occurrence of sandy shorelines per degree latitude, where the dashed line shows the latitudinal distribution of sandy shorelines reported by Hayes and Leatherman (1979). The lower subplot presents the relative occurrence of sandy shorelines per degree longitude. The curved, dashed grey lines in the main plot represent the boundaries of the ice-free shorelines considered in the analysis. The underlined percentages indicate the percent of sandy shorelines for each continent. Reproduced from Luijendijk et al. (2018).

2. SGD and associated geochemical fluxes

2.1. Fresh and saline SGD components

Discharge of fresh or saline groundwater from coastal aquifers into adjacent surface water is defined as submarine groundwater discharge (SGD). Owing to different terrestrial and marine driving mechanisms, SGD is a mixture of land-derived fresh groundwater and marine-derived recirculated saltwater. The fresh component of SGD (FSGD) is driven by the large-scale land-sea hydraulic gradient that is determined by hydrologic processes on land and the sea surface elevation. FSGD is estimated to be 6-10% of global river runoff (Zektser and Loaiciga, 1993) and can be higher in more localized areas. For example, in the Mediterranean Sea karstic areas border 60% of the coastline and are estimated to contribute ~75% of the total freshwater input to the sea: much of it via SGD (UNESCO, 2004; Garcia-Solsona et al., 2010). Wang et al. (2015); Wang et al. (2020) found that FSGD into Laizhou Bay, China was comparable to annually-averaged discharge of the Yellow River, the second longest river in China. Seawater recirculated through coastal sediments (RSGD), driven by any of the mechanisms discussed in this work, is substantially greater than fresh SGD, with estimates that rival or exceed surface runoff (Church, 1996; Moore, 1996b, 2010; Rodellas et al., 2015). In the upper Atlantic Ocean, RSGD is estimated to be 80%-160% of river discharge (Moore et al., 2008).

Due to distinct chemical compositions in fresh and saline SGD, accurate quantification of these two components is critical to management of nearshore water resources and evaluation of marine ecological systems. Early studies that quantified SGD commonly assumed that SGD is simply a linear sum of the SGD components driven by different terrestrial/oceanic drivers (Li et al., 1999; Taniguchi et al., 2002; Burnett et al., 2006b). For instance, Taniguchi et al. (2002):

$$SGD = FSGD + RSGD_w + RSGD_T + RSGD_C \tag{1}$$

Where SGD is composed of FSGD, discharge driven by waves ($RSGD_W$), tides ($RSGD_T$), and density or thermal gradients ($RSGD_C$). However, interactions between SGD components are likely nonlinear (Robinson et al., 2007a; King, 2012; Xin et al., 2015). Robinson et al. (2007a) showed that an increase in tidal amplitude could intensify both tide-induced recirculation and density-driven recirculation. Xin et al. (2010) revealed that saline SGD driven by a combination of tide and wave forcing is less than the sum of the two saline SGD components separately. In addition to the magnitude of SGD, the combined effects among different driving forces can increase tempo-spatial variability of FSGD and RSGD. Geng and Boufadel (2015c) showed that combined wave and tide forcing significantly shifts the location of intertidal flow paths compared to the scenarios with only tide forcing. Kuan et al. (2019) found that the interaction between density-driven and tide-induced circulations and inland freshwater input is nonlinear; in the

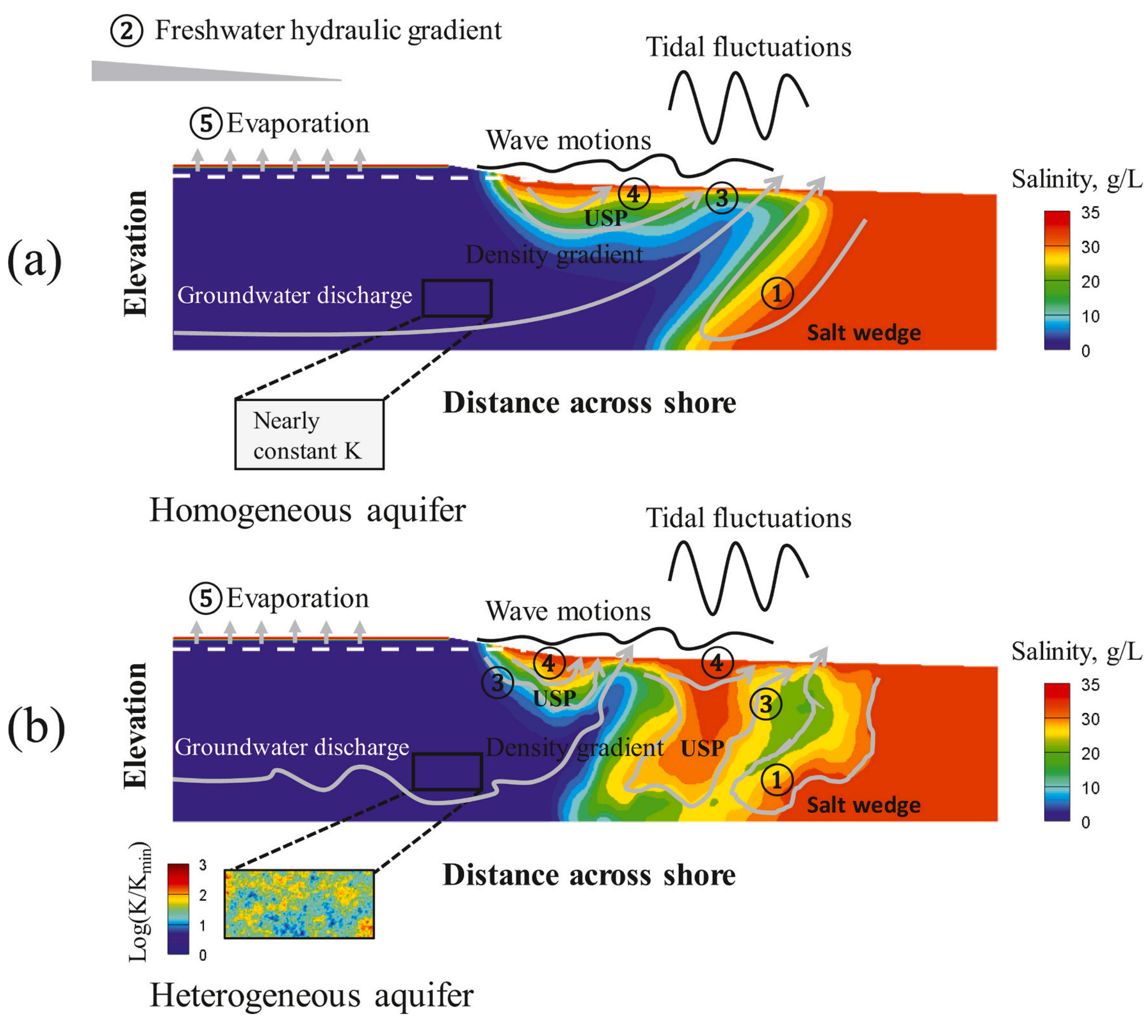

Fig. 2. Schematics of groundwater flow and salt transport processes in (a) homogeneous and (b) heterogeneous coastal aquifers. Process (1) denotes groundwater circulation due to density gradients formed along the dispersed interfaces between fresh water and saltwater. Process (2) denotes inland freshwater hydraulic gradient, driving terrestrial groundwater discharge seaward. Processes (3) and (4) denote groundwater flow driven by tides and waves, respectively. Process (5) represents upward pore-water flow driven by evaporation. The effects of heterogeneity on creating complex flow patterns and salt fingers is illustrated in panel b.

Table 1
Some key concepts derived from major physical stressors, geologic heterogeneity, and nearshore morphology acting on beach aquifers.

Concept	References*
Density-driven convective saltwater circulation	(Cooper, 1959; Kohout, 1960)
Ripple-flow interaction	(Webb and Theodor, 1968)
Saltwater wedge	(Badon-Ghyben, 1889; Herzberg, 1901)
Groundwater overheight	(Nielsen, 1990; Raubenheimer et al., 1999)
Tide-induced circulation cell/upper saline plume	(Lebbe, 1999; Boufadel, 2000)
Seepage flow	(Naba et al., 2002; Li et al., 2008)
Freshwater discharge tube	(Michael et al., 2005; Robinson et al., 2006)
Wave-induced circulation cell	(Xin et al., 2010; Geng et al., 2014)
Fingering-type salinity distributions and infiltration	(Greskowiak, 2014; *Geng et al.*, 2017)
Benthic fluxes	(Boano et al., 2014; Huettel and Gust, 1992)
Heterogeneity-induced mixing and reaction hotspots	(*Heiss et al.*, 2020; Wallace et al., 2020)
Heterogeneity-induced preferential flow	(Michael et al., 2016; Yu and Michael, 2019)
Heterogeneity-induced chaotic advection	(Trefry et al., 2019; Geng et al., 2020d)
Heterogeneity-induced capillary barrier in swash zone	(Geng et al., 2020b)

* References list representatives where the concept was introduced and implemented.

presence of tides, the percent increase in SGD is likely lower than the percent increase in inland freshwater input.

2.2. Significance of SGD

SGD has been well-recognized as an important source of nutrients, metals, carbon, and natural radioactive tracers from coastal aquifers to the sea. The transport of geochemical compounds (e.g., trace elements, nutrients, metals, and dissolved inorganic and organic carbon) to the sea via SGD is a critical process affecting coastal marine ecosystems as coastal fresh groundwater usually contains higher concentrations of nutrients and other pollutants than surface water discharge (Johannes, 1980; Moore, 1999; Slomp and Van Cappellen, 2004). For example, SGD supplies critical nutrient sources for coral reefs (Paytan et al., 2006). Conversely, excess nutrient input via SGD may lead to harmful algal blooms in coastal waters (Hwang et al., 2005; Lee et al., 2010) and other ecological problems (Boesch, 2002). Site-specific studies have found that SGD is a major source of a variety of chemical constituents to tidal flats, estuaries, coral reefs, and other communities near the shoreline and on the continental shelf (Hwang et al., 2005; Waska and Kim, 2011; Charette et al., 2013; Niencheski et al., 2014). For instance, Hwang et al. (2005) found that SGD represents as much as 90% of the total dissolved inorganic nitrogen load to Bangdu Bay in Jeju, Korea, and such excess submarine input is a major nutrient source for benthic eutrophication. In the Patos Lagoon system along the southern coast of Brazil, Niencheski et al. (2007) revealed that total dissolved inorganic nitrogen fluxes in SGD may represent as much as 55% of the total nitrogen flux to the adjacent shelf environment. Zhang et al. (2020b) suggested that the SGD associated nutrient fluxes of China accounted for >50% of the total nutrient inputs, and they have important influences on nutrient budgets and primary production of coastal waters at small and large scales. Therefore, understanding the exchange of water and chemicals across the land-sea interface is essential for managing coastal marine ecosystems.

