Estuarine, Coastal and Shelf Science 207 (2018) 93–103

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

# Saltwater-freshwater mixing fluctuation in shallow beach aquifers

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ARTICLE INFO

*Keywords:*
Coastal aquifer
Saltwater-freshwater mixing fluctuation
Tidal effects
Mixing quantification
Upper saline plume
Subterranean estuary

ABSTRACT

Field measurements and numerical simulations demonstrate the existence of an upper saline plume in tidally dominated beaches. The effect of tides on the saltwater-freshwater mixing occurring at both the upper saline plume and lower salt wedge is well understood. However, it is poorly understood whether the tidal driven force acts equally on the mixing behaviours of above two regions and what factors control the mixing fluctuation features. In this study, variable-density, saturated-unsaturated, transient groundwater flow and solute transport numerical models are proposed and performed for saltwater-freshwater mixing subject to tidal forcing on a sloping beach. A range of tidal amplitude, fresh groundwater flux, hydraulic conductivity, beach slope and dispersivity anisotropy are simulated. Based on the time sequential salinity data, the gross mixing features are quantified by computing the spatial moments in three different aspects, namely, the centre point, length and width, and the volume (or area in a two-dimensional case). Simulated salinity distribution varies significantly at saltwater-freshwater interfaces. Mixing characteristics of the upper saline plume greatly differ from those in the salt wedge for both the transient and quasi-steady state. The mixing of the upper saline plume largely inherits the fluctuation characteristics of the sea tide in both the transverse and longitudinal directions when the quasi-steady state is reached. On the other hand, the mixing in the salt wedge is relatively steady and shows little fluctuation. The normalized mixing width and length, mixing volume and the fluctuation amplitude of the mass centre in the upper saline plume are, in general, one-magnitude-order larger than those in the salt wedge region. In the longitudinal direction, tidal amplitude, fresh groundwater flux, hydraulic conductivity and beach slope are significant control factors of fluctuation amplitude. In the transverse direction, tidal amplitude and beach slope are the main control parameters. Very small dispersivity anisotropy (e.g., $\alpha_L/\alpha_T < 5$) could greatly suppress mixing fluctuation in the longitudinal direction. This work underlines the close connection between the sea tides and the upper saline plume in the aspect of mixing, thereby enhancing understanding of the interplay between tidal oscillations and mixing mechanisms in tidally dominated sloping beach systems.

## 1. Introduction

Submarine groundwater discharge (SGD) represents an important transport pathway for terrestrial nutrients, carbon, metals, anthropogenic substances and persistent organic pollutants into the coastal ocean (Burnett et al., 2001; Moore, 2010). Discharge from unconfined near-shore aquifers to the ocean is a significant component of SGD, including discharges of fresh groundwater, recirculating seawater, and mixed saltwater-freshwater. These discharges are dynamic processes, controlled by tidal fluctuations, wave set-up, storm events, winds, seasonal changes and density dependent flow along the saltwater-freshwater mixing zone (Guo et al., 2009; Santos et al., 2012; Xin et al., 2015; Itugha et al., 2016). Saltwater-freshwater mixing processes have been proven to accelerate chemical flux from aquifers to the ocean, alter geochemical conditions, change habitat species and affect biogeochemical reactions in aquifers (Slomp and Van Cappellen, 2004; Anschutz et al., 2009; Moore, 2010; Charbonnier et al., 2013).

Saltwater-freshwater mixing in beach aquifers has long been thought to occur mainly in the salt wedge (see Fig. 1) dispersion zone (Cooper et al., 1964; Robinson et al., 2007a; Pool et al., 2014). However, integrated field salinity measurements (Robinson et al., 1998; Urish and McKenna, 2004; Michael et al., 2005; Robinson et al., 2007b; Vandenbohede and Lebbe, 2006, 2007; Abarca et al., 2013; Heiss and Michael, 2014) and electrical resistivity tomography profiles (Turner and Acworth, 2004; Morrow et al., 2010; Befus et al., 2013; Buquet et al., 2016) in intertidal regions, confirm the existence of another

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https://doi.org/10.1016/j.ecss.2018.03.027
Received 22 September 2017; Received in revised form 23 March 2018; Accepted 30 March 2018
Available online 03 April 2018
0272-7714/ 

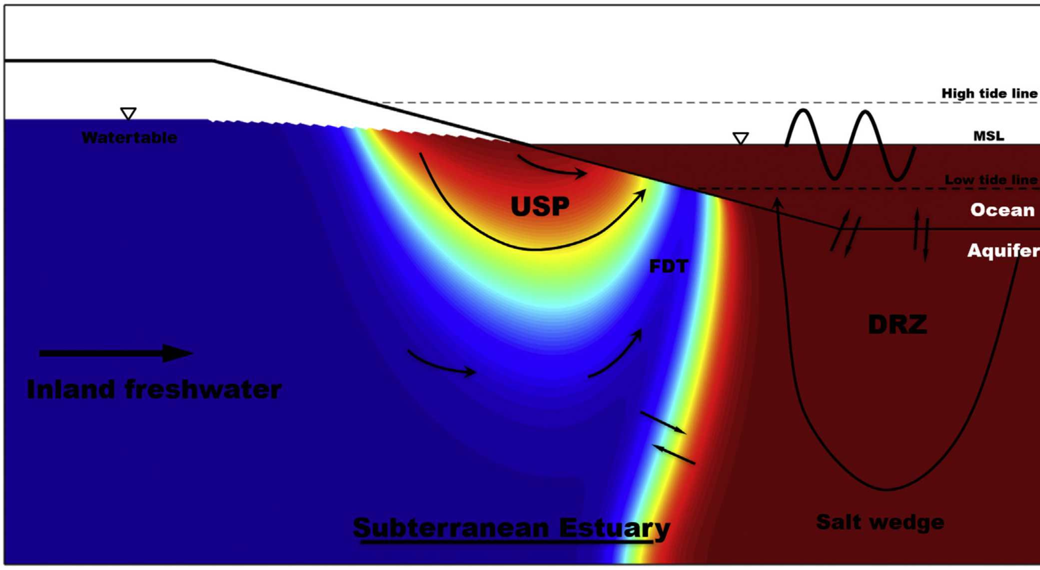


**Fig. 1.** Conceptual diagram of subterranean estuary including major nearshore circulations. Showing upper saline plume (USP), freshwater discharge tube (FDT), salt wedge (SW) and density driven recirculation zone (DRZ). The darker color indicates higher salinity. (For interpretation of the references to color in this figure legend, readers are referred to the web version of this article.)

