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Shape of the shallow aquifer at the fresh water–sea water interface on a high-energy sandy beach

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ABSTRACT

Inland aquifers are connected to the ocean through permeable coastal sediments. The mixing zone between sea water and fresh-groundwater forms a so-called subterranean estuary. The dynamics and the shape of this interface influence fluxes of fresh water to the coastal zone. On tidal sandy beaches, tide and waves actions lead to the formation of an intertidal saline circulation cell that complements the structure of the subterranean estuary between sea water and fresh water. The upper beach corresponds to the recharge zone, where large volumes sea water penetrate the sediment at high tide, whereas the lower beach corresponds to the discharge zone of older pore water that remains in the sand for several tidal cycles. The objective of our study was to characterize the shape and the evolution of this saline cell in a high-energy macro-tidal beach, the Truc Vert beach (SW France). In order to assess the distribution of saline, brackish and fresh water in this high-energy beach aquifer, we conducted electrical resistivity tomography (ERT) measurements from the lower beach face to the sand dune in winter 2012–2013. We also measured water table elevation and salinity in three piezometers situated at the base of the dune and in pore waters at low tide on tidal cross-shore transects. Results show that the intertidal saline plume can be identified and localized with the ERT method. The fresh-saline water interface is almost vertical in the upper beach. The saline circulation cell occupies the upper part of the tidal beach over a thickness of 5 m deep. Below this saline cell, a brackish water flows to the ocean: about 30% of fresh water was found in pore water in the lower part of the beach. Shifting of the vertical front between saline and fresh waters of about 2–5 m occurred during the spring–neap tidal cycle. This migration is small relative to the beach size, suggesting that the transition zone is relatively stable. The variations in salinity of the circulation cell suggest that the position of the saline plume is controlled by the spring tide level. Our results differ slightly from studies based on modelling and piezometric measurement made in less exposed micro-tidal sandy beaches. Our data would allow to better constrain numerical models that would enable to quantify water residence time and solute fluxes in subterranean estuaries of high-energy beaches.

1. Introduction

The population growth, the expansion of coastal cities and the climate change have made the study of the sea water–fresh water interface essential for several years (Van Dam, 1997; Creel, 2003). The world's population is mainly located along coasts. This population uses coastal aquifers for drinking water, agriculture and industry (Cheng and Ouazar, 2003) making them more sensitive to the salt water intrusion. Both knowledge of the hydrogeological context, of the coastal dynamics and of the evolution of water needs are key elements to assess the risk induced by the infiltration of saltwater into fresh water aquifers.

Recent studies have shown that a mixing between groundwater and sea water in a coastal aquifer defines an area of important biogeochemical reactions. These reactions are characterized by a

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strong physical and chemical gradient. This area, called subterranean estuary may influence the cycle of trace elements and reduces the impact of continental anthropogenic contaminants for the ocean (Kroeger and Charette, 2008; Charette and Sholkovitz, 2002).

From a hydrogeological point of view, the first works made to characterize the fresh water–saltwater interface was done by Badon-Ghyben (1889) and Herzberg (1901). Two kinds of approaches coexist to characterize fresh water–saltwater interface: models with sharp interface, where fresh water flows from the continent to the ocean on a static salty groundwater; models of diffuse interfaces where we consider the convergence of the flows of fresh and salt water from the continent to the ocean in a mixing zone (Boufadel, 2000; Robinson et al., 2007).

Recently, Bakhtyar et al. (2012) have used the code SEAWAT (Guo and Langevin, 2002). This code couples MODFLOW for the flow (McDonald and Harbaugh, 1988) and MT3DMS for multispecies solute transport (Zheng and Wang, 1998). The authors have achieved a numerical analysis to characterize the transport with variable density. The model combines the flows in the groundwater and the transport of dissolved substances with different physical forcing. In these studies, the authors have incorporated the effect of the tide and waves on transfers taking place in a beach aquifer. The modelling showed that in addition to the characteristic shape of the salt water intrusion as defined by the model of Ghyben Herzberg, wave action and the tide induce the formation of a saline circulation cell on the beach. With a constant hydraulic gradient upstream, the effect of tide is more important than the effect of waves to form the salt water cell. Their combined effects are additive (Bakhtyar et al., 2012). The upper beach corresponds to the recharge zone of the cell, where large volumes of sea water penetrate the permeable sediment at high tide, whereas the lower beach corresponds to the discharge zone of older pore water that can remain in the sand for several tidal cycles.