2.3. Geochemical composition

SGD includes both inland-derived fresh groundwater and recirculated seawater, which are different in their geochemical compositions. Terrestrial fresh groundwater is often enriched in nutrients and other terrestrially-derived solutes due to intensive agricultural and industrial activities. Kroeger and Charette (2008) estimated that dissolved inorganic nitrogen (DIN) in fresh SGD was 3.5 times greater than the flux in recirculated marine groundwater in Waquoit Bay, Massachusetts, USA. Santos et al. (2009a) showed that fresh SGD contributes 50% of the total dissolved nitrogen inputs at a beach site in the Gulf of Mexico while accounting for only 5% of total SGD. Similarly, Weinstein et al. (2011) found that fresh groundwater was the main conveyor of DIN and silica to coastal waters. In contrast, seawater is relatively nutrient-poor; however, the recirculated saline component of SGD sometimes may contain high concentrations of nutrients due to relatively long residence times and biogeochemical reactions between saline groundwater and sediments in coastal aquifers (Moore et al., 2006). Since coastal groundwater nutrient concentrations are usually higher than in coastal surface waters, nutrient input through SGD may greatly alter the Redfield ratio (Redfield, 1934; Wang et al., 2018) in coastal ecosystems and therefore shift nearshore surface water from typical N-limiting to P-limiting conditions (Slomp and Van Cappellen, 2004).

In coastal aquifers, fresh groundwater mixes with seawater prior to discharge, which triggers a wide range of biogeochemical reactions that modify chemical fluxes to surface water. Depending on local hydrogeology, these biogeochemical processes can be either a source or sink for nutrients (Slomp and Van Cappellen, 2004; Kroeger and Charette, 2008; Sanders et al., 2012; Heiss et al., 2017; Reckhardt et al., 2017; Waska et al., 2021). Seawater infiltration across the beach face transports dissolved organic carbon (DOC) and O_2 into the aquifer that can support nitrification in shallow beach sediments (Ullman et al., 2003; Rivett et al., 2008; Anschutz et al., 2009). At depth, dissolved oxygen concentrations decrease as oxygen is consumed along circulating flow paths, leading to anoxia and favorable conditions for denitrification. In these deeper sediments and along the boundaries of the intertidal circulation cell, denitrification is sustained by mixing between nitrate-rich fresh groundwater and DOC-rich recirculating seawater (Beck et al., 2017; Heiss et al., 2017; Kim et al., 2019). Beaches can also serve as sources of nitrogen and phosphorus through DOC mineralization and subsequent release of N and P (McLachlan and McGwynne, 1986; Kroeger and Charette, 2008; Spiteri et al., 2008b). Other biogeochemical transformations observed in coastal aquifers include hydrocarbon degradation (Anschutz et al., 2009; Geng et al., 2015), aerobic respiration (Slomp and Van Cappellen, 2004; Charbonnier et al., 2013), nitrification (Ullman et al., 2003; Fan et al., 2015), anaerobic ammonium oxidation (Slomp and Van Cappellen, 2004; Spiteri et al., 2008a), sulfate reduction (Brown et al., 1999; McAllister et al., 2015), and iron oxidation (Penn et al., 2001; Charette and Sholkovitz, 2002). These biogeochemical processes are highly variable and depend on local mixing dynamics.

2.4. Field measurement approaches for beach aquifers

There are numerous approaches that have been developed to measure and estimate subsurface flow and biogeochemical processes in and across coastal aquifers (see brief review in Kim and Heiss, 2021 for beach aquifers). The instruments and techniques for estimating fluid flow include pressure sensors (Robinson et al., 2006), conductivity-temperature-depth (CTD) sensors (Housego, 2021), moisture sensors (Heiss et al., 2014), seepage meters (Lee, 1977; Michael et al., 2005), lysimeters (Heiss et al., 2015; Grünenbaum et al., 2020b), plaster of Paris or gypsum cards (Crabtree and Trudgill, 1984; Thompson and Glenn, 1994), potentiomanometers (Winter et al., 1988), and heat as a tracer (Befus et al., 2013; Schilling et al., 2019). For solute transport, the main instruments/techniques are: multiport sampling wells (Charette and Allen, 2006; Gibbes et al., 2007; Geng et al., 2015; Kim et al., 2017), geophysical techniques (Choudhury et al., 2001; Henderson et al., 2010; Zarroca et al., 2011; Dhakate et al., 2016), and radiological isotopes (Ramasamy et al., 2009; Al-Trabulsy et al., 2011; Geng et al., 2019). For example, dissolved oxygen concentrations can be continuously measured in-situ using an oxygen chamber with an optical sensor (Boufadel et al., 2010). More commonly, sediment or water samples are collected from the field and later analyzed in the lab (Boufadel et al., 2016; Geng et al., 2016a; Kim et al., 2017; Guimond et al., 2020b).

Manual seepage meters (Lee, 1977) are the most commonly used device for directly measuring groundwater-surface water exchange. They consist of a cylinder that is open at the bottom and vented at the top to a plastic collection bag. The deployment of seepage meters involves inserting the cylinder into the sediment, and thereafter the change in the volume of water in the collection bag over a measurement period is used to determine the total fluid flux across the sediment-water interface. Seepage meters have been widely used to measure SGD across the sediment-water interface in a variety of coastal environments (Cable et al., 1997a; Michael et al., 2005; Burnett et al., 2006a; Povinec et al., 2006; Smith et al., 2009; Mejías et al., 2012). However, the utility of seepage meters is limited by their relatively small footprint that usually covers less than a square meter. As a result, a large number of seepage meter measurements may be required in heterogeneous systems in order to accurately characterize spatial variability in SGD (Michael et al., 2003; Russoniello et al., 2013; Duque et al., 2020). In addition, seepage meters are difficult to reliably deploy in high-energy environments.

Indirect measurements of SGD involve the use of natural geochemical tracers in groundwater. Such techniques rely on the enrichment of the tracer in groundwater relative to seawater, and require measurements of tracer activity (or chemical concentration) in both groundwater and seawater. The most commonly used tracers are ^{222}Rn and four radioisotopes of Ra (^{224}Ra, ^{223}Ra, ^{228}Ra, ^{226}Ra) (Cable et al., 1996; Moore, 1996a; Moore and Arnold, 1996; Burnett et al., 2002). SGD can be estimated using mass balance models that quantify sources and sinks of the tracers while assuming a groundwater endmember concentration (Moore, 1996a). However, estimating the groundwater endmember concentration can pose a challenge when applying tracer-based methods (Copenhaver et al., 1993; Rama and Moore, 1996; Gonneea et al., 2008) because concentrations and activities of natural tracers (e.g. Ra) can vary by orders of magnitude in the subsurface (Michael et al., 2011; Wang et al., 2019). Thus, in the case of Ra, total SGD is not easily quantifiable using a single endmember activity. Additional factors such as geologic heterogeneity, sorption processes, complex flow patterns, and reactions can also introduce errors and uncertainty into tracer-based SGD estimates (e.g., Burnett et al., 2002; Lambert and Burnett, 2003; Mulligan and Charette, 2006; Dulaiova et al., 2008; Michael et al., 2011; Schutte et al., 2016).

Geophysical approaches have also been widely used to identify SGD locations in marine settings. Subsurface electrical conductivity (or its inverse, resistivity) is a typical geophysical measurement used to characterize zones of fresh and saline SGD (Kontar and Ozorovich, 2006; Swarzenski et al., 2006; Breier et al., 2009; Cardenas et al., 2010; Evans and Wilson, 2017; Evans et al., 2020). The measurements capitalize on the contrast between less conductive freshwater and more conductive saltwater; however, interpretation of electrical conductivity surveys can be challenging due to the effects of sediment type, composition, and organic carbon content, potentially leading to freshwater false positives.

In-situ electrical conductivity surveys can involve multiple types of acquisition arrays to measure subsurface resistivity (e.g., Dipole-dipole array, Schlumberger array, and Wenner array), each with advantages and drawbacks that depend on the nature of the system and study objective (Samouëlian et al., 2005). In addition, raw electrical resistivity measurements must be inverted for interpretation (Loke and Barker, 1996); however, mathematical inversions usually magnify uncertainty (or errors) (Beck and Arnold, 1977). Geophysical techniques are quite efficient for large-scale groundwater surveys, and therefore have been widely deployed to characterize offshore freshwater resources and associated submarine groundwater discharge (Hoefel and Evans, 2001; Manheim et al., 2004; Haider et al., 2015; Evans and Key, 2016; Srnka and Constable, 2017; Gustafson et al., 2019). While they are useful for identifying salinity distributions and locations of fresh SGD, they cannot be used alone to estimate SGD rates.

3. Effects of physical stressors on SGD and associated geochemical fluxes

3.1. Density gradients

In coastal aquifers, terrestrial fresh groundwater flows seaward and mixes with saline groundwater prior to discharge into the ocean. Therefore, buoyancy forces resulting from the density difference between terrestrial freshwater and seawater are a primary control on coastal groundwater flow. Under steady-state hydraulic boundary conditions (i.e., in absence of other terrestrial and oceanic drivers), this density difference causes terrestrial fresh water to float above the lower freshwater-saltwater interface (also called saltwater wedge) and discharge from the aquifer to the sea (Fig. 2, process 1). The fresh water flows upward along the interface and flow converges toward the beach surface. Due to diffusion and dispersion, mixing between fresh groundwater and saltwater occurs, leading to convective circulation along the wedge interface (Cooper, 1959; Kohout, 1960). The location and shape of the saltwater wedge is determined by aquifer properties, inland groundwater recharge, and the resulting large-scale hydraulic gradient between inland and sea (Fig. 2, process 2) (Werner et al., 2013), as well as geologic heterogeneity (e.g., Pool et al., 2015).

