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Saltwater circulation patterns within the freshwater–saltwater interface in coastal aquifers: Laboratory experiments and numerical modeling

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SUMMARY

Groundwater flow patterns within the freshwater–saltwater interface in coastal aquifers include rotation in the flow direction of saltwater that originates from the sea and circulates in the aquifer. Using two types of tracer experiments we analyze the configuration of the rotating flow-lines. The experimental results are numerically reconstructed and quantitatively compared to the salinity distribution along the interface. The results show that the rotation in the direction of the saltwater flow-lines begins at the lowermost part of the interface (i.e. contour $C/C_{max} = 99\%$), and completes within its lower tenth (contour $C/C_{max} = 94\%$). At the upper part of the interface, after the rotation is completed, the flow is dictated by the freshwater flow seaward. Based on these results, the well-known chemical freshwater–saltwater interface is divided into two different parts, defined by their physical properties: (1) the lower part is the "Flow Rotation Region", defined by convective circulating flow-lines; and (2) the upper part is the "Dispersive Region", defined by dispersive dilution. Sensitivity analysis shows that the physical configuration of the interface depends on the transversal dispersivities. At higher dispersivities the rotation width increases, but completes within the lower third of the interface, at most. The sensitivity analysis also shows that the rotation begins at the lowermost part of the interface for dispersivities. Therefore, since no flow occurs below a line of 99%, the saline water that flows seaward is always diluted with respect to its original salinity. These flow patterns might affect coastal processes such as submarine groundwater discharge (SGD) and chemicals transport through the aquifer.

1. Introduction

The circulation of saltwater in coastal aquifers is a well-known phenomenon (Bear, 1979; Cooper, 1959; Henry, 1964; Todd, 1980). Its flow patterns vary from short-time-scale, such as wave and tidal driven (Robinson et al., 2007a; Robinson et al., 2007b, 2014, 1998; Xin et al., 2010, 2014) through seasonal scale (Michael et al., 2005), up to long term time-scale of density-driven dispersive circulation (Cooper, 1959). This study focuses on the density-driven dispersive circulation flow patterns.

The long term, density-driven, circulation (Cooper, 1959) is a natural phenomenon that occurs due to density differences between fresh groundwater and saline water from the sea. These water bodies come into contact at the Freshwater–Saltwater Interface (FSI), which defines the mixing zone, as defined by the salt concentration gradient (i.e. the zone between contours of $C/C_{max} = 99\%$ to $C/C_{max} = 1\%$ of saltwater concentration). Kohout (1960) argued that hydrodynamic dispersion drives the saltwater circulation and causes continuous inflow of water from the saltwater body into the aquifer, and continuous outflow seaward, along the FSI. Cooper (1959) showed that the FSI is not sharp, but is rather a mixing zone between the fresh groundwater and the saltwater, known as the zone of dispersion.

Understanding the configuration of the long term circulation is important with regard to processes like submarine groundwater discharge (SGD), and for mass balances of coastal areas (Moore, 1996; Simmons Jr, 1992). This circulation is also counted as a major component in hydrogeochemical processes which determine the chemical composition of the FSI (Russak and Sivan, 2010), and for transport of pollutants and nutrients (Smith, 2004). More broadly, it is highly important with regard to water resource management and planning in coastal areas (Van Dam, 1999).

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Various studies examined and quantified the density-driven circulation of saltwater using several techniques. The flow dynamics and transport of salts has been studied in the field (e.g. Kiro et al., 2008; 2012; Kohout, 1960; Michael et al., 2005) and by numerical simulations (e.g. Abarca et al., 2007; Kiro et al., 2008; Lee and Cheng, 1974; Lu et al., 2009; Lu and Luo, 2010; Oz et al., 2011; Simpson and Clement, 2004). The effect of the saltwater circulation on SGD was studied numerically by Smith (2004), who demonstrated a strong dependence of the convective circulation on the aquifer dispersivities.

Physical models in the laboratory were also used to gain information about the density-driven circulation of saltwater. These studies combined the experimental setup with numerical simulations of the same scale in order to quantify and to better understand the process. Chang and Clement (2012), Abdollahi-Nasab et al. (2010), and Kuan et al. (2012) showed the effect of changes in the boundary conditions on the saltwater circulation. Luyun et al. (2009, 2011), Lu et al. (2013) and Oz et al. (2014) examined the effects of complex hydrogeological systems on the saltwater circulation. Chang and Clement (2013) studied the dynamics of groundwater flow and transport processes occurring within a saltwater wedge. They used dye tracers injected at specific points and tracked their spatial location through time, and compared the mixing and transport processes occurring above and below the saltwater wedge.

The objective of this study is to combine laboratory experiments with numerical simulations to analyze the detailed flow patterns within the FSI, in order to understand its configuration not only by its chemical characteristics (by means of salinity) but also by its physical ones.

