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Numerical study of wave effects on groundwater flow and solute transport in a laboratory beach

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ABSTRACT

A numerical study was undertaken to investigate the effects of waves on groundwater flow and associated inland-released solute transport based on tracer experiments in a laboratory beach. The MARUN model was used to simulate the density-dependent groundwater flow and subsurface solute transport in the saturated and unsaturated regions of the beach subjected to waves. The Computational Fluid Dynamics (CFD) software, Fluent, was used to simulate waves, which were the seaward boundary condition for MARUN. A no-wave case was also simulated for comparison. Simulation results matched the observed water table and concentration at numerous locations. The results revealed that waves generated seawater–groundwater circulations in the swash and surf zones of the beach, which induced a large seawater–groundwater exchange across the beach face. In comparison to the no-wave case, waves significantly increased the residence time and spreading of inland-applied solutes in the beach. Waves also altered solute pathways and shifted the solute discharge zone further seaward. Residence Time Maps (RTM) revealed that the wave-induced residence time of the inland-applied solutes was largest near the solute exit zone to the sea. Sensitivity analyses suggested that the change in the permeability in the beach altered solute transport properties in a nonlinear way. Due to the slow movement of solutes in the unsaturated zone, the mass of the solute in the unsaturated zone, which reached up to 10% of the total mass in some cases, constituted a continuous slow release of solutes to the saturated zone of the beach. This means of control was not addressed in prior studies.

1. Introduction

In the last two decades, studies have revealed the groundwater system near the coastline is an important transport pathway for pollutants to enter the marine environment (Bakhtyar et al., 2012a; Boufadel et al., 2007; Moore, 1996; Santas and Santas, 2000; Xin et al., 2010). The near-shore groundwater system can be affected by many factors, such as tides (Bobo et al., 2012; Guo et al., 2010), waves (Boufadel et al., 2007; Nielsen, 1999), pumping and climatic stresses (Alley et al., 2002; Calow et al., 1997). Gravity waves can affect beach groundwater circulation patterns, and subsequently influence solute transport in near-shore aquifers (Boufadel et al., 2007; Bradshaw, 1974; Horn et al., 1998). Understanding the effects of waves on groundwater flow and subsurface solute transport is important for solving coastal environmental issues such as

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submarine groundwater discharge (Xin et al., 2010), transport of contaminants to the ocean (Kersten et al., 2005; Robinson et al., 2006), bioremediation of oil spills (Santas and Santas, 2000), deducing tsunami inundation processes (Goseberg et al., 2013), nutrient recycle in beach aquifers, and nutrient fluxes to oceans (Charbonnier et al., 2013; Rocha et al., 2009).

Experimental studies (Baldock and Hughes, 2006; Boufadel et al., 2007; Longuet-Higgins, 1983; Sous et al., 2013) and numerical studies (Bakhtyar et al., 2012a, 2012b; Li and Barry, 2000; Li et al., 2002; Turner and Masselink, 1998) have demonstrated the effects of waves on hydrodynamics in near-shore aquifers. Experimental studies are usually carried out to reveal wave-related hydrodynamic phenomena in coastal aquifer systems. Longuet-Higgins (1983) provided an experimental illustration of wave effects on groundwater flow in the surf zone based on experiments conducted on a laboratory beach. He reported that waves approaching a sloping beach induced a tilt (wave set-up) in the mean water level within the surf zone. This wave set-up helped to drive an offshore bottom current between the shoreline and the breaker line. The earliest experimental study to quantify groundwater flow and solute transport in response to waves and tides was conducted by Boufadel et al. (2007). They performed tracer studies on a laboratory beach to study subsurface pollutant mixing and transport processes under the influences of waves. They observed that waves created a steep hydraulic gradient in the swash zone and a mild one landward of it; waves also modified the transport pathways for the tracer plume discharge across the beach surface and subsequently increased its residence time in the beach. Sous et al. (2013) studied groundwater circulation and percolation (through-bed) flows in a sandy laboratory beach in response to wave forcing. Their experimental results showed that in the swash zone, the main tendency is downward infiltration flow; flow exfiltration was not observed in this zone during the uprush–backwash cycle. Seaward of the swash zone on the beach surface, cycles of infiltration–exfiltration were observed in response to free surface waves.