Studies on the dynamics of the saltwater wedge and associated convective circulation have been conducted since the 1900s. The characterization of the saltwater wedge started from the well-known Ghyben-Herzberg approximation which predicts that the depth to the freshwater-saltwater interface below mean sea level (MSL) is approximately 40 times the water table elevation above MSL (Badon-Ghyben, 1889; Herzberg, 1901) for the density contrast between fresh water and seawater. Glover (1959) formulated the pattern of terrestrial groundwater flow near the wedge interface under steady flow conditions. Henry (1964) developed the first solution for the steady-state salt distribution in a confined coastal aquifer system. Thereafter, numerous studies have improved the numerical models to better characterize the convective circulation and associated mixing dynamics along the saltwater wedge interface (Lee and Cheng, 1974; Segol and Pinder, 1976; Frind, 1982; Galeati et al., 1992; Boufadel et al., 1998; Ranjan et al., 2004). Evaluation of the saltwater wedge has also been conducted using field measurements. Direct measurements of pore-water pressure and salinity were conducted in numerous studies to characterize tempo-spatial patterns of the saltwater wedge (Johnston, 1983; Reilly and Goodman, 1985; Uddameri et al., 2014; Müller et al., 2018; Post et al., 2018). Dynamics of the saltwater wedge can also be characterized by other pore-water measurements such as temperature-depth profiles (Taniguchi, 2000; Molina et al., 2002) and geoelectrical resistivity (Gorhan, 1976; El-Waheidi et al., 1992; Islami, 2011). In addition, laboratory meter-scale beach systems have been used to investigate dynamics of the groundwater-seawater interface in response to various physical stressors (Boufadel, 2000; Goswami and Clement, 2007; Abarca and Clement, 2009; Kuan et al., 2019; Nguyen et al., 2020).

3.2. Density effects

Density-driven circulation along the saltwater wedge can have a marked impact on SGD and associated chemical fluxes into the ocean. A tracer study conducted on the southern shore of Indian River Bay, DE revealed that the discharge in the interface between saltwater and freshwater was characterized by higher activities of the longer-lived isotopes (^{226}Ra and ^{228}Ra), which is due to relatively long flow path and residence time controlled by density gradients (Duque et al., 2019). Density-driven seawater recirculation along the saltwater wedge also affects the ratio of FSGD to RSGD (Wilson, 2005; Thompson et al., 2007; Haider et al., 2015). Numerous studies have revealed the significance of biogeochemical reactivity along the saltwater wedge on moderating nutrient concentrations and fluxes from coastal aquifers to marine waters (Slomp and Van Cappellen, 2004; Santoro et al., 2006; Kroeger and Charette, 2008; Santoro et al., 2008; Santoro, 2010). For example, geochemical measurements suggest that, like shelf sediments, the saltwater wedge is an active area of nitrogen (N) cycling and harbors microbial communities involved in N-mineralization, nitrification, denitrification, Dissimilatory nitrate reduction to ammonium (DNRA), and potentially anaerobic ammonium oxidation (Korom, 1992; Sáenz et al., 2012; Fan et al., 2015; Schutte et al., 2015). Santoro et al. (2008) characterized the diversity and composition of denitrifying bacteria across the transition zone, and identified shifts in the relative abundance of ammonia-oxidizing bacteria and archaea across the saltwater wedge according to the salinity change. More recently, Adyasari et al. (2019) found a strong relationship between marine microbial communities and environmental variables (e.g., salinity and temperature) in coastal groundwater.

3.3. Oceanic forcing

3.3.1. Tides

Tidal fluctuations and flows are an important driver for nearshore flow and transport processes. The marine intertidal zone, defined as the beach zone exposed to air at low tide, and inundated with seawater at high tide, has been identified as an active hydrologically and biogeochemically dynamic region affecting coastal marine ecosystems (Jickells, 1998; Boehm et al., 2006; Li et al., 2009). Tidal fluctuations result in a persistent hydraulic gradient driving seaward flow within beach aquifers (a groundwater “overheight” under the upper beach), at least partly because the groundwater table in nearshore aquifers rises rapidly with rising tides but drains more slowly and lags the tide (Philip, 1973; Nielsen, 1990; Li and Jiao, 2003). Tides also create a groundwater circulation cell, also called an upper saline plume (USP), beneath the intertidal zone where through-flowing fresh groundwater mixes with seawater flowing downward from the upper beach face and seaward to the low tide line (Fig. 2, process 3). Terrestrial fresh groundwater discharges from the beach aquifer near the low-tide mark between the upper circulation cell and the saltwater wedge (Lebbe, 1999; Boufadel, 2000; Mango et al., 2004; Robinson et al., 2007c; Li et al., 2008; Heiss and Michael, 2014). The spatial extent of the circulation cell is affected by episodic rainfall (Yu et al., 2017) and tidal amplitude (Werner and Lockington, 2006), as well as seasonal water table fluctuations, spring-neap cycles, tidal stage, and storm events (Heiss and Michael, 2014). Saltwater-fresh water mixing within and along the boundaries of the circulation cell is affected strongly by ocean-groundwater interactions in the intertidal region of sandy ocean and estuarine beaches (Robinson et al., 2006; Li et al., 2008; Abarca et al., 2013). Laboratory experiments and numerical simulations demonstrate the important roles of tide and buoyancy effects in tempo-spatial patterns of groundwater flow and mixing along with the upper circulation cell and lower saline wedge in beach aquifers (Boufadel, 2000; Kuan et al., 2012). The intensity of mixing and flushing time for solutes within the upper circulation cell depends on beach (e.g., slope and permeability) and tidal properties (e.g., tidal amplitude and period) (Li et al., 2007). Other measurement approaches include time series and spectral analysis, which have been useful to identify fluctuation characteristics of water table elevation, groundwater flow, and salinity in response to tidal oscillations (Geng and Boufadel, 2017a; Yu et al., 2019).

3.3.2. Tide effects

The importance of tide-driven circulating seawater as a percent of total SGD has been identified in numerous studies. For example, numerical simulations demonstrated that the amount of tide-driven SGD is comparable to that driven by density gradients (Robinson et al., 2007b), and higher amount of tide-driven SGD likely occurs when the ratio of tidal to inland forcing becomes larger (Robinson et al., 2007a). Field studies suggest that recirculating seawater driven by oceanic forcing accounted for approximately 74% total SGD for an unconfined beach aquifer during the summer (Boehm et al., 2006). Significant impacts of tidal actions on temporal patterns of SGD are reported in Taniguchi (2002) and Heiss and Michael (2014). In areas with spring-neap tidal cycles, total SGD and the relative fresh and saline components fluctuate with a semi-monthly period due to the changes in recirculated seawater outflow from variable tidal forcing. In addition, SGD rates may change with diurnal and semi-diurnal periods due to changes in the hydraulic gradient between the groundwater and surface water.

Tidal actions also influence the fate of chemicals and fluxes transported from the aquifer to coastal waters. Biogeochemical reactions and transformations in the groundwater-seawater mixing zone are an important control on the net flux of nutrients, heavy metals, and other contaminants from SGD to the coastal ocean. Numerical studies revealed an important control of tidal actions on bulk denitrification rates in the beach, with up to 70-100% of nitrate removed prior to discharge, depending on beach slope, K, tidal amplitude, and fresh water flux (Anwar et al., 2014; Heiss et al., 2017). On Cape Cod, MA, USA, Kroeger and Charette (2008) observed concurrent removal of NO_3^- and NH_4^+ both in freshwater and near the base of the intertidal circulation cell, while rapid flushing limited biogeochemical activity within the shallow zone of the beach due to a short water residence time. Field measurements showed that biogeochemical reactions can lead to the large-scale enrichment of Ba and depletion of U in groundwater-seawater mixing zone (Charette et al., 2005). The significant depletion of U in groundwater is mostly a result of SGD-driven circulation of seawater through reducing permeable sediments. The release of dissolved Ba to the water column of surface estuaries is frequently attributed to an ion-exchange process whereby seawater cations react with Ba from river suspended clay mineral particles at low to intermediate salinity. Beach aquifers can also serve as a source of mercury to estuaries in quantities that exceed atmospheric deposition and riverine input (Bone et al., 2007). Santos et al. (2009a) observed a large variability in nutrient concentrations (i.e., N, P, and Si) over tidal cycles. At high tide, nutrient concentrations in shallow beach groundwater were low as a result of dilution caused by seawater recirculation. During the falling tide, the concentrations increased until they reached a maximum just before the next high tide. The dominant form of nitrogen was dissolved organic nitrogen (DON) in freshwater, nitrate (NO_3^-) in brackish waters, and ammonium (NH_4^+) in saline waters. The discharge of chemical flux across the beach face was also affected by spring-neap tidal cycles. De Sieyes et al. (2008) observed a larger fresh discharge component during neap tides at Stinson Beach, California, which raises surf zone silicate, dissolved inorganic nitrogen (DIN), and soluble reactive phosphate by 14%, 35%, and 27%, respectively, relative to spring tides. Tidal fluctuations can also lead to tempo-spatial patterns of physicochemical parameters (e.g., salinity, temperature, DO, pH, and ORO) within freshwater-saltwater mixing zones ((Liu et al., 2018).

3.3.3. Waves

In addition to tides, ocean water levels fluctuate due to storm surge (amplitudes roughly 1 to 6 m, periods hrs to days, including atmospheric pressure effects and wind-driven setup), breaking-wave-driven setup (typical amplitudes up to 2 m, periods hrs to days), seiches, shelf-trapped waves, and meteo-tsunamis (typical amplitudes 1 to 5 m, periods min to hrs), infragravity waves (typical amplitudes up to 2 m at the shoreline, storm amplitudes can be higher, periods 1 – 4 min), and wind-generated waves (amplitudes up to 10 m on the inner shelf, typically less than 2 m at the shoreline, periods 2 to 25 s). Several recent reviews have noted the importance of interactions among wind-generated waves, breaking-wave-driven setup, and infiltration and exfiltration to shallow-water ocean processes (Elfrink and Baldock, 2002; Bakhtyar et al., 2009; Briganti et al., 2016; Chardón-Maldonado et al., 2016). Likewise, these interactions are important to groundwater processes.