important mixing zone, the upper saline plume (USP) (see Fig. 1), where saltwater-freshwater mixing is faster than that in the classical salt wedge. USP is an inverted structure with dense saltwater above light freshwater in shallow beach aquifers (Ataie-Ashtiani et al., 1999; Boufadel, 2000; Mango et al., 2004). In the USP, pore-water has faster flow rates and significantly lower transit times than that in the dispersion zone of the classical salt wedge (Robinson et al., 2007a). Therefore, this plume represents a potentially more dynamic zone for mixing and reaction than the salt wedge dispersion zone and may play a crucial role in geochemical transformation and coastal ecosystems (Charette and Sholkovitz, 2002; Moore, 2010).

Four essential conditions, namely, large enough oceanic oscillations, suitable terrestrial fresh groundwater flux, appropriate sloping intertidal topography, and moderate heterogeneity, are considered to be responsible for the formation of USP. Evans and Wilson (2016) noted that the development of an USP under a beach requires high rates of recirculation to create strong salinity gradients. This requires the infiltration of sufficient volumes of seawater into the beach aquifer, and necessitates that the groundwater flush through the beach is not too rapidly. Tides, which generates the main oceanic oscillations, have three main possible effects on saline recirculation in a beach: (i) tidal forcing making seawater intrude inland during flood phases and making brackish water percolate during ebb phases (Nielsen, 1990; Li et al., 1997; Cartwright et al., 2004); (ii) widening the zone of dispersion (Ataie-Ashtiani et al., 1999; Li et al., 2008; Kuan et al., 2012); and (iii) causing seawater to infiltrate into a beach directly from wave runup (Kang et al., 1995; Bakhtyar et al., 2013; Geng and Boufadel, 2015). The slope of a beach would intensify (e.g., a flatter slope) or weaken (e.g., a steeper slope) the infiltration of saltwater (Ataie-Ashtiani et al., 1999; Li et al., 2008). High heterogeneity of a sloping beach will increase both the spatial connectivity and effective permeability in a porous beach to reduce the degree of mixing as well as the extent of USP (Fiori and Jankovic, 2012).

Tidal fluctuation will cause hydraulic head fluctuation and pore water salinity oscillation (Erskine, 1991; Abdollahi-Nasab et al., 2010; Heiss and Michael, 2014; Elad et al., 2017). Tide-induced hydraulic gradients can result in a transient increase of the solute transfer rate more than 20 times higher than the average rate in the aquifers that undergo saltwater intrusion (Li et al., 1999) and likely contribute to fluctuations in submarine seepage rates (Burnett et al., 2002). However, the transient behaviour of solute migration and the associated mixing processes under highly variable groundwater flow have remained largely unexplored so far. Several studies have been conducted to investigate some aspects of tidal fluctuations on the mixing patterns in shallow unconfined coastal aquifers. Numerical studies have concluded that salinity distribution does not fluctuate significantly over the tidal cycle (Ataie-Ashtiani et al., 1999; Mao et al., 2006; Robinson et al., 2007a; Pool et al., 2014). However, the conceptual models suggest that the width of the freshwater discharge tunnel (FDT) contracts and expands over the semi-diurnal period (Barry and Parlange, 2004; Urish and McKenna, 2004), which is supported by laboratory experiments and field investigation (Boufadel, 2000; Robinson et al., 2006, Shalev et al., 2009; Kuan et al., 2012, Abarca et al., 2013; Heiss and Michael, 2014). Such discrepancy shows that there still exists a knowledge gap for a full understanding of the behaviour of solute migration and the associated mixing processes under tide-dominated groundwater systems. Moreover, the magnitude of mixing between seawater and fresh groundwater in the USP has not been properly quantified. This is partly due to the difficulties in measuring and quantifying the mixing process in groundwater systems under complex spatiotemporal flow variations. When tidal conditions include variable-density flows in a saturated-unsaturated aquifer with unpredictable seepage face, the strong nonlinearity makes full understanding of the beach hydraulics a challenging task, even for spatially and temporally varying saltwater-freshwater mixing (Bear, 1972; Simmons et al., 2001; Smith, 2004; Boufadel et al., 2011). The recently developed mesh-free numerical modelling technique, such as SPH (Shao, 2012), could be an effective method for simulating saltwater-freshwater mixing.

This study is motivated by investigating the fluctuation of salinity distribution, examining whether the tidal driven force acts equally in the mixing behaviours at the upper saline plume and lower salt wedge, and exploring the factors controlling the mixing fluctuation features, thus filling the knowledge gap in this field. To this end, we constructed variable-density, saturated-unsaturated, transient groundwater flow and solute transport models for a wide range of major hydrogeological parameters. The objectives of this study are (i) to evaluate the transient location and shape of the salinity distribution in the aquifer, considering tidal fluctuation effects, saturated-unsaturated flow and the seepage face developed at the aquifer-air interface and (ii) to further gain a quantitative understanding of the mixing behaviour under the