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# Tide-induced seawater–groundwater circulation in shallow beach aquifers

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Solute transport

**Summary** In this paper, we investigated the tide-induced seawater–groundwater circulation in shallow beach aquifers using the finite element model MARUN. The numerical solutions were generalized using a dimensionless formulation. From a dimensionless tidal period and a dimensionless beach slope of 10%, we obtained results that apply to a wide range of beach permeabilities from $10^{-4}$ m/s to $10^{-3}$ m/s, beach slopes from 3.16% to 31.6%, tidal amplitude (0.3 m-2 m) and period (diurnal or semidiurnal). The numerical simulations demonstrated the following: The maximum Darcy velocity always occurs at the intersection of the watertable and the beach surface. The offshore beach groundwater is almost stagnant compared with the onshore groundwater flow, which may explain the previous observations that the major portion of the seaward groundwater seepage usually occurs in the shallow part of the submerged beach. The outflow from the seepage face accounts for 41–97% (average 55%) of the outflow from the intertidal zone. The amount of seawater infiltrating into the intertidal zone in a tidal cycle increases with the beach permeability and decreases when the inland recharge increases, and ranges from 35.5 $m^3$ $yr^{-1}$ $m^{-1}$ to 505.8 $m^3$ $yr^{-1}$ $m^{-1}$ for all the cases considered. Smaller beach slopes, smaller inland freshwater recharges, and/or greater beach permeability lead to larger saltwater plumes in the intertidal zone of the beach. The results are in line with the existing results of field observations and numerical simulations by previous researchers.


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## Introduction

Beaches and intertidal zones play important roles in coastal ecological systems and biodiversity because of the interactions of freshwater from inland and the seawater from the ocean as well as the combined actions of the tides and waves. Therefore, it is important to understand the dynamics of exchange of saltwater and freshwater along with water flows. Such an understanding is also needed if bioremediation is adopted following an oil spill on a beach (Venosa et al., 1996; Li et al., 2007). Numerous analytical (e.g., Nielsen, 1990; Li et al., 2000; Teo et al., 2003; Jeng et al., 2005; Cartwright et al., 2006; Li et al., 2007b; Li et al., 2007c), numerical (e.g., Turner, 1993; Li et al., 2005; Mao et al., 2006; Robinson et al., 2006; Werner and Lockington, 2006; Li et al., 2007a; Robinson et al., 2007), and experimental (e.g., Nielsen, 1990; Turner, 1993; Wrenn et al., 1997; Uchiyama et al., 2000; Cartwright et al., 2004; Robinson et al., 2006) studies have been conducted for the groundwater hydraulics and/or solute transport in coastal aquifer systems. Recently, the tidal effects on the submarine groundwater discharge in subterranean estuaries have been frequently investigated with field measurements and numerical simulations (e.g., Taniguchi, 2002; Li and Jiao, 2003; Prieto and Destouni, 2005; Robinson et al., 2006; Taniguchi et al., 2006; Robinson et al., 2007). Even in the absence of waves on beaches, rigorous quantification of beach hydraulics is challenging because of non-linearity resulting from both the dependence of water density on salt concentration (Frind, 1982) and water flow in the unsaturated zone. The presence of a seepage face introduces additional non-linearity due to the fact that the seepage face location cannot be known a priori (Neuman, 1973; Boufadel, 2000; Naba et al., 2002).

Various studies elucidated salinity distribution within the beach. Examples include the laboratory scale and numerical works of Ataie-Ashtiani et al. (1999b) and Boufadel (2000). The primary goal of this article is to evaluate exchange flows of the beach with both the sea and the landward aquifer. A secondary goal is to further elucidate the dynamics in tidally-influenced beaches.

The beach domain to be investigated is reported in Fig. 1a. The vertical extent of domain is $L_z^*$. The tide is assumed to be sinusoidal with a period $T^*$, and the tidal sea level is given by

$$h_{\text{sea}}^*(t^*) = h_m^* + A^* \cos\left(\frac{2\pi}{T^*} t^*\right), \tag{1}$$

where $t^*$ is time and $h_m^*$ is the mean sea level, and $A^* = L_z^*/5$ is the tidal amplitude (Fig. 1a). Starred quantities are dimensional and they will be converted in this manuscript to non-dimensional where then the stars are removed.

In contrast with the existing numerical studies with deep coastal aquifers (20-150 m) such as Prieto and Destouni (2005), Werner and Lockington (2006), and Robinson et al. (2006, 2007), here we only focused on relatively shallow beach aquifers shown in Fig. 1a. Shallow aquifers are commonplace in reality, e.g., the sandy beach aquifer on the southwestern shore of Delaware Bay (Wrenn et al., 1997), the aquifers of the Florida coast reported by Cable et al. (1997) and the glacial deposits along the North East coast of the USA (Valiela, 1990; Portnoy et al., 1998). In addition, studies have noted that the major portion of the seaward groundwater seepage usually occurs in the shallow part of the submerged beach and the magnitude of the seaward groundwater seepage decreases with seaward distance away from the coast (Bokuniewicz, 1980; Cable et al., 1997; Taniguchi, 2002; Slomp and Van Capellen, 2004; Taniguchi et al., 2006). Thus, even for deep aquifers, understanding the exchange occurring in the shallow part is of major importance.

The layout of the paper is as follows: First a dimensionless formulation is introduced to highlight the relative role of important mechanisms, and to generalize the results to beaches of various properties, such as the hydraulic conduc-

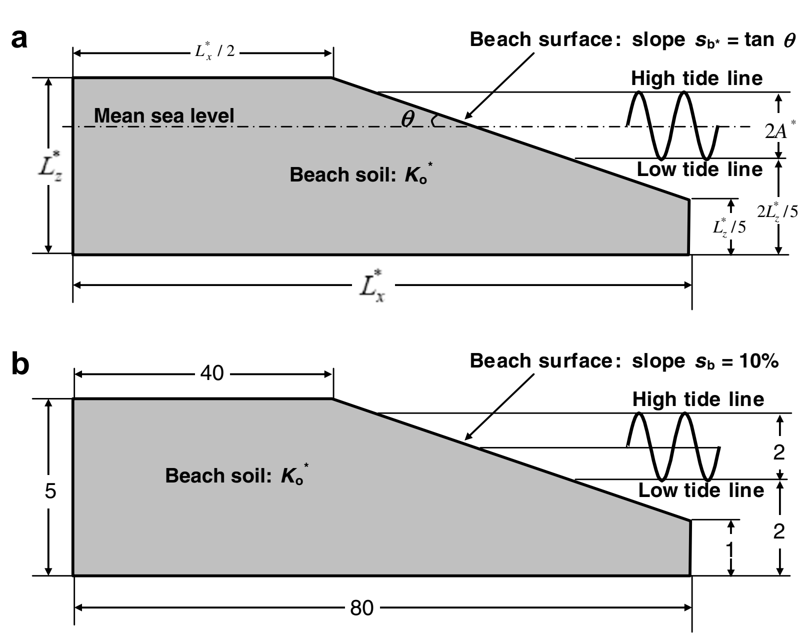


**Figure 1** Beach cross-sectional domains for (a) real dimensional and (b) dimensionless model formulations.