As waves propagate into shallower water, wave heights increase and wavelengths decrease in accordance with conservation of momentum (Dean and Dalrymple, 1991). When the water depth becomes shallow relative to the wave amplitude (depth-limited), waves break and become bores that lose energy flux shoreward and transfer momentum to increased water levels (breaking-wave-generated setup) and mean currents. Waves reaching the shore, run-up and down the beach in the “swash” zone (the region within the intertidal region that is exposed and covered by waves). Swash motions drive significant seawater into beach aquifers, generating a groundwater circulation cell with infiltration in the upper part of the swash zone and exfiltration in the lower part of the swash zone (Longuet-Higgins, 1983; Sous et al., 2013; Sous et al., 2016) (Fig. 2, process 4). Surface and subsurface measurements also revealed a dynamic response of subsurface saturation to swash events; in particular, surface saturation was decoupled from the intersection between the water table and the beachface due to swash motions (Heiss et al., 2015) (Fig. 3).

Modeling groundwater and solute transport dynamics driven by individual waves (i.e., resolving the wave phases) is computationally expensive. Phase-resolving modeling of surface waves including explicit reproduction of the sea surface and velocity field evolution often is achieved by coupling hydrodynamic models with turbulence closure methods (e.g., coupling Reynolds Averaged Navier Stokes models with k-ε model, k-ω model) and using the Volume-Of-Fluid (VOF) technique (Hirt and Nichols, 1981; Wilcox, 1993, 1998) to predict multiphase (air, water, sand) free-surface flow. Simulated phase-resolving wave motions can then be coupled with groundwater flow models to further investigate wave effects on coastal groundwater systems. Numerous numerical modeling studies, complemented with experimental data, revealed the important role of wave motions in coastal groundwater dynamics. For example, it has been found that waves significantly increased the residence time and spreading of inland-applied solutes in the beach, altered solute pathways, and shifted the solute discharge zone seaward (Boufadel et al., 2007; Geng et al., 2014). Along the swash zone, wave-induced seawater infiltration increases with increasing hydraulic conductivity (K), resulting in faster downward penetration of moisture and a flatter water table mound under the swash zone, whereas a thicker capillary fringe trapped moisture near the beach surface (Heiss et al., 2015; Geng et al., 2017b).

There is a computational challenge of using phase-resolving wave simulations to study groundwater processes that can be overcome by upscaling groundwater flow and solute transport in beach aquifers

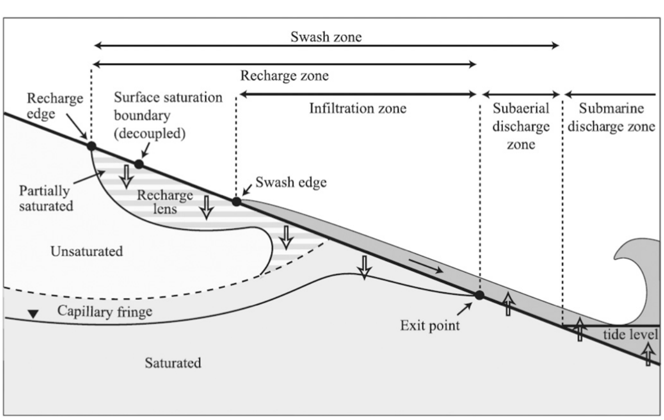

Fig. 3. Schematic of surface water and groundwater levels in the swash zone. The locations of the infiltration, recharge, and discharge zones move across the beachface with tide. Adapted from Heiss et al. (2015).

subjected to waves. For example, a phase-averaged approach considers wave effects as the (time-averaged) breaking-wave-driven setup of the water level (Xin et al., 2010), which has been used in numerous wave relevant studies (Anwar et al., 2014; Robinson et al., 2014; Malott et al., 2016, 2017; Rakhimbekova et al., 2018). In an alternative temporal-upscaling approach (termed ‘net inflow’), spatially varying infiltration rates along the beach surface averaged over several wave periods were adopted as inflow boundary conditions to represent wave forcing (Geng and Boufadel, 2015c). While the aforementioned upscaling approaches greatly reduce computational costs, the response of subsurface flow and moisture content to individual waves cannot be captured, and therefore, the phase-resolving approach is still essential for exploring swash zone dynamics.

3.3.4. Wave effects

Wave setup and wave swash can result in the infiltration of large volumes of seawater into the beach subsurface (Xin et al., 2010; Geng et al., 2014; Robinson et al., 2014; Heiss et al., 2015). At low-wave-energy beaches, tides often play a relatively more important role in SGD. At Cape Shores, USA, a tide-dominated beach, wave-driven (wave setup and unsaturated infiltration) flow was found to make up 27% of tidal circulation, with equal volumes (0.2 $m^3 m^{-1} d^{-1}$) of setup-driven and unsaturated infiltration (Heiss et al., 2014). In contrast, at high-wave-energy beaches, waves can be a primary mechanism driving seawater-groundwater exchange. For example, along high-energy beaches on the US east coast, the average volume of wave-driven seawater infiltration into beaches has been estimated to be 6 $m^3 m^{-1} d^{-1}$, reaching 15-20 $m^3 m^{-1} d^{-1}$ (Riedl and Machan, 1972) and 1.4 $m^3 m^{-1} d^{-1}$, ranging from 1.0 to 2.1 $m^3 m^{-1} d^{-1}$ (Heiss et al., 2014). In steep, microtidal beaches with large swash amplitudes, wave-induced seawater infiltration can be as high as 73 $m^3 m^{-1} d^{-1}$ (McLachlan et al., 1985).

The transport of dissolved solutes and particulate matter into the beach by wave infiltration and subsequent mixing with underlying fresh groundwater can cause geochemical changes to pore water in intertidal sediments. Anwar et al. (2014) used numerical simulations to demonstrate that mineralization of DOC from wave-induced infiltration of seawater can be greater than DOC mineralization supported by tides. The degradation of DOC was coupled to the reduction of terrestrially-derived nitrate, which resulted in a net nitrate removal efficiency of 89% for a 2.0 m significant wave height. The study also showed that waves can lead to greater iron oxide precipitation onto beach sediments due to increased availability of dissolved oxygen. Studies have also observed changes to reactive species due to wave forcing, As, Fe, Mn, and S (Jung et al., 2009; Jung et al., 2012; Rakhimbekova et al., 2018; Waska et al., 2019). The results of Rakhimbekova et al. (2018) suggest that waves may periodically form hydrologic and geochemical conditions in the aquifer. Such dynamic hydrologic and geochemical conditions could lead to episodic release of As to coastal waters. Closer to the beach surface, high frequency wave-driven velocities are an important control on sorption processes of fecal bacteria on sand grains. Malott et al. (2017) suggested that the rapid drop in fecal indicator bacteria that is often observed with increasing depth below the water table (Alm et al., 2003; Wu et al., 2017) may be attributed in part to the attenuation of vertical pore water velocity with depth below the swash zone surface.

Infiltration of seawater in the upper swash zone affects groundwater-seawater mixing and biogeochemical reactivity (Charbonnier et al., 2013). With increasing sea level, storm surge, beach erosion, or king tides, wave motions can reach higher on the beachface, and subsequent evaporation likely creates hypersaline environments (Javor, 2012), which play an important role in altering supratidal biogeochemical processes (Des Marais, 1995, 2003). Near the supratidal swash zone, seawater is a major source of dissolved oxygen (Charbonnier et al., 2013; Mouret et al., 2020) and organic matter originating from planktonic material that increases pore water respiration and carbon mineralization (Charbonnier et al., 2016). Aerobic respiration of organic matter infiltrating the beach surface in seawater can also cause N and P to mineralize, resulting in release of nitrate and phosphorous to supratidal beach sediments. While these studies provide important insights into geochemical responses to waves, the effects of waves on the fate of reactive species in beach aquifers and on chemical fluxes to coastal waters has received less attention relative to tides, likely due to the aforementioned modeling challenges and difficulties in deploying field instruments in energetic wave conditions.

3.4. Evaporation

As a fundamental component of the hydrologic cycle, evaporation is a critical driver for exchange of water and energy fluxes between the surface and subsurface (De Vries, 1958; Mahfouf and Noilhan, 1991; Parlange et al., 1998; Fujimaki et al., 2006; Shokri and Or, 2011). In the absence of salt/density effects, evaporation drives pore water to flow upward, with a magnitude dependent on meteorological conditions (e.g., temperature, relative humidity, and wind speed) and subsurface water content (Ham and Heilman, 1991; Mahrt, 1996; Liu et al., 2006; Smits et al., 2011).

The influences of evaporation on coastal pore water flow are more complex as shallow beach sediments are mostly saline. In such cases, saline groundwater is drawn upward as evaporation occurs, leading to salt accumulation and the formation of brine near the sediment surface (Fig. 2, process 5). The brines form saline plumes that can penetrate downward with a 'finger' shape; the subsequent density gradient drives pore water to circulate around the fingers, which has been substantially investigated for inland aquifer systems (e.g., dry lakes) (Wooding et al., 1997a; Wooding et al., 1997b; Boufadel et al., 1999a; Zimmermann et al., 2006; Geng and Boufadel, 2015a; Zhang et al., 2020a). In coastal beaches with a shallow water table, oceanic forcing (e.g., waves and tides) generally increases moisture content in beach sediments with large tempo-spatial variability, which further complicates beach groundwater evaporation processes. This interaction is expected to be more pronounced in the supratidal zone of beaches due to relatively long periods of subaerial exposure. Geng and Boufadel (2015b) showed that evaporation can double the near-surface pore-water salinity in the intertidal zone, compared to the scenario where no evaporation occurs. Such increases in pore-water salinity caused by evaporation are strongly correlated with tides. The simulations showed that spring tides intensify the evaporation-induced increase in the intertidal pore-water salinity, while neap tides increase salinization in the supratidal zone because the sediments are subaerial for a longer duration. Geng et al. (2016a) observed that due to evaporation, the salinity of beach pore water could vary over a large range within only a few hours and within a short distance, reaching up to 200 g/l (Fig. 4). Although hypersaline conditions have been widely identified in the shallow layer of beach sediments, density instabilities and salt fingering related to the hypersaline layer has not been observed in the field. This is likely because tidal actions prompt the horizontal mixing of salt in the beach, and therefore diminish finger-type downward migration of salt (Geng and Boufadel, 2017b). Swash motions drive seawater infiltration farther inland and likely exacerbate evaporation-induced onshore salinization; however, the combined effects of evaporation and waves on pore water flow and salinity has not been studied.