2. Materials and methods

2.1. Laboratory setup

The laboratory experiment was conducted in a two-dimensional rectangular flow tank made of 12-mm-thick Plexiglas, simulating a phreatic coastal aquifer (Fig. 1). The flow tank was divided into three distinct chambers: a central flow chamber, which contains the porous medium (the aquifer), and two side chambers, which maintain constant water heads and formed the boundary conditions. The left chamber represents the saltwater boundary at the seaside, and the right chamber represents the inland boundary of the regional fresh groundwater. These chambers are separated from the porous medium by a fine net in order to prevent the passage of granular material from the main chamber to the side ones. At the backside of the flow tank septum caps were placed within drilled holes in order to inject the tracers.

Three different types of water were used in the experiments: (1) colorless fresh groundwater; (2) red saltwater; and (3) green saltwater (Table 1). The last two were used as tracers and had the same exact density value (1100.1 kg m^{-3}). These were prepared prior to the experiment by dissolving NaCl in tap water, and by adding 10 g of commercial red food color (AmeriColor Ltd), or Pyranine (green color, 8-Hydroxypyrene -1,3,6- trisulfonic acid, trisodium salt; 75%) to 20 l of the solutions, forming the red tracer or the GST, respectively. The densities of the waters were measured by a digital density meter (Kyoto Electronics, DA130N) normalized to a temperature of 25 °C.

The initial conditions and the boundary conditions throughout the experiment were determined by the water levels within the side chambers. These levels were controlled by a system of elevators, pipes and pumps, as shown schematically in Fig. 1. The fresh groundwater flows into the chamber through pipe A. The fresh groundwater is pumped from the supply reservoir with a peristaltic pump (a_2) into an overflow bottle, located on an elevator, and connected to pipe A. The water level within the chamber is thus maintained. The fresh groundwater flows through the porous media and out from the saltwater chamber through Pipe B. The saltwater is pumped from the supply reservoir with a peristaltic pump (a_1), flows into the saltwater chamber from pipe C, and out into the overflow collector through pipe B. The height of this outflow (pipe B) determines the water level within the saltwater chamber, which represents the level of the open saltwater body.

Silica sand was used as a porous medium. The sand was sieved to a diameter range of 500–850 μm, and washed with distilled water to remove dust and clay minerals. The oxide coating of the quartz grains were removed by hydrochloric acid to prevent the sorption of the tracers (Magal et al., 2008). The packing of the sand was carried out under saturated conditions, with the sand being poured through the water to avoid entrapment of air bubbles. The packing procedure caused anisotropy in the porous medium as a slight horizontal stratification was formed. The value of K was calibrated to be $3 \cdot 10^{-3}$ m s^{-1} (described in Section 3.1.2). The porosity of the sand was measured directly using a volumetric method, and yielded an average value of 0.37. The longitudinal dispersivity of 0.003 m was calculated from a breakthrough curve, and the transversal dispersivity is estimated to be 0.0003 m, 10 times smaller than the longitudinal dispersivity (Johannsen et al., 2002).

Throughout the experiment, the distribution of the dye within the tank was documented using a digital camera. The documentation was done at varying time intervals, depending on the rate of changes in the location of the water types.

2.1.1. Tracer experiments

Two types of tracer experiments, a front source and a point source, were used to track the circulation flow patterns. In both, one saltwater solution was replaced by the other with a different

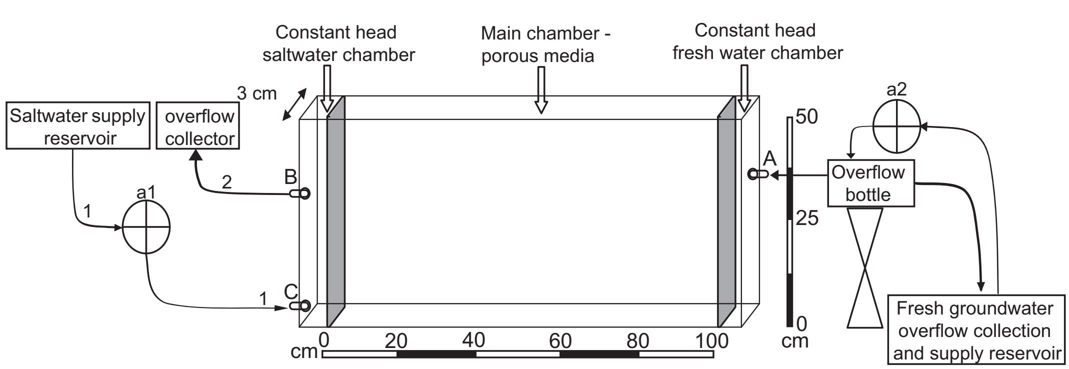

Fig. 1. A schematic diagram of the laboratory set up, including the experimental sand tank and its side chambers. The symbols a_1 and a_2 are peristaltic pumps.