Numerical models were also developed to better understand the effects of wave forcing on groundwater and associated subsurface solute transport in coastal beaches. Li et al. (1997a) developed a modified kinematic boundary condition (BC) approach to represent high-frequency water table fluctuations due to wave run-up. Their simulation results showed similar features of water table fluctuations observed in the field. However, associated solute transport was not considered in their study. Bakhtyar et al. (2012b) investigated transport of variable-density solute plumes in beach aquifers subjected to tidal and wave forcing. In their paper, fluid motion in the ocean was simulated using the Reynolds-Averaged Navier–Stokes (RANS) equations; variable-density groundwater flow and solute transport in a near-shore beach subject to oceanic forcing were simulated using SEAWAT. Their simulation results confirmed that both tide- and wave-forcing induced an upper saline plume beneath the beach face. The results also further demonstrated the effect of wave and/or tidal forcing on the solute plume's pathways, residence time and discharge rate across the beach face. However, most previous modeling studies are based on numerical experiments by using saturated groundwater flow models (Bakhtyar et al., 2009, 2012a, 2012b; Li and Barry, 2000; Li et al., 2002). Studies have found that in saturated flow models, the water table becomes an impermeable boundary for water flow and solute transport, which is not realistic; while, in variably saturated models, the water table is merely the locus of points where the water pressure is zero, and thus water and solute can traverse it both downward and upward (Boufadel, 2000; Boufadel et al., 1999a, 2011). Xin et al. (2010) presented a numerical model to examine and quantify the individual and combined effects of waves and tides on groundwater flow and salt transport in near-shore aquifer systems. They simulated density-dependent flow in the beach groundwater system by coupling a near-shore wave model BeachWin and a density-dependent variably saturated groundwater flow model SUTRA. The modeling results demonstrated a wave-generated onshore tilt in phase-averaged sea level; the resulting hydraulic gradient induced groundwater flow circulations in the near-shore zone of the coastal aquifers and subsequently formed an upper saline plume similar to that formed due to tides. Robinson et al. (2014) used the SUTRA model to investigate groundwater flow and salt transport in a subterranean estuary driven by intensified wave conditions. However, to our knowledge, no prior numerical models on wave-induced groundwater flows have been validated against field or experimental data.

The objective of this paper is to examine and quantify groundwater flow and subsurface solute transport in beaches subjected to waves. Specifically, we used a 2-D (vertical slice) finite element model MARUN (MARine UNsaturated model) for density-and-viscosity-dependent groundwater flow and solute transport in variably saturated porous media (Boufadel, 2000; Boufadel et al., 1999a). Fluent (www.ansys.com), a Computational Fluid Dynamics (CFD) modeling software, was used in 2-D (vertical slice) to simulate wave-induced sea level oscillations to provide the seaward BC for the MARUN model. The modeling was “ground truth” by comparison to experiments performed in a laboratory beach subjected to waves (Boufadel et al., 2007). Besides the validation of the new conceptual model, the results of Boufadel et al. (2007) have never been modeled, and they are one of the few well-controlled results of solute migration in a beach due to waves. With the goal of evaluating wave-induced groundwater flow and solute transport within the beach, the following specific goals were targeted: (1) The plume's trajectory, residence time, migration speed, spreading, discharge zone, and discharge rate were quantified; (2) Random walk particle tracking (RWPT) algorithm was adopted to predict pathways and transit time of the particles released at the different locations of the beach; and (3) sensitivity analyses were conducted to identify the impact of beach properties, such as permeability and capillarity, on the wave-induced groundwater flow and solute transport processes.

2. Experiments and methodologies

2.1. Experimental setup

Boufadel et al.'s (2007) experiments were performed in a carbon steel tank (8 m long × 2 m high × 0.6 m wide), with a transparent long side wall. Sand was placed in the tank