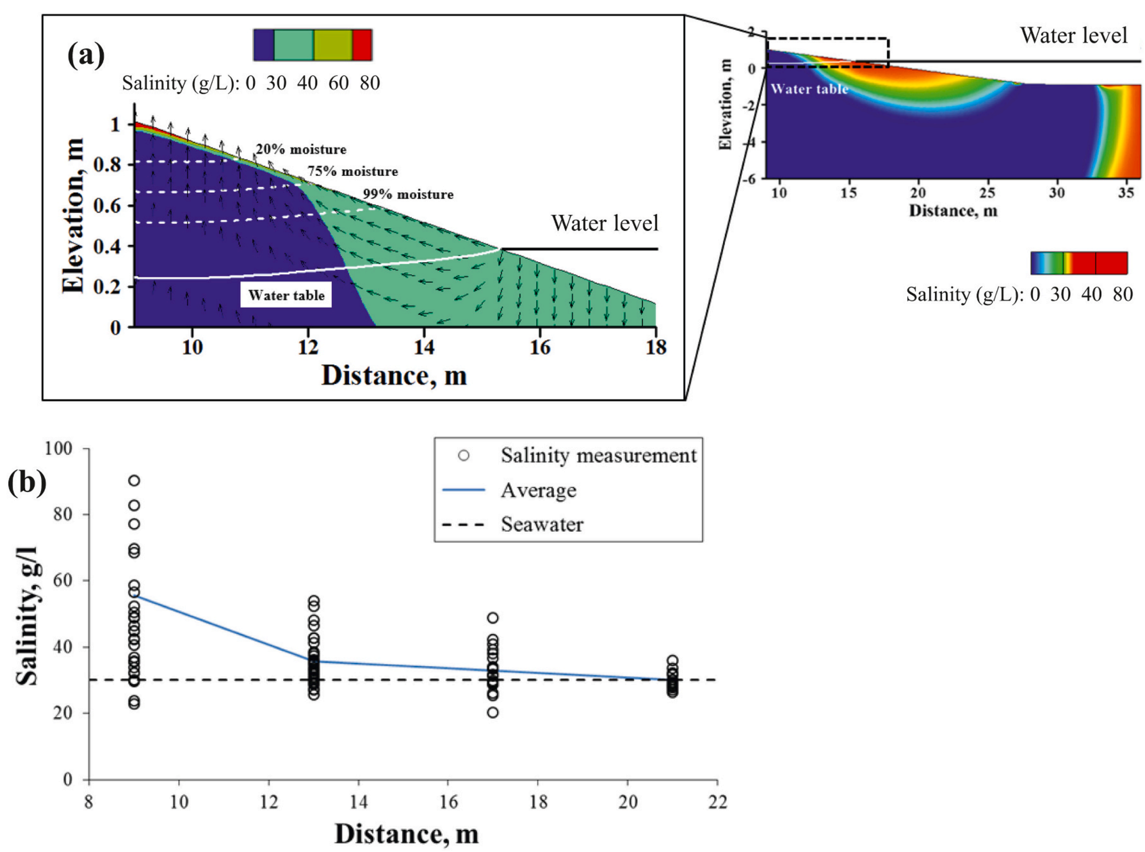

Fig. 4. (a) Simulated salinity contour. White dashed lines denote moisture content (percentage by volume) and the white solid line denotes the groundwater table. The velocity vectors indicate only the pore-water velocity direction, but not its magnitude. Also, note that due to the exaggeration of the vertical scale, the velocity vectors do not appear perpendicular to the beach surface (as the beach slope was visually increased). Extremely high pore-water salinity was measured near the upper intertidal zone in the top 5 cm; in contrast, pore water salinity at other depths and/or locations was almost the same as seawater. The simulated salinities indicate that a high saline layer formed along the beach surface due to evaporation. (b) Observed salinity profile in the top 5 cm layer of the beach sampled ~every 2 h over complete tidal cycles for 7 discontinuous days over summer period. Two values 160 g/l and 220 g/l are not reported in the fig. for visual clarity, but were considered when calculating the average value. Adapted from Geng et al. (2016a).

Parameterization of evaporation could involve solving a set of differential equations for water, vapor, and energy (heat) along with considerations for various means of transport (Parlange et al., 1998). However, the impact of this increased evaporation (due to vapor transport) is typically limited to the top 10 cm of most soils (e.g., Fujimaki et al., 2006; Bittelli et al., 2008). A simpler approach could use a 'mass transfer formulation' to simplify the approach by assuming that the water flux is proportional to the difference in moisture between the atmosphere and the pore space, with a proportionality constant determined empirically (Mahfouf and Noilhan, 1991; van de Griend and Owe, 1994; Mahrt, 1996). This is known as the 'bulk aerodynamics method', which provides an explicit relation between the evaporation flux at ground surface and the near-surface atmospheric water content. Using this approach, one needs to acquire atmospheric conditions and the specific humidity at the ground surface. Evaporation of water from groundwater systems has been coupled with groundwater models in numerous studies on inland systems (Allison and Barnes, 1985; Duffy and Al-Hassan, 1988; Bauer et al., 2004). In coastal beach systems, evaporation must be integrated with oceanic drivers to further explore the combined effects on flow and transport processes. For example, Geng and Boufadel (2015b) coupled the bulk aerodynamic model to a variably saturated density-dependent groundwater model to investigate combined evaporation and tidal effects of intertidal pore water flow and salinity dynamics. Geng and Boufadel (2017b) developed a T-MARUN model, incorporating heat and vapor transport processes into the widely used variably-saturated density-dependent MARUN model to investigate evaporation effects on pore-water flow and salt dynamics in the supratidal zone of beaches.

3.5. Evaporation effects

Alternating evaporation and precipitation creates recharge cycles across different time scales and subsequently alters SGD. Numerous studies have observed a seasonal pattern of SGD that is out of phase with inland recharge cycles (Moore, 1997; Kelly and Moran, 2002). For example, radium measurements conducted over several years along the South Atlantic Bight indicate that discharge is larger in the summer than in the winter and spring (Moore, 1996b). Groundwater fluxes estimated from radium measurements in Rhode Island also peak in the summer (Kelly and Moran, 2002). Michael et al. (2005) showed that seasonal patterns in saline SGD, as well as the observed time lags between SGD and seasonal forcing, are controlled by shifts in the fresh water-saltwater interface that result from seasonal oscillations in the water table elevation. Along the East Coast of the United States, where these studies were conducted, recharge is lowest in the summer when evapotranspiration is highest. Such seasonal oscillations of SGD can greatly affect nearshore biogeochemical fluxes. Gobler et al. (2005) observed that dissolved inorganic nitrogen-to-phosphorus ratios decreased from above 100 during winter to below one during summer within Mecox Bay, which is most likely due to seasonal reductions in FSGD that would otherwise serve as a source of DIN to the bay. Degenhardt et al. (2020) identified seasonal dynamics of microbial diversity at a sandy high energy beach. Over the investigated time period, they found that the microbial community structure along the beach was disturbed by a subsurface bloom of individual genera, yet showing a strong resilience by returning to an equilibrium state. Seasonality of organic matter degradation has also been found to alter nutrient and metal net fluxes discharging from coastal aquifers into coastal waters (Ahrens et al., 2020). The influence of evaporation on coastal subsurface biogeochemical reactions and associated discharge processes could also be reflected by its impacts on pore water salinity. Studies indicate that interstitial salinity greatly affects microbial community structure and biodiversity in intertidal ecosystems (Snelgrove, 1998). Armonies (1988) found that interstitial salinity affects the number of meiofauna moving from intertidal sediments to coastal water columns. Lercari and Defeo (2006) revealed that salinity variability is a key factor shaping macroscale patterns in species richness in sandy beach environments. They found that the number of species along the Uruguayan coast markedly decreased at the middle of the main estuarine axis, where the salinity range was maximum, irrespective of the morphodynamic state. Climate change has large influences on land precipitation and evaporation. Historical records of precipitation and drought indices all indicate increased aridity since 1950 over many land areas (Dai, 2011b; a). The subsequent environmental changes such as thawing of permafrost, sea-level rise, change in global precipitation, and evaporation pattens were identified to have substantial impacts on the quantity and quality of coastal groundwater discharge (Knee and Paytan, 2011b). For example, the thawing of marine permafrost could cause new groundwater circulation cells generated in the Arctic as ice is replaced with water (Moore and Joye, 2021). Sea-level rise likely reduces fresh SGD, further altering release of nutrients into coastal waters (Gonneea et al., 2013; Lee et al., 2013).

3.6. Vadose zone processes

The vadose zone extends from the top of the groundwater table to the beach surface and contains water at a pressure below atmospheric (Horn, 2002). The vadose zone includes a near-saturated portion above the water table known as the capillary fringe, and an unsaturated portion spanning from the tip of capillary fringe to the sand surface where pore spaces are partly filled with water and air. Variably-saturated sediment conditions are ubiquitous along shorelines where periodic oceanic forcing (tides and waves) occur, and therefore is of critical importance for coastal groundwater and solute transport processes. Seawater infiltrating the beach can be temporally stored in the vadose zone and gradually released downward into the saturated portion of the beach (Naba et al., 2002; Heiss et al., 2014); meanwhile, biogeochemical reactions occurring in the vadose zone can alter pore water chemistry, and result in distinct chemical compositions of deep groundwater and surface water, therefore affecting biogeochemical processes in coastal aquifers (Geng et al., 2015; Geng et al., 2016b).

Modeling studies that neglect the unsaturated zone in beach aquifers can miss important processes, including moisture dyanamics and mixing that occur due to oscillating water tables. Depending on the questions being asked, the application of a saturated groundwater model might be reasonable for coarse textured media (e.g., gravel and pebbles), where moisture content in the vadose zone tends to be low due to considerable drainage, but may not be suitable for fine-textured media (e.g., fine sand and clay). In variably saturated groundwater flow models, water and solutes can move vertically both downward and upward (Lin et al., 1997; Boufadel et al., 1999b; Voss, 1999; Boufadel et al., 2011; Yang et al., 2013; Yu et al., 2016).