The shape and the dynamics of saline cells has been identified from direct measurements based on piezometer placed on cross-shore transect of tidal beaches (e.g. Turner and Acworth, 2004; Charette et al., 2005; Heiss and Michael, 2014). In high-energy beaches, the installation of piezometer on cross-shore profiles is precluded, because of topographic changes due to sand movements. Geophysics can be used to provide information on the fresh water–salt water interface and its evolution as a function of forcing (Swarzenski et al., 2007a, 2007b). Among the geophysical methods, direct current methods can be used to characterize the interface because the resistivity of the soil depends on the conductivity of the pore water and water saturation (Archie, 1942). The large electrical resistivity contrast between sand saturated with sea water (0.2 Ω m) and brackish to fresh water (>5 Ω m) makes it possible to map the subsurface groundwater salinity distribution using geophysical techniques. Three types of electrical methods have been commonly used in coastal environments: vertical electrical survey (VES, 1D) (Van Dam and Meulenkamp, 1966; Nowroozi et al., 1999; Wilson et al., 2006; Goes et al., 2009; Oulaaross et al., 2009), electrical resistivity tomography (ERT, 2D) (Chouteau et al., 2012; Dimova et al., 2012; Stieglitz et al., 2008; Wilson et al., 2006; Abdul Nassir et al., 2000; Morrow et al., 2010; Ogilvy et al., 2009), and induced polarization (IP) (Slater and Sandberg, 2000). These methods allowed to measure spatial variations in subsurface resistivity and to map the interface between fresh and salt water and therefore discharges of groundwater (Chouteau et al., 2012; Dimova et al., 2012; Stieglitz et al., 2008). Two-dimensional resolution of ERT is more suitable than the VES for complex interfaces (saline plume, dipping broadcast area...). Recent devices reduce acquisition time.

ERT measurements were performed on different beaches (Lanyon et al., 1982), and the tide impact on continental groundwater has been described in many studies. The electrical data obtained by Slater and Sandberg (2000) showed a phase shift between salinity changes and groundwater level in the coastal subsurface during a tidal cycle. Previous studies have estimated the water recirculation flow and solute fluxes in high energy beaches. These results were obtained using modelling (e.g., Nielsen, 1990; Robinson et al., 2007; Chassagne et al., 2012; Bakhtyar et al., 2012), tracer experiments (Heiss and Michael, 2014) or direct quantification based on the results of ERT under appropriate conditions (Dimova et al., 2012; Stieglitz et al., 2008). Our study shows for the first time ERT data on high-energy macrotidal sandy beach. It provides information on the geometry of the subterranean estuary. This data will be useful to better understand the biogeochemical fluxes (Anschutz et al., 2009; Charbonnier et al., 2013a, 2013b) and to constrain the coupled transport-biogeochemistry model (Chassagne et al., 2012) in this context.

2. Material and methods

2.1. Study site

The study site is located in the southwest of France, on the Aquitaine coast (Fig. 1). The sandy coastline is 240 km long. It is located between the Gironde and Adour estuaries and is bordered by high sandy dunes. From a geological point of view, the first 40 m of our prospection area are characterized by marine, lake and ancient paths rivers deposits (Féniès and Lericolais, 2005).

Truc Vert Beach is representative of the Aquitaine coast beaches with a system of double bars (Castelle et al., 2007). Sandy formations (dune, interdune and foreshore) are an aquifer with high transmissivity and permeability. The foreshore is sand with an average grain size of 300–400 microns and a porosity between 0.38 and 0.42 (Charbonnier et al., 2013b). Less permeable zone with more clay, corresponding to the Pliocene would be present at a depth of −30 to −40 m (based on Féniès and Lericolais, 2005). Prospected volumes consisted of the sandy sediment exclusively.

The topography of this area is explained by the presence of recent dunes deposited by wind and the present of sand deposited by the ocean on the beach. It can be modified cross-shore depending on the swell, tidal regime and meteorology. Accretions or erosions of more than 1 m were observed within two weeks (Charbonnier et al., 2013b). The precise topographic survey was done for each measurement survey.

The average tidal range is 3.2 m, up to 5 m during spring tides. This range is under conditions of high energy with swell average amplitude of 1.5 m. This amplitude can reach 10 m during winter storms (Butel et al., 2002). The 0 m NGF (Fig. 1) corresponds to the mean sea level.

2.2. Electrical survey

We performed geophysical investigations, which could provide large-scale information on the aquifer. We realized five electrical resistivity tomography (ERT) profiles (see location on Fig. 1). ERT is an active geoelectrical prospecting technique used to obtain 2D images of the subsurface electrical resistivity distribution. The electrical resistivity of soils is highly dependent on their water content, ionic concentrations and clay content. This geoelectrical method consists in the injection of current into the ground through a set of electrodes, and the measurement of the resulting electrical potential differences between another set of electrodes at the surface. The mathematical association between electric currents and voltage measurements provides the apparent resistivity distribution of the ground called pseudo-sections. In order to have a better spatial resolution, we used a Dipole–dipole configuration. For 2D