The significance of unsaturated flow within beach aquifers has been quantified in numerous studies. Parlange and Brutsaert (1987) introduced an additional term into the Boussinesq equation to take into account the water flux crossing the water table due to capillary effects. This method estimated the total water volume in the vadose zone by introducing an equivalent capillary fringe thickness, which has been widely used in subsequent coastal analytical studies. For example, Barry et al. (1996) applied a periodic boundary condition to the analytical model developed by Parlange and Brutsaert (1987), and indicated the significance of capillarity effects in relatively low K, fine-grained media. By adopting a similar correction term in the model, Li et al. (1997) identified that capillarity effects can provide a critical mechanism for high-frequency beach water table fluctuations as responses to wave runup. Cartwright (2014) conducted sand column experiments to investigate moisture-pressure dynamics above an oscillating water table. The experimental results revealed that for long oscillation periods, the moisture profile in the unsaturated zone behaves similar to that described by the static, equilibrium moisture-pressure relationships; in contrast, for shorter oscillation periods, the moisture-pressure loops do not follow the static equilibrium wetting or drying curves, but are consistent with the loops generated by the hysteresis theory proposed in Mualem (1984). Significant flow through unsaturated sediments in coastal beach systems has been identified in numerous field studies (Atherton et al., 2001; Cartwright et al., 2006; Heiss et al., 2014; Heiss et al., 2015; Heiss et al., 2020b). Flow through the capillary fringe has also been identified to play an important role in seepage face development in tidally influenced beach systems (Naba et al., 2002).

3.7. Vadose zone effects

The unsaturated zone plays an important physical and biogeochemical role in controlling reactive solute fluxes from surface water to the larger beach groundwater system. Studies identified that permeable sediments could trap and decompose significant amounts of organic matter (Pabich et al., 2001; Kroeger et al., 2006; Szymczycha et al., 2017). Near the shoreline, seawater infiltration through the vadose zone provides a major source of dissolved oxygen that enhances sedimentary respiration and mineralization reactions (Anschutz et al., 2009; Santos et al., 2009a; Geng et al., 2015). For example, Anschutz et al. (2009) observed significant depletion of dissolved oxygen and an increase in dissolved nitrate and dissolved inorganic phosphorus within near-surface beach sediments, indicating that organic matter respiration occurs along percolating flow paths in the unsaturated zone. Geng et al. (2015) showed significant depletion of dissolved oxygen in near-surface intertidal oiled sediments. Geng et al. (2017a) conducted numerical simulations to investigate subsurface release and fate of benzene and toluene in a tidally influenced beach, and showed that reactivity in the unsaturated zone accounted for 40% contaminant biodegradation, which was comparable to that in the saturated zone.

4. Effects of geologic heterogeneity on SGD and associated geochemical fluxes

4.1. Geologic heterogeneity

Geological media are ubiquitously heterogeneous, thus groundwater and solutes are subjected to significant tempo-spatial variations as they move through aquifers (Adams and Gelhar, 1992; Gelhar, 1993). Spatial variability in K can produce chaotic velocity fields similar to turbulent flow fields (Weeks and Sposito, 1998). While most studies of coastal groundwater flow and solute transport neglect heterogeneity in order to simplify already complex variable-density processes, those that consider it reveal its importance. Dagan and Zeitoun (1998) investigated effects of layered, 1-D heterogeneity using a sharp-interface approach and showed that heterogeneity led to uncertainty in predicting the shape of the saltwater wedge and the extent of saltwater intrusion. A sharp-interface approach was used to investigate heterogeneity effects on coastal saltwater intrusion processes and found that the standard deviations of the position of the saltwater wedge can be typically on the order of several meters (Al-Bitar and Ababou, 2005). A 2-D closed-form solution for the first two statistical moments of the saltwater wedge fluctuations revealed that the correlation scale of log-K plays an important role in increasing the variability of saltwater wedge; in contrast, recharge variations do not appreciably affect the variance of the location of the saltwater wedge (Chang and Yeh, 2010). While the sharp-interface approach provides important insights into characterizing saltwater wedge in heterogeneous aquifers, its applicability is limited to scenarios where a relatively narrow saltwater-fresh water transition zone is present. In areas where a wide transition zone exists, the sharp-interface approach likely produces unreasonable results (Dokou and Karatzas, 2012).

Numerical studies of the effects of geologic heterogeneity on fresh water-saltwater mixing in coastal aquifers were investigated using the classic benchmark problem for variable density flow: the Henry problem (Henry, 1959; Held et al., 2005; Abarca, 2006; Lu et al., 2013). Held et al. (2005) used homogenization theory to derive expressions for the effective K and dispersivity in 2D isotropic and anisotropic heterogeneous permeability fields. Their numerical results showed that heterogeneities in permeability primarily affect the transient evolution of saltwater intrusion, whereas the steady-state salinity distribution is less sensitive to spatially varying permeability and longitudinal dispersion. Abarca (2006) integrated natural heterogeneity into the Henry problem, indicating strong impacts of geologic heterogeneity on the formation of the saltwater wedge such as its width, slope, and landward extent. In particular, the shape of the interface and the saltwater flux strongly correlate with the distribution of permeability in each geological realization. Lu et al. (2013) conducted laboratory experiments, complemented with numerical simulations, to investigate the effects of heterogeneity on the steady-state fresh water-saltwater mixing zone in stratified coastal aquifers. Their results demonstrate significant impacts of aquifer stratification on the spatial extent of the fresh water-saltwater mixing zone. For example, in an aquifer with a low-K layer underlain by a high-K layer, upward flow along the fresh water-saltwater interface refracts at the boundary between the two layers, leading to streamline separation and broader mixing zone in the low-K layer. Nofal et al. (2015) used lithological data to assess effects of heterogeneity on saltwater intrusion processes in Nile Delta aquifers. The results of stratigraphy and hydrochemistry assessments identified a multi-wedge system in the Nile Delta aquifer. The shape and direction of the saltwater wedge differs between the different layers of the aquifer according to the salinity and density of the groundwater in each layer. Michael et al. (2016) and Kreyns et al. (2020) investigated geologic influence on groundwater-seawater mixing through coastal and offshore aquifers. Their simulation results showed that heterogeneity generates spatially complex subsurface salinity distributions that can extend tens of kilometers offshore, with salinity gradients that drive high rates of saline SGD.

Studies have been also conducted to investigate combined effects of heterogeneity and oceanic forcing on flow and transport processes in coastal aquifers. Pool et al. (2015) investigated the combined effects of geologic heterogeneity and tidal oscillations on mixing and spreading of the fresh water-seawater interface along the salt wedge in coastal aquifers. Their simulation results indicated that heterogeneity causes the toe of the interface to move inland and the width of the interface to increase. In addition, as tidal oscillations are considered, combined effects of heterogeneity and tides on mixing and spreading of the interface attenuate as the degree of heterogeneity increases.

Recently, efforts have been made to characterize the topology of pore-water flows and its ramifications for transport and mixing processes in coastal aquifers. Flow topology allows delineation of geometrical characteristics of fluid streamlines (Sposito, 2001). Mixing of solutes in groundwater is mainly caused by stretching and folding of fluid filaments; in such a manner, the boundary areas of the solute plume become highly irregular in shape and enlarged, while concentration gradients normal to the stretched fluid filaments are increased greatly (Weeks and Sposito, 1998). Thus, the topology of the flow field and its tempo-spatial structure are fundamental for investigating subsurface flow dynamics and associated mixing and reaction processes (Sposito, 2001; Borgne et al., 2014; Chiogna et al., 2014; Chiogna et al., 2015; Ye et al., 2015; Dentz et al., 2018; Lester et al., 2019; Trefry et al., 2019; Geng et al., 2020a). The Okubo-Weiss parameter Θ is a quantitative measure of flow topology and is a function of shear and stretching deformation and vorticity (Okubo, 1970; Weiss, 1991). In 2D flow fields where Θ applies, shear and stretching deformation represents the change in shape of a fluid filament by normal and shear strain, while vorticity measures local fluid rotation, defined as the curl of the velocity vector. Trefry et al. (2019) explored chaotic advection of groundwater flow in a tidally influenced confined aquifer using a conventional linear groundwater flow model. They found that aquifer heterogeneity generates coherent Lagrangian vortices and chaos, significantly augmenting fluid mixing and transport. Geng et al. (2020d) conducted a numerical study, complemented with laboratory beach experiments conducted in

Boufadel et al. (2006), to investigate impacts of geologic heterogeneity on tempo-spatial evolution of a tracer plume in a laboratory beach system. The study revealed that heterogeneity enhances the tempo-spatial variation in the spreading of the saline intertidal circulation cell in the beach. It was also found that geologic heterogeneity creates highly transient preferential flow paths within the circulation cell, which greatly alters the spatial extent of mixing and induces variable transit times along the circulating flow paths. Geng et al. (2020c) conducted numerical simulations, incorporating realistic representations of aquifer heterogeneity, to investigate the influence of nonuniform permeability on intertidal flow topology and associated mixing dynamics in a tidally-influenced beach aquifer. The study found that heterogeneity creates transient preferential flow paths within the intertidal zone and can form multiple circulation cells and fingering-type salinity distributions. Due to heterogeneity, strain-dominated (intense mixing) and vorticity-dominated (low mixing) flow regions coexist at small spatial scales, and their spatial extent reaches peaks at high tide and low tide (Fig. 5).

Studies on heterogeneity affecting swash zone groundwater hydrodynamics are rare. A numerical study conducted in Geng et al. (2020b), complemented with field data measured in Heiss et al. (2015), showed that both heterogeneous capillary and permeability play a critical role in swash zone groundwater hydrodynamics. Heterogeneous capillarity causes spatial variability in the height of capillary rise above the groundwater table. In response to swash motions, heterogeneity forms capillary barriers that create pockets of elevated moisture content

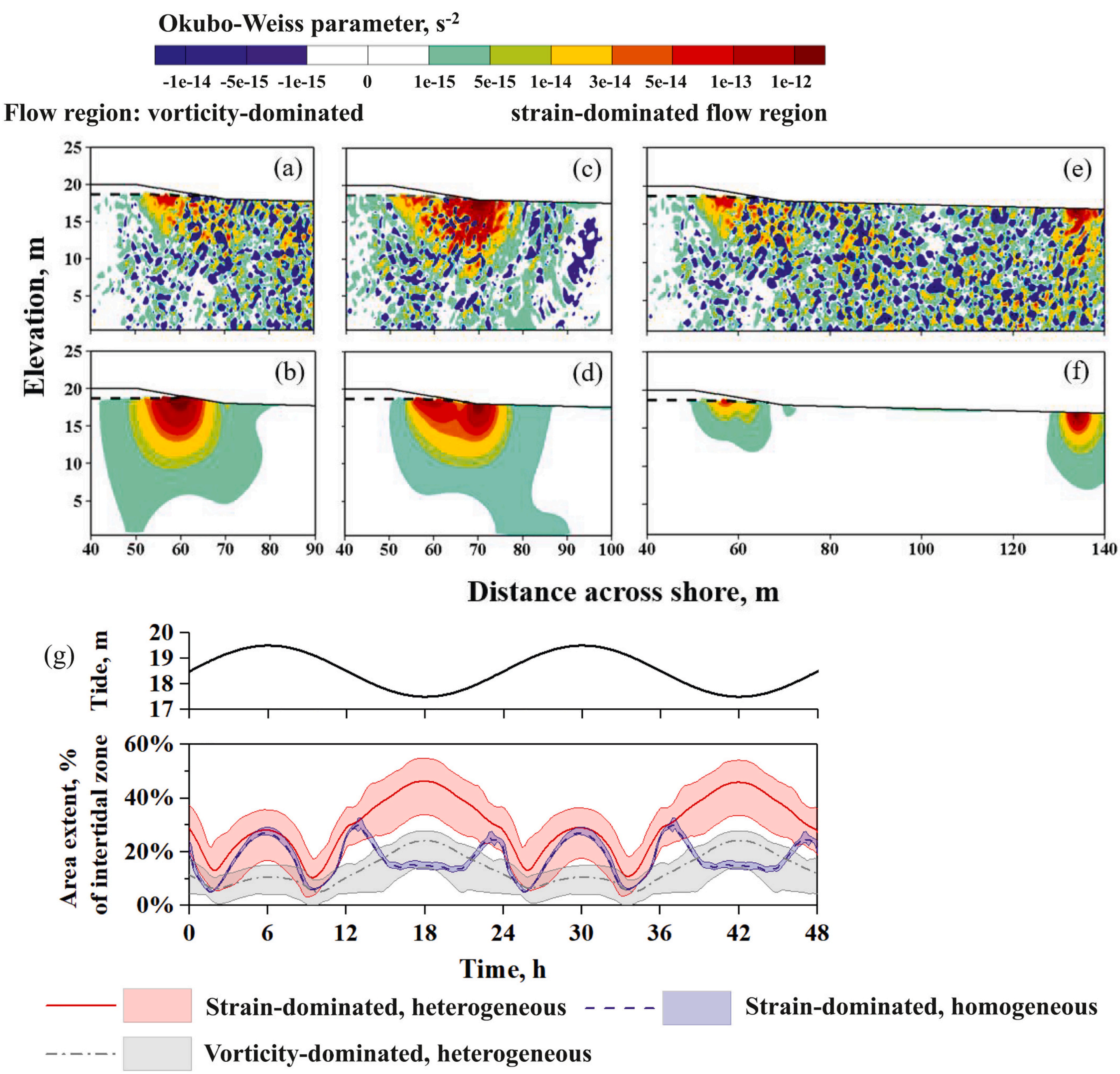

Fig. 5. Okubo-Weiss parameter values for heterogeneous sediments (a, c, e) and equivalent homogeneous cases (b, d, f) at falling high tide, mid-tide, and low tide, respectively. The temporal evolution of the areal extent of strain-dominated and vorticity-dominated flow regions in response to tides is shown in Fig. 3g for 60 geologic realizations. The areal extent is represented as a percent of the intertidal zone. The solid lines and shades represent the mean and the range between the minimum and maximum areal extents among the realizations, respectively. Taken from Geng et al. (2020c).

beneath the swash zone. These moisture hotspots persist within the unsaturated zone even at the ebb tide when the swash motions recede farther seaward. Heterogeneous K greatly alters the total amount of seawater infiltration into the swash zone and modulates the spatial distribution of infiltration along the beach surface. Due to heterogeneous K and capillarity, highly tortuous preferential flow paths were generated beneath the swash zone, creating both strain-dominated and vorticity-dominated flow regions as tides and waves move across the beach surface.

4.2. Heterogeneity effects

The spatial patterns of SGD can be highly variable in heterogeneous aquifer systems, which poses challenges when measuring and modeling fluid and chemical fluxes across the aquifer-ocean interface (Michael et al., 2003; Michael et al., 2013; Russoniello et al., 2013; Guimond et al., 2019; Guimond et al., 2020a). For homogeneous geologic settings, SGD is predicted to occur nearshore, decreasing exponentially with distance offshore (Bokuniewicz, 1992). However, numerous field measurements identified spatially anomalous discharge patterns at nearshore and offshore locations, which can be attributed to geologic heterogeneity (Moore and Wilson, 2005; Charette et al., 2015; Russoniello et al., 2017). For example, Cherkauer and Nader (1989) reported SGD measurements from 26 sites on the upper Great Lakes. They found that the decrease in SGD with distance offshore was only observed at 7 of the sites; in contrast, 17 of the sites had offshore SGD that substantially exceeded those at some locations closer to shore. Cable et al. (1997b) observed large spatial and temporal variability of SGD along transects extending hundreds of meters offshore, located about 80 km south of Tallahassee, Florida. Charette et al. (2015) measured elevated levels of radium isotopes in the North Atlantic, indicating significant SGD along the continental shelf. Numerical simulations of groundwater flow along the land-sea margin that incorporate aquifer heterogeneity show that active groundwater discharge can extend tens to hundreds of kilometers offshore along continental shelves with significant temporal and spatial variability (Mulligan et al., 2007; Michael et al., 2016). Geologic heterogeneity is also a critical factor affecting the magnitude of SGD (Cherkauer and Nader, 1989; Mulligan et al., 2007; Schornberg et al., 2010; Russoniello et al., 2013). Studies found that heterogeneity can significantly increase seawater circulation (Kerrou and Renard, 2010; Michael et al., 2016), thereby increasing the saline component of SGD (Stieglitz et al., 2008; Kalbus et al., 2009).

Geologic heterogeneity has strong impacts on biogeochemical processes within beach sediments. For example, heterogeneity-induced complex evolution of the intertidal circulation cell can strongly influence intertidal mixing-dependent reactivity (e.g., denitrification) while more tortuous flow paths and resulting variable travel time could further complicate intertidal reactivity (Heiss et al., 2020a). Biogeochemical hotspots in coastal marine environments have been identified in numerous field studies (Schutte et al., 2015; Schutte et al., 2018; Kim et al., 2019). Schutte et al. (2015) observed high nitrous oxide production driven by a hotspot of nitrate consumption that removes bioavailable nitrogen from the coastal environments. Numerical simulations conducted in Heiss et al. (2020a) show that heterogeneity can increase mixing between fresh and saline groundwater and increase residence time, resulting in up to 80% higher nitrate removal relative to equivalent effective homogeneous aquifer sediment. The models showed that denitrification hotspots form along the boundary of the intertidal circulation cell in high permeability structures where DOC and nitrate are readily supplied, which provide a physical explanation for the formation of denitrification hotspots observed in beach aquifers. In both variable-density (e.g., Heiss et al., 2020a) and single-density (freshwater rivers; e.g., Wallace et al., 2020) systems under tidal influence, nitrate removal efficiency increases with an increase in the proportion of silt to sand due to a combination of longer residence times (Heiss et al., 2020a) and greater DOC dissolution from organic-rich silt sediments (Wallace et al., 2020). Beach wrack buried in intertidal sediments can form reactive hotspots in beach aquifers by serving as a spatially discontinuous source of organic matter to fuel redox processes, indicating that chemical heterogeneity may also explain the existence of chemical hotspots observed in other studies (Heiss, 2020). The depth to bedrock underlying intertidal sediments is also important, as shallow bedrock in pocket beaches can isolate beach aquifers from terrestrial flow paths, which controls the relative contribution of recycled and new nutrients to the coastal environment (Mouret et al., 2020).

5. Effects of shoreline morphology and bathymetry on SGD and associated geochemical fluxes

5.1. Shoreline morphology and bathymetry

Coastal groundwater flow and transport processes are influenced significantly by nearshore morphology and bathymetry, including topographic features (barrier islands, dunes, bluffs, nourishments, and ponds with scales of 100 m – 10 km), beach properties (slope, berm, cusps with scales of 10 – 100 m), and submerged features (sandbars and ripples with scales 10 cm – 100 m) (Santos et al., 2012). Water level differences between the sound and ocean sides of barrier islands, as well as effects of rainfall on mid-island groundwater head levels, determine the groundwater flow direction through the aquifer (Bokuniewicz and Pavlik, 1990; Chanton et al., 2003; Niencheski et al., 2007; Rapaglia et al., 2010; Santos et al., 2012; Sous et al., 2013; Turner et al., 2016).

Coastal topographic features such as ponds, dunes, barrier islands, creeks, and channels likely have a strong impact on surface-subsurface flow interactions and associated salinization processes (Lebbe, 1981; Michael et al., 2013; Qu et al., 2014; Zhou et al., 2014; Ketabchi et al., 2016). For instance, "runnel and ridge" beach morphology could cause multiple circulation cells to occur within the intertidal zone (Waska et al., 2019; Grünenbaum et al., 2020a). The variable beach morphology and seasonal storm floods may also lead to strong spatio-temporal variability of hydrodynamic and transport patterns that distort the classical salinity stratification (Heiss and Michael, 2014; Greskowiak and Massmann, 2021; Housego, 2021). During typical conditions, the inland reach of the ocean, and thus the onshore extent of the upper circulation cell, may be limited by a dune toe, or coastal bluff. In addition, large dunes and beach nourishments can absorb additional ocean water during periods of high ocean water levels (Li, 2004; Robinson et al., 2014; Trglavcnik et al., 2018; de Schipper et al., 2020). Meanwhile beach nourishments also may trap additional precipitation, increasing fresh groundwater availability (Huizer et al., 2016; Huizer et al., 2018a; Huizer et al., 2019).

Shallow-water microtopography (scales cm to m) affects groundwater advection and solute fluxes in marine sediments. Pressure gradients generated by ocean currents over ripples and benthic organisms cause patterns of infiltrating and exfiltrating fluids and particles (Thibodeaux and Boyle, 1987; Huettel and Gust, 1992; Huettel and Rusch, 2000; Jahnke et al., 2000). The total flux exchange across the water-sediment interface has been identified to be higher across a rippled interface than across a flat bed. The water exchange increases with increasing ripple slope and the strength of the ocean current (Shum, 1992; Shum, 1993). Tracer studies suggest that ripple-flow interactions generate groundwater circulation cells in marine sediments with flows infiltrating in the ripple troughs and exfiltrating from crests (Webb and Theodor, 1968) (Fig. 6). Density-driven exchange through ripples can also occur in areas with freshwater upwelling into saline surface water bodies (Konikow et al., 2013). Benthic flux increases with increasing sediment permeability, ripple slope, and current/wave height (Boano et al., 2014; Russoniello et al., 2017). Effects of boundary flow-topography interaction on benthic exchange are significant when the sediment permeability exceeds 10^{-12} m^2, which is typical for sandy seafloors (Huettel et al., 2003). Groundwater discharge emanating from deep sediments can attenuate the spatial extent of current-bedform

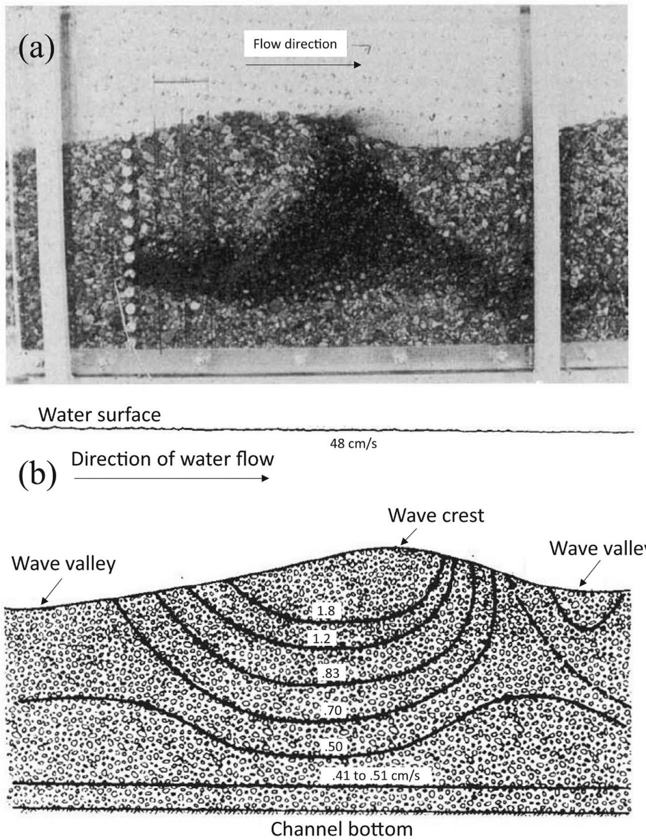

Fig. 6. (a) Typical tracer experiments of currents over a bedform showing flushing of the tracer out of the subsurface and discharge of the dye on the leeward side of the bedform. (b) Composite fluid dynamic diagram showing flow streamlines, zones of surface water inflow and groundwater discharge, and the magnitude of porewater velocities. Scale marker = 6 cm. Taken from Thibodeaux and Boyle (1987).

induced groundwater advection (Cardenas and Wilson, 2006).

5.2. Shoreline morphology and bathymetry effects

During storms or unusually high tides, ocean waves and surge may overtop coastal topographic features resulting in significant infiltration of saline ocean water that can persist for many years (Anderson Jr and Lauer, 2008; Terry and Falkland, 2010; Ataie-Ashtiani et al., 2013; Yu et al., 2016). The flushing time and depth of saline penetration also increase with increasing vertical and decreasing horizontal permeability, decreasing hydraulic gradient, and decreasing recharge rate (Yang et al., 2018). Numerical simulations conducted by Yu et al. (2016) showed that the role of topographic connectivity on overland flow is the primary factor controlling overwash groundwater salinization. In addition, surface depressions that trap and store inundating water (e.g., with low connectivity) increase the amount of seawater entering into the aquifer, leading to longer flushing times. Alongshore variable topography, such as that associated with tidal creeks, also can drive alongshore groundwater flows and modify intertidal pore water pressures, salt transport, and residence times in the beach (Zhang et al., 2016). The topography of underlying bedrock can also affect the salinization of coastal aquifers that are temporarily inundated by seawater (i.e. tsunamis) by allowing dense seawater to migrate along the slopes of bedrock, affecting flushing times (Liu and Tokunaga, 2019).

The slope of the intertidal beach affects the size of the upper circulation cell, the presence of a seepage face, and the groundwater overheight (Nielsen, 1990; Raubenheimer et al., 1999; Evans and Wilson, 2016). The upper circulation cell may be larger in steep beaches with high K (Evans and Wilson, 2016). Beach slope also may influence salt-fingering in the upper circulation cell, with unstable finger-type plumes occurring in homogeneous, tidally influenced beach aquifers with gentle topographic slopes (e.g., 0.02) (Greskowiak, 2014). Laboratory experiments suggest that salt-fingering flow greatly increases the tempo-spatial variability of SGD, with several freshwater discharge points that vary with time (Röper et al., 2015). The salt fingers can alter the transport of terrestrial contaminants flowing to the fresh discharge zone (Shen et al., 2019). On moderately steep beaches (0.05), the topographic depressions landward of the berm can result in elevated water levels below the depression that drive local circulation beneath the berm (Robinson et al., 2006). Saltwater ponding in topographic depressions in the backshore on steep beaches (0.1) can result in a larger circulation cell, while having little effect on overall salinity dynamics (Heiss and Michael, 2014). Similarly, ocean inundation into low-lying areas can result in salt fingers that evolve for years following a large storm surge (Yang et al., 2013). Furthermore, the long-term freshwater discharge rates at the aquifer-ocean interface can vary considerably when finger-type flow is present, compared to a stable upper saline plume (Evans and Wilson, 2016). Depending on the hydrological situation, these non-periodic variations may even be of higher magnitude than the variations induced by seasonally changing groundwater recharge (Greskowiak, 2014; Röper et al., 2015). However, salt-fingering has only been identified in laboratory beach systems, and has not been observed in natural systems.

Groundwater circulation owing to microtopography-flow interactions also can affect sedimentary respiration and mineralization reactions resulting from accumulation and burial of organic matter. On sandy continental shelves, algal material can accumulate in ripple troughs and be buried as the ripples migrate (Steele et al., 1970; Jenness and Duineveld, 1985; Kim et al., 2019). Oxygen consumption estimates suggest the in-situ production of benthic diatoms could only account for 10% of the carbon requirement of the sand (Steele et al., 1970). Infiltration owing to current-bedform induced groundwater circulation can be a major source of dissolved oxygen for decomposing organic matter. An oxidized surface layer over sandy sediments may reduce release of metal species to the water column by flow-topography interactions (Huettel et al., 1998). Groundwater circulation brings organic matter and oxygen into the sediment, creates horizontal concentration gradients that can be as strong as the vertical gradients, and increases the flux of groundwater constituents across the sediment-water interface (Shum and Sundby, 1996). Therefore, microscale topological gradients provide an important mechanism for enhancing mineralization of organic matter in marine sediments.

6. Future perspective

Investigations of coastal groundwater dynamics and associated discharge of water and chemicals across the land-sea interface have been conducted for decades, and have contributed to an improved understanding of coastal flow and transport processes over a wide range of scales. Still, there are knowledge gaps for which additional research is needed.

We suggest that more work is needed to address feedbacks between flow and erosion/accretion. Shorelines are usually characterized as dynamic sedimentary environments, subjected to substantial erosion and/or accretion caused by periodic oceanic forcing (e.g., tides and waves), increased incidence of storms and hurricanes, long-term environmental change (sea-level rise and climate change), and human alterations (e.g., beach nourishment, coastal fortification (green/gray), and land use change). However, studies linking beach morphology and shoreline evolution across multiple spatio-temporal scales to coastal subsurface flow and transport processes are scarce (e.g., Huizer et al., 2018b; Greskowiak and Massmann, 2021). Therefore, there is a need to better quantify the interplay between coastal subsurface transport processes and shoreline morphology, such as the impact of sandbars and alongshore variability of bathymetry and topography on ocean-groundwater interactions. In particular, coupling changes in shoreline morphology to variably saturated flow and reactive transport models will be essential to advance our understanding of temporal variability in the role of coastal aquifers on moderating chemical fluxes to marine environments.

Coastal aquifers are often hotspots for biogeochemical cycling where nutrients and contaminants are processed prior to discharge to the ocean. The dynamic nature of the subsurface mixing between terrestrial fresh water and saltwater is a critical control on aquifer reactivity. While considerable efforts have been made to develop numerical models for a better characterization of coastal biogeochemical processes, most of the models would benefit from data for further validation (e.g., Anwar et al., 2014; Geng et al., 2015; Heiss et al., 2017; Kim et al., 2020). This is likely due to the challenges of incorporating all physical and geochemical mechanisms observed in the field into a numerical model. These include geologic heterogeneity, transient hydrologic drivers such as tides and waves, variably saturated sediment conditions, comprehensive reaction networks, and representative rate constants. Therefore, we need improved modeling schemes to better represent biogeochemical reactions in real aquifers and should supplement models with sufficient measurements of chemical attenuation efficiencies and localized and bulk rates of various biotic and abiotic chemical reactions for model calibration.

The physical processes that control the formation and distribution of reactive zones in beach aquifers, including tides, waves, density gradients, precipitation, episodic ocean events, and evaporation, often operate over a wide range of spatio-temporal scales. The majority of studies elucidating these physical processes are deterministic, and thus do not readily reflect the spatial correlation and the ensuing temporal connectivity. While stochastic approaches have been widely adopted for analyzing the transport of solutes in inland aquifer systems, they have not been applied as widely in coastal systems (e.g., Geng and Boufadel, 2017a). In particular, major drivers modulating coastal transport processes are periodic (e.g., tides and waves), and aquifers are ubiquitously observed to be heterogeneous (Geng et al., 2020c; Moosdorf et al., 2021), which further highlights the importance of frequency-domain analysis on nearshore flow and transport processes, and a call for more studies across multiple scales.

Declaration of Competing Interest

None

Acknowledgements

This work was supported in part by the Multi Partner Research Initiative project Oil Translocation from the Department of Fisheries and Oceans, Canada, by the US National Science Foundation (EAR1151733, EAR1933058, PO1848650 and EAR1933010), and by the US Coastal Research Program. However, it does not necessarily reflect the views of the funding entity, no official endorsement should be inferred. All data are accessible at https://centers.njit.edu/nrdp.

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